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### **Progress in Nuclear Energy**

DOI: https://doi.org/10.1016/j.pnucene.2021.103752

Published: 01/07/2021

Peer reviewed version

Cyswllt i'r cyhoeddiad / Link to publication

Dyfyniad o'r fersiwn a gyhoeddwyd / Citation for published version (APA): Bolukbasi, M., Middleburgh, S., Dahlfors, M., & Lee, B. (2021). Performance and economic assessment of enriched gadolinia burnable absorbers. *Progress in Nuclear Energy*, 137, Article 103752. https://doi.org/10.1016/j.pnucene.2021.103752

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# Performance and economic assessment of enriched gadolinia burnable absorbers

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### Abstract

As a burnable absorber, gadolinium oxide (Gd<sub>2</sub>O<sub>3</sub>) is widely used in light water reactors due to the high neutron absorption cross section of several gadolinium isotopes and its good solid solubility in UO<sub>2</sub>. However, some isotopes of natural Gd cause residual reactivity suppression, while some are not efficient neutron absorbers, reducing the efficiency of the burnable absorber when implemented. In this study, fuel assemblies utilising gadolinium oxide enriched with <sup>157</sup>Gd isotope were modelled using Monte Carlo particle transport methods and compared to fuel with a natural Gd based absorber. Reactivity gains were examined over the life of the assembly utilising <sup>157</sup>Gd-enriched absorber as compared to natural gadolinia. A preliminary economic evaluation is also made to assess the commercial benefits of using <sup>157</sup>Gd-enriched burnable absorber. Use of enriched gadolinium oxide is shown to eliminate residual reactivity caused by natural gadolinium oxide, and similar reactivity properties (and therefore criticality margins) can be achieved with less burnable absorber in the fuel. The financial cost of incorporating enriched Gd isotopes into nuclear fuel has also been estimated.

Keywords: Gadolinium oxide, Enriched gadolinium, Burnable absorber, Monte Carlo.

### 1. Introduction

Nuclear fuel assembly design is generally optimised to support the economical operation of a reactor, enabling it to reach the highest possible capacity factor. To achieve best economic performance, it is typically necessary to operate for as long a period as possible between refuelling operations or outages. Extending the fuel cycle in this way will increase the total amount of power produced and thus minimise the number of outage days during the reactor lifetime (Ozer and Edsinger, 2006). The longer fuel cycle length requires a combination of improvements to the fuel, including loading a higher fuel enrichment (Durazzo *et al.*, 2018) or higher uranium density fuel, for example through the Advanced Technology Fuel (ATF) developments (Middleburgh *et al.*, 2020). As a result of the higher enrichment/higher U density, a range of reactivity suppression methods can be employed to ensure the safety margins are maintained and the reactor is controllable when the fuel is fresh (Galahom, 2017).

Burnable absorbers (BAs) represent one such method to suppress the reactivity of fresh fuel (Frybortova, 2019), preventing excessively high power peaks (Tran *et al.*, 2017). They effectively capture neutrons and in doing so they transmute to isotopes with lower neutron cross sections (i.e. they are burned) enabling the fuel to be efficiently used thereafter. In addition, the most ideal burnable absorbers are those that do not leave any residual absorption in the system after their burn (Santala *et al.*, 1997).

Gadolinium oxide ( $Gd_2O_3$ ) is one of the most regularly employed burnable absorbers because of the high neutron capture cross section of gadolinium isotopes (Uguru *et al.*, 2020). It is used in a limited number of fuel rods to prolong suppression and take advantage of self-shielding effects (Franceschini and Petrović, 2009). Gadolinium provides a means to control the power peak within the assembly and has relatively little impact on the reprocessing of the fuel (Schlieck *et al.*, 2001).

Fig. 1 shows the infinite multiplication constant ( $k_{inf}$ ) of fuel assemblies, which is a measure of their ability to generate power, that have been enriched with 5 wt.% <sup>235</sup>U and contain 1.00 wt.%, 2.00 wt.% 4.00 wt.%

and 6.00 wt.% n-Gd<sub>2</sub>O<sub>3</sub> (Gd<sub>2</sub>O<sub>3</sub> with a natural abundance of its isotopes). The methodology used in obtaining this graph is given in section 2. Although reactivity in the PWR assembly without BA shows a steady decrease, in assemblies that contain BA in the form of n-Gd<sub>2</sub>O<sub>3</sub>, the reactivity first rises and reaches a maximum level at the point where BA is almost depleted. The point at which  $k_{inf}$  is highest is referred to as the "peak reactivity". The  $k_{inf}$  subsequently decreases steadily in parallel with the assembly without BA (Sanders and Wagner, 2002). It can be seen that assemblies with more burnable absorber have a reduced  $k_{inf}$  at the end of cycle due to residual suppression by the additives.



Fig. 1 Infinite multiplication constant ( $k_{inf}$ ) at 5% <sup>235</sup>U enrichment level and containing 1.00 wt.%, 2.00 wt.%, 4.00 wt.% and 6.00 wt.% n-Gd<sub>2</sub>O<sub>3</sub>. Increasing Gd<sub>2</sub>O<sub>3</sub> content suppresses peak point reactivity.

When n-Gd<sub>2</sub>O<sub>3</sub> is used as BA, the isotopes having low thermal neutron absorption cross section impact negatively on reactivity, causing residual absorption in later life (Franceschini and Petrović, 2009). It is possible to negate this negative effect by enriching Gd<sub>2</sub>O<sub>3</sub> with <sup>157</sup>Gd, the most efficient neutron absorbing Gd isotope (Santala *et al.*, 1997). As this enrichment process allows reduction of the amount of Gd<sub>2</sub>O<sub>3</sub> to be used in the fuel pellets, it helps to decrease the negative effect of Gd<sub>2</sub>O<sub>3</sub> on pellet thermal conductivity (Dalle *et al.*, 2013; Qin *et al.*, 2020), which in turn may help to reduce or entirely remove the penalties traditionally imposed on the Thermo-Mechanical Operating Limit (TMOL) for Gd fuel rods. It also reduces the overall uranium oxide (UO<sub>2</sub>) displacement in the fuel matrix (Yilmaz, 2005) so that a higher UO<sub>2</sub> loading is obtained in the assembly.

Natural Gd contains seven stable isotopes: <sup>155</sup>Gd (14.80%) and <sup>157</sup>Gd (15.65%) are the isotopes with the highest neutron absorption cross sections :  $61,000\pm500$  barns and  $254,000\pm2000$  barns, respectively (Oprea and Oprea, 2014). When <sup>157</sup>Gd captures a neutron that would have otherwise initiated a fission event, it transmutes to <sup>158</sup>Gd that has a significantly lower neutron cross section and has thus "burned" away. However, when <sup>156</sup>Gd (~20 wt.% of the natural abundance of Gd and the product of neutron capture of <sup>155</sup>Gd) absorbs a neutron, it produces <sup>157</sup>Gd (the efficient absorber). This production of neutron absorbing isotopes reduces the efficiency of the burnout of the burnable absorber causing residual reactivity suppression. Another absorber regularly used in fuel: <sup>10</sup>B (often in the form of ZrB<sub>2</sub> (Simmons *et al.*, 1988)) absorbs a neutron and breaks down into two low neutron absorbing isotopes: <sup>4</sup>He and <sup>7</sup>Li – however the efficiency of neutron capture by <sup>10</sup>B is lower than <sup>157</sup>Gd and incorporation of boron into the fuel matrix has also been an engineering challenge. The oxide of boron, B<sub>2</sub>O<sub>3</sub>, when in UO<sub>2</sub> solution causes poor properties of the pellet and its volatility during sintering makes commercial production extremely challenging. Other boron containing compounds and boron composites are being researched at present(Kardoulaki et al., 2020) and ZrB<sub>2</sub> coatings have been applied to pellets(Franceschini and Petrović, 2009), avoiding many chemical compatibility issues.

