Flexibility of the Gas Cooled Fast Reactor to Meet the Requirements of the 21st Century

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Abstract – *A new generation of reactor designs are being developed that are intended to meet the requirements of the 21st century. In the short term the most important requirements are increased competitiveness and efficiency, low construction and operating costs, inherent safety characteristics and low proliferation risk. In the longer term there is a need to establish sustainability of fuel and the need to minimise stocks of separated plutonium and minor actinide waste. The concept of the gas cooled fast reactor has recently seen renewed interest owing to its flexibility for plutonium and minor actinide management and its favourable safety characteristics compared to liquid metal cooled fast reactors. This paper presents the neutronics performance and safety characteristics for a conventional mixed oxide fuelled gas cooled fast reactor with a carbon dioxide coolant. The significant flexibility of this concept for plutonium management is demonstrated by the evaluation of a wide range of possible future scenarios. These include a core configuration capable of high rates of plutonium consumption, a configuration with a negligible breeding gain aimed at sustainability, and a core design that has been optimised for plutonium breeding. Evidence is also provided to demonstrate the potential of this gas cooled fast reactor concept for minor actinide transmutation. One way in which this can be achieved is homogeneous recycling by the addition of small amounts of minor actinides in the mixed oxide fuelled pins. This is compared with the alternative option of heterogeneous minor actinide recycling in which minor actinides are loaded in special target sub-assemblies located in either in-core or ex-core locations. Thus, this study demonstrates the significant flexibility of gas cooled fast reactor designs toward fuel utilisation and fuel cycle management.*

I. INTRODUCTION

In recent years there has been increased interest in gas cooled fast reactor systems for the management of plutonium and minor actinide stockpiles. Gas cooled fast reactors offer a number of advantages over liquid metal fuelled core designs. There are significant safety, economic and technical benefits to be gained from using a benign, readily available 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 negligible coolant void coefficient in gas cooled cores, compared to sodium cooled systems, allows the loading of a far greater quantity of degraded plutonium and minor actinide fuels. An additional feature of a gaseous coolant, in terms of minor actinide incineration, is the hard neutron spectrum that exists in gas cooled cores. Gas cooled fast reactors therefore offer considerable flexibility in core design.

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 the investigation of carbon dioxide cooled fast reactor concepts based on Advanced Gas Reactor technology but incorporating core design parameters from the European Fast Reactor[1]. A number of gas cooled fast reactor cores have been considered including a conventional plutonium burning design, a configuration with a negligible breeding gain aimed at sustainability, and a core design that has been optimised for plutonium breeding. The potential of a gas cooled fast reactor concept for minor actinide transmutation has also been investigated[2]. There are two main options for transmutation in a mixed oxide fuelled fast reactor core. One possibility is to smear a small amount of minor actinides homogeneously in the mixed oxide fuelled pins. This is compared with the alternative option of heterogeneous recycling in which minor actinides are loaded in special target sub-assemblies located in either in-core or ex-core locations.

This paper reviews the main gas cooled fast reactor concepts and core designs that have been considered during the course of this work, concentrating on the core physics and safety aspects particularly in terms of plutonium and minor actinide management. The performance and safety characteristics of each core concept are presented, compared and discussed. These studies have confirmed the significant flexibility of gas cooled fast reactor designs toward future fuel and fuel cycle utilisation.

II. CORE DESIGN

The basis of the present work is the demonstration of a feasible design for a gas cooled fast reactor as a generator of electricity having a similar power output to that of a conventional commercially sized sodium cooled fast reactor. Carbon dioxide is less effective than sodium as a heat transfer medium and so a larger pin spacing is required to satisfy the same design limiting criteria, which in turn provides for a reduced fuel rating. The gas cooled fast reactor design concept is based on the Hinkley Point B and Heysham 2 / Torness Advanced Gas Reactors which utilise a single cavity pre-stressed concrete pressure vessel to house the core structure, steam generators and gas circulators. The proposed boiler design, and the limitations imposed by existing fast reactor fuel technology, have resulted in a core inlet and mixed mean core outlet temperature of 252 °C and 525 °C respectively with a coolant inlet pressure of 42 bar.

