GCFR

Gas Cooled Fast Reactor

FP6 Specific Targeted Research Project

GCFR STREP Final Activity Report

Contract Number: 012773 (FI60)

Thematic Priority: Innovative Concepts (NUCTECH-20043.4.1.1-2)

Period covered: 01/03/2005 to 28/2/2009
Date of preparation: April 2009

Start date of project: 01/03/05 Duration: 48 months

Project coordinator name: Richard Stainsby

Project coordinator organisation name: NNC Revision: 0, Final

Project co-funded by the European Commission within the Sixth Framework Programme (2002-2006)		
Dissemination Level		
PU	Public	PU
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the GCFR consortium (including the Commission Services)	
CO	Confidential, only for members of the GCFR consortium (including the Commission Services)	

DISTRIBUTION LIST

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FP6

CONTRACT N°: 012773 (FI60)

ISSUE CERTIFICATE

GCFR

Gas Cooled Fast Reactor
Specific Targeted Research Project

Work Package 5: Coordination

Identification N°: GCFR-EC-113 **Revision: 0**

GCFR STREP Final Activity Report

Nature: EC report
Dissemination level: PU
Issued by: NNC
Status: Final
Other Ref. Nos.:

Summary:
This is the final report of the Euratom FP6 Gas-cooled Fast Reactor project, the GCFR STREP. The GCFR STREP is a four-year project that started in March 2005 and featured ten participants, joined later by an associate member, from seven countries. The achievements of the project are summarised both in chronological order and in more detail in their grouping under work packages. This report serves as an index for all of the output from the project and places this into context within the overall research programme.

	Originator name Affiliation	WP leader name Affiliation	COORDINATOR Affiliation
April 2009			
DATE	Richard Stainsby (NNC) NNC	Richard Stainsby NNC	Richard Stainsby NNC

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1.0 Introduction

Fast Reactors (FRs) have a unique capability as sustainable energy sources both from the point of view of utilisation of natural uranium resource and minimisation of nuclear waste, as well sharing with other nuclear energy systems the benefits from avoiding production of greenhouse gases. The current interest is in exploring the particular advantages of the gas-cooled fast reactor (GCFR) primarily as an economic electricity generator, with good sustainability and safety characteristics, but also capable of minimising nuclear waste via transmutation of minor actinides. GCFR could also support hydrogen production.

There were substantial GCFR development programmes over a number of decades starting in the 1960s and performed in parallel with the development of liquid metal cooled fast reactor (LMFR). They took advantage of the large LMFR development programmes for the fast neutron core and the gas cooled thermal reactor programmes for the gas reactor technology. Many of the leading countries and organisations for nuclear power development participated in these programmes. A number of European countries were active in a coordinated programme through the European Gas Breeder Reactor Association (GBRA) for the design of a series of concepts, culminating in a concept known as GBR4, with a development programme coordinated through the NEA. General Atomics were the first to show interest in the GCFR concept in the early 1960s and produced designs for a commercial size plant and demonstration plants at the preferred 300 MW(e), and also at 750 MW(e). There was also an Existing Technology Gas Breeder Reactor (ETGBR) design which was based most closely on the UK thermal reactor, i.e. the Advanced Gas Cooled Reactor (AGR). Although the GCFR concepts were attractive they did not attract financial support for a prototype or demonstration plant as a second line of development with the sodium cooled fast reactor.

The Gas Cooled Fast Reactor was the subject of a European Commission 5th Framework study which started on 1st September 2000 and lasted two years (see http://cordis.europa.eu/fp5-euratom/src/lib_finalreports.htm). A significant part of the study reviewed the relevant gas cooled reactor experience to 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.

There has been a significant evolution in the goals affecting all nuclear systems in each of the key areas of safety, economics, proliferation resistance and sustainability. These have a particularly important impact on the fast reactors (not just gas cooled fast reactors) but the GCFR characteristics can have advantages that can be exploited in satisfying these goals. At the time of the early GCFR studies the requirements could be summarised as follows:

- High breeding gain and short doubling time required for rapid introduction of FR
- High power densities and high coolant pressures
- Commercial FR required on a very short timescale

The consequence of these requirements was as follows:

- Core technology relied on LMFR development

- Reactor used thermal reactor technology
- Development requirements were limited to the extrapolation in the parameters e.g. higher pressures, higher pumping power, and for the core the changes for the gas coolant.

The fact that the fuel and core were at an advanced stage of development for LMFR, and that there was an established technology base from the thermal reactors, was of significant benefit to the GCFR programme. This made it possible to contemplate commercialisation of the system on the very short timescale that was envisaged, and considered essential, requiring rapid expansion of nuclear power and leading to limited availability of the uranium fuel resource.

However the timescale was a constraint that limited innovation and the achievement of the full potential of GCFRs. The use of LMFR fuel and core technology limited the temperature that could be attained due to the metal clad. The sodium coolant boiling point is also a limit to the benefit that can be gained from developing a core with a higher temperature. With the timescale envisaged today, innovative solutions can be sought that take full advantage of the potential of gas-cooled systems for higher temperatures.