Bejmer and Seveborn investigated the effect of  $Gd_2O_3$  enriched with 70% <sup>157</sup>Gd in the Westinghouse 3loop pressure water reactor and suggested that e-Gd<sub>2</sub>O<sub>3</sub>(Gd<sub>2</sub>O<sub>3</sub> enriched in <sup>157</sup>Gd) did not have any negative effects in the core and extended the fuel cycle length (Bejmer and Seveborn, 2004). Dalle and others (Dalle *et al.*, 2013) performed simulations using e-Gd<sub>2</sub>O<sub>3</sub> at different weight percentages in the fuel composition and determined that the e-Gd<sub>2</sub>O<sub>3</sub> provides an increased and more stable reactivity in late life fuel compared to n-Gd<sub>2</sub>O<sub>3</sub>. Yilmaz *et al.* replaced n-Gd<sub>2</sub>O<sub>3</sub> with the same amount of e-Gd<sub>2</sub>O<sub>3</sub>. They showed that the same reactivity behaviour in the core can be provided with a lower rate of <sup>235</sup>U enrichment, and thus, they stated that savings in fuel costs can be achieved (Yilmaz *et al.*, 2006).

For a nuclear reactor, it is economically advantageous to load fuel with the highest reactivity potential into the reactor core – within given safety margins, so that the fuel cycle cost can be saved by running the reactor longer(Galahom, 2016). The fuel cycle length can be extended using e-Gd<sub>2</sub>O<sub>3</sub>, due to the reactivity-enhancing effect obtained (Schlieck, Berger and Neufert, 2001). The enrichment process with <sup>157</sup>Gd could be performed with traditional techniques (Santala *et al.*, 1997), but the high cost of these techniques made the BA cost of fuel more expensive than the fuel itself (Renier and Grossbeck, 2001). For instance, the cost of magnetic separation with calutron was \$1000 per gram of Gd however this cost has been reduced using new techniques such as PSP (plasma separation process) (Renier and Grossbeck, 2001). Yilmaz determined that the cost of <sup>157</sup>Gd enrichment with PSP is less than 10 dollars gram/<sup>157</sup>Gd (Yilmaz, 2005).

This study investigates the reactivity properties of e-Gd<sub>2</sub>O<sub>3</sub> BA that can be obtained by enriching Gd<sub>2</sub>O<sub>3</sub> with <sup>157</sup>Gd isotopes to eliminate the residual reactivity caused by n-Gd<sub>2</sub>O<sub>3</sub>, and furthermore estimates the financial implications related to assembly cost when incorporating e-Gd<sub>2</sub>O<sub>3</sub>.

## 2. Method

### 2.1. Reactor and fuel modelling

The Serpent 2 Monte Carlo reactor physics code, developed by VTT Technical Research Centre, was used throughout this study (Leppänen *et al.*, 2015). The reactor and assembly level simulation parameters used in the study are shown in Table 1. In this study, it was assumed that the e-Gd<sub>2</sub>O<sub>3</sub>, contains 100 wt.% <sup>157</sup>Gd isotopes after the enrichment process (although it is noted that any enrichment process is likely to leave impurity isotopes) in order to assess the maximum impact of using e-Gd<sub>2</sub>O<sub>3</sub> versus n-Gd<sub>2</sub>O<sub>3</sub>.

Tuble 1.1 urumeters used in S	erpent 2 simulations
Reactor Type	PWR
Number of BA rods	24
Fuel temperature (K)	900
Cladding Temperature (K)	583
Fuel density	95%
Neutron population	30000
(neutrons per cycle)	
Cycles (active/inactive)	300 / 20

Table 1. Parameters used in Serpent 2 simulations.

A range of simulations were carried out to identify designs where  $n-Gd_2O_3$  and  $e-Gd_2O_3$  show similar reactivity characteristics (matching both  $k_{inf}$  and the burnup at which the peak point reactivity occurs). The enrichment of <sup>235</sup>U considered throughout the paper ranges from 3 wt.% to 6%, capturing some potential effects of extending the commercially available enrichment for light water reactors to beyond 5 wt.%. Fuel densities of the models mentioned in this paper were calculated by using data from (IAEA, 1995) and are provided in appendix Table A1.

### 2.2 Reference fuel design

This study was based on the AP-1000 PWR reactor designed by Westinghouse Electric Company and some of its features used while creating the fuel designs in this study are given in Table 2 (Nuclear Regulatory Commission, 2011). The design of the fuel assembly is based on two reference assemblies (see Appendix Fig. A1 and Fig. A2). Although both of the assemblies contain 24 BA rods and 25 control rods, the placement of BA rods differs within the assemblies. The designs of the rods (see Appendix Fig.

A3) is the same for both assemblies. While the fuel in regular rods was UO<sub>2</sub>, BA rods had different proportions of  $Gd_2O_3$  addition as well as UO<sub>2</sub>.

Rod array	17×17
Number of control rods	25
Fuel rod pitch (cm)	1.26
Pellet diameter(cm)	0.819
Rod diameter (cm)	0.949
Cladding material	Zircaloy 4
Cladding thickness(cm)	0.057

Table 2. Fuel design parameters of AP-1000 PWR reactor.

Due to self-shielding effects, it is known that the Gd atoms in the outer layer of the fuel pellet will transmute more rapidly than inner layer as they will absorb neutrons moderated by the coolant water, shielding the gadolinium atoms in the inner portions of the pellet (Pagano *et al.*, 2008). To observe the depletion behaviour of the Gd isotopes in the fuel pellets as a function of radius, the concentration of Gd isotopes in 11 radial layers of equal volume, from the centre of the fuel pellet to the surface was investigated. This method was also carried out to observe changes in <sup>239</sup>Pu breeding. In the study, the reactivity error margins observed for all models varied between approximately 15 to 21 pcm (1 pcm =  $10^{-5}$ ), too small to be of consequence to our results.

### 2.3 Cost calculations

Calculation of the fuel cycle cost is made by considering the unit costs of all components within the cycle. In addition to the performance related calculations, the economic impact of using  $e-Gd_2O_3$  is investigated in terms of its impact on assembly cost by considering the uranium purchase, conversion, enrichment, and fabrication costs.

In calculations, unit prices were calculated to be low, medium, and high to reflect uncertain fluctuations in unit costs that may occur (Ko and Gao, 2012) and unit costs taken from the literature for these calculations are given in appendix Table A2. The calculation of fuel cost formulas as specified by OECD / NEA were used in this study (*The Economics of the Nuclear Fuel Cycle*, 1994) with updated values. An example of the formula used to calculate the cost of each item is given in Eq.1. In this formula,  $X_i$  is the amount of product processed,  $f_i$  is loss factor of operation,  $P_i$  is the per unit cost,  $S_i$  is the escalation rate, t is time and  $t_b$  is the base date of monetary unit.

$$F_i = X_i \times f_i \times P_i \times (1 + S_i)^{t - t_b}$$
(Eq. 1)

On the other hand, <sup>157</sup>Gd enrichment cost was calculated with the Eq. 2 (Yilmaz, 2005) while the purchase cost of BA, was calculated with the Eq. 3. The purchase cost of BA was not included to the fuel fabrication cost and was calculated as a separate item in order to show the difference between  $n-Gd_2O_3$  and  $e-Gd_2O_3$  more clearly.