In common with comparable sodium cooled core designs, the gas cooled core has a thermal output of 3600 MWth with a load factor of 80%. The reactor is assumed to have a net thermal efficiency of 40% which therefore provides an electrical output of 1400 MWe. Conventional mixed oxide fuel pins with metal cladding are included in the core. The thermal hydraulic performance of this core has been assessed to ensure satisfactory cooling of the fuel pins. The gas cooled core design involves little extrapolation beyond present day technology and exhibits adequate thermal hydraulic performance.

As the core height is not constrained by limitations imposed by the coolant void coefficient, as is the case for a sodium cooled fast reactor, a core height of 1.5 m has been chosen. The steel reflector material adjacent to the core fuel, and the outer shielding sub-assemblies, are as currently assumed in comparable sodium cooled core designs. The control and secondary shut off rods are the same as those of equivalent sodium cooled core designs and comprise 24 primary control rods and 9 secondary shut off rods. These design features are common to all of the core configurations considered during the course of this work.

II.A. Plutonium Burning

In order to determine the scope for plutonium management the feasibility of a gas cooled fast reactor core design for high levels of plutonium burning has been investigated. This option is based on a mixed oxide fuel with a high plutonium content of degraded isotopic quality. The feed fuel is the result of uranium oxide output that has been twice recycled in a mixed oxide PWR. The plutonium content is constrained to be no more than 45% by mass to remain within current reprocessing experience using the PUREX method. The use of a high plutonium content fuel can only be achieved by a significant reduction of the fuel inventory for a given core volume. This has been achieved by the introduction of dilution in the form of empty pin positions within the fuelled sub-assemblies. The main core parameters for the plutonium burning option are shown in Table 1.

Table I : Main Core Design Parameters for the Plutonium Burning Gas Cooled Fast Reactor Core Design

Parameter	Value
Number of Fuelled Sub-Assemblies	550
Number of Inner Core Sub-Assemblies	334
Number of Outer Core Sub-Assemblies	216
Number of Pins per Sub-Assembly	169
Fuel Pin Outer Diameter	8.20 mm
Fuel Pin Clad Inner Diameter	7.36 mm
Fuel Pellet Outer Diameter	7.14 mm
Fuel Pellet Central Hole Diameter	2.00 mm
P/D	1.55
Sub-Assembly Pitch	180.61 mm
Wrapper Inside (Across Flats)	167.00 mm
Plutonium Enrichment – Inner Core	31.12 mass %
Plutonium Enrichment – Outer Core	44.94 mass %
Cycle Length	344 efpd
Number of Cycles	5
Peak Pin Burnup	20 % h.a.

II.B. Plutonium Sustainability

The feasibility of a gas cooled fast reactor for fuel sustainability has also been investigated. To sustain the nuclear fuel cycle, and maintain fuel stocks at existing levels, it is intended that this option should neither consume, nor produce, significant amounts of plutonium, and that therefore the core breeding gain should be close to zero. This option is based on a mixed oxide fuel with a lower plutonium content and cleaner isotopic quality in comparison with the plutonium burning option. The feed fuel is the result of a single recycle of uranium oxide fuel in a PWR.

It can be noted that this core design contains 60 diluent sub-assemblies located in inner core positions to balance the peak ratings in the inner and outer core zones. The main core parameters for the sustainability option are shown in Table II.

Table II : Main Core Design Parameters for the Sustainability Gas Cooled Fast Reactor Core Design

Parameter	Value
Number of Fuelled Sub-Assemblies	550
Number of Inner Core Sub-Assemblies	238
Number of Outer Core Sub-Assemblies	342
Number of Diluent Sub-Assemblies	60
Number of Pins per Sub-Assembly	169
Fuel Pin Outer Diameter	8.20 mm
Fuel Pin Clad Inner Diameter	7.36 mm
Fuel Pellet Outer Diameter	7.14 mm
Fuel Pellet Central Hole Diameter	2.00 mm
P/D	1.55
Sub-Assembly Pitch	180.61 mm
Wrapper Inside (Across Flats)	167.00 mm
Plutonium Enrichment – Inner Core	24.35 mass %
Plutonium Enrichment – Outer Core	27.07 mass %
Cycle Length	325 efpd
Number of Cycles	6
Peak Pin Burnup	20 % h.a.