The advent of the US Department of Energy Generation IV initiative in 2001 (see www.gen-4.org/Technology/roadmap.htm) allowed the previous short timescales for GFR development to be relaxed, allowing time for the full potential of a gas-cooled system to be realised, such as high core outlet temperature and the improved safety margins offered by ceramic-clad fuel. As such the GCFR STREP was targeted on the development of the Generation IV GFR system as a sustainable, safe, economic and proliferation resistant high-temperature nuclear energy system.

2.0 GFR and Generation IV Goals

The GFR is one of six reactor concepts selected within the GIF, 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. Subsequently, fast spectrum versions of Molten Salt Reactor (MSR) and the Supercritical Water Reactor (SCWR) have been proposed, now giving the possibility of five of the six Gen IV systems of being fast reactors. 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. GFR acts as a bridge between the technologies of large commercial gas cooled thermal reactors (such as the UK Advanced Gas-cooled Reactors – AGRs), helium cooled high temperature reactors such as MHTGR in the short term and VHTR in the longer term, and sodium cooled fast reactors. For most of the plant, GFR requires little or no extrapolation from each of these technologies individually, the main challenges, therefore, lie in the integration of these technologies into a single reactor system and the development of new fuel forms and safety systems. These latter two areas remain the focus of much research effort and are impacted by the combination of a high operating temperature, a high power density fast neutron spectrum core and a low-density helium coolant

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 and are summarised as follows:

- Sustainability. This is the key objective for the GFR system. This means full utilisation of uranium resources and calls for the recycling of plutonium, uranium and actinides in a closed cycle.

- Non-proliferation. 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 actinide recycling results in spent fuel characteristics (isotopic composition) that are unattractive for handling.

- 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 and design for cost-effective decommissioning are also considered.

- Safety. The design objective is for no off-site 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. These are key to the system reaching its full potential and largely set the developmental timescale. The power density has a wide-ranging influence, affecting economics (simultaneously minimisation of fuel inventory, fuel cycle cost and size 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 a sodium-cooled fast reactor power density of about 400 $MWth/m^3$.

3.0 The Challenges

The unique combination of the GFR characteristics and ambitious design objectives presents three major challenges:

- The development of an innovative fuel with a high fissile atom density, able to sustain high levels of operating temperatures, fast flux, and burn-up and compatible with a close confinement strategy for the fission products
- The development of the associated fuel cycle technologies, with the aim to implement the integral recycling of actinides. While the technologies at the heart of the process (grouped extraction of actinides, co-conversion) may have a lot in common with the SFR, the head-end and back-end of the processes (access to material, dissolution, re-fabrication) remain very specific to the options taken for GFR fuel

- The design and safety development a coherent system (fuel, reactor, cycle options) with a self-generating core, a robust safety approach and an attractive level for the power density. It should be noted that the power density range envisaged for the GFR is between 50 and 100 MW/m^3; this is significantly less than earlier GCFR concepts (e.g. for GBR4 it approached 200 MW/m^3, which had the target to match LMFR breeding gain and to minimize fuel inventory). Here, we must recall that the objective is to optimize a fast spectrum system for helium cooling and with that respect the GFR power density range illustrates the optimization to be made between economics, safety and sustainability considerations.

4.0 GFR Design Options

From the start of the Generation IV programme, a number of design options are identified, which through sharing the technical work amongst the participants, will be studied and from these, the preferred concepts, and promising alternatives, will be selected. It features a high temperature (850°C) helium-cooled fast spectrum reactor with a direct-cycle helium turbine for electricity production as reference (see Figure 1 for an illustration). It is associated with a closed fuel cycle. A range of plant sizes are considered from 600 to 2400 MW(th) and the option of an indirect supercritical CO_2 cycle is included which can offer increased design margins for the core whilst still achieving high thermal efficiencies.

A key issue for the GCFR safety is the depressurisation event, which has a strong influence on the selection of the parameters. The choice of power density is the result of a compromise between considerations affecting safety, economics and the cycle. The range of interest for the GFR (50-100 MW/m^3) remains comparable to that of LWR's but is half way between the HTRs (5-10 MW/m^3) and the higher LMFRs and the old GCFRs (> 200 MW/m3). In this range, a good safety level is available and depends mainly on heat evacuation under any circumstances by the gas (forced convection by very low powered circulators, loops working in natural convection with systems keeping a minimum helium pressure in the system). Such an approach, different from the one used for HTRs as well as for old GCFRs, opens the door to high power capacities of the order of 1 GWe or greater. The refinement of the safety approach and the search for reliable and robust safety systems associated to or additional to the use of gas, is a very important part of the R&D. The objective to develop self-generating GFR cores implies low reactivity loss during the cycle, allowing control rods with low reactivity worths and hence reduced consequence of rod withdrawal faults to be achieved.