$F_{Gd\ enrichment} = M_{Gd} \times P_{er}$	$_{1} \times 1000$	(Eq. 2)
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$$F_{\rm Gd\ purchasing} = M_{Gd} \times P_{Gd} \tag{Eq. 3}$$

Where  $M_{Gd}$  is the mass of Gd<sub>2</sub>O<sub>3</sub> used in assembly,  $P_{en}$  is the <sup>157</sup>Gd enrichment cost of per gram Gd<sub>2</sub>O<sub>3</sub>, and  $P_{Gd}$  is the purchase cost of per kilogram Gd<sub>2</sub>O<sub>3</sub>.

The total cost of fuel per assembly is obtained by summing each cost item. All formulae related to cost calculations can be found in Appendix A. In addition, while the parameters of the formulas are given in

appendix Table A3, the fuel cycle data required for the calculation of costs are given in appendix Table A4.

### 3. Results and discussion

### 3.1. Assembly design and <sup>235</sup>U enrichment

Fig. 2 shows the  $k_{inf}$  of different n-Gd<sub>2</sub>O<sub>3</sub> additions to the two assembly designs A1 and A2 highlighting that small changes in the location of the BA rods within the fuel assembly do not cause a significant effect on the overall reactivity behaviour within the assembly. As expected, the larger addition of n-Gd<sub>2</sub>O<sub>3</sub> causes a larger suppression in  $k_{inf}$  and also shifts the peak point reactivity towards higher burnups. As a result of these behavioural trends, all subsequent simulations were performed using the A1 assembly layout.



Fig. 2 Infinite multiplication constant ( $k_{inf}$ ) for 5 wt.% <sup>235</sup>U with no BA, and 1.00 wt.%, and 4.00 wt.% n-Gd<sub>2</sub>O<sub>3</sub> in two different assembly layouts (A1 and A2).

Fig. 3 shows the multiplication factor ( $k_{inf}$ ) trends in models with different <sup>235</sup>U enrichment levels in assembly A1 (with 2.00 wt.% n-Gd<sub>2</sub>O<sub>3</sub> BA rods). As expected, the total reactivity increases due to the increasing <sup>235</sup>U content. For each enrichment value, BA-containing models have a lower multiplication factors at the beginning of cycle (i.e. they are suppressed). As burnup proceeds, the multiplication factor rises until the <sup>155</sup>Gd and <sup>157</sup>Gd isotopes are mostly depleted (see Fig A4). With the depletion of these isotopes, the full fissile content of the assembly is exposed and begins depleting with multiplication factors of the assemblies declining again in close proximity to the reactivity curve of the reference model without BA additions.



Fig. 3 Burnup behaviour of models containing 4 wt.%, 5 wt.% and 6 wt.%  $^{235}\text{U}$  and 2.00 wt.%  $Gd_2O_3$  and their reference models without BA.

It is also noticeable that after the depletion of Gd isotopes (i.e. beyond ~10 MWd/kgU), there is a slight decrease in the reactivity of BA using assemblies compared to those without BA – this is the residual reactivity suppression. In addition, because  $^{235}$ U is also a neutron absorber, with increasing concentration of  $^{235}$ U in the fuel composition, the depletion of Gd isotopes is delayed and these results agree with those of Dalle and others (Dalle *et al.*, 2013). For all subsequent calculations in the main body of this article, 5 wt.%  $^{235}$ U enrichment of the UO<sub>2</sub> is utilized as the general behaviour is expected to be similar.

Simulations were performed to investigate the differences in reactivity behaviour occurring when equal amounts of  $n-Gd_2O_3$  and  $e-Gd_2O_3$  are used in BA rods. Fig. 4 compares reactivity behaviour of model fuels with 1.00 wt.% of  $n-Gd_2O_3$  and 1.00 wt.% of  $e-Gd_2O_3$ , both with 5 wt.% <sup>235</sup>U enrichment. As can be seen, the reactivity is suppressed in the  $e-Gd_2O_3$  and flattened compared to that with  $n-Gd_2O_3$  addition. The cause of this behaviour can be traced to the greater amount of <sup>157</sup>Gd in the  $e-Gd_2O_3$  assembly. Also, the burn of <sup>155</sup>Gd in the  $n-Gd_2O_3$  pellet burns away more slowly compared to <sup>157</sup>Gd\_(see Fig. A4)-, a result of the lower neutron capture cross section. The suppression of the reactivity in the  $e-Gd_2O_3$  assembly is significantly stronger and remains absorbing for longer than when  $n-Gd_2O_3$  is used, results that are in agreement with (Renier and Grossbeck, 2001).



Fig. 4 Infinite multiplication constant (*k*<sub>inf</sub>) as a function of burnup for model fuels with 5 wt.% <sup>235</sup>U and 1.00 wt.% n-Gd<sub>2</sub>O<sub>3</sub>, 5 wt.% <sup>235</sup>U and 1.00 wt.% e-Gd<sub>2</sub>O<sub>3</sub>, and fuel model with 5 wt.% <sup>235</sup>U and without BA.

Based on these results, we now investigate how a lower amount of  $e-Gd_2O_3$  can be utilized to provide a similar (or enhanced) reactivity suppression compared to  $n-Gd_2O_3$ .

# 3.2. Comparison natural $Gd_2O_3$ and enriched $Gd_2O_3$ showing similar reactivity behaviours

### 3.2.1. Reactivity behaviour

Three matches with similar peak reactivity behaviour (Fig. 5a, 5b and 5c) and another three matches with equal highest reactivity rates (Fig 5d, 5e and 5f) for  $n-Gd_2O_3$  and  $e-Gd_2O_3$  in fuels were identified and further examined.



Fig. 5. Infinite multiplication constant for (a) 2.00 wt.% n-Gd<sub>2</sub>O<sub>3</sub>, and 0.65 wt.% e-Gd<sub>2</sub>O<sub>3</sub>, (b) 4.00 wt.% n-Gd<sub>2</sub>O<sub>3</sub>, and 1.10 wt.% e-Gd<sub>2</sub>O<sub>3</sub>, (c) 6.00 wt.% n-Gd<sub>2</sub>O<sub>3</sub>, and 1.55 wt.% e-Gd<sub>2</sub>O<sub>3</sub> (d) 2.00 wt.% n-Gd<sub>2</sub>O<sub>3</sub>, and 0.85 wt.% e-Gd<sub>2</sub>O<sub>3</sub>, (e) 4.00 wt.% n-Gd<sub>2</sub>O<sub>3</sub>, and 1.45 wt.% e-Gd<sub>2</sub>O<sub>3</sub> (f) 6.00 wt.% n-Gd<sub>2</sub>O<sub>3</sub>, and 2.00 wt.% e-Gd<sub>2</sub>O<sub>3</sub>.

