A Moderated Target Sub-Assembly Design for Minor Actinide Transmutation

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Abstract – *In recent years there has been increased interest in the gas cooled fast reactor (GCFR) for the management of minor actinide stockpiles. Several studies have taken place on GCFR systems concerning heterogeneous minor actinide recycling involving target sub-assemblies. These studies have shown that the heavy atom burnup within the targets is limited due to residence time restrictions imposed by clad damage limits. Potentially, multi-recycling of the target fuel is required to reduce to a minimum the mass of minor actinides entering the waste stream. To remove the need for multi-recycling it is necessary to achieve a very high level of mass destruction within the target during a single irradiation. The introduction of a moderator within the target has the potential to extend the target residence time and increase the burnup, while retaining the existing design limit on the fuel clad damage. A significant concern when introducing moderator materials is the possibility for localised power peaking leading to excessive temperatures, and even the possibility of fuel and clad melting. This paper presents the work that has been carried out to optimise a moderated target design for the GCFR. Two particular aspects have been addressed in detail, the use and performance of different moderator materials and the utilisation of different burnable poisons to mitigate the resulting effect on the localised power peaking. Results for core performance and safety parameters are presented and discussed. These studies have been performed within the context of the European CAPRA/CADRA project and are sponsored by BNFL.*

I. INTRODUCTION

Several countries world wide have decided to take effective steps for the management of their long-lived waste stockpiles. Accordingly, a considerable amount of work is currently underway aimed at reducing the mass inventory and the radiotoxicity of the long lived nuclear waste by transmutation and recycling in a variety of reactor concepts employing various techniques of waste management. Two modes for minor actinide transmutation are possible : homogeneously, where the minor actinides are directly mixed in with the core fuel, and heterogeneously, where the minor actinides are separated from the reactor fuel and loaded into specially designed target sub-assemblies. Heterogeneous minor actinide recycling scenarios include the loading of target sub-assemblies in locations within the core (in-core), or alternatively in ex-core locations in the first row of the radial reflector.

In addition, there are two options for the management of the minor actinide target sub-assemblies : multi-recycling, where part of the minor actinide inventory at the end of each reactor cycle is utilised in the following cycle, and a once-through cycle where a very high level of mass destruction is achieved within the target during a single irradiation.

In a gas cooled reactor, the level of mass destruction required in the once-through cycle is only achievable by the introduction of a moderator material within the target sub-assembly. This increases the heavy atom burnup while retaining the design limit on the peak clad damage. However, a significant concern exists when introducing moderator materials due to the possibility of localised power peaking, leading to excessive temperatures, and even the possibility of fuel and clad melting.

This paper presents the work that has been carried out to optimise a moderated target sub-assembly design for use in a gas cooled fast reactor. Two particular aspects have been addressed in detail, the use and performance of different moderator materials and the utilisation of different burnable poisons to mitigate the resulting effect on the localised power peaking. Burnable poisons have large capture cross sections at low energy and therefore reduce the number of thermalised neutrons that can leak from the target sub-assembly into the neighbouring core fuel. The results obtained for core performance and safety parameters are presented and discussed. These studies have been performed within the context of the European CAPRA/CADRA project and are sponsored by BNFL.

II. CORE AND TARGET DESIGN

The basic gas cooled fast reactor core design used as part of these studies is based on the technology of the Advanced Gas Cooled Reactor (AGR), but incorporates design features of a large liquid metal cooled fast reactor such as the European Fast Reactor (EFR). The core is rated at 3600 MWth with a net thermal efficiency of 40.5%, a load factor of 80% and an electrical output of 1458 MW. The core employs a CO_2 coolant at a pressure of 42 bar with core inlet and outlet temperatures of 252°C and 525 °C respectively. The core has a fissile height of 1.5 m and contains a total of 580 fuelled sub-assemblies divided into two enrichment zones, with inner and outer core enrichments of 24.35% and 27.07% (mass of Pu/(Pu+U)) respectively. The are 238 fuelled sub-assemblies in the inner core and 342 in the outer core. Each fuel sub-assembly has a pitch of 18.061 cm and contains 169 fissile pins with clad inner and outer diameters of 7.36 mm and 8.20 mm respectively. The pellet fuel is mixed oxide with an outer diameter of 7.14 mm and a central hole diameter of 2.00 mm. The core also contains 60 diluent sub-assemblies in order to achieve balanced inner and outer core powers; the diluents containing 169 steel pins. The core has no axial or radial breeders, being surrounded instead by two rows of steel reflector. Outside the steel radial reflector sub-assemblies is a single ring of B_4C shield sub-assemblies. The core contains a total of 24 control rods (CSD) and 9 diverse shutdown rods (DSD). The core layout is shown in Figure 1.

