A HELIUM COOLED PARTICLE FUEL REACTOR FOR FUEL SUSTAINABILITY

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Abstract

Sustainability is a key goal for future reactor systems. This calls for a self generating core with a breeding gain close to zero. The concept of the gas cooled fast reactor has recently seen renewed interest owing to its flexibility for plutonium and minor actinide management. However, the use of steel clad pin fuel imposes an onerous constraint on the maximum allowed clad temperature, resulting in a plutonium inventory which is too high to be considered practical. This paper describes studies that have been undertaken to establish a helium cooled fast reactor core design with a plutonium inventory reduced to a more practical level. The fuel consists of fuel particles, mixed with a matrix material, that are packed inside a pin, block, or plate type geometry. The use of ceramic fuel materials allows for a significant increase in the peak clad/matrix temperature and higher linear ratings, thus allowing a reduction in the fuel content, and hence the plutonium inventory within the core.

* This work has been sponsored by BNFL

Introduction

A new generation of reactor designs is being developed that are intended to meet the requirements of the 21st century. Sustainability is a key goal for these systems. This calls for a self generating core with a breeding gain close to zero, and the integral recycling of the plutonium and minor actinides within the spent fuel. Given available plutonium stocks it is foreseen that the initial plutonium inventory within future reactor cores should be comparatively small, preferably less than 20 tonnes.

The concept of the gas cooled fast reactor has recently seen renewed interest owing to its flexibility for plutonium and minor actinide management and some of its favourable safety characteristics compared to liquid metal cooled fast reactors. These advantages, combined with the extensive UK experience gained in the successful design and operation of the carbon dioxide cooled Advanced Gas Reactors, has led to several recent studies of carbon dioxide cooled fast reactor concepts [1,2]. While these studies have shown the feasibility and potential of using carbon dioxide cooled fast reactors for the effective management of plutonium and minor actinides, the use of a steel clad pin fuel imposes an onerous constraint on the maximum allowed clad temperature, resulting in a plutonium inventory which is too high to be considered practical.

This paper describes studies that have been undertaken to establish a gas cooled fast reactor core design with a plutonium inventory reduced to a more practical level. Two modifications have been made to the carbon dioxide cooled core concept : the replacement of the steel fuel cladding with a ceramic material and the use of a helium coolant in place of carbon dioxide. The fuel consists of fuel particles, mixed with a matrix material, that are packed inside a pin, block or plate type geometry. The use of ceramic fuel materials allows for a significant increase in the peak clad/matrix temperature and higher linear ratings, thus allowing a reduction in the fuel content, and hence the plutonium inventory within the core. The core is cooled by helium to take advantage of the efficiency gains originating from operating at higher temperatures.

Within this work a thermal hydraulic study has been undertaken to produce a design capable of meeting the higher peak linear rating and clad/matrix temperature limits with a reduced plutonium inventory. The neutronic performance of this core design has then been assessed. The neutronics design and performance studies presented have been performed using the ERANOS code and data system developed as part of the European collaboration on fast reactors. The nuclear data used for all calculations originates from the French ERALIB1 adjusted nuclear data library. These studies have been sponsored by BNFL.

Core Concept

The helium cooled core design considered in this study is rated at 2400 MW(th) with a net thermal efficiency of 40.5% and a load factor of 80%. The general core design parameters have been defined from the results of a thermal hydraulic sensitivity study. Reference values, based on experience of the AVR and THTR-300 high temperature reactors in Germany, and the design of the Eskom PBMR reactor currently under development in South Africa, have been assumed for the helium coolant pressure, 60 bar, and the core inlet and outlet temperatures, 530 °C and 900 °C respectively. It has also been assumed that there is an upper limit on the coolant pressure drop of 3 bar.