More generally, the GFR will have Defence in Depth, including natural characteristics and passive systems and a safety approach, which includes the design goal of incredibility of core melt, to be achieved by a combination of natural characteristics and engineered systems. There is a spectrum of possibilities between the role of natural characteristics and engineered systems. HTR (at least small units) can have good natural characteristics but for economic competitiveness must take benefit of this in a reduced number of safety qualified systems. Good natural characteristics are an important goal for GFR, but the balance is different.

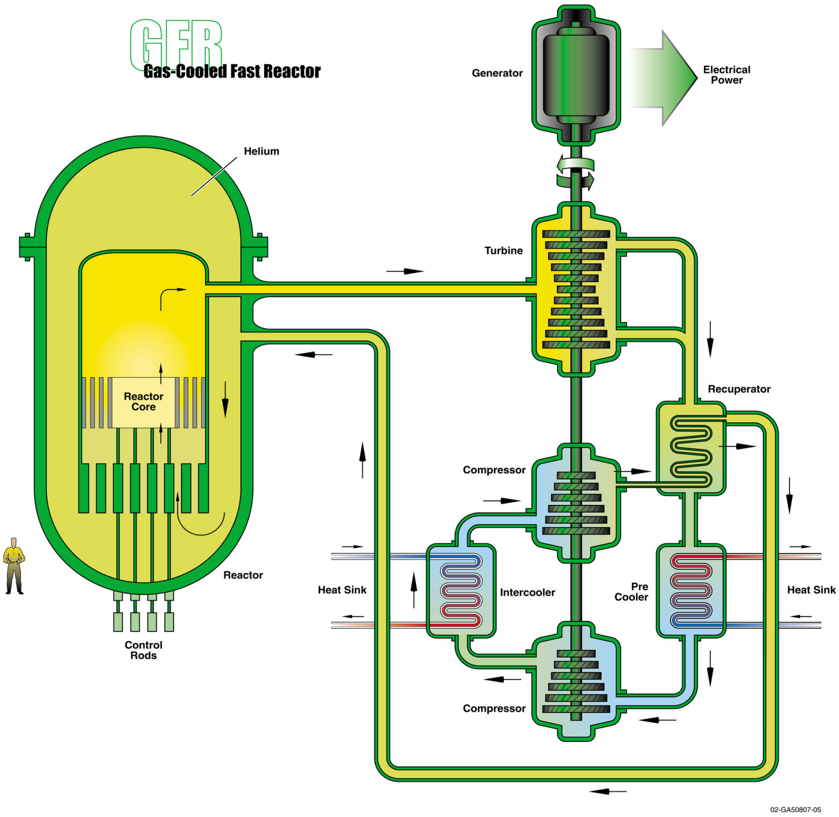

Figure 1 Gas-cooled fast reactor with a direct-cycle helium turbine for electricity production

5.0 EURATOM Contribution to the Generation IV International Forum

The decision was taken at the outset to dedicate the GCFR STREP contribution to the Generation IV International Forum R&D Plan on gas cooled fast reactors (GFR). It therefore forms, together with the JRC fuels R&D programme, the EURATOM contribution to the GFR system. It makes best use of the experience and skills of the STREP consortium members and is a coherent, self-standing contribution to key areas, including:

- GFR direct indirect cycle comparison
- Actinide transmutation
- Safety approach and harmonisation with other reactor systems
- Passivity and risk minimisation
- Safety analysis
- Code benchmarking
- Innovative fuel and fuel cycle process

The R&D programme, established under the umbrella of the Generation IV International Forum, aims at establishing the viability of the GFR by 2012, and to complete a conceptual design by 2019. Moreover, an experimental GFR of limited power (called ETDR) is foreseen in this period (2015) to qualify key GFR technologies and to help making the decision for building a prototype GFR.

The participating countries in the GFR System are France, Japan, and Switzerland together with EURATOM. The R&D Plan for the GFR System describes in detail the needs to establish the viability phase of the GFR, and the performance phase of the development plan envisioned in the Technology Roadmap for the Generation IV Nuclear Energy Systems.

The Gas-cooled Fast Reactor (GFR) is one of the six systems selected for viability assessment in the GEN IV programme. The GFR occupies a unique position as one of the four GEN IV fast neutron systems together with Sodium-cooled Fast Reactor (SFR), Lead cooled Fast Reactor (LFR) and Supercritical Water Cooled Reactor (SCWR) in its fast spectrum version, as well as one of the two Gas Cooled systems with the Very High Temperature Reactor (VHTR). Therefore the GFR combines the advantages of fast spectrum systems (long-term resource sustainability, in terms of use of uranium and waste minimization, through fuel multiple reprocessing and grouped recycling and fission of long-lived actinides) with those of the VHTR (high thermal cycle efficiency, and the possibility of hydrogen production).

The GFR system therefore offers, for fast spectrum systems, a complementary approach to liquid metal cooling:

- With the intention to fully benefit from the potential advantages offered by the helium coolant: its chemical inertness, the absence of phase change, its quasi neutron transparency which should permit attractive reactivity effects with no threshold behaviour
- By aiming to implement a refractory, robust and highly confining fuel which could offer an increased resistance to severe accident, with the attractive features of the HTR particle fuel in mind.