When designs with similar peak reactivity behaviour (Fig. 5a, 5b and 5c) are examined, assemblies where  $e-Gd_2O_3$  was used are more suppressed at the beginning of the cycle for the two lower Gd contents considered (Figs. 5a and 5b). From low-to-intermediate burnups (~5MWd/kgU),  $e-Gd_2O_3$  provides a higher reactivity compared to the n-Gd<sub>2</sub>O<sub>3</sub> for the rest of the cycle. Of significance, for the composition

containing the highest e-Gd<sub>2</sub>O<sub>3</sub> content (Fig. 5c), the e-Gd<sub>2</sub>O<sub>3</sub> assembly provided a higher reactivity than n-Gd<sub>2</sub>O<sub>3</sub> throughout the cycle.

In Figures 5a-5c, assemblies with e-Gd<sub>2</sub>O<sub>3</sub> have higher peak  $k_{inf}$  values than models having n-Gd<sub>2</sub>O<sub>3</sub> and then follow the no-BA  $k_{inf}$  values efficiently for the rest of the operation. The increase in  $k_{inf}$  can be explained by two important factors for these matching models: (1) an absence of Gd isotopes that have low neutron absorption cross-section but transmute and cause residual reactivity in the composition of e-Gd<sub>2</sub>O<sub>3</sub>; (2) use of lower amounts of Gd<sub>2</sub>O<sub>3</sub> when utilizing e-Gd<sub>2</sub>O<sub>3</sub>, which reduces the BA percentage in the fuel composition, to achieve a similar reactivity behaviour to n-Gd<sub>2</sub>O<sub>3</sub>, thus resulting in a lower amount of UO<sub>2</sub> displacement.

On the other hand, when designs with equal highest reactivity rates are examined in Figs. 5d-5f, assemblies incorporating  $e-Gd_2O_3$  suppress the reactivity more than  $n-Gd_2O_3$  from the beginning of the cycle until the Gd isotopes are completely depleted in the assembly. However,  $e-Gd_2O_3$  provides higher reactivity in the rest of the cycle (beyond the BA burn-out). This increase in the rest of the cycle can be explained by the absence of isotopes in the fuel composition that causes residual reactivity and the higher fissile U loading due to the use of lower volume of BA, as also observed in models with matching peak reactivity behaviour.

The reactivity differences ( $\Delta k_{inf}$ ) between the models with n-Gd<sub>2</sub>O<sub>3</sub> and e-Gd<sub>2</sub>O<sub>3</sub> in Fig. 5 are reported in Fig. 6, in units of pcm. As noted earlier, the e-Gd<sub>2</sub>O<sub>3</sub> reactivity is suppressed compared to n-Gd<sub>2</sub>O<sub>3</sub> during early stages of irradiation. To calculate the difference that e-Gd<sub>2</sub>O<sub>3</sub> will cause on the total reactivity, accumulated reactivity gain for each match also was computed (see Fig. A5). For matching of similar peak reactivity behaviours, the use of e-Gd<sub>2</sub>O<sub>3</sub> provides a higher total reactivity gain than the amount reduced at the beginning of life in the matches reported in Fig. 5a (2.00 wt.% n-Gd<sub>2</sub>O<sub>3</sub> and 0.65 wt.% e-Gd<sub>2</sub>O<sub>3</sub>) and Fig. 5b (4.00 wt.% n-Gd<sub>2</sub>O<sub>3</sub> and 1.10 wt.% e-Gd<sub>2</sub>O<sub>3</sub>). The assemblies shown in Fig 5c (6.00 wt.% n-Gd<sub>2</sub>O<sub>3</sub> compared to 1.55 wt.% e-Gd<sub>2</sub>O<sub>3</sub>) show a reactivity benefit from the beginning of life. These values indicate that the comparative benefit of reactivity increases with increasing amount of burnable absorber added to the assembly.

On the other hand, in the matches reported in Figures 5d and 5e, with equal highest reactivity rates, e- $Gd_2O_3$  reduces the reactivity at the beginning of the cycle more than the gain in  $k_{inf}$  provided at the late of the cycle. The situation changes in Figure 5f, and e- $Gd_2O_3$  provides a higher reactivity gain in the rest of the cycle than the amount reduced at the beginning of the cycle. This will have a subsequent impact on the cost of an assembly (see Section 3.4).



Fig. 6 Delta- $k_{inf}$  for (a) 2.00 wt.% n-Gd<sub>2</sub>O<sub>3</sub>, and 0.65 wt.% e-Gd<sub>2</sub>O<sub>3</sub>, (b) 4.00 wt.% n-Gd<sub>2</sub>O<sub>3</sub>, and 1.10 wt.% e-Gd<sub>2</sub>O<sub>3</sub>, (c) 6.00 wt.% n-Gd<sub>2</sub>O<sub>3</sub>, and 1.55 wt.% e-Gd<sub>2</sub>O<sub>3</sub>, (d) 2.00 wt.% n-Gd<sub>2</sub>O<sub>3</sub>, and 0.85 wt.% e-Gd<sub>2</sub>O<sub>3</sub>, (e) 4.00 wt.% n-Gd<sub>2</sub>O<sub>3</sub>, and 1.45 wt.% e-Gd<sub>2</sub>O<sub>3</sub>, (f) 6.00 wt.% n-Gd<sub>2</sub>O<sub>3</sub>, and 2.00 wt.% e-Gd<sub>2</sub>O<sub>3</sub>

Fig. 7 summarises the patterns obtained after similar reactivity characteristics (similar peak reactivity behaviours and equal highest reactivity rates) were detected in the investigation of models containing 1.00 to 6.00 wt.% n-Gd<sub>2</sub>O<sub>3</sub> and 0.30 to 2.00 wt.% e-Gd<sub>2</sub>O<sub>3</sub> in 3 wt.%, 4 wt.% 5% and 6 wt.% UO<sub>2</sub> fuel.



Fig. 7. Graph summarising n-Gd<sub>2</sub>O<sub>3</sub> and e-Gd<sub>2</sub>O<sub>3</sub> models with similar reactivity characteristics in fuels with different <sup>235</sup>U enrichment levels: (a) matches with similar peak reactivity behaviour and (b) matches with equal highest reactivity rates.

Considering patterns in Fig. 7, two different equations were obtained to estimate the approximate  $Gd_2O_3$  level in the assembly that will provide a similar behaviour to  $n-Gd_2O_3$  when considering: the assembly's peak reactivity behaviours match (in Eq. 4), and when the assembly's highest reactivity rate (in Eq. 5).

$$M1_{e-Gd_2O_3} = 0.2917 \times M_{n-Gd_2O_3}$$
(Eq. 4)

$$M2_{e-Gd_2O_3} = 0.4167 \times M_{n-Gd_2O_3}$$
(Eq. 5)

Where  $M_{n-Gd_2O_3}$  is the mass of n-Gd<sub>2</sub>O<sub>3</sub>,  $M1_{e-Gd_2O_3}$  is the mass of e-Gd<sub>2</sub>O<sub>3</sub> required to match peak reactivity with n-Gd<sub>2</sub>O<sub>3</sub>, and  $M2_{e-Gd_2O_3}$  is the mass of e-Gd<sub>2</sub>O<sub>3</sub> required to match highest reactivity with n-Gd<sub>2</sub>O<sub>3</sub>.

