OPTIMISATION OF THE CO_2 COOLED FAST REACTOR FOR PLUTONIUM AND MINOR ACTINIDE MANAGEMENT

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ABSTRACT

The concept of the gas-cooled fast reactor has been around since the 1960's but has recently enjoyed renewed interest owing to its flexibility for plutonium and minor actinide management and its favourable safety characteristics compared to liquid-metal cooled fast reactors. In this context, NNC and BNFL have investigated gas-cooled fast reactor systems based around existing technology but conforming to present day fast reactor objectives. This paper describes the neutronic and thermal hydraulic optimisation of one such system. The pressure vessel and primary circuit are based on AGR technology whilst the core is based on EFR. This design has good safety characteristics and thermal hydraulics and requires little extrapolation beyond existing technology. The core can easily be configured for plutonium burning or breeding, making it a flexible tool for plutonium management. Homogeneous or heterogeneous consumption of minor actinides should also be possible with little effect on core performance.

1. Introduction

The concept of the gas-cooled fast reactor (GCFR) has been around since the 1960's but has recently enjoyed renewed interest owing to its flexibility for plutonium and minor actinide management and its favourable safety characteristics compared to liquid-metal cooled fast reactors (LMFRs). GCFRs have a number of advantages over liquid metal cooled concepts. There are obvious safety, economic and technical advantages of using a relatively benign, readily available and optically transparent, gaseous coolant which is compatible with both air and water, compared to sodium which reacts vigorously with water and requires specialist handling and disposal. The significantly smaller coolant void reactivity effect in gas-cooled cores offers an additional safety advantage, as does the absence of a phase change. These features also allow the potential for loading greater quantities of minor actinide isotopes, which leads to unacceptably large positive coolant void effects in sodium-cooled cores.

These advantages, coupled with the extensive UK experience gained in the successful design and operation of the CO_2-cooled Advanced Gas Reactors (AGRs), has led to the investigation of CO_2-cooled fast reactor concepts based on AGR technology but incorporating core design parameters derived from the European Fast Reactor (EFR). Core concepts considered include a conventional plutonium burning design, a plutonium breeding design and a dedicated minor actinide burning design, fuelled almost entirely by minor actinides. These studies have considered core design, core performance, safety parameters and preliminary transient studies and have confirmed the significant flexibility of gas-cooled fast reactors.

The plutonium burning design has recently been studied in more detail. The initial core design was based extensively on EFR but with some modifications to try to account for the poorer cooling performance of gas compared to liquid sodium. This design was later modified to improve the plutonium burning capability. The thermal hydraulic performance of this core has now been assessed, resulting in further modifications to the core design to achieve satisfactory cooling of the fuel pins. This gradual process of optimisation and refinement has resulted in a core that involves little extrapolation beyond present-day technology and one which has good safety characteristics, adequate thermal-hydraulic performance and a high plutonium burning rate. The evolution of this design and a summary of its main characteristics and performance are described below.

2. Initial studies

In the 1970s and 1980s a gas-cooled fast breeder reactor concept, ETGBR [1], based on the then contemporary technology was investigated in some detail, combining the experience of the early AGR and LMFR technologies. NNC reviewed and updated the ETGBR concept [2],[3] resulting in a 3600 MW(th) core based on more recent AGRs along with the EFR core and sub-assembly (S/A) technology. This design concept was based on the Heysham 2 / Torness AGR, which utilises a single-cavity pre-stressed concrete pressure vessel to house the core structure, steam generators and gas circulators.

In 1997, a plutonium burner core design based on the updated ETGBR plant concept was studied. A fuel pin and S/A concept was established and an assessment of performance and enrichment levels for a core capable of achieving a 20% h.a. peak fuel burn-up was carried out. The main core parameters are shown in Table 1. The pins were conventional fast reactor pins fuelled with MOX and clad in the high burn-up, high damage dose cladding material PE16, developed in the UK. For this initial core, it was found that significantly greater plutonium enrichment was required in the outer core than in the inner core. A further, more detailed analysis was therefore carried out with the aim of improving this ratio, to enhance the plutonium burning capability.

Parameter	Value
Reactor thermal output	3600 MW
Nominal electrical output	1400 MW
CO_2 gas pressure	42 bar
Active core height	1500 mm
Number of fuelled S/As	550
No. S/As inner/outer	334/216
Wrapper inside A/F	~167 mm

Parameter	Value
No. fissile pins per SA	169
Pin diameter	8.2 mm
P/D	1.55
Pu enrichment inner/outer	19.8/31.3 %
Cycle length	334 efpd
Number of cycles	5
Peak pin burn-up	20 % h.a

Table 1 Main core design parameters for the initial Pu burning GCFR core.

