GCFR: The European Union's Gas Cooled Fast Reactor Project

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Abstract – *In March 2005, the European Commission (EC) initiated a new 4-year Project on Gas Cooled Fast Reactors (GCFR) within its 6th Framework Programme. The EC and more than 10 participating companies, R&D organizations and universities finance the project in equal parts. The project contributes to the Generation IV ambitious goals requiring innovative solutions in terms environmental impact (robust fuel with no significant radioactive release), sustainability (core which is self sustaining and has the flexibility for waste reduction), proliferation resistant fuel cycle and economics (high coolant temperatures leading to increased thermodynamic efficiency). A matrix has been prepared for the Generation IV GFR studies to facilitate sharing the work between the members, which identifies seven combinations of design options. These option studies will lead to a pre-selection of a reference concept and alternatives and the preliminary GFR viability report.*

The GCFR project, which forms part of the EURATOM contribution to the Generation IV International Forum (GIF) has responsibility for the direct cycle and indirect cycle 600MW options. In detail, the GCFR project will examine; the GFR (600MW options) and ETDR, core and system design; GFR and ETDR safety analysis, including the analysis of selected transients; the qualification and benchmarking of the transient analysis codes through a series of benchmark exercises; and a review of candidate fuels and core materials, including their fabrication and irradiation. Education and communication to foster understanding of the growing needs for nuclear power in general and for the technology of the GCFR in particular is specific goal of the EU project.

I. INTRODUCTION

After a successful review of the existing gas fast reactor technology base in the European Commission's (EC) 5th Framework Programme, the EC initiated a new 4-year Project on Gas Cooled Fast Reactors (GCFR) within its 6th Framework Programme in March 2005. The organizations participating in the GCFR project consist of the CEA and Framatome ANP from France, NNC and BNFL from the UK, TU of Delft and NRG from the Netherlands, a consortium of universities (CIRTEN) from Italy, Empresarios Agrupados from Spain the European Commission Joint Research centres of ITU and IE, and the Paul Scherrer Institute from Switzerland. With the EC and the 11 participating companies, R&D organizations and universities financing the project in equal parts, the GCFR project focuses on some of the key technology questions and challenges, while making use of the synergy with the high temperature gas reactor projects in common areas such as the development of high temperature materials and balance of plant (direct cycle) components. One of the main objectives of the GCFR project is to contribute towards the development of the 50 MW Experimental Technology Demonstration Reactor (ETDR), which is designed to be the first gas cooled fast reactor to be constructed. The ETDR will be fuelled initially with "traditional" fast reactor MOX fuel in stainless steel cladding and will progressively test advanced GFR fuels including dense (carbide/nitride) fuels contained in a ceramic matrix.

A matrix has been prepared for the Generation IV GFR studies to facilitate sharing the work between the members, which identifies seven combinations of design options. These option studies will lead to a pre-selection of a reference concept and alternatives and the preliminary GFR viability report 2 years later. The GFR options are 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 Supercritical CO_2 (S-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

(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) case

The GCFR project forms part of the EURATOM contribution to the Generation IV International Forum (GIF) is fully integrated in the GFR collaborative programme. The GCFR project, which was launched with the benefit of earlier CEA studies takes responsibility for options 1 and 2.

It covers the following areas:

- GFR core and system design and integration of the 600 MW direct and indirect cycle concepts;
- ETDR core and system design and integration, with emphasis on the ETDR start-up core;
- GFR safety analysis, including the analysis of selected transients;
- EDTR safety analysis, leading to a preliminary safety analysis report;
- Qualification and benchmarking of the codes to be used for transient analysis through a series of benchmark exercises;
- A review of candidate fuels and core materials, including their fabrication and irradiation;
- Education and communication to foster understanding of the growing needs for nuclear power in general and for the technology of the GCFR in particular.

Finally the GCFR project takes advantage of the strong links with other EU projects including the RAPHAEL and ExtreMat projects in the areas of high temperature components, materials and waste management, as well as other EU and international fast reactor projects.

The following paper provides an early stage review of the EURATOM GCFR contribution to the Generation IV GFR project.