### 3.2.2. Depletion behaviour of Gd isotopes

Fig 8 shows the Gd isotope depletion behaviour of the 1.55 wt.%  $e-Gd_2O_3$ , and 6 wt.%  $n-Gd_2O_3$ , reported in Fig 5. The <sup>157</sup>Gd isotopes in  $e-Gd_2O_3$  are depleted faster than the <sup>155</sup>Gd in  $n-Gd_2O_3$ . Similar behaviour was detected for all comparable  $e-Gd_2O_3/n-Gd_2O_3$  systems (i.e. those reported in Fig. 5).



Fig. 8 Depletion of <sup>155</sup>Gd and <sup>157</sup>Gd isotopes in model has 1.55 wt.% e-Gd<sub>2</sub>O<sub>3</sub>, and 6.00 wt.% n-Gd<sub>2</sub>O<sub>3</sub>.

The averaged depletion behaviour of <sup>155</sup>Gd and <sup>157</sup>Gd isotopes in  $n-Gd_2O_3$  (see Fig A6a and A6b) and <sup>157</sup>Gd isotopes in  $e-Gd_2O_3$  (see Fig A6c) for 24 BA rods in models with 4.00 wt.%  $n-Gd_2O_3$  and 1.10 wt.%  $e-Gd_2O_3$  were exterminated. The results show that, the effect of self-shielding on the depletion of Gd isotopes is clear because, as expected, both <sup>155</sup>Gd and <sup>157</sup>Gd isotopes are depleted at the pellet surface faster than at the pellet centre.

### 3.2.3. Breeding behaviour of <sup>239</sup>Pu isotopes

To understand if the inclusion of e-Gd<sub>2</sub>O<sub>3</sub> in the assembly could impact the breeding of <sup>239</sup>Pu, potentially providing a benefit to  $k_{inf}$ , the formation of <sup>239</sup>Pu is considered and compared to designs with n-Gd<sub>2</sub>O<sub>3</sub>. Fig. 9 shows the delta-<sup>239</sup>Pu functions obtained by comparing the three chosen models against the reference assembly model without BA rods.

It was shown that in the well-moderated and homogeneous geometry of a PWR, an increase in  $^{239}$ Pu results from an increase in BA within the assembly with both n-Gd<sub>2</sub>O<sub>3</sub> and e-Gd<sub>2</sub>O<sub>3</sub>. In addition, the use of e-Gd<sub>2</sub>O<sub>3</sub> promoted more  $^{239}$ Pu breeding when compared to n-Gd<sub>2</sub>O<sub>3</sub>, which exhibits similar reactivity properties. It is also clear that models matched with n-Gd<sub>2</sub>O<sub>3</sub> according to the equal highest reactivity caused higher  $^{239}$ Pu breeding than models matched with similar peak reactivity behaviour. The increase in  $^{239}$ Pu may provide additional reactivity during operation, thus contributing towards the higher  $k_{inf}$  later in life in the e-Gd<sub>2</sub>O<sub>3</sub> assemblies.



Fig. 9. Excess <sup>239</sup>Pu breeding (a) with n-Gd<sub>2</sub>O<sub>3</sub> and e-Gd<sub>2</sub>O<sub>3</sub> matches with similar peak reactivity behaviour and, (b) with n-Gd<sub>2</sub>O<sub>3</sub> and e-Gd<sub>2</sub>O<sub>3</sub> matches with equal highest reactivity rates, as compared with the reference without BA.

As is expected, a higher burnup was obtained on the pellet surface than the centre in fuel rods with BA due to self-shielding effects. Following this, the <sup>239</sup>Pu mass density measurements were taken from BA rods with 4.00 wt.% n-Gd<sub>2</sub>O<sub>3</sub> and 1.25 wt.% e-Gd<sub>2</sub>O<sub>3</sub> to determine if the use of e-Gd<sub>2</sub>O<sub>3</sub> caused any changes to <sup>239</sup>Pu breeding behaviour within the fuel pellets. It was shown that e-Gd<sub>2</sub>O<sub>3</sub> does not cause significant changes (see Fig. A7), and in both fuel models the amount of <sup>239</sup>Pu increases from the pellet centre towards the pellet surface and peaks at the surface.

### 3.4. Cost assessment

The matching set of models that have similar peak reactivity behaviour (see Figs. 5a, 5b and 5c), equal highest reactivity rates (see Figs. 5d, 5e and 5f) were evaluated from an economic perspective. Since the use of  $e-Gd_2O_3$  enables use of more  $UO_2$  in the fuel composition, there is an increase in fuel cost in all components directly or indirectly related to uranium (i.e. the cost of uranium, conversion, and enrichment). For the nominal costs, while the highest component cost for all models is cost of uranium enrichment, the lowest is purchasing the BA.

Comparing the costs for the set with the lowest additions of  $Gd_2O_3$  with 2.00 wt.% n-Gd\_2O\_3 and 0.65 wt.% e-Gd\_2O\_3 (see Table A5), each assembly containing e-Gd\_2O\_3 is nominally ~ 6.1 kUSD more expensive than the model with n-Gd\_2O\_3 (this cost varies between ~4.1 kUSD and ~10 kUSD). For the models with 4.00 wt.% n-Gd\_2O\_3 and 1.10 wt.% e-Gd\_2O\_3 (see Table A6), each assembly containing e-Gd\_2O\_3 is nominally ~11.5 kUSD more expensive than those with n-Gd\_2O\_3 (this cost varies between ~7.7 kUSD and ~19.4 kUSD). For the models with 6.00 wt.% n-Gd\_2O\_3 and 1.55 wt.% e-Gd\_2O\_3 (see Table A7), each assembly containing e-Gd\_2O\_3 is nominally ~16.8 kUSD more expensive than those with n-Gd\_2O\_3 and this cost varies between ~11.1 kUSD and ~28.6 kUSD depending on the lowest and highest unit prices in the sensitivity range.

On the other hand, comparing the costs for models with 2.00 wt.%  $n-Gd_2O_3$  and 0.85 wt.%  $e-Gd_2O_3$  (see Table A8), each assembly containing  $e-Gd_2O_3$  is nominally ~ 6.9 kUSD more expensive than those with  $n-Gd_2O_3$  (this cost varies between ~4.5 kUSD and ~10.9 kUSD). For the models with 4.00 wt.%  $n-Gd_2O_3$  and 1.45 wt.%  $e-Gd_2O_3$  (see Table A9), each assembly containing  $e-Gd_2O_3$  is nominally ~12.8 kUSD more expensive than those with  $n-Gd_2O_3$  (this cost varies between ~8.7 kUSD and ~20.7 kUSD). For the models with 6.00 wt.%  $n-Gd_2O_3$  and 2.00 wt.%  $e-Gd_2O_3$  (see Table A10), each assembly containing  $e-Gd_2O_3$  is nominally ~18.5 kUSD more expensive than the model has  $n-Gd_2O_3$  and this cost varies between ~12.5 kUSD and ~30.0 kUSD depending on the lowest and highest unit prices in the sensitivity range.