The use of ceramic materials, rather than steel clad, permits a significant increase in the peak clad/matrix temperature, allowing higher volumetric ratings and a reduction in the plutonium inventory. A significant amount of research, including the irradiation of experimental pins, was undertaken into the possible use of ceramic cladding for a Mark III carbon dioxide cooled thermal reactor, considered as a possible replacement for the Advanced Gas Cooled Reactors [3]. The experimental results indicated that temperatures up to 1200 °C and volumetric ratings up to 200 MW/m^3 are achievable. A peak clad/matrix temperature of 1000 °C, and a peak volumetric rating of 180 MW/m^3, have been conservatively adopted for the purposes of the current study.

The core uses a mixed oxide fuel. The isotopic fuel vector is derived from a fuel cycle scenario with a mixed park of Pressurised Water Reactors (PWRs), European Fast Reactors without blankets (EFRs) and helium cooled particle fuelled reactors. The EFRs are fuelled with a mixture of the plutonium coming from their own spent fuel and the plutonium arising from the spent PWR fuel. The PWR fuel is assumed to be once through as no MOX recycling in the PWRs has been included.

The fuel is in the form of coated particles mixed with a silicon carbide matrix material. The fuel particle consists of a fuel kernel surrounded with coatings of, respectively, porous carbon to provide a buffer against fuel swelling, dense pyrocarbon to provide physical strength, silicon carbide to retain gaseous and volatile fission products, and an outer dense pyrocarbon layer. A fuel kernel diameter of 0.85 mm, and a particle packing density of 60 volume %, close to the maximum achievable values, have been assumed to maximise the fuel density. This results in a fuel density within the matrix of 1.8 g/cm^3 and a volume fraction of the actinide compound, within the matrix, of 15%. The low fuel content is a result of the nature of the particulate fuel, the thickness of the coating materials, and the achievable packing fraction of the particles. Details of the fuel particle specification are given in the following table.

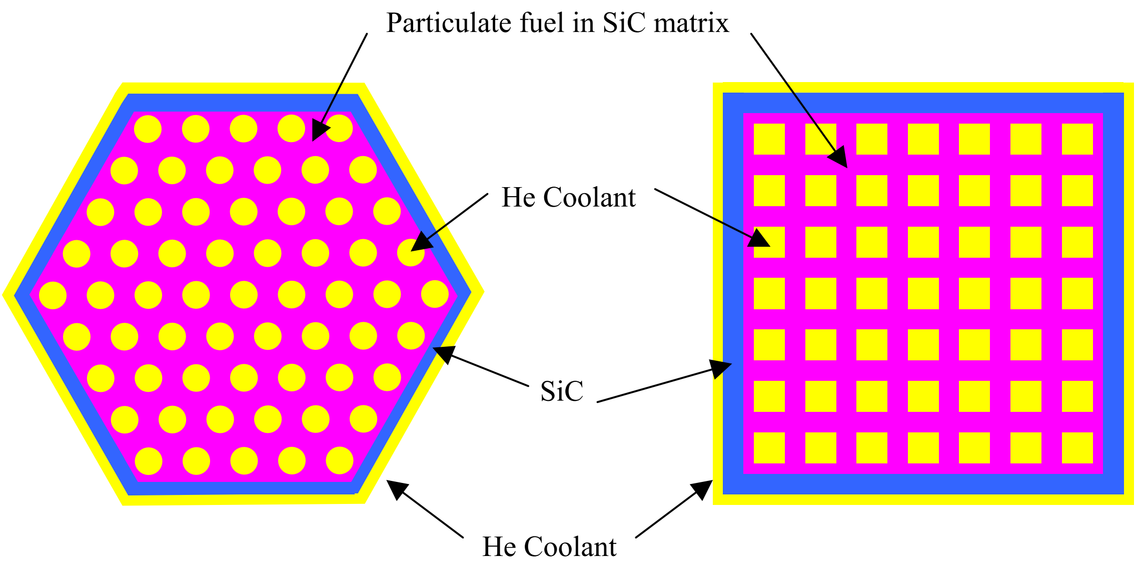
Parameter	Units	Value
Fuel Density	g/cm^3	11.46
Fuel Kernel Radius	cm	0.0425
Outer Fuel Particle Radius	cm	0.0635
Particle Coatings	-	C / C / SiC / C
Coating Density	g/cm^3	1.05 / 1.90 / 3.18 / 1.90
Coating Thickness	cm	0.0095 / 0.0040 / 0.0035 / 0.0040
Coating Outer Radius	cm	0.0520 / 0.0560 / 0.0595 / 0.0635