With the GCFR STREP, the technical work was structured into six work packages in two projects, which are directly aligned to the two established Generation IV GFR projects, “System Integration and Design and Safety” and “Fast neutron fuel, other core materials and specific fuel cycle process”. A specific work package ensures the efficient interface with other FP6 projects (including the RAPHAEL, EXTREMAT and EUROTRANS Integrated Projects), with two further work packages were dedicated to the interface with Gen IV and project co-ordination.

6.0 The GCFR STREP Consortium

The GCFR STREP consortium consisted of ten original partners from six countries. The ten original partners were joined in the last year of the project by Imperial College, London, as a self-funded associate member.

Acronym	Organisation	Country
NNC	National Nuclear Corporation Limited	UK
BNFL	British Nuclear Fuels plc (later to become Nexia Solutions Ltd)	UK
CEA	Commissariat d'Energie Atomique	France
EA	Empresarios Agrupados Internacional S.A	Spain
FANP SAS	Framatome ANP SAS (later to become AREVA NP SAS)	France
JRC	Joint Research Centre – Institute for Energy and Institute for Transuranium Elements.	EC
NRG	Nuclear Research and Consultancy Group	Netherlands
PSI	Paul Scherrer Institut	Switzerland
TUD	Delft University of Technology	Netherlands
CIRTEN-UNIPI	InterUniversities Consortium for Nuclear Technological Research - University of Pisa	Italy
Imperial	Imperial College of Science, Technology and Medicine (joined as a self-funded associate in 2008)	UK

7.0 A Chronological Review of Project Achievements

The project launch was in two steps; the first a workshop hosted and prepared by CEA at Cadarache in November 2004, which was attended by all the GCFR STREP partners. The objective for the workshop, which was an initiative taken prior to the receipt of the GCFR STREP contract, was to establish a common understanding of the status of the Generation IV GFR and ETDR projects. The second step was the kick-off meeting, which was hosted by the coordinator (NNC) at Knutsford and held on the first day of the contract, 1st March 2005, and concentrated on the project organisational arrangements, the work package scope, lead roles and clarified each partner's tasks. To give the participants in the FP6 GCFR STREP consortium a historical perspective, a summary report of the 5th Framework Programme GCFR project was made available to all participants.

The project management arrangements were also discussed at the kick-off meeting and were subsequently implemented. A project website (www.gcfr.org) was designed specifically for the GCFR STREP and this went live within the first three months of the project.

The GCFR STREP started during the exploratory phase of the Generation IV GFR programme. The work of the exploratory phase was shared between the then partners (France, Japan, Switzerland, US, UK and Euratom) and organised within the Generation IV GFR Design and Safety Project management Board (PMB). As there were many options to be evaluated during the exploratory phase, the partners agreed to share between themselves, the work on several combinations of options with the goal to try to cooperate together at the end of the exploratory phase on a first down-selection of options.

The combinations of options (seven) were defined as follows:

1. 600 MWth case : high volumetric power, challenging dispersed fuel (high ratio fuel/matrix) and high temperature direct cycle
2. 600 MWth step to case 1 : high volumetric power, challenging dispersed fuel (high ratio fuel/matrix), He at lower temperature as primary coolant and SC CO_2 as secondary coolant
3. 2400 MWth cercer case : high volumetric power, more accessible dispersed 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
   (1 to 5 with dense fuel - carbide or nitride - as actinide compound)
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)

Euratom, through the GCFR STREP took responsibility for cases 1 and 2 and the other cases 1, 3 and 7 were taken by France, Case 3 by Switzerland, Case 4 by USA , Case 5 by Japan and Case 6 by the UK.

For the Case 1 direct cycle concept, various alternatives to the main design options were considered by the GCFR STREP. These options included the configuration of the decay heat removal (DHR) system, upwards or downwards flow through the core, turbine design (vertical or horizontal), control rod drive mechanism (CRDM) position (either from above or below the reactor vessel), and fuel handling. The second case considered by the GCFR STREP, Case 2 - the indirect supercritical CO_2 cycle design option, was interesting because it offered the promise of high thermal efficiency with a lower core outlet temperature to offer improved margins for the core. The decision was taken to use a common design for the core and reactor pressure vessel for cases 1 and 2, whilst it was accepted that this reactor design was not optimised for the latter power cycle.

Tracks of work on ETDR design and safety studies and fuel development (for both GFR and ETDR) were carried out in parallel with the GFR design and safety studies. To start the ETDR studies, CEA presented the status of the ETDR at the time start of the GCFR STREP.

A suitable transient analysis benchmark problem was devised based on the ETDR design information presented by CEA. The first step in the benchmark exercise was for the participants to name the code (or codes) that they wished to use in the exercise together with their validation status. The second step was to agree an a suitable transient and the specification and the final step was to execute the benchmark exercise were published 18 months later in GCFR-DEL-021.

