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A STUDY ON PLATE-TYPE FUEL IN A GENERATION-IV GFR

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ABSTRACT

A plate-type fuel cell of a gas-cooled fast reactor (GFR) configuration based on ALLEGRO project was evaluated in terms of k_{eff}. The project is a leading helium-cooled GFR demonstrator and the goal was to assess its viability as such a prospect. A geometry design has been studied for a standard GFR MOX fuel using the SCALE6.0 code system. The parameter evaluated was the effective neutron multiplication factor. The results showed that despite having achieved too high criticality values, this design is very promising. The analysis of the data obtained will give preliminary information to further study the feasibility of this methodology in GFR systems.

1. INTRODUCTION

The global objectives in development of nuclear power technology decided at the Information Conference HTR2006 set the directives for research on Generation IV nuclear reactors (GEN IV), intended to be safer, more versatile and sustainable in terms of economics, environment and non-proliferation [1]. Six design baselines were chosen and adopted by the Generation IV International Forum, namely three thermal reactors - the Very-High Temperature Reactor (VHTR), Molten-Salt Reactor (MSR) and Supercritical Water-cooled Reactor (SCWR) - and three fast reactors: the Gas-cooled Fast Reactor (GFR), Sodium-cooled Fast Reactor (SFR) and Lead-cooled Fast Reactor (LFR) [2]. Amongst those designs, the GFR presents a great potential in relation to what is to be expected from the GEN IV, even though all of them are still in R&D phase. The earliest perspectives expect to start commissioning in 2030, but that will most likely happen only after 2040. One such initiative is the ALLEGRO project, developed by the V4G4 Center of Excellence European consortium, which aims to build a small, modular type demonstrator GFR, using helium as a coolant and ceramic fuel. It was considered as reference for the studies performed in this paper [3].

2. STATE OF THE ART

The development of the earliest stages of ALLEGRO development dates back to 2007, with the European Union Framework Programme 6 and 7 (FP6 & FP7) STREP, GoFastR and ADRIANA projects. Its precedent conceptual design, called GFR2400, focused on achieving a feasible fully ceramic model, important for keeping the high temperatures needed for GFR operation whilst maintaining structural integrity. It introduced refractory plate-type fuel sub-assemblies concept, using silicon carbide fiber reinforced silicon carbide (SiCf/SiC) cladding and uranium plutonium carbide (UPuC) fuel, which were maintained and further enhanced throughout the development of the project and still feature in ALLEGRO design [4]. It is important for GFR purposes that core elements have a very high heat resistance due to its high operation temperature. Therefore, those ceramic composites were chosen to ensure their feasibility, following the criteria that they should maintain fission products integrity up to 1600°C and preserve their geometry up to 2000ºC [1].

However, GFR2400 and ALLEGRO have very different purposes, and therefore very different characteristics. The GFR2400 project was only a conceptual design produced to test and justify the viability of those reactors, so it is large in size and power wield, generating 2400 MWh. ALLEGRO, however, is an experimental reactor, intended to be a prototype developed in long term to demonstrate helium-cooled GFRs actually working. Therefore, it does not aim to produce electrical energy, as would be the case with industrial-grade reactors [5].

In recent stages, a (SiCf/SiC) honeycomb binding matrix is used for containing cylindrical fuel pellets, sandwiched between two plates of the same composite silicon carbide that act as cladding, as shown below on Fig. 1. Such enclosed plates are stacked and attached into a larger hexagonal prism structure, which is divided in three sections for plate fitting. Those sturdy sub-assemblies, illustrated on Fig. 2, ensure that the core remains stable and mechanically inert, while avoiding fission products scattering and maintaining the necessary parameters for heat and gas flow [1].

