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Prismatic core high temperature reactor fuel modelling incorporating fuel rotation

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Abstract

The use of prismatic-core High Temperature Reactors (HTRs, has not yet reached commercialisation, as they are few in operation, and mainly developmental in nature. This work examines numerous models for fuel rotation, thus enhancing and further optimising the fuel lifecycle of a generic HTR. Several rotational scenarios were examined both axially and radially, with radial rotations giving rise to the largest in life extension. Included in the model is a complex analysis of how TRistructural-ISOtropic (TRISO) fuel behaves in operando, increasing the reliably of the model in predicting the benefits of fuel rotation. Finally, an economic assessment was undertaken, which indicted that fuel costs could be reduced by 42%, further increasing its economic benefit and efficiency.

Introduction

It has long been accepted that for a low carbon, reliable energy mix there is a place for nuclear energy [1]. However, there are two main concerns regarding nuclear energy. Firstly is the funding required for the initial cost of new nuclear plant, as for example, the recently confirmed Hinkley Point C power plant has an estimated construction cost of ~£18bn, with funding from private sources. The second concern is safety, with public concern over such technology rising after the incident at Fukushima in 2011. Combining a lower capital cost with enhanced safety, due to developments in passive safety features, the concept of Small Modular Rectors (SMR) has started to gain growing momentum [2].

The work presented here examines the impact of fuel element rotation within the core, designed to increase fuel lifetime within the core, thus enhancing its overall economic efficiency. Nuclear fuel rotation is common across most power reactors, e.g. the Advanced Gas Cooled Reactors (AGR) and Light Water Reactors (LWR). However prismatic core HTR's have not seen this practice implemented. One explanation is down to the lack of commercial HTR's where such fuel life extension could be undertaken, although this process is physically possible. The two major considerations for this work include the economic viability of fuel rotations over a reactor lifetime, taking into account the remote nature of planned operation and how it would modify operational parameters.

Design Concept

The design considered is loosely based off the U-Battery which aims for a fast deployment using readily available technology, by utilising existing prototypes prismatic core reactors such as Japanese high temperature test rector (HTTR) as a source of reliable and pertinent information. The HTTR has been operating since 1998 allowing for critical parts of the design to be well understood and easy to deploy.

A new core design with the radial and axial design shown in figure 1.

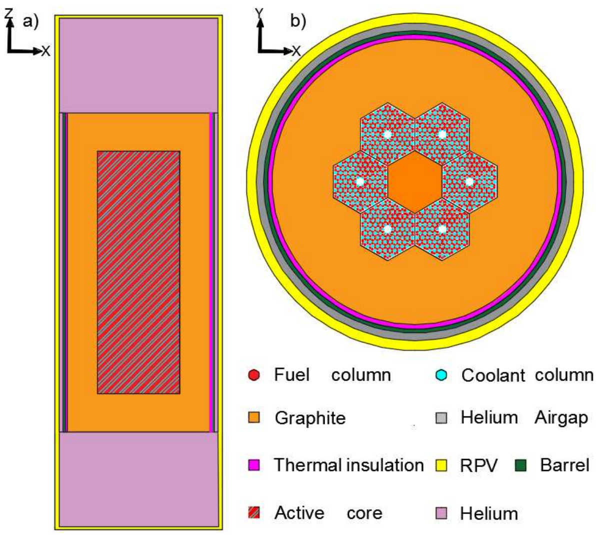

Figure 1 – Core layout a) axial schematic of the core. b) Radial representation scaled by a factor of two to highlight the detail.

Methodology

In most operational nuclear reactors, fuel is rotated around the core maximising burnup and ensuring the flux across the core is as even as possible. For example, in the AGR, fresh fuel starts at the edges of the active core to increase the flux, and during operation the fuel then moves inwards, increasing burn up. This allows fresh fuel to provide a higher flux of neutrons in the outside of the core where fission is less common than at the centre of the core, where it would require enhanced management to prevent rapid burnup. Such a process allows for higher levels of burnup to be achieved. In the case of HTRs fuel has not traditionally been used in such a manner, primarily due to the nature of the fuel, i.e. either fused into fuel blocks or the process of fuel rotation being too difficult or not economical.

As in the case of the reactor designed there are large amounts of U235 remaining after the first cycle. Our first investigation was to identify those areas where the U235 is not being fully utilised. To model the design, Serpent 2.1.26 was used [3], Serpent is a Monte-Carlo based neutronics package using the JEFF 3.1.1 libraries. In this case the TRISO fuel was heterogeneously modelled in 10 cm sections axially across the fuel blocks as shown in figure 2, each sections contains the same fuel material as in TRISO kernels. The material compositions were then compared after the fuel cycle to further elucidate the changes in fuel composition.