Plant layouts for the 600MWth direct cycle options (Case 1) were developed by AREVA. In parallel, NNC performed thermodynamic studies for the supercritical CO_2 energy conversion cycle and developed a cycle suitable for the 600MWth indirect cycle option (Case 2).

The first major Generation IV GFR milestone occurred at the end of the exploratory phase, at the end of 2005, and this was the down-selection from 7 options such that the remaining options would serve as the focus of the studies towards preliminary viability assessment due at the end of 2007. However, in the absence of signed Project Arrangements it was agreed between the Generation IV GFR partners that a workshop would be held where the results of the exploratory phase could be presented and decisions taken on the down-selection of options. This was an acceptable procedure within Generation IV as long as the decisions were unanimous so that conflicts would not arise and prevent the signing of the Project Arrangements at a later date. The workshop was held in January 2006 in Cadarache Chateau and, following an exchange between the partners, the preliminary conclusions were drawn at a Gen IV GFR Integration, Design and Safety PMB meeting on 21st January 2006.

Following the January 2006 Generation IV GFR workshop the recommendations for a selection of the options were prepared and agreed at the March 2006 PMBs and endorsed by the Gen IV GFR Steering Committee. After agreeing the options there was a preliminary agreement on the division of tasks between the Gen IV partners, including Euratom. The GCFR STREP contributed to the comparison between the direct and indirect cycle with a recommendation, which has been accepted, that both should be retained up to the preliminary viability stage at the end of 2007, although these studies would now be for the larger unit size of 2400 MWth. Therefore, one year into the project and with the encouragement of the European Commission, the direction of the work of the GCFR STREP was changed to concentrate on the larger unit size. This meant that a certain amount of the GFR design work had to be re-done which had the knock-on effect of delaying the production of designs that could form the basis of the GFR transient analysis activities.

The implications of the increase in unit size for the direct cycle design were assessed by AREVA and incorporated into a revised design specification. Similarly, the up-scaling of the plant had an effect on the design of the indirect supercritical CO_2 cycle, such that this work was revised and the specifications of the larger plant developed. Later, an optimisation and comparison of both of these cycles was carried out by EA.

An important result from the ETDR design work package was the ETDR option selection, which served as the basis for the deeper design studies on particular aspects of the system by the partners. In the area of safety the GCFR STREP has contributed to proposing a safety approach for GFR, and the report on ETDR safety options.

An important role for the fuels tasks was to review previous experience and R&D on the fuel and core materials of interest. A review was conducted of the thermophysical and thermochemical properties of unirradiated candidate fuel, cladding and fuel element materials, together with a review of relevant past irradiation programmes. Two studies were carried out to look at the feasibility of creating high temperature fuel forms. Nexia Solutions documented, the properties of silicon carbide with respect to its proposed role as a cladding material for refractory fuels, whilst JRC-ITU reviewed the fabrication techniques for oxide, nitride and carbide fuel pellets. Reprocessing options for GFR fuels were reviewed by Nexia.

The requirements were documented for the main plant components, drawing on experience gained from high temperature thermal reactor projects such as RAPHAEL and the AREVA ANTARES project. Again drawing on experience gained with HTRs, NNC catalogued the materials requirements on a component by component basis.

Detailed physics studies of the ETDR starting core were completed by CEA and reported. The results of these studies became a major reference for the subsequent ETDR transient analysis activities following completion of the benchmark. Detailed proposals for designs for the ETDR starting core fuel sub-assemblies were developed by Nexia. NNC proposed designs for the ETDR absorber rods and determined their worths. The requirements for the control and instrumentation system for ETDR was devised by NNC and refined through discussions with the project partners. A major piece of work was undertaken and completed by NRG on developing designs for the reflector and shielding systems and assessing these through the use of Monte Carlo radiation transport codes. The work of the GCFR STREP on ETDR was consolidated and incorporated in the major report produced by CEA detailing the ETDR reference option and alternatives, as a deliverable to Generation IV.

Inclusion of minor actinides in the core of GFR degrades the safety performance of the system. TUD and CIRTEN calculated the feedback coefficients of core containing minor actinides for differing actinide vectors and loading scenarios. This work showed that the core behaviour was satisfactory for practical loadings of minor actinides. This work was well advanced at the time when the decision was made to shift the emphasis of the project from the 600 MWth core to the 2400 MWth core. Hence, the actinide transmutation safety studies were completed based upon the smaller core size.

Transient analyses of both GFR and ETDR were foreseen to be major parts of the work programme for both systems. Unfortunately, the up-rating of the power output of GFR after one year into the project meant that the design was not sufficiently developed to carry out meaningful transient analysis. As a result, the emphasis was switched to allow a more complete analysis of ETDR transients to be undertaken, facilitated by the advanced state of the ETDR conceptual design. A limited amount of GFR transient analysis was carried out by PSI, however under-developed state of the GFR design prevented a more thorough analysis, but did allow resources to be reocussed on the assessment of ETDR transients. The additional effort placed on ETDR transient analysis, allowed the following classes of transient to be analysed; loss of flow, loss of coolant accident, cross-duct leakage accident, reactivity insertion, loss of heat sink, and a fuel subassembly blockage event.