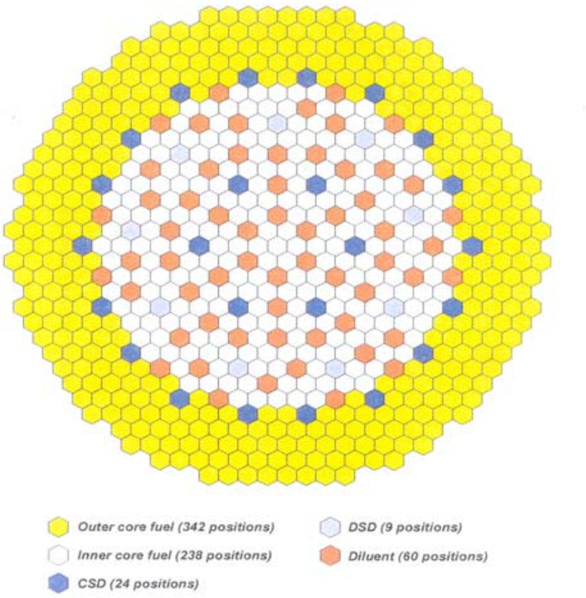

Figure 1. Gas Cooled Fast Reactor Core layout

The design of the moderated target sub-assemblies employed in this study is based on a mixture of actinide and moderator pins, as shown in Figure 2. The moderated target contains 312 actinide pins and 157 moderator pins. The pins are arranged on a hexagonal lattice with each moderator pin surrounded by six actinide pins. The actinide material assumed throughout this work is a mixture of AmO_2 and CmO_2 dispersed in an inert spinel ($MgAl_2O_4$) matrix which extends over the 1.5 m fissile core height.

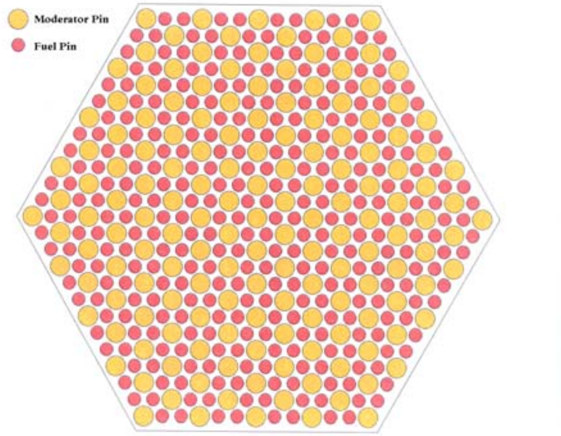

Figure 2. Moderated Target Sub-Assembly Design

Two options for heterogeneous minor actinide recycling have been considered within the basic core design. In the first of these, the in-core option, fuel and diluent sub-assemblies within the core are replaced by moderated target sub-assemblies. Preliminary investigations were carried out to determine the required number and positions of the moderated target sub-assemblies consistent with maintaining an adequate power distribution. In the first instance moderated target sub-assemblies replaced the diluent sub-assemblies in all 60 core locations. However, with this layout it was found that ratings were considerable increased towards the core centre and depressed in the outer core. It was subsequently found necessary to move certain target assembly positions and to include additional moderated targets in the outer core to maintain an acceptable power profile. The final selection of the core layout for the in-core option is shown in Figure 3. The chosen layout includes 90 moderated target sub-assemblies. It was also found necessary to add a further 17 fuelled sub-assemblies to the outer core to maintain an acceptable value for the absolute core reactivity. The core layout for the in-core option therefore contains a total of 597 fuelled sub-assemblies, with 240 fuelled sub-assemblies in the inner core and 357 in the outer core.

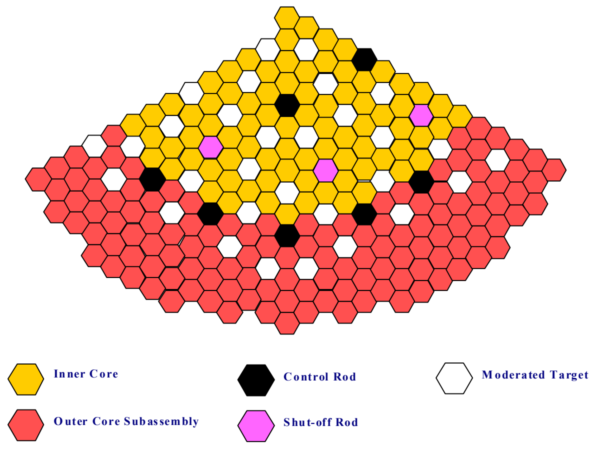

Figure 3 : Core Layout with In-Core Moderated Targets

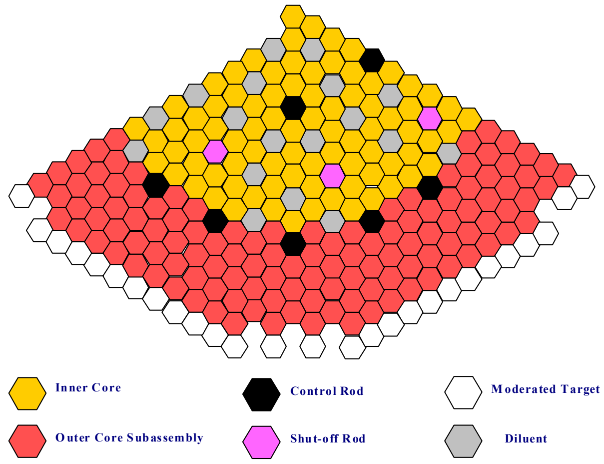

Figure 4 : Core Layout with Ex-Core Moderated Targets

The second option, the ex-core option, considers the replacement of the first ring of radial reflector sub-assemblies by moderated target sub-assemblies. As in the basic gas cooled fast reactor core, the core includes 60 diluent sub-assemblies. Investigations were performed to determine the required number and position of moderated target sub-assemblies in the first row of radial reflector consistent with maintaining an adequate core power distribution. Initially, moderated target sub-assemblies replaced all first row radial reflector sub-assemblies. However, with this layout it was found that the ratings were considerably increased in the outer ring of fuelled sub-assemblies, in particular for the corner sub-assemblies that were immediately neighbouring two or more moderated targets. It was therefore found necessary to leave some of the available positions for moderated targets vacant. The final selection of the core layout for the ex-core option is shown in Figure 4. The chosen layout includes 81 moderated target sub-assemblies. It was also found necessary to add a further 15 fuelled sub-assemblies to the outer core to maintain an acceptable value for the absolute core reactivity. The core layout for the ex-core option therefore contains a total of 595 fuelled sub-assemblies, 238 in the inner core and 357 in the outer core.