Three different geometrical arrangements for the fuel particles and matrix material have been considered:

- a more conventional pin concept in which the fuel pins, contained within an hexagonal wrapper, are formed by vibro-packing the fuel particles, mixed with the matrix material, into a hollow silicon carbide cladding that has been extruded and sintered separately.

- a prismatic or block type geometry in which the fuel particles and matrix material form a hexagonal block containing cylindrical channels to allow for cooling.
- a plate or slab type geometry in which the fuel particles and matrix material form a rectangular block containing square channels to allow for cooling.

A diagrammatic representation of the block and plate type sub-assemblies is shown in the Figure below.



Core loading patterns have been optimised for each geometry type, depending on the number of sub-assemblies identified in the thermal hydraulics sensitivity study. Each core contains two fuel enrichment zones, with optimised numbers of control and shutdown rods (CSDs) and diverse shutdown rods (DSDs). The enrichment, enrichment zone size, absorber rod positions and number of fuel batches are varied during the optimisation to achieve equal ratings in each zone, a small excess core reactivity at the end of cycle and a peak burnup of about 20% heavy atoms. The core is surrounded by two rows of steel reflector sub-assemblies and a single ring of boron carbide shield sub-assemblies, there are no axial of radial breeder assemblies.

Calculation Models and Methods

Neutronics

All the core configurations evaluated have been modelled using version 1.2 of the European Fast Reactor code scheme ERANOS along with the ERALIB1 nuclear cross section data library [4]. Within the ERANOS code scheme the cell code ECCO uses the subgroup method to treat resonance self shielding effects to prepare broad group self shielded cross sections and matrices for each material in the core model. A fine group slowing down treatment is combined with the sub group method within each fine group to provide an accurate description of the reaction thresholds and resonances for the heterogeneous geometry of each type of critical and sub-critical sub-assembly. Whole core flux and depletion calculations have been performed in 3 dimensional geometry for each core configuration studied using finite difference diffusion theory in 33 energy groups. It has been shown that the use of these standard methods for a gas cooled core requires a correction to the whole core reactivity to account for residual transport, heterogeneity and neutron streaming effects. A correction of +2.45% has been applied to all calculations of absolute core reactivity.

Thermal Hydraulics

In the thermal hydraulics calculations it is assumed that the maximum clad surface temperature occurs at the core outlet but that, pessimistically, that the power generation in the fuel at this height is the same as the average power in the peak rated pin in the reactor. This allows the maximum pin clad edge temperature to be determined using standard thermal hydraulic equations and methods. Using this as a boundary condition allows the clad and average temperatures in the fuel pin to be calculated. A uniform heat production across the fuel particle/matrix containing region is assumed and a one dimensional radial conduction model in annular geometry is solved. For the fuel pin geometry, temperatures are calculated in each of a series of annuli within the pin and using average temperatures in each annulus as a boundary condition particle temperatures are calculated by solving a simple spherical heat conduction problem.