II.C. Plutonium Breeding

To demonstrate the capability of the gas cooled fast reactor to satisfy the wide range of fuel cycle scenarios that may occur in the 21st century a gas cooled fast reactor core design for plutonium breeding has been investigated. The basic details of the core are similar to those of the sustainability option. As part of this breeder core design axial breeder regions of 35 cm and 25 cm thickness were included below and above the core respectively. Furthermore, two rows of radial breeder sub-assemblies were included around the outer edge of the core.

The breeder sub-assembly dimensions were identical to the fuel and the dimensions and the number of fertile pins per breeder sub-assembly was the same as for the fuel sub-assemblies. However, no central hole is present in the radial breeder pins. A typical uranium oxide breeder fuel was assumed for the breeder pins, with depleted uranium containing 0.25% by mass of U^{235}. The main core parameters for the breeder option are shown in Table III.

Table III : Main Core Design Parameters for the Breeder Gas Cooled Fast Reactor Core Design

Parameter	Value
Number of Fuelled Sub-Assemblies	550
Number of Inner Core Sub-Assemblies	238
Number of Outer Core Sub-Assemblies	342
Number of Diluent Sub-Assemblies	60
Number of Breeder Sub-Assemblies	198
Upper Axial Breeder Blanket	250 mm
Lower Axial Breeder Blanket	350 mm
Number of Pins per Sub-Assembly	169
Fuel/Breeder Pin Outer Diameter	8.20 mm
Fuel/Breeder Pin Clad Inner Diameter	7.36 mm
Fuel/Breeder Pellet Outer Diameter	7.14 mm
Fuel Pellet Central Hole Diameter	2.00 mm
P/D	1.55
Sub-Assembly Pitch	180.61 mm
Wrapper Inside (Across Flats)	167.00 mm
Plutonium Enrichment – Inner Core	22.14 mass %
Plutonium Enrichment – Outer Core	25.68 mass %
Cycle Length	448 efpd
Number of Cycles	6
Peak Pin Burnup	20 % h.a.

III. NEUTRONICS METHODS

All of the gas cooled core configurations have been modelled neutronically using the European fast reactor neutronics code scheme ERANOS Version 1.2 along with the ERALIB1 nuclear cross section data library[3]. Broad group resonance self shielded cross sections have been produced for each core material using the ECCO cell code. 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 each type of critical and sub-critical sub-assembly.

For conventional applications, such as the sodium cooled fast reactor, the cross sections are then condensed and homogenised in the required broad group scheme to provide effective cross sections that correctly treat the spatial heterogeneity of the sub-assembly structure. However, for situations involving low density regions and strongly anisotropic neutron streaming, such as the gas cooled fast reactor, these conventional formulations are insufficient. Hence additional methods have been used to treat these specific characteristics correctly.

The strong anisotropy of the streaming is taken into account by the use of directional collision probabilities. For low density regions, consideration of the equivalence between the limiting behaviour of the diffusion coefficient as the buckling and the cross section tend to zero has resulted in an alternative derivation of equivalent buckling dependent cross sections. In this way homogenised cross sections have been produced for each material in the gas cooled fast reactor core in 33 neutron energy groups.

Whole core flux and depletion calculations have then been performed in 3-dimensional diffusion theory for each core configuration studied. The control rods have been modelled with a reduced B^{10} content to allow for the transport, heterogeneity and mesh effects that are not included in the simplified homogeneous control rod representation employed during these studies.