III. CALCULATION MODELS AND METHODS

In order to arrive at a feasible moderated target sub-assembly design which satisfies all of the neutronic and thermal hydraulic constraints imposed by current fast reactor design criteria, both thermal hydraulic and neutronics core performance studies have been undertaken. A description of the codes and methods employed during these studies is given below.

III.A. *Neutronics*

Neutronic modelling of all core configurations has been performed using Version 1.2 of the European fast reactor neutronics code scheme ERANOS along with the adjusted ERALIB1 nuclear cross section data library [1]. 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. A two region pin cell model has been employed for the core fuel regions and a fully heterogeneous cell model has been established for the moderated targets.

Whole core flux calculations have been performed using finite difference diffusion theory with HEX-Z geometry in 33 neutron energy groups. The control and safety 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. Previous studies have shown that in a gas cooled fast reactor, the use of the standard diffusion theory approximation combined with a simplified representation of the core fuel sub-assembly heterogeneity, requires a supplementary correction to be applied to the absolute core reactivity to allow for remaining heterogeneity and neutron streaming effects [2]. A correction of + 2.45% ΔK has been applied to all calculations of absolute core reactivity.

Consistent flux, isotopic compositions and macroscopic cross section data corresponding to each equilibrium core burnup state have been produced using a detailed modelling of the individual fuel and target batches. Firstly, a diffusion solution is used to derive the clean core flux distribution and the core is then burnt up for a single cycle. The first batch of core and any appropriate target fuel is then replaced with unburnt sub-assemblies. The flux distribution is then re-derived before burning the core for another cycle, at the end of which the next batch of fuel and appropriate target sub-assemblies are replaced. This process is then repeated until all the fuel and target sub-assemblies have been replaced. This series of steps is then repeated several times until an equilibrium is achieved. A further set of cycles is then repeated to determine the equilibrium core neutronic performance.

It should be noted that the criteria used to determine the residence time for the fuel and target sub-assemblies are different. The core fuel sub-assemblies remain within the core until an end of life peak burnup of 20% heavy atoms has been achieved, within a peak clad damage limit of 200 dpa NRT Fe (after Norgett, Robinson and Torrens). For the moderated targets the aim is to attain a very high level of mass destruction, the main constraint on the target residence time is the peak clad damage limit of 200 dpa NRT Fe. This means that the targets may have a longer residence time than the core fuel and that there may be more batches for the target sub-assemblies than for the core fuel sub-assemblies. In modelling the fuel cycle it is assumed that cycling through until all target sub-assemblies have been replaced at least once is sufficient to achieve a quasi-equilibrium state for the target fuel. The core fuel will therefore undergo more than one equilibrium cycle in establishing the equilibrium target fuel condition.

III.B. *Thermal Hydraulics*

To develop and optimise a moderated target sub-assembly design which satisfies the design constraints imposed on power and temperature a series of thermal hydraulics calculations have been performed. The objective of this analysis has been to determine the magnitude of the coolant gas flow rate, and hence the imposed pressure drop, that would occur for different arrangements of fuel, moderator and burnable poison within the target sub-assembly. Consequently the efficiency of the heat transfer from the fuel to the other sub-assembly materials (clad, coolant, moderator and burnable poison) has been evaluated. For a potential moderated target sub-assembly design to be considered viable the pressure drop in the target must be the same as in the neighbouring core fuel sub-assemblies.

Furthermore, it is necessary to verify that the peak linear ratings, and hence the fuel, clad and moderator temperatures are within acceptable limits. The thermal hydraulics studies have been carried out using a simplified mathematical analysis based on standard methods. The thermal hydraulic behaviour of the core and moderated target sub-assemblies has been modelled with a certain number of assumptions. The core design employed in these studies has a mean core pressure of 42 bar and core inlet and outlet temperatures of 252 °C and 530 °C respectively. The mass flow rate, and hence the pressure drop in the core and target sub-assemblies, is determined so as to satisfy the imposed limit on the core outlet temperature. The target pin surface roughness is assumed to be the same as that of the standard core fuel sub-assemblies. The radial variation of core and target sub-assembly powers has been taken from the core neutronics calculations. The effects of fuel management are therefore included. The axial power distribution is modelled as a truncated cosine centred at the core mid-plane. The same axial power shape is assumed to apply to all core fuel and moderated target sub-assemblies.

IV. ISSUES TO BE CONSIDERED

In order to design a moderated target sub-assembly for use in a gas cooled fast reactor it has been necessary to perform a coupled neutronic and thermal hydraulic analysis. The aim of this evaluation is to identify the most suitable moderator and burnable poison materials, and to define the optimised target sub-assembly geometry and pin dimensions. The main performance criteria are described briefly below :

- *minor actinide burnup* : a parameter that is important when determining the performance of a reactor system (core and targets) is the heavy atom burnup, or mass destruction, that can be achieved. This parameter determines the mass of minor actinides that will need to be multi-recycled and re-fabricated, the mass flow into the waste stream and the fuel cycle end game arisings. A moderator material is used within the target sub-assembly to improve the transmutation rate. In a once through cycle the aim is to remove the requirement for multi-recycling of the targets. This requires a level of mass destruction during a single core residence time that is sufficient to give minimal waste arisings. The level of mass destruction has been evaluated by comparing the end of cycle heavy atom inventory with the clean core inventory, as a percentage of the clean core inventory.