Early in the programme, NRG undertook a study looking at the optimisation of the GFR design to improve passive safety. This was a detailed study, using NRG's SPECTRA code but based on an early design of the GFR system. The study concentrated on the action of injecting a heavy gas into the primary circuit following a loss of coolant event for a range of breach size and locations. The work was presented together with the work of JRC-IE on innovative passive safety features.

AREVA and EA, developed comparisons of the direct and indirect energy conversion cycle concepts. AREVA's work compares the performance and plant layouts for both cycle options, whilst EA's work concentrates on the comparative safety of the two concepts. The latter focuses on the relative performance of the shutdown, heat removal and containment systems.

The main subject of the closing months of the project were the production of deliverables for, or contribution to the deliverables of, the Conceptual Design and Safety project management board (PMB) of the Generation IV GFR system. The first of these was to provide Euratom's contribution to the ETDR mission report. The ETDR mission report provides an overview for the viability demonstration and qualifications for the key technologies of GFRs such as the fuel, fuel S/As and safety systems, and for the whole GFR System. It also reflects the flexibility that should be achieved with ETDR to meet the R&D needs, dentified in the GFR Preliminary Viability Report and the potential feedback from the design, construction and operation of ETDR to GFR. The second deliverable to Generation IV was Euratom's contribution to the GFR Preliminary Viability Report itself. This contribution took the form of the Coordinator working on a joint document with CEA and PSI, within the Gen IV GFR Conceptual Design and Safety PMB.

The final technical deliverable from the fuels work package documented the design and planning of an irradiation experiment for a specimen of GFR high temperature fuel.

In November 2008, the 3rd call for Euratom's 7th Framework Programme on Nuclear Fission and Radiological Protection was published, calling for project proposals on lead and gas cooled fast reactors. A proposal was prepared and submitted for a further GFR project, named GoFastR.

In addition to 39 contractual technical deliverables, 12 formal reports have been produced and reviewed to the same standards as the contractual deliverables, the so-called non-contractual deliverables (NCDs). One such report documented the feedback from the panel members of the Advisory Review Panel (the ARP). A whole day meeting was held at Cadarache, in the 28th month of the project, in which presentations covering the whole project were given by a selection of the GCFR STREP work package and task leaders to an invited panel of international experts. The feedback from the ARP was both favourable and insightful. Much of this ARP feedback was considered in the preparation of the FP7 GoFastR proposal.

8.0 Education and Training

The contribution of the GCFR STREP was presented to the Advisory Review Panel and claimed as a great success for Education & Training of students and post docs. With a relatively small budget, 14 students followed the course Fast Reactor Physics at TU-Delft (spring 2006) and around 17 young professionals (students/graduates) received E&T and work experience in the field of GFR technology as follows:

Organisation	Level (BSc/MSc/PhD)	Person-months	Year
TU-Delft	BSc	4	2006
TU-Delft	MSc	12	2005-2006
TU-Delft	Post-MSc	4	2006
TU-Delft	PhD	48	2003-2006
CIRTEN-UNIPI	PhD	36	2004-2006
CIRTEN-UNIPI	MSc	18	2005-2006
CIRTEN-UNIPI	MSc	18	2005-2007
EPFL/PSI	MSc	4	2005/06
EPFL/PSI	MSc	4	2006/07
EPFL/PSI	PhD	48	2004-2008
EPFL/PSI	PhD	48	2005-2008
EPFL/PSI	PhD	48	2006-2009
ISTIL/NNC	BSc	2	2007
Birmingham/NNC	MSc	3	2007
JRC-IE	Post-doc	36	2006 -2009
JRC-IE	Post-doc	12	2005-2006
Birmingham/NNC	MSc	3	2008

9.0 Use and Dissemination of Knowledge

Information generated within the project is disseminated on three levels. The first level is confidential to the members of the GCFR STREP consortium and the European Commission. The second level is information that has formally been identified as to be exchanged with the Generation IV International Forum, and the third level is information that can be published in the open literature and in conference proceedings.

As the GCFR STREP is the EURATOM contribution to the Generation IV GFR system, dissemination to the appropriate Project Management Board and Steering Committee partners is the important commitment for the project. These deliverables have been declared as part of the EURATOM contribution. Neither of the Gen IV project arrangements have yet been signed at the end of the GCFR STREP, so consequently, no formal exchange of deliverables has been made, although informal contributions to joint deliverables with other Gen IV partners have been issued (contributions to the end of exploratory phase report, and the GFR preliminary viability report are two such examples). Formal exchange of the identified deliverables will occur when the Project Arrangements come into force. In addition to the identified deliverables, the entirety of the output from the GCFR STREP will be made available to Generation IV.