Consistent flux, isotopic compositions and macroscopic cross section data corresponding to each equilibrium core burnup state have been produced using detailed modelling of the individual fuel batches. The fuel cycle lengths have been determined by the criterion of attaining a peak clad damage over the lifetime of the fuel within the core close to 180 dpa NRT Fe. The inner and outer core feed fuel enrichments for each core configuration have been chosen to give balanced inner and outer core peak ratings and a calculated end of cycle reactivity close to unity with all control rods withdrawn. The control rod insertions at start of cycle and middle of cycle are then adjusted to obtain core reactivity values close to unity. The core performance and safety parameters have then been calculated for the start of cycle, middle of cycle and end of cycle conditions.

IV. PLUTONIUM MANAGEMENT

In order to assess the capability of the gas cooled fast reactor for plutonium management three core designs intended for plutonium consumption, plutonium sustainability, and plutonium breeding have been established. For each core design performance and safety parameters have been calculated at the start and end of each equilibrium cycle. A summary of the main core performance and safety parameters, averaged over all equilibrium cycles, is given in Table IV.

The results obtained for all three options of this gas cooled fast reactor core design illustrate the viability of the concept and show no major difficulties with respect to core performance or safety. The peak pin 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 in all cases. The peak linear ratings, delayed neutron fraction and prompt neutron lifetime are consistent with equivalent values obtained for the European Fast Reactor.

The distribution and characteristics of the control rods, extrapolated from those of the European Fast Reactor, appear adequate as the necessary shutdown margins have been satisfied. The Doppler constant, strongly dependent on the core uranium content, is reasonable, even for the design optimised for plutonium consumption where the contribution from U^{238} capture is at its lowest.

Table IV : Main Core Performance Parameters for the Gas Cooled Fast Reactor Core

	Plutonium Management		
	Consumption	Sustainability	Breeding
Peak Pin Burnup (% h.a.)	18.52	18.48	19.37
Peak Linear Rating (W/cm)	230	331	267
Peak Clad Damage (dpa)	180	167	172
Doppler Constant (pcm)	-346	-576	-886
Coolant Void Reactivity (pcm)	+276	+341	+166
Water Ingress Reactivity (pcm)	-3435	-2752	-3130
Total β-effective (pcm)	337	350	348
Prompt Neutron Lifetime (10^{-7}s)	7.52	7.46	7.63
Reactivity Loss Over Cycle (pcm)	6364	3118	1478
Plutonium/Minor Actinide Consumption (kg/TWhe)	+52.4 / -4.7	+31.8 / -4.8	-3.4 / -4.9
Breeding Gain	-0.38	-0.05	+0.12

As expected, the coolant void reactivity coefficient for the gas cooled fast reactor, at approximately +250 pcm, is very much smaller than that associated with sodium cooled fast reactor cores where the void reactivity worth can approach +2000 pcm. This confirms the significant safety advantage of the gas cooled core compared to liquid metal cooled cores. 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. It can be seen the effect is large and negative for this gas cooled fast reactor core design.

These results demonstrate the significant flexibility with respect to plutonium management that is afforded by this gas cooled fast reactor core design. It is possible to change from high rates of plutonium consumption, in excess of 50 kg/TWhe, to moderate plutonium breeding, or to sustain existing plutonium stocks, with only small modifications to the basic reactor design. Furthermore, this degree of flexibility is achievable within the constraints imposed by existing fast reactor fuel and design technology. Thus, it is shown that the gas cooled fast reactor is capable of satisfying the wide range of fuel cycle scenarios that may occur in the near and longer term future.

V. MINOR ACTINIDE TRANSMUTATION

To reduce the minor actinide content in long lived waste it is necessary to fission the minor actinide isotopes rather than to transmute them to higher actinides by neutron capture. Transmutation by fission of the long lived minor actinide isotopes requires a hard neutron spectrum. A gas cooled fast reactor provides a suitable environment for transmutation.

Options for the introduction of minor actinides in a fast reactor core include their introduction homogeneously as a small percentage of the fuel or heterogeneously in special target sub-assemblies located in and around the core. Both these options have been considered.

V.A. Equilibrium Minor Actinide Transmutation

The study discussed in this section of the paper is based on the plutonium consumption gas cooled fast reactor design. The core design has been optimised to investigate the possibility of burning both plutonium and minor actinides in proportions such that the minor actinides from a partitioned waste stream of a uranium oxide and mixed oxide fuelled reactor fleet are consumed, along with those produced within the gas cooled core itself. This is the notion of equilibrium in the consumption of plutonium and the minor actinides.