- *clad damage* : this is an important design parameter as it forms the main limitation on the target residence time. The peak clad damage over the target lifetime should not exceed a value of 200 dpa NRT Fe. One of the incentives for using a moderator material is to soften the neutron spectrum, potentially reducing the clad damage rate to allow longer residence times. The peak damage, calculated for both the core fuel and the moderated targets, has been determined by summating the accumulated damage cycle by cycle.

- *peak linear rating and fuel/clad temperature* : for any type of sub-assembly design it is essential to ensure that the pin power, or peak linear rating, and hence the fuel and clad temperatures, do not exceed design safety levels. It is also necessary to retain a sufficient margin to fuel melting to accommodate any operational increases in power that may occur. A key parameter is the peak clad temperature, as this will determine the rate of thermal creep strain and hence the possibility of clad failure due to internal pin pressure. The peak clad temperature limit is taken to be 730 °C for the gas cooled fast reactor design considered here. In order to allow for the uncertainties associated with the calculation of the clad temperature, a hotspot allowance of 96 °C has also been applied. The maximum allowed calculated value of the clad temperature is therefore 634 °C.

  These considerations are further complicated by power peaking in neighbouring core fuel sub-assemblies caused by the use of moderator materials. To examine this effect individual pin peak linear ratings in both the core and moderated target sub-assemblies have been calculated at the start and end of each cycle.

- *plutonium and minor actinide consumption rates* : a basic requirement of a minor actinide target design is that the reactor, core and targets, should be capable of achieving an equilibrium consumption of both plutonium and minor actinides. This requires that the plutonium and minor actinides arising from the external feed fuel (a partitioned waste stream from a fleet of nuclear reactors) are consumed, together with those produced within the gas cooled fast reactor itself. The proportions of the two feed fuel types will depend on the type and mix of reactors in the fleet as well as the fuel cycle scenario being considered. The plutonium and minor actinide consumption rates have been calculated over the lifetime of the fuel and targets within the core.

V. MODERATED TARGET PERFORMANCE

Before optimising the target design, this study considers a parametric survey of the most suitable moderator and burnable poison materials that provide an optimum burning and transmutation performance. The target design used for this parametric survey contains a mixture of fuel and moderator pins, as shown in Figure 2. The target pins have a clad internal radius of 2.198 mm and an external radius of 2.605 mm. The target material is in the form of solid pellets with a radius of 2.024 mm. The moderator pins are larger with a clad internal radius of 3.651 mm and an external radius of 3.939 mm. The moderator material is also in the form of pellets, with a radius equal to the internal clad radius. The target material assumed throughout this study is a mixture of AmO_2 and CmO_2 in a spinel ($MgAl_2O_4$) matrix with pin volume fractions of 13% and 87% respectively. The burnable poison is located within the moderated target sub-assembly in an inner layer adjacent to the sub-assembly hexagonal wrapper so as to avoid significant modification to the core and target geometry.

The performance of both in-core and ex-core moderated targets has been considered. In both cases the core fuel dwell time was determined on the basis of achieving a peak heavy atom burnup in the core close to 20% heavy atoms. A core fuel dwell time of 2028 effective full power days (efpd), with a six batch cycle and a cycle length of 338 efpd was found to be acceptable for the purposes of the parametric survey.

The moderated target residence time was determined on the basis of achieving a high minor actinide mass destruction within a peak clad damage limit of 200 dpa NRT Fe. The permissible residence time of the in-core targets was determined to be six cycles, or 2028 efpd. The in-core targets were therefore divided into six batches. The batch assignments were chosen so that no adjacent fuel or target sub-assemblies would be reloaded in the same cycle. For the in-core targets, iterations were performed for six cycles starting from clean core, and then calculations were performed for a further six equilibrium cycles. In the case of the ex-core targets the permissible residence time was determined to be twelve cycles, or 4056 efpd. The ex-core targets were therefore divided into twelve batches. Again the batch assignments were chosen so that no adjacent fuel or target sub-assemblies would be reloaded in the same cycle. For the ex-core targets, iterations were performed for twelve cycles starting from clean core, and then calculations were performed for a further twelve equilibrium cycles.

V.A. Moderator

The first part of the parametric survey concerns an evaluation of the performance of different moderator materials. High levels of minor actinide transmutation can only be achieved by the moderation of fast neutrons so as to significantly increase neutron capture by the minor actinide isotopes while retaining the existing design limit on the fuel clad damage. As hydrogen based moderators are the most effective, especially at higher energies, the following moderators have been considered in this study : zirconium hydride ($ZrH_{1.65}$ – hydrogen density 0.039 g/cm^3), calcium hydride ($CaH_{1.99}$ – hydrogen density 0.035 g/cm^3), yttrium hydride ($YH_{1.75}$ – hydrogen density 0.032 g/cm^3), zirconium deuteride ($ZrD_{1.65}$ – deuterium density 0.039 g/cm^3), and calcium deuteride ($CaD_{1.99}$ – deuterium density 0.035 g/cm^3). The main results from the study, for each moderator material, are summarised in Table I for the in-core scenario and Table II for the ex-core scenario.