3. Neutronic optimisation

To improve plutonium burning rates, dilution was incorporated into the inner enrichment zone whilst retaining as conventional a core as possible. Dilution in the form of diluent S/As was adopted so that the same fuelled S/A design could be used in both the inner and outer cores. The diluent S/As are similar to the fuel S/As but with solid steel pins in the active region, instead of fuel. The number and arrangement of diluent S/As was optimised to achieve as flat a radial power-shape as possible with an enrichment ratio as close as possible to unity. To compensate for the loss of fuelled S/As from the inner core, additional S/As were added to the outside of the core and, to further improve the enrichment ratio, the radius of the inner enrichment zone was reduced.

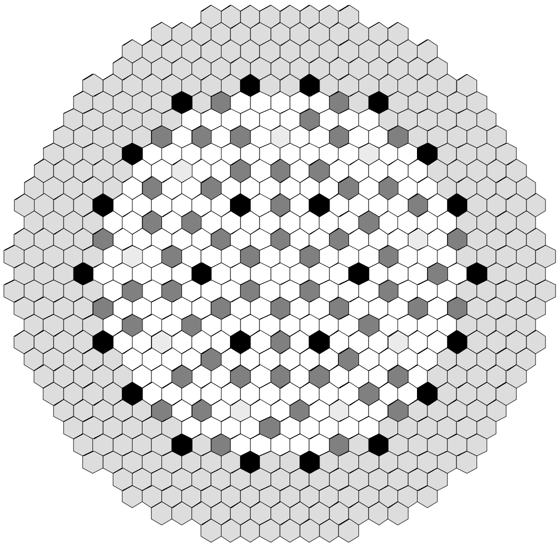

Figure 1 GCPu00 core layout.

It was found that with steel diluents alone, it was not possible to achieve exactly equal enrichments with an acceptable power shape — even with almost all the available positions for diluents occupied, the dilution effect was not sufficient. A compromise was reached for which the enrichment ratio was 0.9 (inner/outer). This required the inclusion of 60 diluent S/As and a net increase in the total number of fuelled S/As to 580. The layout of the optimised core, designated GCPu00, is shown in Figure 1.

A 120° core sector model that explicitly represents batch refuelling was used to assess the core physics performance. Diffusion theory calculations were carried out in 33 neutron energy groups using the European fast reactor code scheme, ERANOS, along with the ERALIB1 cross-section libraries (which are based on Jef2.2). An iterative optimisation procedure was carried out with the aim of achieving a 20% peak burn-up at end-of-life. The main core parameters and results from this study are summarised in Table 2. The reactor power and S/A design are unchanged from those of Table 1.

Parameter	Value
Number of fuelled S/As	580
No. S/As (inner/outer)	238/342
Cycle length	338 efpd
Number of cycles	6
Pu enrichment inner/outer	24.9/27.6%
Clean core Pu inventory	13.2 te
Peak pin burn-up	18.3 % h.a

Parameter	Value
Peak clad damage	167 dpa
Coolant void reactivity	341 pcm
Doppler constant	– 598 pcm
Prompt neutron lifetime	7.5×10^{-7} s
Total β-effective	337 pcm
Reactivity loss over cycle	2911 pcm
Pu/MA burning (kg/TWhe)	31.8 / – 4.8

Table 2 Main core parameters and results for GCPu00 core.

4. Thermal hydraulic optimisation

Up to this point, the thermal hydraulics of the GCPu00 core had not been studied in detail. The design had been extrapolated from that of the early work done in the late 1970's, for which detailed thermal hydraulics calculations had been performed. NNC has therefore developed a model for studying the thermal hydraulics of conventional GCFRs and, using this model, it was found that there was considerable scope for optimising the GCPu00 core design. The parameters and constraints assumed in the thermal hydraulics study are shown in Table 3.

Parameter	Value
Mean core pressure	42 bar
Core pressure drop	3 bar
Peak systematic clad temperature	634 °C
Hot spot allowance	96 °C
Core inlet temperature	252 °C
Core outlet temperature	525°C

Table 3 Thermal hydraulic constraints

In addition to the constraints in Table 3, it was also assumed that the fuel pins were deliberately roughened with transverse ribs (as in an AGR) to improve the heat transfer coefficient and that the S/As were divided into twenty flow groups with fixed gags. The mean core pressure of 42 bar was chosen to be consistent with AGR experience, and the core pressure drop of 3 bar was based on the capability of AGR circulators. The peak clad temperature of 730°C (at the hot spot) includes an allowance of 30°C because the high coolant pressure delays the onset of tensile strain in the PE16 clad. This clad temperature limit is intended to limit the total thermal creep strain at end of life.

In order to satisfy the above constraints it was found necessary to reduce the mean linear rating of the fuel pins by increasing both the number of pins and their active length. This resulted in a rather high plutonium inventory so the constraints were revised and the core design re-optimised. The revised constraints are shown in Table 4.