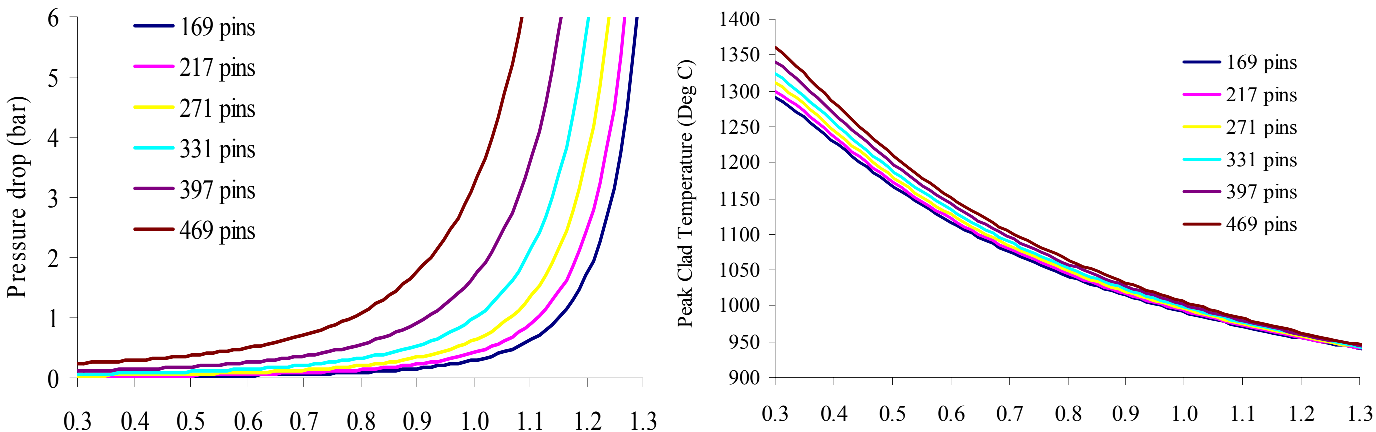
The block and plate type geometries are assumed to consist of a series of identical channels represented by a repeated fundamental sub-cell at the assembly centre, edge effects being neglected. In addition, for the purpose of the temperature calculation, the flow area and fuel area are used to define an equivalent annular cell with coolant at its centre, surrounded by matrix material containing the fuel particles. The flow model is then represented as flow within a tube. The effective hydraulic diameter of the channel is calculated as four times the free flow area divided by the wetted perimeter. The temperature solution for the fuel is then identical to that for a hollow fuel pin except that there is a cooling flow through the central hole.

Fuel Sub-Assembly and Core Design

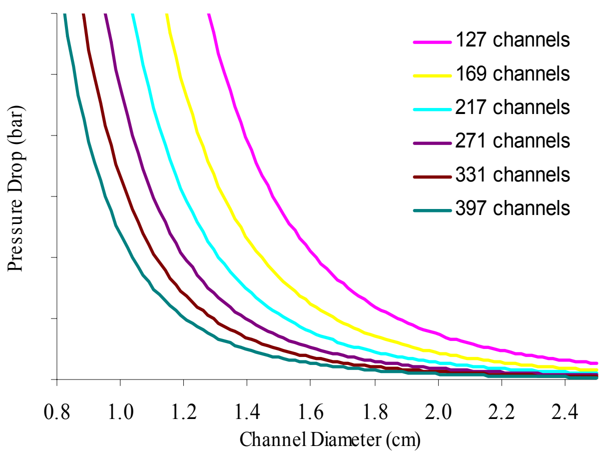
An initial thermal hydraulics study was performed to determine, for each geometry type, the effects of varying the core height and diameter. There is more scope to change the core height than the radial extent of the core and therefore the influence of core diameter changes on parameters such as the core pressure drop, clad/matrix outlet temperature, peak volumetric rating, and the plutonium inventory, were found to be relatively limited. The relatively larger changes possible to the core height, however, has a significant effect especially on the peak volumetric rating. For the core radius considered, a core height of 2 m results in for a peak volumetric rating close to the required design limiting value of 180 MW/m^3. Although increasing the core height has a detrimental effect on the core pressure drop, a core height of 2m gives a pressure drop below the maximum design limit of 3 bar for all of the geometries considered. The peak clad/matrix temperature is also within the acceptable range. Increasing the core height also has the undesirable effect of increasing the plutonium inventory, although at 2 m the inventory is significantly lower than that needed in previously examined carbon dioxide cooled core designs. The value of 2 m has therefore been adopted as a reference value.