TABLE I. Performance Parameters for In-Core Moderated Targets

	Peak Burnup (% heavy atoms)		Mass Destruction (% actinide mass)	Peak Rating (W/cm)		Peak Clad Temperature (° C)		Net Minor Actinide Consumption Rate (kg/TWhe)
Moderator	Core	Targets	Targets	Core	Targets	Core	Targets	
$ZrH_{1.65}$	19.51	90.31	81	554	130	1029	576	+1.51
$CaH_{1.99}$	20.12	81.49	79	578	190	1049	593	+1.46
$YH_{1.75}$	20.75	85.83	76	560	183	1071	586	+1.36
$ZrD_{1.65}$	20.77	48.12	44	356	42	644	551	+0.15
$CaD_{1.99}$	20.71	51.60	43	326	36	630	549	+0.13

TABLE II. Performance Parameters for Ex-Core Moderated Targets

	Peak Burnup (% heavy atoms)		Mass Destruction (% actinide mass)	Peak Rating (W/cm)		Peak Clad Temperature (° C)		Net Minor Actinide Consumption Rate (kg/TWhe)
Moderator	Core	Targets	Targets	Core	Targets	Core	Targets	
$ZrH_{1.65}$	19.27	88.50	84	441	47	665	551	+1.05
$CaH_{1.99}$	18.79	84.20	74	435	69	663	559	+0.40
$YH_{1.75}$	18.78	82.94	79	448	77	667	561	+0.94

Although not included in the table, the fact that the in-core targets and the core fuel accumulate the same peak clad damage in the same dwell time shows, surprisingly, that the presence of the moderator has little effect on damage rates in the targets, and consequentially, on the target residence time. This effect can be understood by comparing the neutron energy spectrum in the core and moderated targets with the microscopic clad damage cross section, as shown in Figure 5.

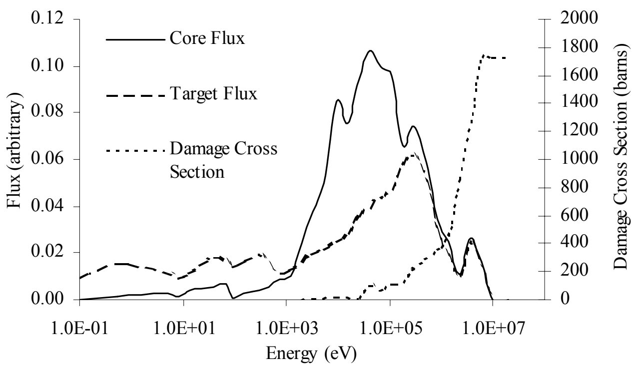

Figure 5 : Neutron Energy Spectrum and Clad Damage Cross Section for In-Core Moderated Targets

The spectrum inside the targets is much softer, due to the introduction of the moderator. However the changes in the energy spectrum occur in an energy domain below that where the clad damage cross section becomes important.

Although the inclusion of moderator in the targets has not significantly increased their lifetime, it has significantly increased the level of mass destruction and the burnup that can be achieved during the target lifetime. A level of mass destruction close to 80% for both in-core and ex-core targets is achieved with hydride moderators. The improved burnup is due to the softer spectrum, and consequently the increased amount of fission, capture, and hence transmutation of the minor actinide isotopes.

The results obtained from the survey of different moderator materials demonstrate that the choice of moderator has a significant effect on both the core and target performance. The power peaking effect is especially sensitive. The hydrogen based moderators give peak linear ratings and peak clad temperatures that are considerably in excess of permitted design limits. The deuteride moderators, $ZrD_{1.65}$ and $CaD_{1.99}$, give peak linear ratings and peak clad temperatures that are more favourable.

However, their burning and transmutation performance is poor when compared to that observed for the hydride moderators, the burnup and mass destruction rate being reduced by almost a factor of two. This is due to the lower effective moderation effect from deuterium relative to hydrogen; it has both a lower scatter cross section at high energy and a more limited range of scatter.

A $ZrH_{1.65}$ moderator provides the best neutronic performance and the optimum compromise between the effects on power peaking, with a peak linear rating of 554 W/cm, and the burning performance that can be achieved, with a mass destruction rate in the in-core and ex-core targets in excess of 80%. It should be noted that the hydride moderators possess relatively poor irradiation behaviour. Operating temperatures are limited to 620 °C, 550 °C and 1000 °C for the $CaH_{1.99}$, $ZrH_{1.65}$ and $YH_{1.75}$ moderators respectively. This arises due to excessive permeability and dissociation at higher temperatures and consequently loss of hydrogen. In this context $YH_{1.75}$ appears to be the better choice of moderator due to its improved thermal performance, although its hydrogen atomic density, and therefore its moderation capability, is less than that of $ZrH_{1.65}$. Therefore, although $ZrH_{1.65}$ remains the optimum choice of moderator, there is considerable interest in increasing the hydrogen density of yttrium hydride ($YH_{1.75} \rightarrow YH_{2.0}$), by optimisation of the fabrication process.

Another important aspect of these results is that although the level of mass destruction achieved in the moderated targets is very high, the actual minor actinide consumption rates are relatively low due to the low minor actinide inventory in the targets. In all cases, however, an equilibrium consumption of minor actinides is achieved with a net, in-core target, consumption rate of 1.51 kg/Twhe in the case of the $ZrH_{1.65}$ moderator. It can also be noted that the net plutonium consumption rate is reduced by some production of plutonium in the moderated targets.