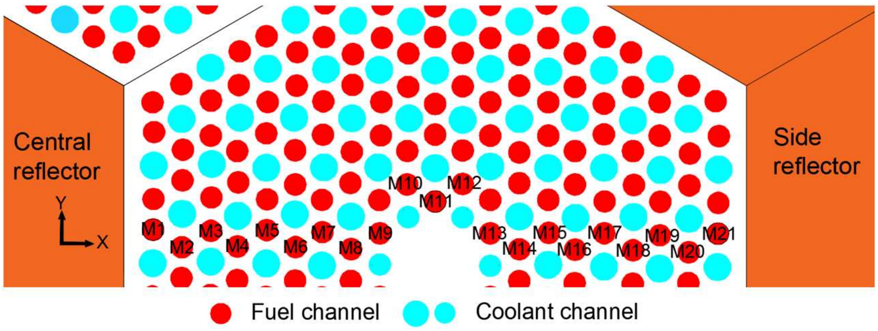

Figure 2 – where M1-21 represents the fuel channels under depletion investigation

As shown in figure 2, the sequence M1 to M21 represents fuel channels which have had their material compositions monitored over a full life cycle within the core. This allows for a radial distribution across the core, providing a representative expected fuel behaviour, and allow for an estimation of expected criticality with time, shown by the calculated keff, i.e. criticality being above 1.

The second study examined the behaviour of fuel burn within the core, with the expected burn being from the centre of the core outwards. As such this test used multiple circles to identify those fuel channels which lie within a radius for the fuel from the centre as shown in figure 3. For speed this test only monitored half the core, more specifically the bottom half.

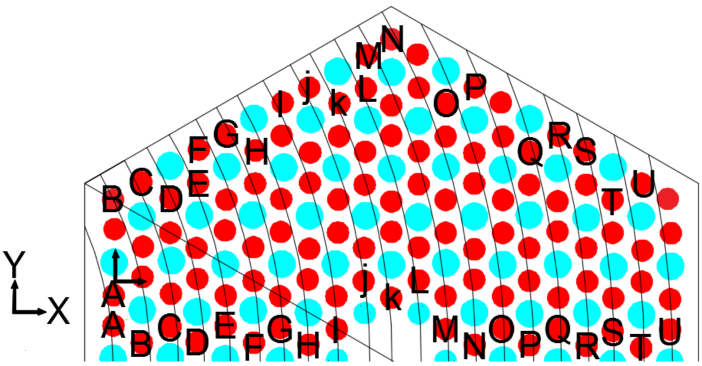

Figure 3 – Half a fuel block. The isolines represent the channels with similar burnup. The corresponding letters highlight channels that are assumed to have similar burnup.

The fuel pins at the back four points, U, T, S and R were modelled separately, allowing for maximum accuracy of the rotational process to account for loss of symmetry across the fuel block. To increase burnup, and thus overall economic efficiency, rotation of fuel blocks was examined. The design consists of 24 fuel blocks, placed around the central reflector, and are designed to burn symmetrically from the centre outwards. The highest burnup was therefore designed to occur at the centre where the neutrons are easily transferred between fuel blocks and the moderation is highest both increasing burnup, shown in figure 4. Despite the core being made of graphite with varying density, burn up was expected to radially decrease going outwards. Coupled to this was the assumption that axial burnup would be highest at the centre of the core, with concomitant decrease the further the fuel was from the centre point. This led to the hypothesis that fuel blocks could be rotated axially and radially to allow for lower burn up sections to be moved to the centre, thus increasing the utilisation of the U235 most effectively, shown in figures 4 and 5.

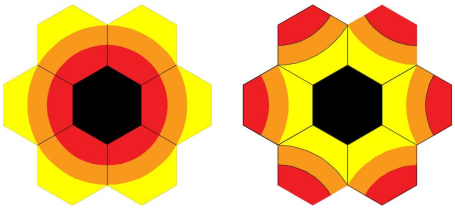

Figure 4 – Radial fuel rotation hypotheses

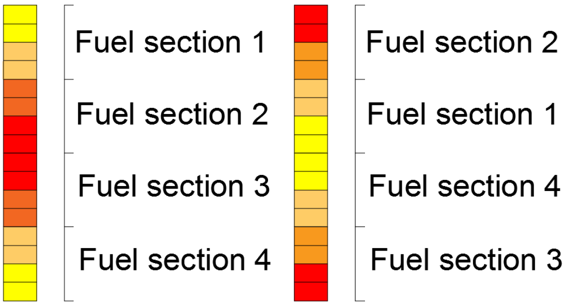

Figure 5 – Axial rotation, left initial core burnup and right the rotated version

The fuelling machine (FM) would be attached to the top of the reactor core, and using a central channel would fully access the entire core allowing for access to each individual fuel block. Since one concern with fuel rotation is increasing the operating costs, a full cost benefit analysis would determine if the process is economically viable.