For homogeneous minor actinide recycling both neptunium and americium are dispersed homogeneously in the mixed oxide fuel. In the case of heterogeneous minor actinide recycling neptunium is mixed homogeneously in the core fuel but americium is introduced into target sub-assemblies located in the first row of radial reflector sub-assemblies around the core. The target sub-assembly design is based on that of the fuel sub-assemblies with each target containing 169 pins. All of the pins in the target sub-assemblies contain americium dispersed in a matrix of inert material ($MgAl_2O_4$ – spinel) which extends over the fissile height of the core. The neptunium and americium content has been adjusted in each case to achieve an equilibrium consumption relative to plutonium. It is assumed that curium has been partitioned and stored. The main core parameters for the plutonium burner core optimised for minor actinide recycling are shown in Table V.

Table V : Main Core Design Parameters for Minor Actinide Recycling in the Plutonium Consumption Gas Cooled Fast Reactor Core Design

	Minor Actinide Recycling	
	Homogeneous	Heterogeneous
Number of Fuelled Sub-Assemblies	550	550
Number of Sub-Assemblies – Inner Core/Outer Core	334/216	334/216
Number of Target Sub-Assemblies	N/A	89
Neptunium Content – Inner Core/Outer Core (Volume %)	1.75 / 2.10	5.48 / 5.52
Americium Content – Inner Core/Outer Core (Volume %)	6.81 / 7.23	N/A
Americium Content – Targets (Volume %)	N/A	13.34
Plutonium Enrichment – Inner Core/Outer Core (mass %)	27.92 / 42.54	33.12 / 44.65
Cycle Length (efpd)	344	396
Number of Cycles	5	4

For each option of minor actinide recycling, core performance and safety parameters have been determined at the start and end of each equilibrium cycle. A summary of the main core performance and safety parameters, averaged over all equilibrium cycles, is given in Table VI. Equivalent results for the reference plutonium consumption core design are also provided for comparison purposes.

All cases exhibit acceptable behaviour with regard to core performance and safety. The peak fuel burnups in the cores are close to the design value of 20% heavy atoms. The peak burnup in the heterogeneous targets is about half of that achieved in the core fuel due to the reduced fluxes at the core periphery. Similarly, the peak damage in the targets is only half that attained in the core fuel. This indicates that a target sub-assembly residence time one and a half times that of the core fuel may be possible if the same clad damage limits are applied.

There is a significant reduction in the Doppler constant for the minor actinide recycling core options due to the inclusion of neptunium in the core fuel. As the coolant void coefficient remains a negligible effect the reduced magnitude of the Doppler constant is acceptable. The reactivity loss over a cycle is also considerably reduced when compared to the reference plutonium consumption core design. Again, this is due to the inclusion of neptunium in the core fuel which leads to the production of additional plutonium. The characteristics of the control rods are adequate and the shutdown margins have been satisfied in all cases.

In the reference plutonium consumption core design 52.4 kg/TWhe of plutonium is consumed and 4.7 kg/TWhe of minor actinides is produced. In both cases of minor actinide recycling the plutonium consumption is reduced to 46 kg/TWhe due to additional plutonium production from neptunium in the core fuel. However, there is now a significant consumption of minor actinides, nearly 9 kg/TWhe for both homogeneous and heterogeneous minor actinide recycling options. The consumption rates are such that an equilibrium consumption of americium and neptunium relative to the partitioned waste stream has been achieved. Thus, it is shown that the recycling of minor actinides can be feasibly undertaken in a gas cooled fast reactor within the constraints imposed by conventional technology.