V.B. *Burnable Poison*

The results presented in the previous section of this paper indicate the sensitivity of the core, and in particular the power distribution, to the use of different moderator materials. Although the moderator allows for high levels of burnup and mass destruction to be achieved, the significant power peaking effect introduced by the hydrogen based moderators results in peak linear ratings and peak clad temperatures that considerably exceed permitted design limits. Burnable poisons can be used to reduce the number of moderated thermal neutrons that leak from the moderated target sub-assembly into the neighbouring core fuel thus reducing power peaking. The burnable poisons that have been considered in this study are cadmium oxide (CdO), hafnium (Hf), gadolinium oxide (Gd_2O_3), and europium oxide (Eu_2O_3).

A parametric survey has been undertaken with each burnable poison for the in-core target scenario, where the effect of power peaking is most pronounced. The preferred choice of moderator, $ZrH_{1.65}$, has been used in all cases. To include the burnable poison inside the moderated target sub-assembly, without significant modification to the core and target geometry, the burnable poison is included as an inner lining to the target sub-assembly hexagonal wrapper. The sensitivity of the core and target behaviour to the mass of burnable poison present (the thickness of the burnable poison layer) has also been examined in the survey study.

The peak linear rating was calculated at the start of cycle for each core and target sub-assembly. The power peaking factor, defined as the percentage increase in the peak linear rating relative to the core with targets but with no moderator or burnable poison present, has then been calculated. The variation in the power peaking factor with burnable poison thickness for the highest rated sub-assembly is given in Figure 6 for each burnable poison.

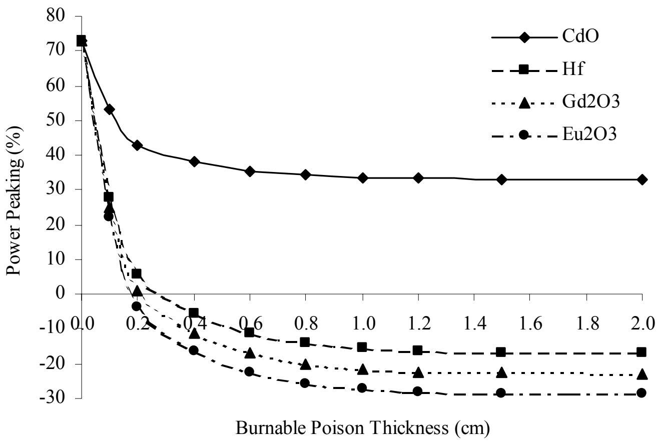

Figure 6 : Power Peaking for In-Core Targets with $ZrH_{1.65}$ Moderator

These results show that the inclusion of a burnable poison results in a significant reduction in power peaking compared to the situation where no burnable poison is present, illustrated by zero burnable poison thickness. Furthermore, only a thin layer, up to a thickness of 0.4

cm, of burnable poison is required to remove any power peaking. No advantage is gained in increasing the thickness of the burnable poison beyond this.

This also confirms that only small changes to the target sub-assembly design are necessary to accommodate the burnable poison. In the case of Hf, Gd_2O_3, and Eu_2O_3, the power peaking effect is virtually eliminated. CdO is much less effective and the power peaking effect is reduced by only a factor of two. This is due to the lower epithermal capture cross section of CdO, only thermal neutrons contributing to the power peaking are absorbed. Eu_2O_3 is the most effective burnable poison, its capture cross section being larger than the other burnable poisons at higher energies.

Although the reduction in power peaking is significant, the burnable poison does impose a penalty as it reduces the peak burnup and the level of mass destruction that can be attained within the target. This is reflected in Figure 7 which shows the mass destruction rate achieved for each burnable poison.

These results suggest that the capture cross sections of the burnable poison isotopes have some influence at higher energies, in addition to the large amount of neutron capture that takes place at lower thermal energies. A further consequence of the burnable poison is a reduction in the net minor actinide consumption rate, as shown in Figure 8. In all cases, the core and target system becomes a net producer of minor actinides if the thickness of the burnable poison layer is too large.

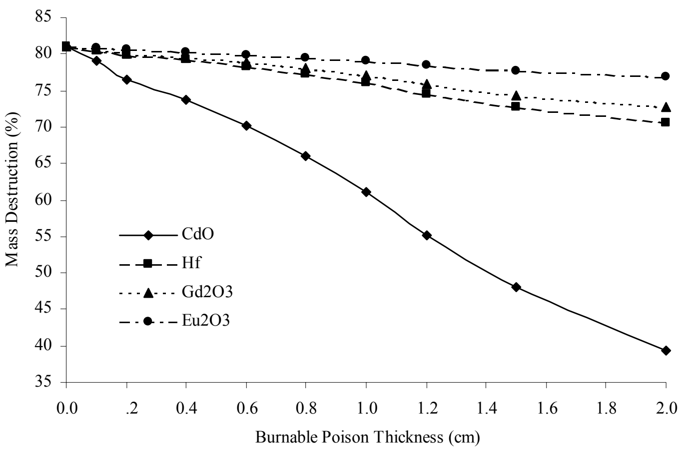

Figure 7 : Mass Destruction for In-Core Targets with $ZrH_{1.65}$ Moderator

On the basis of these results Eu_2O_3 is the preferred choice of burnable poison as it provides for a significant reduction in power peaking while having the smallest impact on the peak burnup and the level of mass destruction within the target.