Parameter	**Value**
Mean core pressure	60 bar
Core pressure drop	3 bar
Peak systematic clad temperature	680 °C
Hot spot allowance	80 °C
Core inlet temperature	300 °C
Core outlet temperature	525°C

Table 4 Revised thermal hydraulic constraints

The mean core pressure has been increased to 60 bar, which is still within the capability of an AGR-like pre-stressed concrete pressure vessel. The peak clad temperature at the hot spot has been increased to 760°C. This requires justification because the properties of PE16 are not well known above 730°C. Moreover, the coolant pressure provides a compressive stress on the pins, whereas the available data on PE16 pins is based on the effects of tensile stress. This is one area where further development work is required. The core inlet temperature has also been increased because this was found to be beneficial for the thermal hydraulics.

Parameter	**Value**
Active core height	2000 mm
Wrapper inside A/F	~177 mm
Pin diameter	8.0 mm
P/D	1.69

Table 5 Optimised design parameters

The modified design parameters after the re-optimisation are given in Table 5. The core layout was unchanged from the GCPu00 design, as was the number of pins per S/A. However, the pin diameter was reduced to 8.0 mm and the pin pitch to diameter ratio was increased to 1.69, requiring a small increase in the S/A width. The mean linear rating of the core was reduced by increasing the active length to 2 m. This new design, designated GCPu01, has been optimised neutronically in a similar manner to the GCPu00 core. The results of this optimisation are shown in Table 6.

Parameter	**Value**
Cycle length	428 efpd
Number of cycles	6
Pu enrichment inner/outer	23.8/26.3%
Clean core Pu inventory	16.7 te
Peak pin burn-up	20.0 % h.a
Peak clad damage	175 dpa

Parameter	**Value**
Coolant void reactivity	763 pcm
Doppler constant	– 620 pcm
Prompt neutron lifetime	8.7×10^{-7} s
Total β-effective	333 pcm
Reactivity loss over cycle	3074 pcm
Pu/MA burning (kg/TWhe)	31.8/ – 5.3

Table 6 Neutronics performance of the GCPu01 core

It can be seen that the performance of the thermal hydraulically optimised core is very similar to that of the GCPu00 core that preceded it. The reduction in the mean linear rating has resulted in a somewhat larger plutonium inventory, which in turn has resulted in a somewhat longer cycle length. The coolant void reactivity (all coolant removed from the core) is significantly higher due to the increased gas pressure and core height, but is still much lower than that of an LMFR. The Doppler constant, kinetics parameters and reactivity loss over cycle are all quite similar to those of GCPu00 and the plutonium consumption rate is unchanged. An analysis of the thermal hydraulics of this core has been performed using the detailed power density information from the neutronics model. The core pressure drop was found to be 3.0 bar and the mean core outlet temperature was found to be 527°C. Detailed transient analysis remains to be performed for this core but preliminary studies on the GCPu00 core indicated a satisfactory performance with no apparent characteristics that would preclude further study.

5. Breeding option

An initial study of a plutonium-breeding version of the GCPu01 core has also been performed. The 60 diluent S/As were replaced by fuel and two rows of radial breeder and 60 cm of axial breeder (35 cm lower, 25 cm upper) were added. The total plutonium production rate was 3.4 kg/TWhe (breeding gain 0.08). This design is not fully optimised however as the mean linear rating is lower than necessary for the thermal hydraulics so there is scope to reduce the number of S/As or the height of the fuel column. Furthermore, the breeding gain could be increased by reducing the width of the outer core and by enlarging the breeder regions. Alternatively, the breeding gain could be reduced to zero by reducing the size of the breeder regions. This flexibility makes the GCFR a useful tool for plutonium management.

6. Minor actinide management

Previous studies have shown that a considerable advantage of GCFRs over LMFRs is that significant quantities of minor actinides can be included in the core inventory without seriously degrading the safety parameters of the core. Indeed, an initial design study of a GCFR fuelled almost entirely by minor actinides has been reported [4]. It is therefore anticipated that the inclusion of minor-actinide fuelled target S/A's within or around the GCPu01 core is eminently feasible from the core physics point of view. A study of moderated minor actinide targets in the GCPu00 core has been reported [5] in which it was shown that it is possible to achieve a net consumption of minor actinides with a relatively small quantity of minor actinides in the targets. Homogeneous recycling is also a possibility.

7. Summary and conclusions

A design for a gas-cooled fast reactor that is both neutronically and thermal hydraulically optimised has been presented. The process by which the core design has evolved from early studies to the present design has been described. It has been shown that the GCPu01 core design has good safety characteristics and thermal hydraulics and can easily be configured for plutonium burning or breeding, making it a flexible tool for plutonium management. Homogeneous or heterogeneous consumption of minor actinides should also be possible with little effect on core performance.

8. Acknowledgements

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