Table VI : Minor Actinide Recycling in the Plutonium Consumption Gas Cooled Fast Reactor Core Design

	Reference Plutonium Consumption Core	Minor Actinide Recycling	
		Homogeneous	Heterogeneous
Peak Pin Burnup (% h.a.)	18.52	24.44	19.82 (10.61 targets)
Peak Linear Rating (W/cm)	230	233	231 (175 targets)
Peak Clad Damage (dpa)	180	198	178 (109 targets)
Doppler Constant (pcm)	-346	-233	-236
Coolant Void Reactivity (pcm)	+276	+335	+346
Water Ingress Reactivity (pcm)	-3435	-3236	-3197
Total β-effective (pcm)	337	295	315
Prompt Neutron Lifetime (10^{-7}s)	7.52	6.29	6.57
Reactivity Loss Over Cycle (pcm)	6364	3761	4816
Plutonium Consumption (kg/TWhe)	+52.4	+45.7	+46.7
Minor Actinide Consumption (kg/TWhe)	-0.38	+9.97	+8.32

V.B.. Optimised Minor Actinide Transmutation

An evaluation of minor actinide transmutation has also been performed on the plutonium sustainibility gas cooled fast reactor core design. To fully investigate the scope for homogeneous minor actinide recycling a mixed americium and curium oxide fuel has been added to the mixed oxide core fuel, with a loading of 3%, 7% and 10% by volume of minor actinides. As the core reactivity is modified due to the differing capture rates of the minor actinide isotopes the plutonium enrichment has been adjusted to maintain the same value for the core reactivity at the end of cycle.

The heavy atom burnup in the targets is limited by their residence time, which is in turn restricted by the peak clad damage. A multi-recycling of the targets is therefore required to reduce to a minimum the mass of minor actinides entering the waste stream. To completely remove the requirement for multi-recycling it is necessary to achieve a very high level of mass destruction within the target in a single irradiation, corresponding to a heavy atom burnup approaching 90% heavy atoms.

The introduction of a moderating material within the target, and the consequent softening of the neutron spectrum, reduces the peak clad damage while also increasing the minor actinide transmutation rate. Thus, a moderator material can be effectively used to extend the target residence time and hence increase the heavy atom burnup while retaining the existing limit on the fuel clad exposure.

A significant concern with the utilisation of moderator materials is the possibility for localised power peaking, leading to excessive fuel and clad temperatures, either inside the target or in immediately neighbouring core fuel sub-assemblies. However, a burnable poison can be used within the target to reduce this power peaking effect as the large capture cross section at low energy reduces the number of thermalised neutrons that leak from the target sub-assembly into the neighbouring core fuel.

A study of heterogeneous minor actinide recycling has been performed for the plutonium sustainability core design using moderated targets located in both in-core and ex-core locations. The target design contains 312 target pins and 157 pins containing a zirconium hydride moderator. The target pins have an external radius of 3 mm with a clad thickness of 0.5 mm. The target material is a mixed americium and curium oxide located in an inert spinel matrix. The moderator pins are larger with an external radius of 3.5 mm and a clad internal radius of 3.2 mm. The target also contains a europium oxide burnable poison located in a layer of 4 mm thickness situated inside and adjacent to the target sub-assembly hexagonal wrapper. The main core parameters for the plutonium sustainability core optimised for minor actinide recycling are shown in Table VII.

Table VII : Main Core Design Parameters for Minor Actinide Recycling in the Plutonium Sustainability Gas Cooled Fast Reactor Core Design

	Homogeneous Recycling (volume %)			Heterogeneous Recycling	
	3	7	10	In-Core	Ex-Core
Number of Fuelled Sub-Assemblies	550	550	550	597	595
Number of Inner Core Sub-Assemblies	334	334	334	240	238
Number of Outer Core Sub-Assemblies	216	216	216	357	357
Number of Diluent Sub-Assemblies	60	60	60	N/A	81
Number of Target Sub-Assemblies	N/A	N/A	N/A	90	81
Plutonium Enrichment – Inner Core (mass %)	23.24	21.82	20.96	25.46	24.55
Plutonium Enrichment – Outer Core (mass %)	25.76	24.32	23.31	29.63	28.12
Cycle Length (efpd)	338	338	338	338	338
Number of Cycles	6	6	6	6	12

A summary of the main core performance and safety parameters, averaged over all equilibrium cycles, is given in Table VIII.