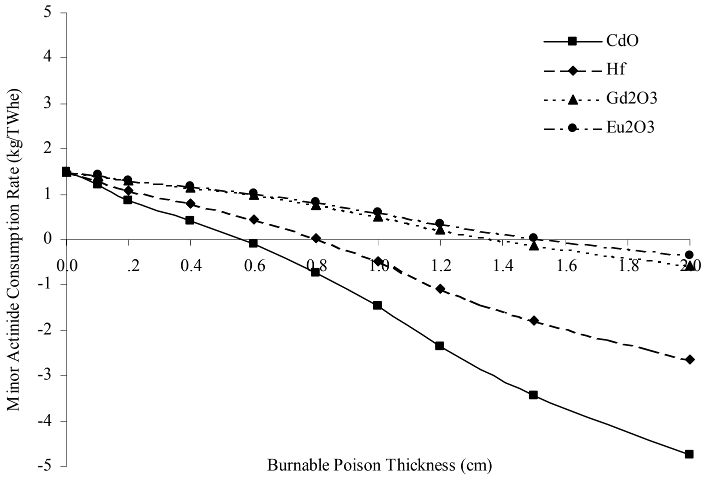

Figure 8 : Net Minor Actinide Consumption for In-Core Targets with $ZrH_{1.65}$ Moderator

VI. MODERATED TARGET DESIGN OPTIMISATION

To optimise a moderated target sub-assembly design that is suitable for use in a gas cooled fast reactor, the following design options are recommended on the basis of the results of the parametric survey :

- *moderator* : a zirconium hydride ($ZrH_{1.65}$) moderator contained in pins within the target subassembly.
- *burnable poison* : a europium oxide (Eu_2O_3) burnable poison located in a layer of 0.4 cm thickness situated as an inside lining of the target sub-assembly hexagonal wrapper.

The inclusion of a burnable poison has a significant influence on the neutronic and thermal behaviour of the fuel and target sub-assemblies within the core. Therefore, a coupled neutronic and thermal hydraulic survey has been undertaken to define a parameter space, or a range of fuel and moderator contents, that satisfy the main design and performance criteria.

The surface in parameter space showing the residence time to accumulate the 200 dpa design clad damage limit is shown in Figure 9. The surface in parameter space showing the residence time required to achieve an ambitious 90% minor actinide mass destruction within the moderated target sub-assembly is shown in Figure 10.

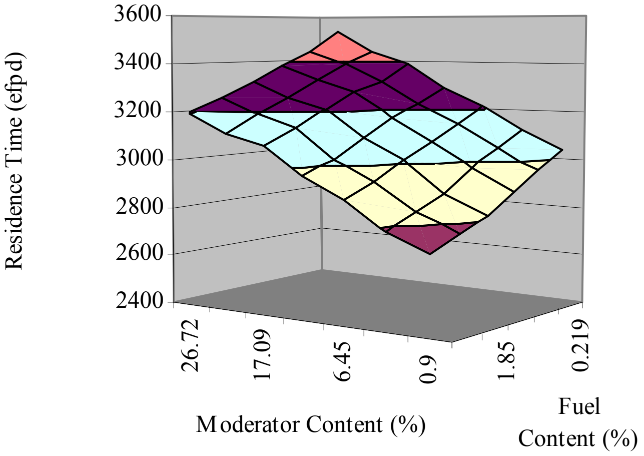

Figure 9 : Residence Time Required to Reach 200 dpa Clad Damage for In-Core Moderated Targets

Similar surfaces in parameter space have also been established for the peak linear rating, peak clad temperature and the pressure drop across the target sub-assembly for a range of fuel and moderator pin sizes.

The target residence time required to reach the 200 dpa peak clad damage limit is relatively insensitive to either the fuel or the moderator content. However, the time taken to achieve a 90% level of mass destruction is more strongly dependent on the fuel, and especially the moderator content. There is no part of the parameter space where both of these aims are achieved.

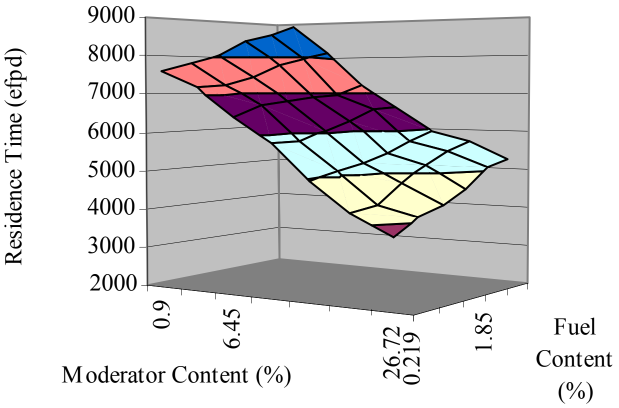

Figure 10 : Residence Time Required to Reach 90% Mass Destruction for In-Core Moderated Targets

Due to the inclusion of the burnable poison the maximum mass destruction level achievable respecting clad damage limits is about 70%. However, the reduction in power peaking brought about by the burnable poison allows an increase in the fuel content within the target sub-assembly. Therefore, although the percentage level of mass destruction has been reduced, the mass of actinides consumed has been increased.