The benefits of the e-Gd2O3 with respect to the integral reactivity is clear for the cases presented in Fig 5a-c and e. In addition to this benefit, there is an additional performance improvement when considering the mid-cycle and end of life reactivity compared to n-Gd<sub>2</sub>O<sub>3</sub> in all cases in Fig 5. The reactivity benefit at the end of life can be estimated in terms of an extension of burnup for a given reactivity. For example, in Figure 5f, at a reactivity of kinf=1.1, the e-Gd<sub>2</sub>O<sub>3</sub> has a larger burnup value of 23.9 MWd/kgU vs 22.9 MWd/kgU (equivalent to 2%). This 2% increase over the lifetime of a fuel (typically 54 months) equates to approximately 33 days of excess operation. Even though the assembly cost is ~18.5kUSD higher than the n-Gd<sub>2</sub>O<sub>3</sub> assembly, this will manifest as an improvement to fuel cycle cost when considered in further full core analysis. Applying the same scenario with fuel models given in Fig 5d, with the use of e-Gd<sub>2</sub>O<sub>3</sub> instead of n-Gd<sub>2</sub>O<sub>3</sub>, an extension of 0.7%, roughly equating to 11 days over its reactor residence period, more than making up for its small increase in cost per assembly of ~6.9kUSD and benefiting the overall levelized cost of electricity (LCOE). Further work building upon these results will be carried out considering the full core, multi-cycle behaviour.

### 4. Conclusion

The operational effect of  $Gd_2O_3$  enriched with <sup>157</sup>Gd isotopes has been studied. The impact of  $e-Gd_2O_3$  compared to  $n-Gd_2O_3$  has been assessed with respect to reactivity, depletion behaviour of BA and <sup>239</sup>Pu breeding. Some preliminary economic assessments have also been carried out to guide future studies incorporating full-core analysis. The conclusions from this study are as follows:

- In agreement with previous work(Renier and Grossbeck, 2001), utilizing  $e-Gd_2O_3$  can provide a similar reactivity behaviour to  $n-Gd_2O_3$  whilst using a smaller volume of BA. Thus, because a lower proportion of  $Gd_2O_3$  will be added to the fuel composition, lower proportion of  $UO_2$  is displaced from the fuel providing higher reactivity.
- Also, in agreement with previous work(Renier and Grossbeck, 2001), the use of e-Gd<sub>2</sub>O<sub>3</sub> provides a reduction in the amount of Gd isotopes that cause residual reactivity, from the fuel matrix, resulting in cleaner burn of the BA in fuel.
- Pairing the  $n-Gd_2O_3$  and  $e-Gd_2O_3$  by correlating peak reactivity behaviour, the use of  $e-Gd_2O_3$  allows to obtain higher reactivity than  $n-Gd_2O_3$ . The amount of gained-reactivity rises significantly with the increase in  $n-Gd_2O_3$  /  $e-Gd_2O_3$  ratio.
- Pairing the  $n-Gd_2O_3$  and  $e-Gd_2O_3$  when considering the equal highest reactivity,  $e-Gd_2O_3$  provides the same total reactivity only with high proportions of BA in the fuel composition.
- At high Gd contents, e-Gd<sub>2</sub>O<sub>3</sub> is found to outperform n-Gd<sub>2</sub>O<sub>3</sub> in terms of reactivity gains over the irradiation life of the fuel also in the case with equal highest reactivity; this provides a means for designing modern fuel assemblies for high burnup duty.
- Depletion of BA isotopes in the fuel is prevented as a result of the self-shielding effect, which is exacerbated by the increase of <sup>235</sup>U increasing the amount of neutron absorbing atoms in the fuel composition as a result of using e-Gd<sub>2</sub>O<sub>3</sub>.
- The rate of <sup>239</sup>Pu breeding reaches highest concentration where BA isotopes are depleted and the e-Gd<sub>2</sub>O<sub>3</sub> produces a slightly higher amount of <sup>239</sup>Pu than the n-Gd<sub>2</sub>O<sub>3</sub> ratio. In addition, the amount of <sup>239</sup>Pu increases from the centre of the fuel pellet to its surface and this increase shows an expected peak at the surface. The slight increase in <sup>239</sup>Pu content may provide an additional increase in  $k_{inf}$  during operation of fuel containing e-Gd<sub>2</sub>O<sub>3</sub>.
- In the scenarios considered, the use of  $e-Gd_2O_3$  increases the cost of the assembly due to the cost of enrichment process of  $Gd_2O_3$  but predominantly as a result of the increased use of

 $UO_2$  in fuel composition. Also, the use of e-Gd<sub>2</sub>O<sub>3</sub> can promote the acquisition of the reactivity properties exhibited by n-Gd<sub>2</sub>O<sub>3</sub>, with lower enrichment of uranium. Savings may be possible if using e-Gd<sub>2</sub>O<sub>3</sub> to lower the enrichment of <sup>235</sup>U in fresh fuel as previously discussed by (Yilmaz, 2005).

• In this context, the number of effective full power days of reactor operation can be increased due to the increase in  $k_{inf}$  in a number of the scenarios considered. Thus, the total fuel cycle duration can be prolonged with the use of e-Gd<sub>2</sub>O<sub>3</sub>.

Further work, using 3D core analysis of the full reactor, is necessary to determine shutdown and thermal margins, as well as to calculate the levelized cost of electricity for the fuel cycle or plant lifetime for estimation of a realistic profit margins, but this study highlights the potential economic and performance benefits that moving towards e-Gd<sub>2</sub>O<sub>3</sub> can provide.

### Acknowledgements

The authors would like to thank, Ministry of National Education of the Turkish Republic. SCM, MD and WEL are funded through the Sêr Cymru II programme by Welsh European Funding Office (WEFO) under the European Development Fund (ERDF). We also acknowledge the support from the VTT Technical Research Centre of Finland and the OECD NEA Data Bank for providing access to Serpent 2. We also acknowledge the BEIS funded Advanced Fuel Cycle Programme led by NNL for their contribution and Dave Goddard is especially thanked for his support. In this study, all calculations were made on Supercomputing Wales.

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### Appendix A

Fuel densities used in simulations are shown in Table A1.

Table A1. Fuel densities (wt.%)				
Fuel Composition	Density (gr/cm <sup>3</sup> )			
3 wt.% <sup>235</sup> U	10.408			
4 wt.% <sup>235</sup> U	10.407			
5 wt.% <sup>235</sup> U	10.406			
6 wt.% <sup>235</sup> U	10.404			
4 wt.% $^{235}$ U + 2.00 wt.% n-Gd <sub>2</sub> O <sub>3</sub>	10.341			
5 wt.% $^{235}$ U + 1.00 wt.% n-Gd <sub>2</sub> O <sub>3</sub>	10.373			
5 wt.% $^{235}$ U + 2.00 wt.% n-Gd <sub>2</sub> O <sub>3</sub>	10.340			
5 wt.% $^{235}$ U + 4.00 wt.% n-Gd <sub>2</sub> O <sub>3</sub>	10.273			
5 wt.% $^{235}$ U + 6.00 wt.% n-Gd <sub>2</sub> O <sub>3</sub>	10.207			
6 wt.% $^{235}$ U + 2.00 wt.% n-Gd <sub>2</sub> O <sub>3</sub>	10.338			
5 wt.% $^{235}$ U + 0.65 wt.% e-Gd <sub>2</sub> O <sub>3</sub>	10.384			
5 wt.% $^{235}$ U + 0.85 wt.% e-Gd <sub>2</sub> O <sub>3</sub>	10.378			
5 wt.% $^{235}$ U + 1.00 wt.% e-Gd <sub>2</sub> O <sub>3</sub>	10.373			
5 wt.% $^{235}$ U + 1.10 wt.% e-Gd <sub>2</sub> O <sub>3</sub>	10.369			
5 wt.% $^{235}$ U + 1.45 wt.% e-Gd <sub>2</sub> O <sub>3</sub>	10.358			
5 wt.% $^{235}$ U + 1.55 wt.% e-Gd <sub>2</sub> O <sub>3</sub>	10.354			
5 wt.% $^{235}$ U + 2.00 wt.% e-Gd <sub>2</sub> O <sub>3</sub>	10.340			

Fuel assembly designs used in simulations are given in Fig. A.1 and Fig. A.2.