II. GFR DESIGN

Studies are being performed on the 600 MWth reactor with both the direct Brayton helium cycle (comparable to the GT-MHR project) and an indirect cycle using S-CO_2 as the secondary coolant. The same core is used for both studies. The fuel concept is still open due to the long term development requirements, but for the purpose of the current studies, CERCER (70/30) made of (70%) dispersed ceramic carbide fuel within (30%) ceramic SiC matrix, was considered. The characteristics of the core used in this study are given in Table I.

TABLE I

Main core characteristics

Fuel type	Plates of carbide CERCER (70/30)
Unit Power	600 MWth/275MWe
Helium pressure	70 bar
Power density	100 MW/m^3
Core outlet temperature	850 °C direct cycle; 680°C indirect cycle
Core inlet temperature	480 °C
Mass flow rate	330 kg/s; 577 kg/s indirect cycle
Fissile core volume (H, D, H/D)	6 m^3 (1.95m, 1.95m, 1)
Core pressure drop	0.52 bar direct cycle; 3 bar indirect cycle
Volumetric fraction of structure/helium/fuel	10/55/35 %
Fuel	CERCER (U, Pu)C – SiC (70/30) 16% TRU
Max fuel temperature	1125 °C
Heavy atoms mass (Pu Mass/GWe)	16 tons (9 tons/GWe)
Core management	3 X 441 EFPD
Burnup	5% FIMA
Reactivity coefficients Doppler/β/ Helium void (10^{-5})	-1145/367/309

In line with preliminary safety considerations, the proposed design includes:

- A guard containment around the primary system able to provide a backup pressure in case of a helium leak,
- A reactor building able to sustain the residual pressure after failure of both the primary containment and guard containment,
- DHR loops characterized by the following operating conditions:
  - natural convection for full pressure conditions ie ~ 7 MPa,
  - battery supplied forced convection during the first 24/48h for depressurized situations with a guard containment residual pressure, followed by natural convection (if necessary) after 24/48 h,
  - forced convection with battery supply during the first 30 minutes after the failure of both the primary containment and guard containment
- Provision for a core catcher.

Various options are currently being reviewed with regard to the turbine (i.e. horizontal or vertical), the vessel flow direction (i.e. upwards or downwards) and the location of the control rod drive mechanism (CRDM) (i.e. on top or below the core). The impact of the different options on the reactor building size has also been considered. As a result of the initial analysis, the options proposed for the first consistent design shown in figure 1 are:

- vertical turbo-machine fully integrated in the reactor building,
- An upward flow direction to ensure the rapid onset of natural circulation for decay heat removal,
- CRDM located at the top of the reactor to avoid neutron flux loading on the actuator mechanism.

The design of the guard containment, which is necessary to provide an efficient DHR system, is a compromise between an acceptable and sustainable pressure, the blower power that can be accommodated from batteries for the first 24/48 hours and the resultant core flow rate needed to limit the increase in the fuel temperature. Given that the first requirement is to satisfy the fuel temperature limit (set here at 1600°C) and an acceptable blower power of ~ 10 kW a reasonable backup pressure of 1 - 1.2 MPa is proposed. From these considerations it is possible to propose a guard containment, which could be made of reinforced concrete with a steel liner of limited thickness (< 40 mm). The reasonable backup pressure would allow some distance between the guard containment and primary system and this would ease in service inspection (ISI) and operation and maintenance (O&M).

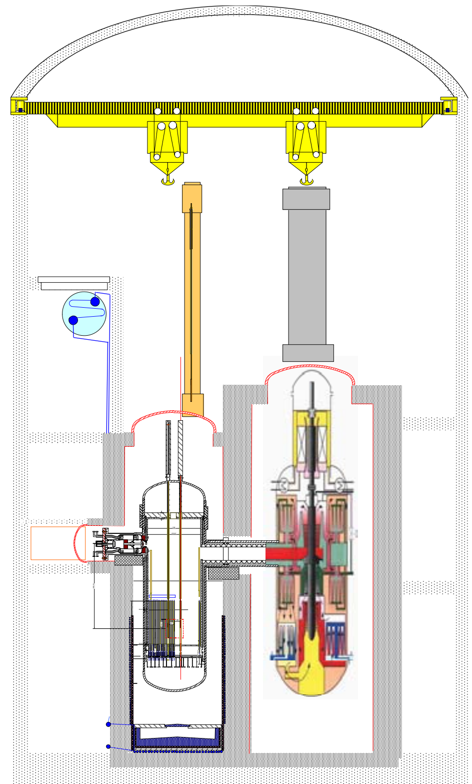

Fig. 1. GFR 600 MWth direct cycle first consistent design layout.