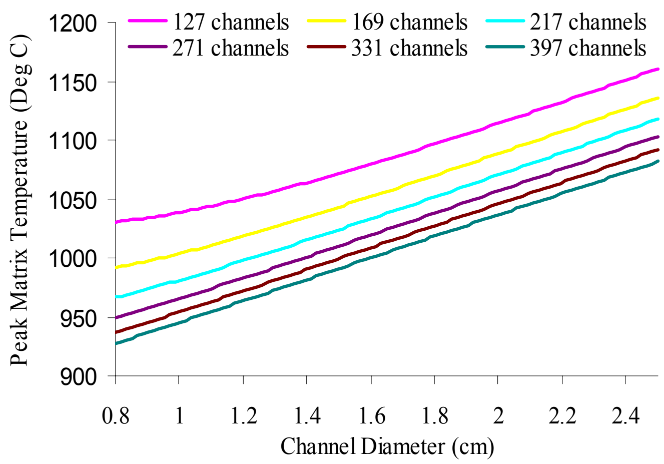
In the thermal hydraulics assessment the effect of changing the number of fuel pins per sub-assembly, or flow channels for the block and plate core, was examined to determine the sensitivity of the main design parameters. A fixed sub-assembly pitch of 25.30 cm was assumed. The variation in the core pressure drop and the peak clad/matrix temperature is shown for each geometry type in the Figures below.

Core Pressure Drop and Peak Clad Temperature for the Pin Sub-Assembly Geometry

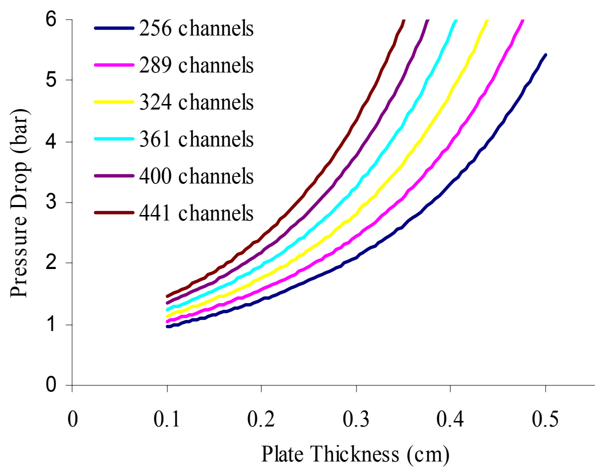


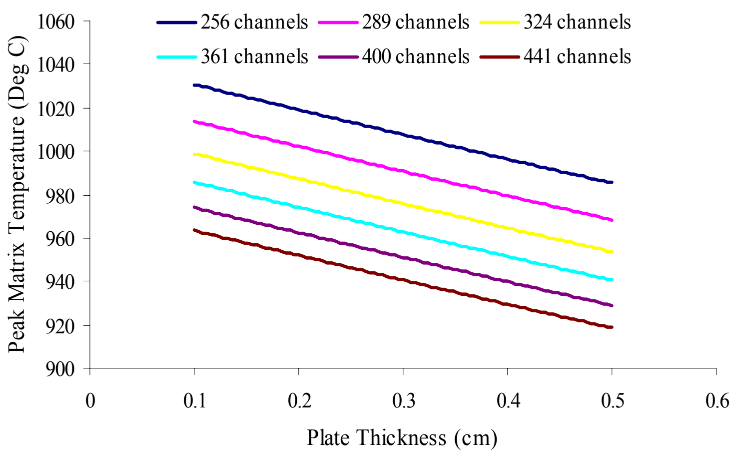
Core Pressure Drop and Peak Matrix Temperature for the Block Sub-Assembly Geometry





Core Pressure Drop and Peak Matrix Temperature for the Plate Sub-Assembly Geometry





In the case of the pin sub-assembly geometry, increasing the fuel pin diameter and the number of pins has the beneficial effect of reducing the peak clad temperature while also increasing the fuel volume content. However, it also has the detrimental effect of increasing the required mass flow and core pressure drop. A total of 271 pins per sub-assembly, with a pin diameter close to 1.1 cm, provides an optimum solution giving peak volumetric ratings, peak clad temperatures and the core pressure drop within the design range. It is also a solution that, as far as possible, maximises the core fuel volume.

