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Core neutronics characterization of the GFR2400 Gas Cooled Fast Reactor

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A B S T R A C T

The Generation IV initiative was launched with the goal of developing nuclear reactors which surpass current designs in safety, sustainability, economics and non-proliferation. From the six most promising concepts the Gas Cooled Fast Reactor (GFR) represents a challenging and innovative idea that is prominent in the sustainability aspect with the ability to have a closed fuel cycle and the potential to burn minor actinides (MAs). The European FP7 GoFastR project was one of the latest steps in the development and further optimization of GFRs.

This paper presents a comprehensive overview of the neutronic performance of GFR2400 which was considered as a conceptual design for a large scale GFR within the collaboration. This reactor is the newest on the evolutionary path of fully ceramic GFRs featuring ceramic fuel and structural materials allowing high temperatures and efficiency using helium coolant. An important innovation of the current design is the application of refractory metallic liners to enhance the fission product retention of the cladding, resulting in a significant neutronic penalty during normal operation, at the same time being advantageous under transient conditions involving spectrum softening.

Using the ERANOS and SCALE code systems several parameters were determined for beginning of life (BOL) conditions, including excess reactivity, various reactivity effects such as depressurization, Doppler or thermal expansion effects, as well as kinetic parameters. An extensive sensitivity and uncertainty analysis of these parameters was also done with the 15 group BOLNA and 44 group SCALE covariance libraries. Open and closed fuel cycle operations were investigated and the transmutational capabilities were studied with the GFR connected to traditional light water reactors in a symbiotic system.

The presented analysis shows that the GFR2400 design is a major improvement compared to previous concepts. All preliminary constraints are respected resulting in a manageable initial Pu inventory of 10 t/GWel at 45% plant efficiency, a low MA mass fraction of 1% by self-recycling and a near zero breeding gain without the use of fertile blankets. At the same time the reactor has acceptable safety features precluding super-prompt-criticality in depressurized conditions at BOL and in open cycle equilibrium. Either of the two planned control devices is sufficient to shut down the reactor independently of the other and the

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refractory liners introduce significant negative reactivity in case of water ingress. However the occurrence of hot spots when all control rods are inserted needs further analysis.

The design also shows promising closed fuel cycle and transmutational performance. However – as is the case in other fast reactors – the fuel cycle closure causes safety related parameters to degrade, most importantly the depressurization reactivity effect to exceed the effective delayed neutron fraction in the current design. To assess the acceptability of this deterioration further analysis is needed.

Finally, it can be concluded that current commercial codes are satisfactory for such analysis; however there is a need for better covariance data. Several parameters exceed their target uncertainty value, most notably the *k*-effective by a factor of 6, the main source of the uncertainty being the inelastic scattering of ^{238}U.

1. Introduction

The Gas Cooled Fast Reactor (GFR) is one of six advanced reactor concepts selected by the Generation-IV International Forum (US DOE, 2002) – a cooperative international endeavor organized to carry out the needed research and development (R&D) for the assessment of the feasibility and performance capabilities of the next generation of nuclear energy systems.

The majority of the selected concepts are fast neutron spectrum reactors, including gas, sodium and lead cooled systems, as well as the non-moderated version of the molten salt reactor. They were chosen due to their potential of recycling all actinides and closing the fuel cycle. This would allow fast reactors to substantially improve fuel utilization particularly by making it possible to feed the reactors in equilibrium with only natural or depleted uranium. Furthermore the quantity, the radiotoxicity and the decay heat of radioactive waste could be reduced by only having to dispose of fission products and reprocessing losses in an ideal case.

The specific merits of modern GFR designs compared to other fast reactor systems originate from the use of helium as the primary coolant. Since it introduces practically no moderation the GFR's neutron spectrum is one of the hardest among fast reactors, making it ideal for recycling all actinides, including minor actinides (MAs). Helium is inert and transparent, eliminating most problems related to coolant interaction with structural materials and making online visual inspection of the core possible. Due to its low density and neutronic transparency the void reactivity effect is low, which is obviously advantageous for reactor safety. Last but not least, the core outlet temperature is not limited by the coolant characteristics, making it attractive for potential hydrogen production and other process heat applications.

The GFR fuel and core concept has been developed during the last decade within the framework of successive European projects (Stainsby et al., 2011). This evolution included designs of coated particle fuel with or without a binding matrix, silicon carbide blocks with dispersed microparticle fuel inside, the idea of silicon carbide plates with fuel pellets arranged in honeycomb structure, finally arriving to the current design of a hexagonal lattice of cylindrical fuel rods consisting of a column of fuel pellets inside the composite silicon carbide cladding (van Rooijen et al., 2005; Bosq et al., 2006; da Cruz et al., 2006; Chauvin et al., 2007; Dumaz et al., 2007; Perkó et al., 2012; Zabiego et al., 2013).

This paper summarizes the main results of the neutronic studies performed in the framework of the European FP7 GoFastR project (Stainsby et al., 2011) for the GFR2400 design, a large scale helium cooled fast spectrum reactor with 2400 MWth thermal power. The most essential parameters characterizing the core were determined both for beginning of life conditions as well as during burnup, accompanied by their respective uncertainties originated from deficiencies in the current knowledge of nuclear data and the fuel manufacturing process. Several safety related quantities have been evaluated and the transmutational capabilities of the design have been assessed.

Following the description of the core in Section 2 the computational tools used for our analysis are introduced in Section 3. The most important neutronic parameters for the start-up core – including excess reactivity, power distribution, as well as kinetic parameters – are presented in Section 4 with various reactivity effects being detailed in Section 5. Finally, Section 6 outlines the results of fuel cycle and transmutational studies, whereas in Section 7 the main conclusions of the presented work are drawn.

By reporting the current status of the neutronic studies for the GFR core in Europe this paper can be especially useful for follow-up R&D studies related to neutronics and safety analysis of Gas Cooled Fast Reactors.

2. The European 2400 MW Gas Cooled Fast Reactor design

The starting point of a new core design in the GoFastR project was the plate-type concept featuring carbide fuel with silicon carbide fiber reinforced silicon carbide (SiCf/SiC) cladding that was studied in the preceding GCFR FP6 STREP project (European Commission, 2006, page 210–225). The goal was to achieve a more realistic and feasible, fully ceramic model which would satisfy all the ambitious GFR requirements. An original optimization study carried out at CEA resulted in such a design, which was called the GFR2400 "academic core" (or shortly GFR2400) and was considered as a reference concept for a commercial size Gas Cooled Fast Reactor (Richard et al., 2010). The remainder of this section is devoted to a detailed description of this reactor focusing on the active core, for more information the reader is referred to the companion paper by Stainsby et al. (2014).

2.1. General design description

The most important parameters of GFR2400 are summarized in Table 1. The reactor is a large scale Gas Cooled Fast Reactor with 2400 MWth thermal power and uses helium coolant at a high

Table 1
Basic design parameters of GFR2400. The concept features a large scale He cooled GFR with ceramic fuel and cladding.

Parameter	Value	Parameter	Value
Thermal power [MW]	2400	Primary coolant	He
Primary pressure [MPa]	7	Pressure drop in core [MPa]	0.143
Mass flow rate [kg/s]	1213	Bypass flow rate [kg/s]	60
Core inlet temp. [°C]	400	Core outlet temp.[a] [°C]	780
Secondary coolant	20%He, 80% N_2	Secondary pressure [MPa]	6.5
IHX inlet temp. [°C]	346	IHX outlet temp. [°C]	750

[a] After mixing with bypass flow.