For the indirect cycle option, the core helium outlet temperature is reduced to 680 °C with a consequential increase in the core mass flow rate. As a result the operating pressure loss is larger than for the direct cycle case, but the same core geometry ensures the same resistance under natural circulation conditions.

The S-CO_2 cycle is a re-compression cycle featuring an auxiliary compressor and two recuperators as studied previously by MIT [1].

The main conclusions of the current analysis of the S-CO_2 indirect cycle are the following:

- An efficient S-CO_2 cycle (shown in figure 2) has been designed that complies with all of the design constraints (i.e. maximum primary gas temperature from the reactor ~ 680°C, minimum secondary-side gas temperature ~30°C, a maximum temperature for the gas returning to the reactor of 480°C),
- The reactor inlet temperature limit restricts the maximum turbine inlet temperature that can be used – not the reactor outlet temperature,
- The simplest fix is simply to use a large enough S-CO_2 mass flow rate to limit the turbine inlet temperature to be about 610°C,
- It is more efficient to control reactor inlet temperature by lowering the turbine inlet temperature than to use a de-optimised

recompression cycle, or to deliberately under-recuperate to reject more heat through the pre-cooler,

- An intermediate heat exchanger (IHX) with integrated power conversion unit (PCU) has been designed that fits within the direct cycle PCU envelope (see figure 3)

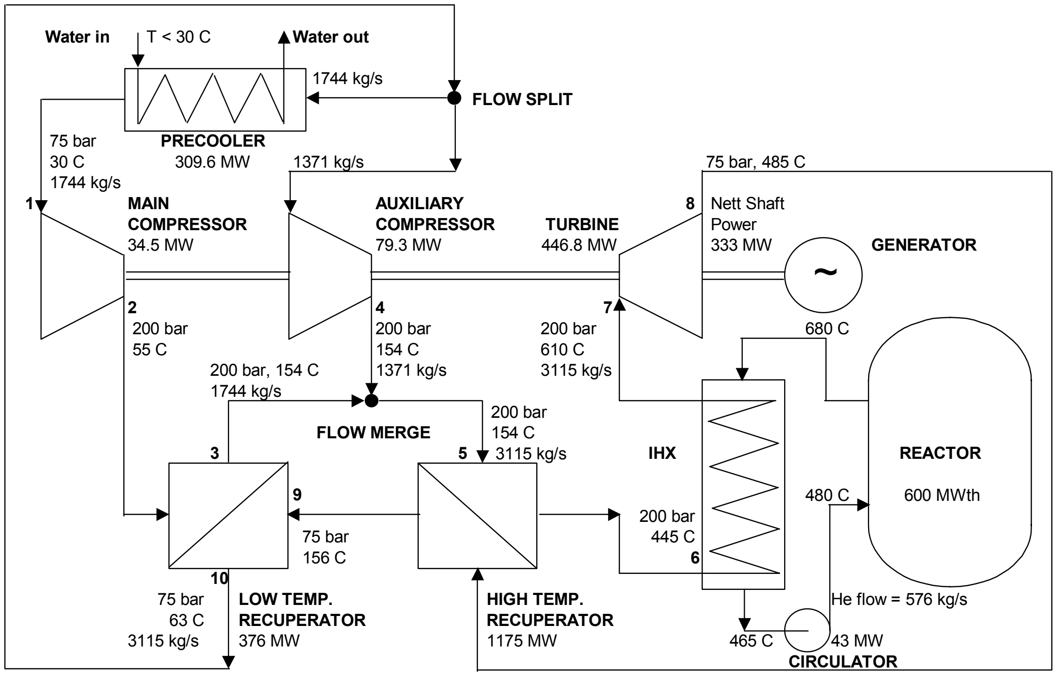

Fig. 2. 600 MWth indirect S-CO_2 cycle characteristics.