In the case of the block sub-assembly geometry it is a reduction in the size and number of coolant channels that leads to an increase in the core pressure drop. A total of 271 coolant channels per sub-assembly with a channel diameter close to 1.1 cm was found to provide the optimum thermal hydraulic performance while again maximising the volume available for the core fuel.

Similarly, in the case of the plate sub-assembly geometry it is a reduction in the size and number of coolant channels, or an increase in the plate thickness, that has the effect of increasing the core pressure drop. A total of 289 coolant channels, or a plate thickness close 0.35 cm, was found to provide the optimum solution.

The thermal hydraulic results have been used to define the initial design parameters for the pin, block and plate geometry cores. Values are given in the table below. Using these values it was then possible to perform a neutronics study to define a core layout consistent with maintaining an adequate core power distribution, reactivity and peak end of life dpa. Requirements for the CSD and DSD absorber rods were assumed to be similar to those found for previous carbon dioxide cooled core designs.

	Geometry		
	Pin	Block	Plate
Coolant Pressure (bar)	60		
Coolant Pressure drop (bar)	3		
Core Power (MW)	2400		
Core Inlet Temperature (°C)	530		
Core Outlet Temperature (°C)	900		
Peak Clad/Matrix Temperature (°C)	1000		
Core Height (m)	2		
Number of Fuelled Sub-Assemblies			
Inner Core	61	61	48
Outer Core	120	120	118
Sub-Assembly Pitch (cm)	25.299		
Wrapper Thickness (cm)	0.44		
Inter Sub-Assembly Gap (cm)	0.50		
Number of Pins/Channels per Sub-Assembly	271	271	289
Pin/Channel Diameter (cm)	1.1396	1.1032	1.1000
Fuel Sub-Assembly Volume Fractions			
Actinide	6.49	8.01	7.29
C + SiC (matrix/particle coatings/wrapper/clad)	50.08	43.29	40.48
He Coolant	43.43	48.70	52.23

Results and Discussion

Core performance calculations have been carried out for the pin, block and plate geometry core designs. The fuel dwell time was determined on the basis of achieving a peak heavy atom burnup close to 20% heavy atoms. The inner and outer core enrichments have been chosen to give balanced inner and outer core volumetric ratings while maintaining a k-effective of unity at the end of cycle with all control rods withdrawn. The core performance and safety parameters are summarised in the table below.

	Geometry		
	Pin	Block	Plate
Plutonium Enrichment (mass %) Inner Core Outer Core	 53.0 54.5	 40.5 43.5	 40.0 43.1
Fuel Dwell Time (efpd)	4 x 188	4 x 188	4 x 188
Peak Volumetric Rating (MW/m^3) Inner Core Outer Core	 186 182	 175 178	 186 187
Peak Burnup (% heavy atoms) Inner Core Outer Core	 20.8 19.9	 20.3 20.4	 20.1 20.7
Peak Damage (dpaNRT Fe)	85	94	97
Reactivity Loss per Cycle (pcm)	5326	4448	3716
Delayed Neutron Fraction (pcm)	299	305	306
Prompt Neutron Lifetime (10^{-6}s)	1.95	1.65	1.62
Plutonium Consumption (kg/TWhe)	75.5	59.3	59.6
Minor Actinide Production (kg/TWhe)	-9.4	-9.0	-8.9
Plutonium Inventory – Start of Life (tonnes)	6.9	7.1	7.0
Doppler Coefficient (pcm)	-686	-593	-595
Coolant Void Worth (pcm)	-260	-187	-181
Water Ingress Reactivity Effect (pcm)	+557	+414	+407