The results for the minor actinide recycling options of the plutonium sustainability core design illustrate the feasibility of homogeneous minor actinide recycling in the gas cooled fast reactor. A minor actinide consumption rate of 30.6 kg/TWhe has been achieved for a 10% minor actinide content in the core fuel.

Table VIII : Minor Actinide Recycling in the Plutonium Sustainability Gas Cooled Fast Reactor Core Design

	Homogeneous Recycling (vol. %)			Heterogeneous Recycling	
	3	7	10	In-Core	Ex-core
Peak Pin Burnup (% h.a.)	17.8	17.6	17.5	20.3 (88.5 targets)	19.7 (86.7 targets)
Peak Linear Rating (W/cm)	329	336	343	353 (140 targets)	354 (50 targets)
Peak Clad damage (dpa)	175	178	180	188 (194 targets)	185 (197 targets)
Doppler Constant (pcm)	-475	-387	-333	-545	-532
Coolant Void Reactivity (pcm)	+364	+385	+392	+344	+352
Water Ingress Reactivity (pcm)	-3236	-3244	-3268	-2764	-2758
Total β-effective (pcm)	322	302	289	348	354
Prompt Neutron Lifetime (10^{-7} s)	7.06	6.54	5.98	7.42	7.49
Reactivity Loss Over Cycle (pcm)	2477	1625	1099	3254	3212
Plutonium Consumption (kg/TWhe)	+26.1	+16.7	+10.1	+36.8	+26.3
Minor Actinide Consumption (kg/TWhe)	+6.5	+20.6	+30.6	+8.5	+8.8

However, this is balanced by a low plutonium consumption rate of 10.1 kg/TWhe due to additional plutonium production by the minor actinide isotopes. The minor actinide consumption rate from homogeneous recycling compares favourably with that obtained from heterogeneous recycling with either moderated or non-moderated targets.

The remaining core performance parameters for the homogeneous minor actinide recycling cases are largely unaffected by the introduction of minor actinides within the core fuel. The reactivity loss over a cycle is strongly decreased with the increase in minor actinide content due to the additional plutonium produced by the minor actinide isotopes. In all of the cases considered the control rod reactivity worth is sufficient to cover the requirements for shutdown allowing for the associated uncertainties.

As observed previously, there is a significant reduction in the Doppler constant when minor actinides are introduced in the core fuel. As the coolant void coefficient remains small and positive in magnitude the reduced Doppler constant is still acceptable. On the basis of these results, a minor actinide content of up to 10% is possible for the gas cooled fast reactor core design without any significant implications for the core safety behaviour.

The results for heterogeneous minor actinide recycling show that high levels of mass destruction can be achieved within poisoned moderated targets without excessive power peaking in the core. A mass destruction rate of 76% and 72% has been attained for the in-core and ex-core targets respectively. This corresponds to a peak burnup of 88.5% and 86.7% heavy atoms. At the same time there is an associated maximum power peaking effect within the core fuel sub-assemblies of no more than 5% with either the in-core or ex-core options. The net minor actinide consumption rate for the in-core and ex-core moderated targets is 8.5 and 8.8 kg/TWhe , which compares to a similar value of 8.3 kg/TWhe achieved with ex-core non-moderated targets. The very high level of mass destruction in the moderated targets indicates that the requirement for multi-recycling of the target material can be avoided in the gas cooled fast reactor.

VI. FLEXIBILITY

A significant constraint exists in the operation of liquid metal cooled fast reactors due to the degeneration of the core safety parameters when poor quality degraded plutonium fuels are utilised. The worsening of the core safety parameters is mainly attributed to the coolant void coefficient as the accumulation of higher plutonium and minor actinide isotopes causes the coolant void coefficient to become increasingly more positive.

The negligible void coefficient in the gas cooled fast reactor ensures that the consequences of using degraded plutonium fuels will be less severe. To evaluate the increased flexibility afforded by the gas cooled fast reactor three different plutonium qualities have been utilised in the plutonium consumption and plutonium sustainability gas cooled core designs, as shown in Table IX.