The optimised moderated target sub-assembly design for the gas cooled fast reactor has a fuel volume content of 2.64% and a moderator volume content of 18.78%. Optimisation of the geometric target subassembly design to match these volume fractions as well as limits on the peak clad temperature gives an optimised moderated target design containing 312 target pins and 157 moderator pins. The target pins have a clad internal radius of 2.498 mm and an external radius of 3.005 mm. The target material is in the form of solid pellets with a radius of 2.424 mm. The moderator pins are larger, with a clad internal radius of 3.251 mm and an external radius of 3.539 mm. The moderator material is also in the form of pellets with a radius that is equal to the internal clad radius.

The calculated power distribution with this design indicates that peak linear ratings and clad temperatures that are within acceptable limits. The thermal hydraulic analysis shows that the pressure drop along the pins of the target sub-assembly, about 2 bars, is comparable with that obtained for a standard core fuel assembly.

The optimised target sub-assembly design has been used in whole core calculations to perform a detailed evaluation of its performance in both the in-core and ex-core scenarios and to re-optimise the fuel dwell time. For the core fuel, acceptable performance is achieved with a dwell time of 2028 efpd using a six batch cycle and a cycle length of 338 efpd. This gives a peak heavy atom burnup in the core close to 20% heavy atoms. The residence time of the in-core targets was also determined to be six cycles of 2028 efpd. Calculations were then carried out for six equilibrium cycles in the case of the in-core targets to determine their performance. The residence time of the ex-core targets was twelve cycles (4056 efpd) and calculations were performed for twelve equilibrium cycles to determine the performance of the ex-core targets. The main results obtained with the optimised moderated target sub-assembly design for both in-core and ex-core configurations are shown in Table III below.

Table III. Performance Parameters for the Optimised Moderated Target Sub-Assembly Design

	Peak Burnup (% heavy atoms)		Mass Destruction (% actinide mass)	Peak Rating (W/cm)		Peak Clad Temperature (° C)		Net Minor Actinide Consumption Rate
Scenario	Core	Targets	Targets	Core	Targets	Core	Targets	(kg/TWhe)
In-Core	20.00	88.50	76	362	140	634	581	+8.48
Ex-Core	19.60	86.72	72	380	50	642	558	+8.78

Although the level of peak burnup and percentage mass destruction has been reduced by the inclusion of a burnable poison, the results of the detailed evaluation show that high levels of percentage mass destruction can be achieved within poisoned moderated targets without excessive power peaking in the core. A percentage mass destruction rate of 76% and 72% has been attained for the in-core and ex-core targets respectively. This corresponds to a peak burnups of 88.50% and 86.72% heavy atoms. At the same time there is a maximum power peaking effect within the core fuel sub-assemblies of no more than 5% for either the in-core or ex-core scenarios. A significant increase in the net minor actinide consumption rate has been achieved with the optimised design. The net minor actinide consumption rate for the in-core and ex-core targets is now 8.48 kg/TWhe and 8.78 kg/TWhe, which compares to values of 1.51 kg/TWhe and 1.05 kg/TWhe achieved prior to optimisation.

VII. CONCLUSIONS

A study has been undertaken to optimise a moderated target sub-assembly design for heterogeneous minor actinide recycling in a gas cooled fast reactor. The introduction of a moderator material is intended to increase the burnup and mass destruction that can be achieved. However, a little surprisingly, there was no significant increase in dwell time due to a reduction in dpa rates with a softer spectrum. It is necessary to attain a very high level of mass destruction within the target to completely remove the requirement for multi-recycling of the target material. The optimised target design developed during the current study is able to achieve a 70% mass destruction of the minor actinides during a single core residence time while not exceeding a peak clad damage of 200 dpa NRT Fe. A significant concern when introducing moderator materials is the possibility for localised power peaking leading to excessive temperatures, and even the possibility of fuel and clad melting. Burnable poisons have been used to reduce power peaking by reducing the number of moderated thermal neutrons that leak from the moderated target sub-assembly into the neighbouring core fuel.

A coupled neutronic and thermal hydraulic analysis has been performed to optimise fuel, moderator and burnable poison contents, as well as a moderated target geometry that satisfies the design criteria on thermal and neutronic performance. This has led to the definition of an optimised moderated target design that can be used in both in-core and ex-core locations in a gas cooled fast reactor. The optimised sub-assembly design contains a total of 469 pins of which 312 are fuelled, and 157 contain $ZrH_{1.65}$ moderator. The moderated target also contains a Eu_2O_3 burnable poison layer of 0.4 cm thickness on the inside of the hexagonal sub-assembly wrapper. The proposed sub-assembly geometry provides for a pressure drop across the target pins which is comparable to that across the core fuel. This target design has been used in a detailed evaluation of moderated target and core performance. The results of this study show the feasibility of the moderated target concept to achieve reasonable levels of minor actinide consumption without a serious deterioration in the core power distribution and thermal performance. A mass destruction rate of 70% and a peak burnup of approximately 85% can be achieved during a single irradiation. A net minor actinide consumption rate of 8.48 kg/TWhe and 8.78 kg/TWhe has been achieved for the in-core and ex-core target scenarios respectively.

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REFERENCES

1. G. RIMPAULT, "The ERANOS Code and Data System for Reactor Neutronic Analyses", PHYSOR 2002, Seoul, Korea (2002).
2. G. RIMPAULT, P.J. SMITH and T.D. NEWTON, "Advanced Methods for Treating Heterogeneity and Streaming Effects in Gas Cooled Fast Reactors", M&C'99, Madrid, Spain (1999).