Due to the differing nature of potential rotation, six different rotational models were investigated, shown in table 1.

Z axis	Rotational procedure
	180 degree rotation
No rotation	60 degrees anticlockwise
	60 degrees clockwise
	180 degree rotation
Axial rotation	60 degrees anticlockwise
	60 degrees clockwise

Table 1 – Rotational models used in the simulations of fuel core rotation

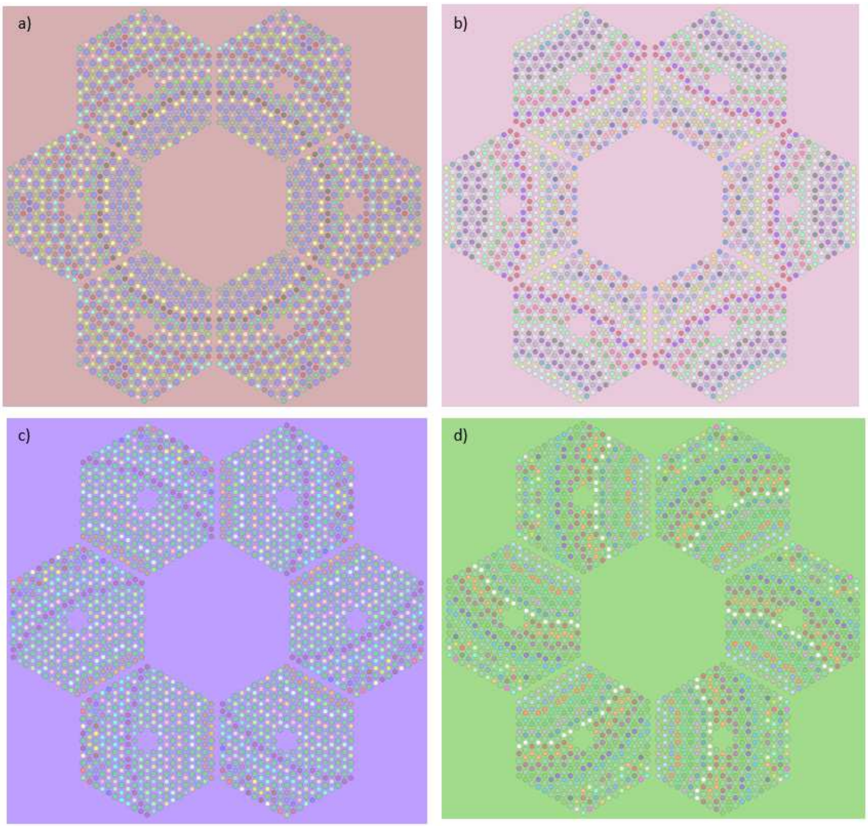

Figure 6 – Rotations of the fuel. a) Standard position, b) 180 degree rotation, c) 60 degree anti clockwise rotation, d) 60 degree clockwise rotation.

The initial loading looks at a simple core layout, shown in Figure 6(a), where the total packing factor in every block is the same and equal to 29%. The simulation then burns the fuel until criticality reduces to below unity, i.e. no longer self-sustaining. At this point the end of cycle has been determined, leading to the next stage where the periods of rotation were isolated.

Two key features in Serpent were used for this, initially a simple universal transformation (utrans) was used to rotate part of the core on the Z axis. The second option was to record material composition after each burnup stage, and then manipulate these compositions location to achieve axial transformation.

The methods used to identify the rotation were considered in reactor-day extension from the initial start, coupled with the overall cost saving over the lifetime of the reactor. Costs included in the U-Battery conceptual design were used and compared these included;

Costs	M€
Fuel handling costs	0.5
264 kg of fuel	3.2

Table 2 - Fuel costs [4]

The costs were based on those proposed in the initial design and scaled accordingly to allow for a comparison to be made, it is important to note that the costs for reloading the fuel are not included in the initial report. Consequently fuel handling costs are assumed to be the cost of transporting the new fuel to site, and loading into the core. Thus the same value was assumed for moving the fuel to site despite this potentially being estimated, and not realistic. However, with lifetime extension these costs would be reduced, as less fuel movement is required. A further key assumption was the reactor performing for the full expectancy of 60 years as stated in the initial design criteria. After the initial cycle, decisions on how to rotate the fuel and what benefits arose were considered, with further simulations identifying the maximum extension that could be added due to the rotation.