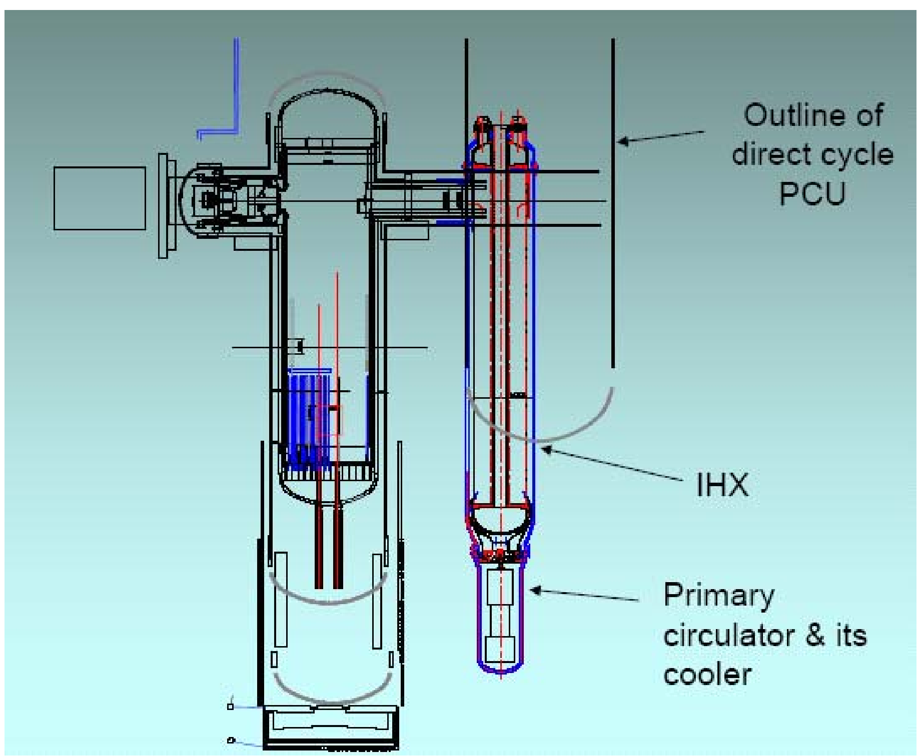

Fig. 3. Arrangement of the indirect cycle PCU.

The IHX would be made of straight Inconel 625 tubes with the tubes arranged to minimize the primary sides pressure losses.

The primary gas circulator would be a single stage centrifugal type with a motor power of 44 MW.

III. ETDR DESIGN

The ETDR is fully integrated into the gas fast reactor development plan. The ETDR will be the first GFR ever built. It is a small power experimental reactor (~50 MWth). Its objective is to demonstrate the viability of the specific technologies of GFRs (fuel, fuel sub-assemblies, safety systems, etc.) and to provide an element of demonstration for the whole of the Gas Cooled Reactor technological range [2], [3] and [4].

For the core design, the general approach includes:

- a start-up core using existing or close to existing technology (MOX pin type S/A with metallic cladding). This will be used for the irradiation of a small number of experimental sub-assemblies to qualify the complete sub-assembly concept,
- a second core or "demonstration core" using GFR reference technology for the qualification of sub-assembly performance (temperature, burn-up).

Table II gives the main characteristics of the ETDR start-up and demonstration cores together with those of the targeted commercial GFR (2400 MWth). It can be seen that ETDR gives acceptable irradiation performances (about – 30 % for the fast neutron flux and for the dose/burnup parameter) when compared to the target design.

Within the GCFR project, the work, which is shared between the partners is concentrated on the design of the start-up core and includes the following; core physics, S/A design, absorber design- control & instrumentation and reflector & shielding design. For the start-up core, the design makes use of previous Sodium Fast Reactor technology (PFR, EFR) with necessary adaptations to gas cooling.