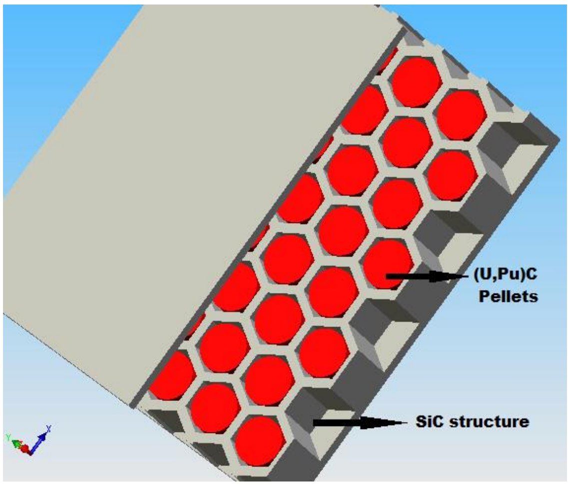

Fig. 1. Ceramic fuel plate

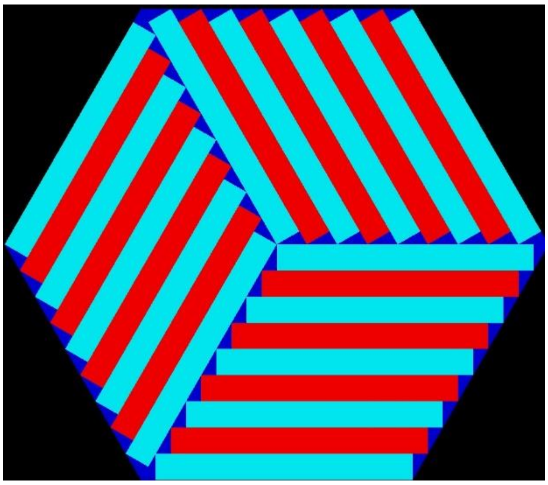

Fig. 2. Diagram of plate disposition in hexagonal sub-assembly

Helium is used as the primary coolant for those reactors, being efficient for this purpose for numerous factors. For instance, it operates well on high temperatures, has a low value of the void coefficient and is non-corrosive, transparent and chemically inert, thus making it easier to inspect and repair the reactor. On the other hand, to be used as a coolant helium needs to operate under high pressure (at least 7 MPa) and does not provide good heat transfer in natural convection conditions. To work that around, the whole reactor vessel operates pressurized, and nitrogen is injected into it to guarantee the necessary cooling conditions [6].

Besides, the GFR technology offers some more advantages. Its fuel cycle is a closed one, it is possible to use depleted fuel or natural uranium on its composition and it also has the potential to transmute by enhancing fission on the minor actinides (MAs), reducing waste radioactivity. Furthermore, the large quantity of decay heat that would be dispersed is fit for industrial applications, such as producing hydrogen gas.

3. METHODOLOGY

A helium-cooled GFR core similar to ALLEGRO's was modelled and simulated for the neutronic assessment carried out using SCALE 6.0 nuclear simulation code package [7]. As the proposed model does not aim to progress to a reactor prototype, ALLEGRO's reduced size was not considered. Nevertheless, the most important parameters were collected in the related bibliography, revised and complemented. The selected values are in Tab. 1 and Tab. 2. The parameters proposed in [8, 9] were used as base values and refined through testing, as well as the geometry scheme used for Monte Carlo simulations in [10]. The fuel composition used is the same as that described in [4] for neutronics characterization of a GFR reactor, which uses natural uranium mixed with plutonium that comes from a twice-recycled mixed oxide (MOX) fuel, in form of a ceramic fuel. Its porosity is 20% and this value is already included in the presented densities.

Tab. 1. Basic core parameters of the proposed GFR

Characteristic	Value
Primary coolant	He
Operating coolant pressure (MPa)	7
Fissile core coolant fraction (%)	22.7
Fuel type and geometry	(U, Pu)C pellets attached to SiC plates
Pu/U+Pu (%)	29.5
Cladding and reflector materials	SiCf/SiC and ZrC
Fuel S/A	Plates arranged in hexagonal SiC structure
Number of plates per S/A	27
Total plate length (cm)	112.7358
Total plate height (cm)	248.6
Total plate thickness (cm)	11.4861
Hexagonal lattice apothem (cm)	6.85
Hexagonal lattice thickness (cm)	0.85
Cladding thickness (cm)	1

Tab. 2. Fuel characteristics

Pu isotopic composition [m/m]%		U isotopic composition [m/m]%	
Pu-238	2.7	U-235	0.72
Pu-239	56.0		
Pu-240	25.9	U-238	99.28
Pu-241	7.4		
Pu-242	7.3	-	-
PuC molar mass [g/mol]	251.6771	UC molas mass [g/mol]	250.0399
PuC density [g/cm³]	10.88	UC density [g/cm³]	10.904

Using those values, three kinds of analysis were conducted for the GFR: the simulation of one single fuel plate, the simulation of 9 parallel-bundled plates (which represents one third of a sub-assembly) and that of the complete hexagonal sub-assembly. The main objective was to evaluate the criticality on the models built, through the KENO-VI code in SCALE 6.0, as to determine their viability.

Furthermore, two cases were tested for each element simulated: one with the detailed geometry aforementioned, and one with homogenized elements, in which the volume of all materials was kept, but the fuel geometry was set to a homogeneous slab surrounded by the coolant and cladding. That was done to compare tests conducted with that homogenization to the regular ones and determine the computational cost-worth of both cases. Overall, six different cases were tested and compared.

The models run are hereby illustrated: the models of the heterogeneous and homogeneous plates are shown in Fig. 3 and Fig. 4, respectively. Fig. 5 depicts one-third of a sub-assembly and Fig. 6, the whole sub-assembly. The alteration for homogenization needs to be done only on the plate, so the cross-section view of both cases for the fuel assembly would be the same. The color scheme used on these images represents the fuel in red, cladding in light blue and coolant in dark blue.