Public dissemination overview table

Planned /actual Dates	Type	Venue	Type of audience	Countries addressed	Size of audience	Partner responsible /involved
May 2005	Project web-site	Internet	GCFR STREP Consortium	Consortium		Coordinator + STREP Consortium
Oct 2005	Project web-site	Internet	Public – all internet	world wide		Coordinator + STREP Consortium
14 Nov 2005	Exhibition CER-2005	Brussels, Belgium	Technical media	Mainly European	1000's	Coordinator
21 Jan 2006	Generation IV Workshop	Cadarache, France	Technical Generation IV	Generation IV (EU, CH, F, UK, US, J)	30	CEA + STREP Consortium
13 Mar 2006	FISA 2006 Conference	Luxembourg City, Luxembourg	Technical Industry management EU Political	Mainly European	300	Coordinator + WP leaders
4 Jun 2006	ICAPP06 Conference	Reno, USA	Technical Industry management	world wide	Many 100's	Coordinator + WP leaders
10-14 Sept 2006	Physor 2006 Vancouver	Vancouver, Canada	Technical Industry	world wide	100s	Consortium (TUD, PSI..)
1-4 Oct 2006	HTR2006 Conference	South Africa	Technical	world wide	100's	NRG
16 Oct 2006	Gen IV workshop	Karlsruhe	Technical Industry management EU Political	Germany + Europe	100+	JRC + Coordinator, STREP Consortium
14-19 May 2007	ICAPP07	Technical Industry management	Technical Industry management	world wide	Many 100's	Coordinator + WP leaders + most partners
9-13 Sept 2007	Global 2007	Idaho, USA	Technical Industry management	World wide	100s	CEA, TUD
5-6 Feb 2008	GEN IV	Paris	Gen IV GFR International Workshop	world wide	Many 10's	Coordinator + WP leaders + most partners
14-19 Sept. 2008	Physor 2008	Interlaken, Switzerland	Technical Industry management	world wide	400+	PSI, CEA, NRG

Planned /actual Dates	Type	Venue	Type of audience	Countries addressed	Size of audience	Partner responsible /involved
22-24 June 2009	FISA 2009 Conference	Prague, Czech Republic	Technical Industry, management, EU Political	Mainly European	450	Coordinator + WP Leaders
26 Aug – 4 Sept 2009	FJOH Summer School 2009	Karlsruhe, Germany	Students, Technical Industry	World wide	200	Coordinator

The following publications were issued throughout the project:

- "GCFR: The European Union's gas cooled fast reactor project", C Mitchell *et al.*, submitted paper no. 6311 to ICAPP06, Reno, USA, June 2006
- W.F.G. van Rooijen, J.L. Kloosterman, H. van Dam, and T.H.J.J. van der Hagen, *Design of a Spherical Fuel Element for a Gas Cooled Fast Reactor,* Proc. Third Information Exchange Meeting on Basic Studies in the Field of High Temperature Engineering, Oarai, Japan (2003).
- W.F.G. van Rooijen, J.L. Kloosterman, H. van Dam, and T.H.J.J. van der Hagen, *Fuel Design and Core Layout for a Gas Cooled Fast Reactor,* Proc. The Physics of Fuel Cycles and Advanced Nuclear Systems: Global Developments (PHYSOR 2004), Chicago, Illinois, USA (2004).
- W.F.G. van Rooijen, J.L. Kloosterman, T.H.J.J. van der Hagen, and H. van Dam, *Fuel Design and Core Layout for a Gas Cooled Fast Reactor,* Nuclear Technology, 151:221-238, 2005.
- The GCFR participated in a joint exhibition stand with RAPHAEL-HYTHEC-GCFR at the "Communicating European Research" (CER-2005) event on 14th-15th November 2005 in Brussels.
- The GCFR STREP contributed a paper and invited lecture to the FISA 2006 Conference hosted by the EC in Luxembourg, on 13th-15th March 2006. This paper was presented at the conference and is available on the GCFR website
- W.F.G. van Rooijen, J.L. Kloosterman, T.H.J.J. van der Hagen, and H. Van Dam, *Definition of breeding gain for the closed fuel cycle and application to a Gas Cooled Fast Reactor,* ANS Topical Meeting on Reactor Physics (PHYSOR 2006), Vancouver, Canada (2006).
- The GCFR STREP contributed with a paper entitled "The European Union's Gas Cooled Fast Reactor Project" to ICAPP '06 in Reno, NV, USA from 4th-8th June 2006
- *"Passive shutdown device for Gas Cooled Fast Reactor: Lithium Injection Module",* W. F. G. van Rooijen *et al.* (Technical University of Delft), submitted paper to Physor06, Vancouver, September 2006.
- *"Definition of breeding gain for the closed fuel cycle and application to a Gas Cooled Fast Reactor",* W. F. G. van Rooijen *et al.* (Technical University of Delft), submitted paper to Physor06, Vancouver, September 2006.
- *"Design optimisation for passive safety",* M. M. Stempniewicz (Nuclear Research Group), submitted paper to HTR06, Johannesburg, South Africa, October 2006.