TABLE II

Comparison of GFR and ETDR core characteristics

	GFR 2400 MWth	ETDR demonstration core	ETDR start-up core
Power (MW)	2400	50	50
Vol. Power (MW/m^3)	100	100	100
Operating Helium pressure (MPa)	7	7	7
THe inlet / outlet (°C)	480 / 850		260 / 560
Fuel form	CERCER honeycomb (U,Pu)C + (SiC+plays)		(U,Pu)O_2 pellet
Fuel S/A	Plates within Hex tube SiCf/SiC structures		Pins within Hex tube metallic structures
Fissile, coolant fraction (vol.% of core)	22.4/40	23.5/31	36.2/42
Gap+ matrix, structure (vol.%)	17.6/20	18.5/27	3.1/18.7
Plate thickness/pin dia. (mm)	7	6.27	6.55
Max. wall/fuel T (°C)	1075/1210	1045 / 1140	615 / 1045
Core pressure drop (bar)	0.6	0.58	0.62
Pu/U+Pu (%)	15.2	34.9	27.3
BUmean / max (at%)	10.1/15.7	5.4 / 8.6	5.2 / 8.8
Fast fluxmax E > 0.1 Mev (n.cm^{-2}.s^{-1})	1.4×10^{15}	0.94×10^{15}	1.1×10^{15}
Fluencemax E > 0.1 Mev (n.m^{-2})	3×10^{27}	1.1×10^{27}	1.6×10^{27}
Dosemax (dpa SiC)	163	61	85
Dosemax/BUmax ratio (dpa SiC/at%)	10.3	7.1	9.7
Doppler EOL (10^{-5})	-1175	- 523	- 360
He depressurization EOL (10^{-5})	+253	- 18	+ 63
Delayed neutron fraction (10^{-5})	344	339	353

The reactor system consists of a helium primary circuit, a secondary water circuit, with the final heat sink being the atmosphere. The DHR strategy, like that for GFR, will rely on a guard containment for depressurization accidents. The DHR loops will also be characterized by a set of operating conditions, which look a priori very similar to GFR for pressurized situations. Nevertheless, for depressurized situations, the low helium inventory and the large guard containment will result in a lower backup pressure (~ 2 bar). As a consequence, the DHR in this case will rely only on forced circulation. More generally, this DHR strategy, as well as other Safety Options, will be confirmed after transient analyses and sensitivity studies. Due to the large number of situations to be analysed, the calculations will be distributed between the GCFR project partners. This work will follow the benchmark study, which will provide a reference point for the different analyses performed by the different project partners using different code systems.

To date the reactor design has progressed with two main objectives:

- to produce a conceptual reactor picture to feed the detailed design and safety studies, and to identify difficulties and propose possible solutions,
- to provide coherent data allowing the description and modelling of the reactor for the safety studies.

The general approach includes:

- no energy conversion (simplification)
- study of the different functional sub-systems (main vessel, main cooling system, DHR, fuel handling),
- integration of the different functions in a consistent design.

The corresponding work is illustrated by figure 4 (showing a possible arrangement of the primary system where hot and cold legs are separated) and figure 5 showing the arrangement inside the reactor building of the primary system, the guard containment and the polar crane dedicated to heavy components handling.