Table IX : Plutonium Isotopic Composition for the Gas Cooled Reactor (mass %)

	Case 1	Case 2	Case 3
Pu^{238}	1.9	5.6	2.2
Pu^{239}	53.3	39.1	31.2
Pu^{240}	25.6	26.7	37.3
Pu^{241}	9.9	13.0	6.9
Pu^{242}	7.9	14.3	19.6
Am^{241}	1.3	1.3	2.7

Case 1 corresponds to plutonium fuel originating from a once through irradiation of uranium oxide fuel. Case 2 is the result of twice recycling the Case 1 output in mixed oxide fuelled reactors. Case 3 corresponds to the multi-recycling of Case 2 fuel in a gas cooled fast reactor and is intended to represent the situation after the long term operation of gas cooled fast reactors whereby an equilibrium has been achieved with the rest of the reactor fleet. For each plutonium fuel core performance and safety parameters have been determined at the start and end of each equilibrium cycle. A summary of the main core performance and safety parameters, averaged over all equilibrium cycles, is given in Table X below.

Table X : Performance Parameters for Plutonium Fuels in the Gas Cooled Fast Reactor

	Plutonium Consumption			Plutonium Sustainability		
	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3
Cycle Length (efpd)	344	344	344	325	325	325
Number of Cycles	5	5	5	6	6	6
Plutonium Enrichment – Inner Core (mass %)	28.9	31.1	33.1	22.1	24.9	27.6
Plutonium Enrichment – Outer Core (mass %)	40.5	44.9	44.9	24.8	27.6	30.1
Peak Pin Burnup (% h.a)	16.9	18.5	18.9	17.9	18.3	18.6
Peak Linear rating (W/cm)	237	230	224	314	324	324
Doppler Constant (pcm)	-346	-336	-315	-561	-585	-629
Coolant Void Reactivity (pcm)	+312	+276	+244	+352	+341	+333
Water Ingress Reactivity (pcm)	-3513	-3435	-3378	-3225	-3209	-3185
Total β-effective (pcm)	327	337	320	345	338	334
Prompt Neutron Lifetime (10^{-7}s)	7.60	7.52	7.45	7.50	7.54	7.63
Plutonium Consumption (kg/TWhe)	+47.7	+52.4	+57.4	+29.1	+31.8	+35.4

The performance results obtained for the different qualities of plutonium composition illustrate the significant amount of flexibility associated with the gas cooled fast reactor. No significant modifications to the core design are required to accommodate a wide range of plutonium isotopics. A small increase in plutonium enrichment is necessary with the degradation in the plutonium quality to compensate for the reduction in the fissile plutonium content. All of the main performance parameters follow similar consistent trends and show no significant deterioration with the change in plutonium quality. This demonstrates that the gas cooled fast reactor is capable of safe operation with a wide range of fuels, and consequently has the flexibility to meet the needs of the many fuel cycle scenarios that may occur in the future.

VII. CONCLUSIONS

An evaluation has been undertaken to investigate the performance of a gas cooled fast reactor core design. Studies have shown that a feasible design for a reactor combining existing UK gas reactor experience with current fast reactor design objectives can be achieved within the limitations of conventional fast reactor fuel and design technology.

This gas cooled fast reactor core design has been evaluated to explore its potential and flexibility for the effective management of plutonium and minor actinide stockpiles. It is possible to change from high rates of plutonium consumption, to moderate plutonium breeding, or to sustain existing plutonium stocks, with only minor modifications to the basic reactor design. It is also shown that the recycling of minor actinides, either homogeneously or heterogeneously, can be feasibly undertaken to achieve an equilibrium minor actinide consumption.

Furthermore, high levels of mass destruction, in excess of 80%, can be attained within poisoned moderated target sub-assemblies in a single irradiation. An investigation of the core safety parameters, including the reactivity effects associated with coolant voiding and water ingress, has shown that this gas cooled fast reactor core design is capable of safe operation with a wide range of plutonium quality fuels. This demonstrates that the gas cooled fast reactor is capable of satisfying the wide range of fuel cycle scenarios that may occur in the near and longer term future.

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