A helium cooled core design has been devised based on a particulate fuel concept consisting of coated fuel particles held within a silicon carbide matrix and clad. The main aim of this design was to significantly reduce the plutonium inventory in comparison to that of a previously studied carbon dioxide cooled fast reactor design. It has been shown that this core concept, with an outlet temperature of 900 °C, a peak clad/matrix temperature of 1000 °C, with a plutonium inventory of about 7 tonnes at the start of life, possesses generally acceptable neutronics and safety performance characteristics. The peak burnup has been determined from the percentage change in heavy atom concentrations over the residence time of the fuel within the core and is close to the target value of 20% heavy atoms for all geometries. The peak volumetric ratings are within design limits. The delayed neutron fraction and prompt neutron lifetime are consistent with values obtained for previous carbon dioxide cooled core designs. The distribution and characteristics of the control rods appear adequate and the necessary shutdown margins have been satisfied. The Doppler constant, strongly dependent on the core uranium content, is comparatively large, even with the high plutonium enrichment, due to the relatively soft neutron spectrum.

As expected, the coolant void reactivity coefficient for the helium cooled fast reactor, approximately -200 pcm, is small in magnitude. This confirms the significant safety advantage of the gas cooled core compared to liquid metal cooled cores on voiding. A fault condition of particular concern in a gas cooled fast reactor is that of water ingress into the core due to leaks in the steam generators. This effect is relatively small, although positive, for the helium cooled fast reactor core design.

However, the particulate fuel concept, with its low fuel volume fraction, makes it difficult to achieve a self generating core with a breeding gain near zero, a strategic requirement for future reactor designs. Also, the high plutonium enrichment required, in particular for the pin sub-assembly geometry, results in reprocessing difficulties using the PUREX process due to solubility of the plutonium at enrichments approaching 45%. Although, the plutonium enrichments are lower for the block and plate geometry cores, due to an increased fuel volume, the plutonium enrichment still exceeds 40%, significantly above the level required to achieve a self generating core.

Exploratory design studies have shown that typical core volume fractions of 40% for the helium coolant, 10% for structural materials, and 50% for the fuel, are required to achieve future core design objectives. For the fuel, at least 50% of the fuel volume should be occupied by the actinide compound, implying an actinide content within the core of between 20 – 25 %. A number of further design modifications can be made to try to achieve this aim :

- the use of high density nitride or carbide fuels to allow an increase in the fuel density and volume content within the core.
- the use of alternative particle coatings, such as ZrC, to allow a reduction in the particle coatings and their thickness in relation to the kernel diameter.
- the use of micro or macro dispersed fuel in which the actinide compound can reach 50 – 70 % of the volume inside the fuel/matrix material.

Significant developments in fuel design and performance will be required to demonstrate the feasibility of these innovative concepts, as well as the more conventional mixed oxide based fuels considered in the current study. Existing fuel particle designs have been developed for a lower power density and are located within graphite blocks or pebbles which provide neutron moderation and allow for efficient heat transfer. These fuel concepts are not adapted to the fast neutron spectrum of the gas cooled fast reactor or the fuel cycle requirements of future reactor designs. Significant optimisation of the fuel particle and core designs will be required to develop alternative dispersed fuel or particle concepts. Alternative coatings and geometries for kernels, buffer and matrix materials will need to be identified and investigated.

Conclusions

Thermal hydraulic and neutronic sensitivity studies have been undertaken to devise pin, block and plate geometry designs of a helium cooled fast reactor that are capable of meeting the increased design limits on the peak volumetric rating and peak matrix/clad temperature allowed by particulate fuels in a ceramic matrix. The volume fraction of the actinide compound within the core designs is about 6 – 8 %, with a plutonium inventory of approximately 7 tonnes at the start of life. The low actinide volume within the core, due to the particulate geometry, leads to a high plutonium enrichment, in excess of 40% for all of the geometries considered.

The neutronics performance the designs has been shown to be acceptable. However, the high plutonium consumption rate in these cores, 60 – 70 kg/TWhe, caused by the high plutonium enrichment, makes it difficult to achieve a self generating core, seen as a key requirement for future reactor designs. Further optimisation of the core design is required to increase the actinide content within the core. Alternative dispersed fuel or particle concepts will need to be identified and investigated.

Acknowledgements

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