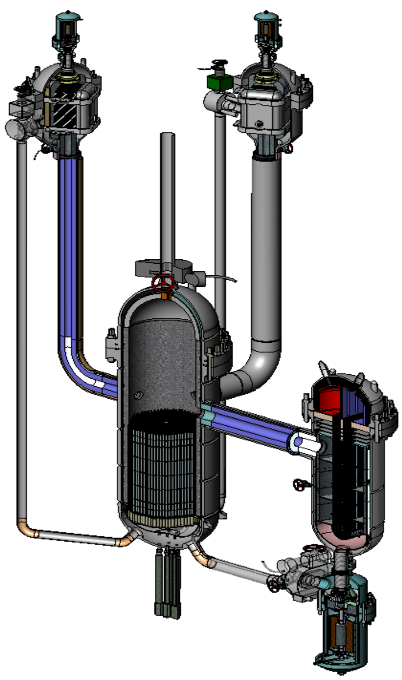

Figure 4: ETDR primary system

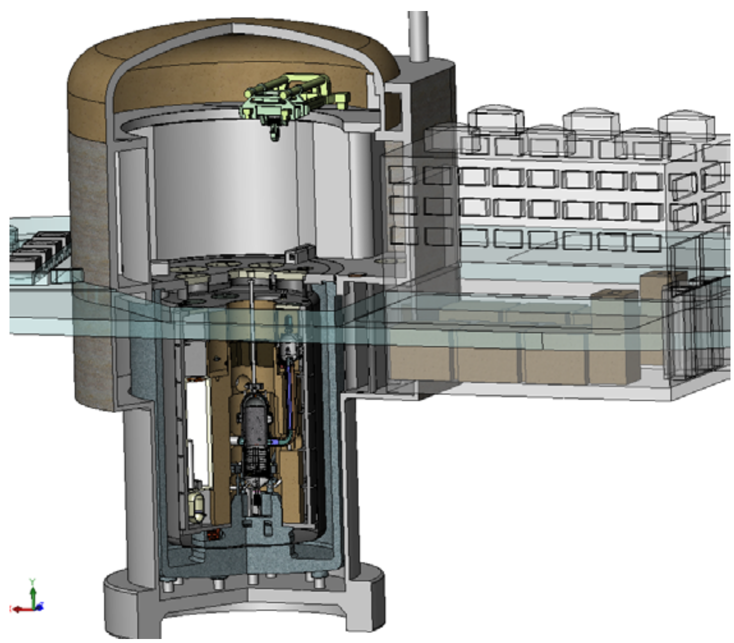

Figure 5: ETDR Reactor building arrangement

IV. SAFETY

IV.A. Overview

The project will build on the preliminary safety approach and analysis performed in the 5th Framework GCFR Concept Review Studies, to provide a significant contribution for both the GFR and ETDR safety system designs.

The safety approaches will be in accordance with requirements for future nuclear systems, aiming at core melt exclusion and taking account of the ambitious targets defined for the GFR safety, fuel integrity and direct cycle. Therefore, a number of safety approaches for future reactors in Europe have been considered, each with basic principles consistent with the IAEA recommendations, including:

- European Fast Reactor (EFR) - this safety approach was the basis of the recommendations from the FP5 study,
- European Utilities Requirements (EUR),
- Modular High Temperature Gas Reactor (MHTGR).

It is important that any safety approach is relevant and adaptable for the different stages of GCFR development, from the pre-conceptual design phase and design validation phase through to potential licensing and construction.

The ETDR studies will generally concentrate on ETDR-specific issues, but will also give consideration to the scale effect and relevance to GFR as far as possible. It is intended that the ETDR safety options will provide essential information and feedback for the GFR concept, although not all will necessarily be relevant for GFR. Therefore is it essential that the safety approaches for ETDR and GFR are compatible and as consistent as possible.

IV.B. Objectives

A fundamental set of safety objectives for all nuclear plants has been defined by the IAEA [5], which must be ensured by fulfilling the Fundamental Safety Functions (FSFs). In addition, a set of specific objectives for future reactors has been proposed with the aim of increasing public confidence in their safety, which include:

- Minimisation of toxic, radioactive waste production and release from normal and incidental operation (ALARA principle) and following abnormal occurrences.
- Need for minimal emergency protection action of the population around the site; and the elimination of any technical justification for offsite emergency response.
- An enhanced resistance to proliferation risks.

Specific safety goals have also been established for the GFR, as part of the Generation IV R&D program [6] - *"The design goal of no off-site radioactivity release requires the efficiency, simplicity, robustness, reliability and economics of all systems and physical barriers. At core level, the use of refractory fuels with a very high capacity to confine fission products at high temperature (1600°C or above) and robust structural materials will be sought."*

With this in mind, consideration will be given throughout the design process to inherently excluding the possibility of core melt. Nevertheless, the safety approach for GFR must also consider the provision of measures to control and mitigate the consequences of core damage events. Similarly, whilst the design goal of no off-site radioactivity release is a sound design target, it is not practical to use a zero-release as an absolute safety limit. Realistic quantitative release and design criteria will be established that can be used in the safety assessment process.

It is also an aim of the project to enhance the inherent safety characteristics of the design and incorporate passive safety systems wherever possible

IV.C. Methodology

The safety objectives for GFR will be achieved through the application of the Defence-in-Depth (DiD) principle. The adequacy of the DiD is established by the number of barriers and the number and quality of systems in each level of defence. The concept of DiD can be applied to safety-related activities and measures, including design, organisational and behavioural factors.