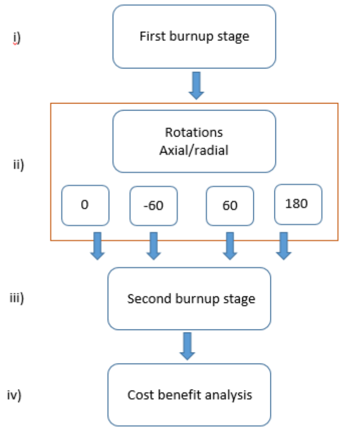

Figure 7 – Step by step process of stages undertaken

Figure 7 goes through the stages to obtain the most beneficial rotation method. The initial burnup step (i) identifies the time the reactor can run before any intervention is required. This stage is used to calculate the maximum effective full power days.

Fuel rotation is step (ii), before a further burnup is simulated in stage (iii) with simulation being completed when criticality is no longer reached. It is at this point the reactors fuel will require a new loading of fuel.

A cost benefit analysis (iv) examines both the operational costs and risks involved with fuel manipulation. It is a simple method, but one in which the financial benefit for such rotation can be estimated.

Results and discussion

The initial study simulated an unbound criticality test, to examine the lifetime of the reactor, purely through determination of when Keff is no longer above 1, i.e no longer critical.

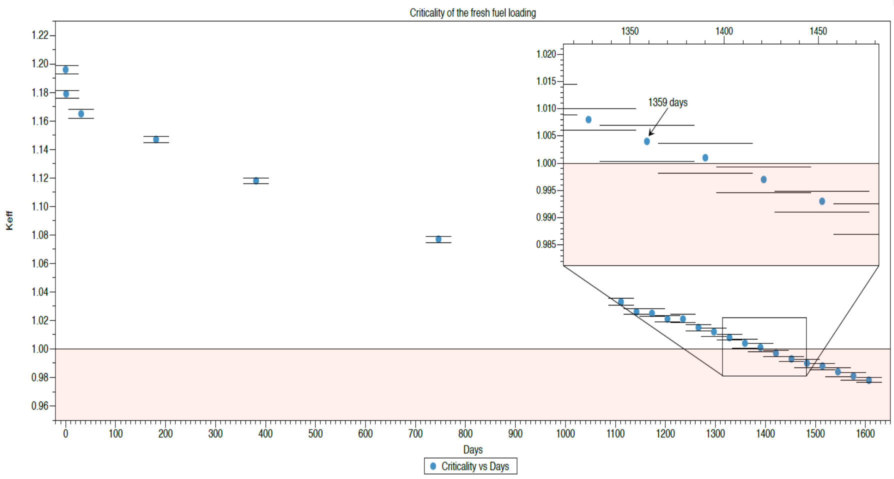

Figure 8 –Criticality as function of time within the core, error bars are set at 95% of confidence, with the shaded area representing a non-critical system.

As can be seen in figure 8 the reactor is predicted to remain critical for ~1359 day under the conditions of the simulation. Following this fuel compositions were taken axially across M1-21, focusing on the U235 content in these 21 fuel rods. An exemplar is shown in Figure 9, where the % of 235U remaining is shown as a function of channel.

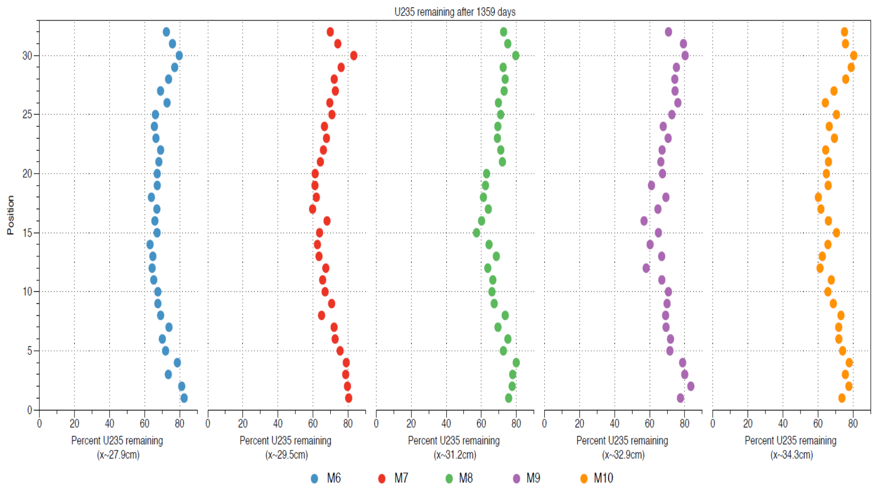

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Figure 9 - Material compositions of of M6-M10