Fig. A2 Assembly 2 (24 BA rods) (Uguru et al., 2020)

Fuel rod design used in simulations is shown in Fig. A3.



Fig A1. Fuel rod cross section

Unit prices used for fuel cost calculation are shown in Table A2.

T IIIId2, 2003)				
Type of component	Unit Prices			
Type of component	Low	Nominal	High	
uranium \$/lb U <sub>3</sub> O <sub>8</sub>	13.1	33.1	114	
conversion \$/kg	6.5	13	19	
Uranium enrichment \$/SWU	97	128	154	
fabrication \$/kg	230	400	575	
Gd <sub>2</sub> O <sub>3</sub> \$/kg*	255	397	516	
<sup>157</sup> Gd enrichment \$/g*	7.4	10	13.6	

Table A2. Unit prices for each component (Asou and Porta, 1997; U.S. department of Energy, 2017; Yilmaz, 2005)

\* High and low unit costs were obtained by assuming that the nominal cost regularly increased and decreased by average USA escalation rate in the period from the year it was stated in the literature to 2020.

Equations used for fuel cost calculation are as follows(*The Economics of the Nuclear Fuel Cycle*, 1994) and the parameters are given in Table A3.

### Cost of uranium

$F_1 = M_f \times f_1 \times P_1 \times (1 + S_1)^{t-t_b}$	(Eq. A1)
where: $M_f = \frac{e_p - e_t}{e_f - e_t} \times M_p$	(Eq. A2)
$f_1 = (1 + l2) \times (1 + l3) \times (1 + l4)$	(Eq. A3)

From all front-end components:  

$$t = t_c - t_b$$
 (Eq. A4)

### Cost of conversion

$$F_2 = M_f \times f_2 \times P_2 \times (1 + S_2)^{t - t_b}$$
 (Eq. A5)

where:

$$f_2 = (1 + l2) \times (1 + l3) \times (1 + l4)$$
 (Eq. A6)

### **Cost of enrichment**

$$F_3 = SWU \times f_3 \times P_3 \times (1 + S_3)^{t-t_b}$$
(Eq. A7)  
where:  
$$SWU = M_n V_n + M_t V_t - M_f V_f$$
(Eq. A8)

$$VO = M_p v_p + M_t v_t - M_f v_f$$
 (Eq. A6)

$$M_t = M_f - M_p \tag{Eq. A9}$$

$$V_{\chi} = (2e_{\chi} - 1) \times \ln \frac{e_{\chi}}{(1 - e_{\chi})}$$
(Eq. A9)

x is subscript for f, p or t

$$f_3 = (1 + l3) \times (1 + l4)$$
 (Eq. A10)

**Cost of fabrication** 

$F_4 = M_f \times f_4 \times P_4 \times (1 + S_4)^{t - t_b}$	(Eq. A11)
where:	
$f_4 = (1 + l4)$	(Eq. A12)

Table A3. Parameter nota	tion for fuel	cost calculations
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Time	t
Base date of monetary unit	t <sub>b</sub>
Date of fuel loading	t <sub>c</sub>
Mass of uranium feed (kg)	$M_{\mathrm{f}}$
Mass of uranium charged in reactor (kg)	M <sub>p</sub>
Mass of uranium in the tails (kg)	Mt
Fraction of <sup>235</sup> U in the uranium feed	$e_{f}(0.711\%)$
Fraction of <sup>235</sup> U charged in reactor	e <sub>p</sub>
Fraction of <sup>235</sup> U in the tails	et
Conversion factor from kg U to lb U <sup>3</sup> O <sup>8</sup>	a (2.6)
(a lb U3O8 per kg U)	
Total component cost	Fi
Unit cost	Pi
Escalation rate	Si
Material losses	li
Total loss factor	fi
Lead or lag time	ti

Where:

i = 1	Uranium purchase	$\mathbf{P}_1 =$	Monetary units per lb U <sub>3</sub> O <sub>8</sub>
i = 2	Conversion	$P_2 =$	Monetary units per kg U
i = 3	Enrichment	$P_3 =$	Monetary units per SWU
i = 4	Fabrication	$\mathbf{P}_4 =$	Monetary units per kg U

Fuel cycle data used for fuel cost calculation are shown in Table A4.

Table A4. Fuel cycle data (Forsberg, 2011; The Economics of the Nuclear Fuel Cycle, 1994)

Lead time of uranium purchase	24 months
Lead time of conversion	18 months
Lead time of Uranium enrichment	12 months
Lead time of fabrication	6 months
Material loss during conversion (%)	0.2
Material loss during enrichment (%)	0.2
Material loss during fabrication (%)	0.2
Tails assay (%)	0.25
Escalation rate (1.9)	1.9

Depletion behaviours for <sup>155</sup>Gd and <sup>157</sup>Gd isotopes of models with different <sup>235</sup>U enrichment levels are shown in Fig A4.



Fig. A4. Depletion of <sup>155</sup>Gd and <sup>157</sup>Gd isotopes in models have 2.00 wt.% n-Gd<sub>2</sub>O<sub>3</sub> and different <sup>235</sup>U enrichment levels

Accumulated reactivity gain, provided by e-Gd<sub>2</sub>O<sub>3</sub> over n-Gd<sub>2</sub>O<sub>3</sub> with increasing average fuel burnup to 50MWe/kgU, of the models reported in Fig. 5 are shown in Fig. A5.



Fig. A5 - Accumulated reactivity gain provided by e-Gd<sub>2</sub>O<sub>3</sub> over n-Gd<sub>2</sub>O<sub>3</sub> with increasing average fuel burnup to 50MWe/kgU for (a) matches with similar peak reactivity behaviours (b) matches with equal highest reactivity rates (c) matches with equal highest reactivity rates

Fig. 6A shows the depletion behaviour of Gd isotopes from the centre to the surface of the fuel pellets with BA.



Fig. A6. Depletion rates of (a)  ${}^{155}$ Gd in 4.00 wt.% n-Gd<sub>2</sub>O<sub>3</sub>, (b)  ${}^{157}$ Gd in 4.00 wt.% n-Gd<sub>2</sub>O<sub>3</sub> and (c)  ${}^{157}$ Gd in 1.25 wt.% e-Gd<sub>2</sub>O<sub>3</sub>.

Fig. 7A shows the <sup>239</sup>Pu breeding behaviour in the assembly from the centre to the surface of the pellets.



Fig. A7. Total  $^{239}\text{Pu}$  breeding assemblies of models with (a) 4.00 wt.% n-Gd\_2O\_3, and (b) 1.25 wt.% e-Gd\_2O\_3.