- *"Definition of breeding gain for the closed fuel cycle and application to a Gas Cooled Fast Reactor",* W. F. G. van Rooijen *et al.* (Technical University of Delft), to be submitted to Nuclear Science and Engineering
- *"Project Presentation for GCFR STREP",* C. Mitchell and M. McDermott (NNC), GCFR-EC-101, available from www.gcfr.org
- *"Neutronic benchmark on the 2400 MW gas-cooled fasdt reactor design".* D.F. da Cruz. A.Hogenbirk, J.C. Bosq, G.Rimpault, G Prulhiere, P.Morris, S.Pelloni, Physor 2006, Vancouver, September 2006
- *"A GFR benchmark comparison of transient analysis codes based on the ETDR concept".* Bubelis E.;, Castelliti D., Coddington P., Dor I., Fouillet C., E. de Geus, Marshall T. D., W. van Rooijen, Schikorr M., Stainsby R Proceedings of the 2007 International Congress on Advances in Nuclear Power Plants - ICAPP'07, May 13-18, 2007. Nice Acropolis, France.
- *"Steady-State and Transient Neutronic and Thermal-hydraulic Analysis of ETDR using the FAST code system".* Pelloni S., Bubelis E., Coddington P. Proceedings of the 2007 International Congress on Advances in Nuclear Power Plants - ICAPP'07, May 13-18, 2007. Nice Acropolis, France.
- *Control Rod Shadowing and Anti-shadowing Effects in a Large Gas-cooled Fast Reactor.* G.Girardin, G.Rimpault, P.Coddington, RChawla paper 7329, ICAPP'07, May 13-18, 2007. Nice Acropolis, France.
- *Status of the ETDR Design* paper 7208 C.POETTE, JC.GARNIER, JC.KLEIN, F.MORIN, A.TOSELLO, I.DOR, F.BERTRAND, C.MITCHELL, D.EVERY, P.CODDINGTON, ICAPP'07 International Congress on Advances in Nuclear Power Plants - ICAPP'07, May 13-18, 2007. Nice Acropolis, France.
- W.F.G. van Rooijen, G.J. van Gendt, D.I. van der Stok and J.L. Kloosterman, *Multi-recycling Minor Actinides in a Gas-Cooled Fast Reactor,* GLOBAL 2007 - Advanced Fuel Cycles and Systems, Boise, Idaho, USA (2007).
- EUROMAT 2007, 10-13 September, Nürnberg, Germany Derek Buckthorpe paper on GFR and VHTR materials.
- W.F.G. van Rooijen, J.L. Kloosterman, T.H.J.J. van der Hagen, and H. van Dam, *Li-6 Based Passive Reactivity Control Devices for a Gas Cooled Fast Reactor,* Nuclear Technology, accepted, 2007.
- W.F.G. van Rooijen, J.L. Kloosterman, T.H.J.J. van der Hagen, and H. van Dam, *Definition of Breeding Gain for the Closed Fuel Cycle and application to a Gas Cooled Fast Reactor,* Nuclear Science and Engineering, accepted, 2007.
- W.F.G. van Rooijen and D. Lathouwers, *"Sensitivity analysis of the kinetic behaviour of a Gas Cooled Fast Reactor to variations of the delayed neutron parameters",* ANS Joint international topical meeting on Mathematics & Computing and Supercomputing in Nuclear Applications (M&C + SNA 2007)
- W.F.G. van Rooijen, D. Lathouwers, *Calculation of the sensitivity to delayed neutron parameters for fast reactors based on Generalized Pertubation Theory*. Workshop on Advanced Reactors with Innovative Fuels ARWIF-2008, Fukui, Japan, 20-22 February 2008.
- *"A 2D Transient Model for Gas-Cooled Fast Reactor Plate-Type Fuel".* P. Petkevich, K. Mikityuk, P. Coddington, R. Chawla. Proceedings of the 2007 International Congress on Advances in Nuclear Power Plants - ICAPP'07, May 13-18, 2007. Nice Acropolis, France.

- *"DESIGN OF THE CONTROL ROD SYSTEM FOR THE 2400 MWth GENERATION IV GAS-COOLED FAST REACTOR",* G. Girardin, P. Coddington, F. Morin, G. Rimpault and R. Chawla , 15th International Conference on Nuclear Engineering, Paper 10466, Nagoya, Japan, April 22-26, 2007
- *Comparative Analysis of the Reference GCFR-PROTEUS MOX Lattice with MCNP-2.5e and ERANOS 2.0 in conjunction with Modern Nuclear Data Libraries",* G. Girardin, S. Pelloni, P. Coddington and R. Chawla, PHYSOR 2006, Vancouver, Canada, September 10-14, 2006
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- *"GCFR: The European Union's Gas Cooled Fast Reactor Project".* Colin Mitchell, Christian Poette, Karen Peers, Paul Coddington, Joe Somers, George Van-Goethem. Proceedings of the 2006 International Congress on Advances in Nuclear Power Plants - ICAPP'06, Reno, NV USA, June 4-8, 2006.
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