The suggested strategy for implementation of DiD for MHTGR [7] is deemed appropriate to adopt for GFRs, particularly given the similar aims for inherent safety characteristics and passive systems. The strategy gives priority to the higher levels of defence, particularly the prevention of accidents and the management of abnormal conditions by:

- robust plant design which minimises the number of failures with potential safety significance,
- implementation of the Lines of Defence (LOD) methodology.

The aim would be minimal reliance on off-site measures to mitigate severe accident consequences due to the effectiveness of the previous levels of defence. The DiD strategy uses as a starting point the method of objective-provision trees (OPTs), which provides a logical framework for assessing the implementation of DiD for the design.

Although some progress has been made in the use of probabilistic methods, the majority of current nuclear plants use deterministic considerations as the basis of the application of DiD. Generally, the plant is deterministically designed against an identified list of normal operating and accident conditions using well-established design criteria to ensure that radiological targets are met. Probabilistic safety assessment, can then verify that there are no vulnerable areas in the design with the potential for high-risk sequences and identify any requirements for additional preventative or mitigating design features.

However, the use of probabilistic safety assessments to verify the reliability and adequacy of protective measures for the reactor can be difficult in the early stages of an innovative reactor design where there are large uncertainties in the reliability data and little or no operating feedback. It is for this reason that the Lines of

Defence (LOD) method was established. Within DiD, combinations of one or more provisions (LOD) must be provided to deal with challenges to each of the levels of defence.

In the LOD methodology, the aim is to show that sufficient lines of defence against loss of a safety function have been provided and are likely to be available following an initiating event. It is important that the LOD method is applied early in the design phase to highlight any areas with insufficient provision of LOD, so that these safety concerns can be addressed.

Application of LOD methodology has already been incorporated into the EFR and Experimental Accelerator Driven System (XADS) safety approaches and includes much of the DiD analysis methods/principles for the initial levels of DiD. However, the consideration of the mitigation measures required in the final levels of DiD are outside the scope of LOD. It is suggested that the development and integration of PSA alongside the deterministic safety analysis into the safety assessment should begin in the conceptual phase, once the basic design is defined.

IV.D. Other safety issues

The safety work in the project will include the assessment of numerous specific safety features of the design, in addition to the performance of transient analysis to assess the overall behaviour of the GFR and ETDR concepts.

A design optimisation study to enhance passive or inherent safety characteristics will be performed for the GFR concept, and will also consider sizing effects including the ETDR core. This will include the analysis of unprotected accidents with the aim of achieving benign behaviour following accident initiation, including the study of the potential for increasing thermal inertia without introducing moderator material in the core.

A comparative safety study of the GFR direct and indirect cycle concepts will be performed, covering the safety systems required to fulfil each of the FSFs.

A specific study is being performed for ETDR devoted to the assessment of innovative concepts for self-actuating, passive devices to minimise risk, covering:

- Reactivity control systems,
- Decay heat removal systems,
- Lithium injection and expansion modules (LIMs and LEMs).

Following completion of the benchmark exercise, transient analysis will be performed for both GFR and ETDR with the aim of demonstrating core melt exclusion. Therefore the emphasis for the analysis will be on design basis and design extension conditions, rather than severe accidents.

IV.E. Gas Cooled Fast Reactor Transient benchmark and safety studies

As a precursor to a detailed deterministic transient analysis of the GFR and ETDR options being studied within the EU GCFR project a GFR transient benchmark study has been initiated. The goal of the study is to "benchmark" the transient analysis codes being used by the GFR partners, which include; RELAP5, TRAC/AAA, CATHARE, MANTA and SPECTRA. The benchmark study is being co-ordinated by the EU GCFR project but is open to all Generation IV partners. As a starting point the benchmark will be based on a main blower failure event in ETDR with reactor scram and will investigate the ability of the different code systems to calculated the transition from forced to natural circulation cooling using the plant decay heat removal system. Following the completion of the benchmark a systematic analysis of a wide range of transients will be performed first for ETDR and then for the two GFR designs. The transients to be analysed will include:

With and without reactor scram -
Loss of forced circulation
Loss of coolant (depressurisation), large, medium and small break
Loss of final heat sink
Transient overpower including -
control rod withdrawal,
core overcooling, due to cold gas injection,
depressurisation of the secondary system.