	2.00 wt.% n-Gd <sub>2</sub> O <sub>3</sub>		0.65 wt.% e-Gd <sub>2</sub> O <sub>3</sub>			
	Low	Nominal	High	Low	Nominal	High
Cost of uranium	221.64	560.03	1,928.81	222.00	560.93	1,931.90
Cost of conversion	42.70	85.40	124.81	42.77	85.53	125.01
Cost of enrichment	493.64	651.40	783.71	494.43	652.44	784.97
Cost of fabrication	148.54	258.38	371.62	148.97	259.09	372.51
Cost of Gd <sub>2</sub> O <sub>3</sub>	0.28	0.44	0.58	0.09	0.14	0.19
Cost Of <sup>157</sup> Gd enrichment	0.00	0.00	0.00	2.69	3.64	4.95
Cost of total fuel for assembly	906.80	1,555.65	3,209.39	910.95	1,561.79	3,219.49
Cost difference to				4,15	6,14	10,01

Table A5. Single assembly fuel cost comparison of models with 2.00 wt.% n-Gd<sub>2</sub>O<sub>3</sub>, and 0.65 wt.% e-Gd<sub>2</sub>O<sub>3</sub> both in 5 wt.%  $^{235}$ U (all values are provided in kUSD).

Table A6. Single assembly fuel cost comparison of models have 4.00 wt.% n-Gd<sub>2</sub>O<sub>3</sub>, and 1.10 wt.% enriched Gd<sub>2</sub>O<sub>3</sub> both in 5 wt.%  $^{235}$ U (all values are provided in kUSD).

	4.00 wt.% n-Gd <sub>2</sub> O <sub>3</sub>			1.10 wt.% e-Gd <sub>2</sub> O <sub>3</sub>			
	Low	Nominal	High	Low	Nominal	High	
Cost of uranium	221.12	558.70	1,924.23	221.88	560.63	1,930.86	
Cost of conversion	42.60	85.19	124.51	42.74	85.49	124.94	
Cost of enrichment	492.46	649.85	781.85	494.16	652.09	784.55	
Cost of fabrication	147.90	257.33	370.30	148.83	258.86	372.21	
Cost of Gd <sub>2</sub> O <sub>3</sub>	0.57	0.88	1.14	0.16	0.24	0.32	
Cost Of <sup>157</sup> Gd enrichment	0.00	0.00	0.00	4.55	6.15	8.37	
Cost of total fuel for assembly	904.65	1,551.95	3,201.77	912.32	1,563.46	3,221.18	
Cost difference				7.67	11.51	19.41	

Table A7. Single assembly fuel cost comparison of models have 6.00 wt.% n-Gd<sub>2</sub>O<sub>3</sub>, and 1.55 wt.% e-Gd<sub>2</sub>O<sub>3</sub> both in 5 wt.%  $^{235}$ U (all values are provided in kUSD).

	6.00 wt.% n-Gd <sub>2</sub> O <sub>3</sub>			1.55 wt.% e-Gd <sub>2</sub> O <sub>3</sub>		
	Low	Nominal	High	Low	Nominal	High
Cost of uranium	220.60	557.39	1,919.71	221.76	560.33	1,929.83
Cost of conversion	42.50	84.99	124.22	42.72	85.44	124.88
Cost of enrichment	491.31	648.32	780.01	493.90	651.74	784.12
Cost of fabrication	147.28	256.29	368.99	148.68	258.62	371.91
Cost of Gd <sub>2</sub> O <sub>3</sub>	0.84	1.31	1.70	0.22	0.34	0.45
Cost Of <sup>157</sup> Gd enrichment	0.00	0.00	0.00	6.41	8.66	11.78
Cost of total fuel for assembly	902.52	1,548.31	3,194.25	913.69	1,565.13	3,222.86
Cost difference				11.17	16.82	28.61

	2.00 wt.% n-Gd <sub>2</sub> O <sub>3</sub>			0.85 wt.% e-Gd <sub>2</sub> O <sub>3</sub>			
	Low	Nominal	High	Low	Nominal	High	
Cost of uranium	221.64	560.03	1,928.81	221.95	560.80	1,931.45	
Cost of conversion	42.70	85.40	124.81	42.76	85.51	124.98	
Cost of enrichment	493.64	651.40	783.71	494.31	652.29	784.78	
Cost of fabrication	148.54	258.38	371.62	148.91	258.99	372.38	
Cost of Gd <sub>2</sub> O <sub>3</sub>	0.28	0.44	0.58	0.12	0.19	0.25	
Cost Of <sup>157</sup> Gd enrichment	0.00	0.00	0.00	3.52	4.76	6.47	
Cost of total fuel for assembly	906.80	1,555.65	3,209.39	911.57	1,562.54	3,220.26	
Cost difference to				4.47	6.89	10.87	

Table A8. Single assembly fuel cost comparison of models have 2.00 wt.% n-Gd<sub>2</sub>O<sub>3</sub>, and 0.85 wt.% e-Gd<sub>2</sub>O<sub>3</sub> both in 5 wt.%  $^{235}$ U (all values are provided in kUSD).

Table A9. Single assembly fuel cost comparison of models have 4.00 wt.%  $n-Gd_2O_3$ , and 1.45 wt.%  $e-Gd_2O_3$  both in 5 wt.%  $^{235}U$  (all values are provided in kUSD).

	4.00 wt.% n-Gd <sub>2</sub> O <sub>3</sub>			1.45 wt.% e-Gd <sub>2</sub> O <sub>3</sub>		
	Low	Nominal	High	Low	Nominal	High
Cost of uranium	221.12	558.70	1,924.23	221.79	560.40	1,930.07
Cost of conversion	42.60	85.19	124.51	42.73	85.45	124.89
Cost of enrichment	492.46	649.85	781.85	493.96	651.82	784.22
Cost of fabrication	147.90	257.33	370.30	148.71	258.67	371.98
Cost of Gd <sub>2</sub> O <sub>3</sub>	0.57	0.88	1.14	0.21	0.32	0.42
Cost Of <sup>157</sup> Gd enrichment	0.00	0.00	0.00	6.00	8.10	11.02
Cost of total fuel for assembly	904.65	1,551.95	3,201.77	913.39	1,564.77	3,222.50
Cost difference				8.74	12.82	20.73

Table A10. Single assembly fuel cost comparison of models have 6.00 wt.% n-Gd<sub>2</sub>O<sub>3</sub>, and 2.00 wt.% e-Gd<sub>2</sub>O<sub>3</sub> both in 5 wt.%  $^{235}$ U (all values are provided in kUSD).

	6.00 wt.% n-Gd <sub>2</sub> O <sub>3</sub>			2.00 wt.% e-Gd <sub>2</sub> O <sub>3</sub>		
	Low	Nominal	High	Low	Nominal	High
Cost of uranium	220.60	557.39	1,919.71	221.64	560.03	1,928.81
Cost of conversion	42.50	84.99	124.22	42.70	85.40	124.81
Cost of enrichment	491.31	648.32	780.01	493.64	651.40	783.71
Cost of fabrication	147.28	256.29	368.99	148.54	258.38	371.62
Cost of Gd <sub>2</sub> O <sub>3</sub>	0.84	1.31	1.70	0.28	0.44	0.58
Cost Of <sup>157</sup> Gd enrichment	0.00	0.00	0.00	8.26	11.16	15.17
Cost of total fuel for assembly	902.52	1,548.31	3,194.25	915.06	1,566.80	3,224.56
Cost difference				12.54	18.49	30.31