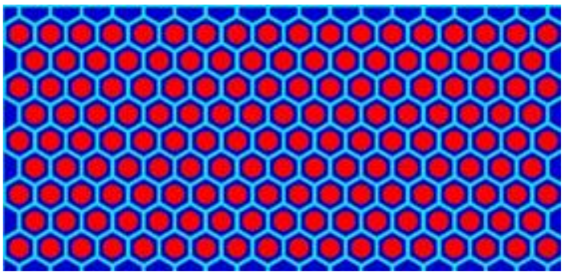

Fig. 3. Fuel plate cross-section, image generated by SCALE 6.0

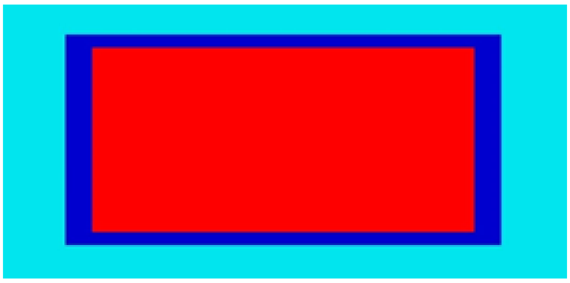

Fig. 4. Homogeneous fuel plate cross-section, image generated by SCALE 6.0

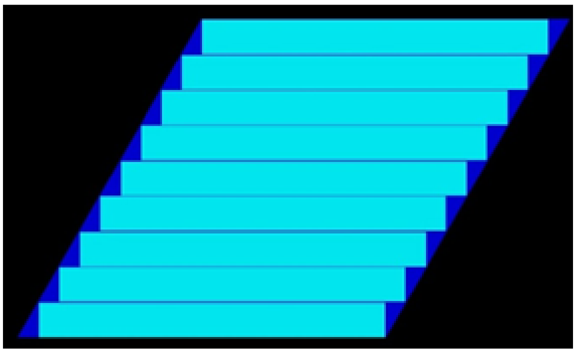

Fig. 5. Sub-assembly piece cross-section, image generated by SCALE 6.0

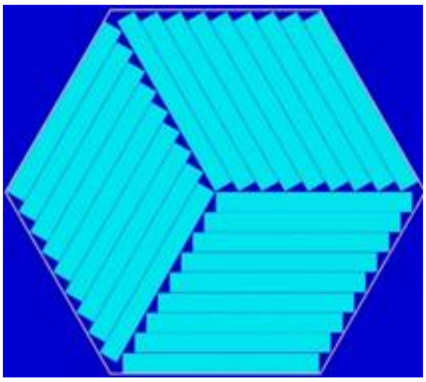

Fig. 6. Sub-assembly cross-section, image generated by SCALE 6.0

3. RESULTS

The criticality analysis of the proposed GFR achieved the following results, presented on Tab. 3.

Tab. 3. Simulation outputs

Simulated element	k_∞ value	Running time (min)
Ceramic fuel plate	1.4612 (± 0.0004)	10.188
Homogenized ceramic fuel plate	1.6096 (± 0.0005)	10.4965
Sub-assembly piece ($\frac{1}{3}$ SA)	1.4514 (± 0.0004)	12.30867
Homogenized sub-assembly piece ($\frac{1}{3}$ SA)	1.5872 (± 0.0004)	12.64
Sub-assembly	1.4599 (± 0.0004)	11.30167
Homogenized sub assembly	1.5706 (± 0.0004)	11.98467

The very high values found for k_∞ indicate that the fuel/coolant ratio used, which was amidst those regularly found for traditional GFR models, might have been larger than necessary [11]. This suggests that less fissile fuel is needed to maintain the criticality of the ALLEGRO core in comparison with a traditional GFR. Meanwhile, the criticality was higher on the homogenized elements and no significant improvement on the CPU processing time was noticed. This leads to believe that this homogenization introduces more reactivity, without improving the model and can be cast aside in future calculations.

However, despite not representing an actually viable reactor core because of the uncontrolled criticality, the proposed and simulated model has the potential to be enhanced and finely adjusted. Having successfully replicated ALLEGRO’s design for a GFR and yielded reasonable results, it might be considered successful for the purposes of a preliminary analysis.

4. CONCLUSION

The neutronic analysis conducted shows optimistic preliminary results. Despite not having achieved realistic values for the criticality parameter evaluated, it shows that the implementation of the ceramic fuel used on this reactor is viable. Nevertheless, the geometry of the model used needs to be enhanced and in order to gather more information regarding the reactor’s behavior, further neutronic analysis has to be done.

Future steps on this research would be to optimize the fuel/coolant ratio in terms of a reasonable criticality, and then carry on more tests using several different types of fuel for comparison, calculating neutron flux in the core and the reactivity coefficient. Finally, after the model is sufficiently advanced, burn-up tests will be conducted to evaluate this reactor’s operation. Furthermore, other variables, such as the influence of helium flow on the critically, are also to be considered.

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