For the analyses without reactor scram the core kinetic parameters and reactivity coefficients will be provided as part of the core design.

The outcome of the analyses will be to determine the maximum and time at maximum, in the cladding and fuel temperatures. The impact of these values on the integrity of the fuel ie release of fission products, the ability to maintain core coolability and margin to fuel melt will need to be determined for each fuel type. For the start-up core of ETDR there is considerable experience from existing sodium cooled fast reactors and operating gas cooled reactors, while for the new fuels only design goals can be specified.

IV.F. Fuel Studies

EURATOM makes a contribution to the GFR Fuel Projects through Work Package 2 of the GCFR project and also through the complementary direct actions of the JRC, and in particular the JRC-ITU. Within the EURATOM GCFR project, the partners (JRC-ITU, CEA, NEXIA Solutions and NRG) have the task to collect a wide range of information that will assist in the selection of the fuels.

Perhaps of all the Generation IV reactor systems, the GFR places the most daunting requirements on the fuel and its encapsulation. The most important design specifications to be met are gas outlet temperatures of 850°C (with the direct cycle power conversion option) and a relatively high actinide volume fraction in the core. Moreover the local structure temperatures will be significantly higher. This immediately eliminates metallic structures as core materials, and places new and challenging demands on the materials required for the fuel encapsulation. (An indirect cycle option operating at lower temperatures would ease the demands on materials but would still present a challenge for metallic structures.)

The main candidate concepts are:

1. Coated particle fuels (but with a different design to those in HTR fuel, i.e. larger kernels and thinner coating layers, as the large volume fraction of carbon is not commensurate with a fast spectrum core)
2. Dispersion fuels in which small particles of the fuel are dispersed in a ceramic matrix, which when sealed forms the first containment.
3. Conventional pellet-cladding configurations, which would then require a ceramic cladding such as SiC, and the means to join and seal the materials.

Concerning the fuel composition, the high density and high thermal conductivity of nitride and carbide fuels could provide potential advantages compared to the oxide. Nevertheless, the choice is far from obvious. Nitride fuels should be enriched in N^{15} to improve the neutron economy and limit C^{14} containing waste. Carbide fuels are pyrophoric requiring special precautions during manufacture and reprocessing. The fuels should also be capable of recycling the minor actinides it produces (few %) consistent with Gen IV proliferation resistance, resource usage and waste minimisation. Although some experience exits with oxide fuels, this is largely an unknown area for carbides and nitrides, and the MA vaporisation in such fuels need verification.

Within GCFR, WP2 is aligned to the GFR Fuel and Materials R&D plan. For encapsulation materials a review of SiC as a confinement material against fission products will be made. The fuel deliverables touch on essentially all aspects of the fuel cycle and reviews will be made on the properties of the unirradiated materials, the irradiation behaviour of nitride and carbide fuels, past experience on the fabrication of the fuels and finally their reprocessing. In recognition of the importance of testing the irradiation performance of fuels NRG is also involved in a study to prepare an irradiation experiment, which will be made hopefully in FP7.

V. CONCLUSION

As the GCFR project approaches the end of the first year of the 4-year project good progress has been made on the EURATOM contribution towards the first stage Generation IV milestones. The EURATOM contribution to GFR is for the 600MW concepts (direct and indirect cycle) where a first reference design has been prepared for the direct cycle. This will serve as the basis for investigating some alternative design features including the safety system, design options and eventually the transient analysis, which will provide feedback to a progressive refinement of the design. A design concept has also been proposed for the indirect S-CO_2 as an alternative to the reference direct cycle. The indirect S-CO_2 cycle can achieve high cycle efficiency at a lower core outlet temperature and is the subject of on-going optimisation. Progress has been made with the overall safety approach and methodologies, whilst the emphasis for the ETDR has been on the start-up core (MOX with Stainless steel clad) and the definition of the transient code benchmark, which will use as a reference the ETDR with the start-up core.

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