Figure 9 looks into the depleted U235 across each of the sections M6-M10 of the core in the fuel channels identified by figure 2. Using the results from this initial simulation, the axial areas identified as the most depleted will be moved to the outer extremities of the core. Thus following this rotation the channels reverse such that in M21 in Figure 2, becomes M1, as can be seen in Figure 6.

The positions towards the centre of the core, positions 10 to 20, contain a significant reduction in U235, particularly when compared to the other fuel channels. However, the peaks in % 235U remaining are ~30cm from the top/bottom of the active core. This arises from the extremities of the core benefitting from the reflector at the top/bottom, which aids fission at the top/bottom. However, at the centre of the fuel blocks such beneficial effects are reduced, indicating that for a reflector to be effective there needs to be a high enough flux that utilises the reflectors.

The increase in burnup at the centre is primarily due to additional flux contribution arising from areas close to the centre. Due to the isotropic nature of fission there remains a high probability of neutrons returning into the core from outside as there is the neutron leaving the centre. Consequently, this can cause the centre of the core to burn up faster than the exterior. Coupled with this the central reflector plays a key role with neutrons thermalizing rapidly at the centre of the core.

In order to estimate optimal time for fuel rotation, different durations were used. The rotation stages are outlined in Table 3.

Stages	Days	Years	Burnup (MW/KgU)
1	746	2	32.07
2	1111	3	47.76
3	1328	3.72	58.42

Table 3 – Stages chosen for switching

These stages were chosen as they are far enough from the initial commissioning to not to cause too much disruption to reactor operation. A duration of two years approximates to half of the estimated final burn up, thus designed to yield increased burn up after rotation.

Examination of material composition radially after 1359 days in the core, which would traditionally be termed the end of life for the core, and comparing gives rise to an average method for comparison. The material compositions of each mirroring 10cm axial section previously shown in figure 3 are compared to each other such via a ratio and then averaged across the fuel channel and the maximum deviation across an isoline was 2.5% over the lifecycle of the fuel, indicating the isoline representation was accurate.

The rotation is split into two stages in Tables 5 and 6. The first stage does not include axial rotation, just movement, as shown in figure 6.

The results from such movement shows a high level of consistency, with method giving rise to a similar level of expected life extension, the results are shown in Table 5. It had been expected that such anticlockwise and clockwise rotations would give rise to similar results, given their similarity geometrically. However, a 180 degree rotation would have been expected to experience a higher degree of burn up in the centre after rotation. This implies however, that as long as the quantity of U235 remains high in the centre of the core, life extension is possible.

Days extended	End of life: 180 degrees	Standard relative error	Anticlockwise	Standard relative error	Clockwise	Standard relative error	Three years: 180 degrees	Standard relative error	Anticlockwise	Standard relative error	Clockwise	Standard relative error
0	1.0080	0.0021	1.0070	0.0011	1.0059	0.0015	1.0347	0.0012	1.0356	0.0011	1.0344	0.0011
1	1.0113	0.0012	1.0092	0.0015	1.0098	0.0022	1.0373	0.0011	1.0380	0.0013	1.0393	0.0016
183	1.0131	0.0013	1.0109	0.0012	1.0109	0.0016	1.0372	0.0012	1.0409	0.0013	1.0392	0.0014
365	1.0085	0.0009	1.0117	0.0015	1.0103	0.0015	1.0387	0.0016	1.0376	0.0012	1.0394	0.0013
396	1.0083	0.0014	1.0087	0.0016	1.0078	0.0015	1.0364	0.0016	1.0362	0.0012	1.0341	0.0013
427	1.0081	0.0009	1.0072	0.0015	1.0064	0.0016	1.0339	0.0015	1.0335	0.0016	1.0356	0.0014
458	1.0052	0.0012	1.0056	0.0016	1.0065	0.0015	1.0331	0.0014	1.0317	0.0013	1.0326	0.0015
489	1.0019	0.0019	1.0018	0.0014	1.0019	0.0014	1.0296	0.0014	1.0298	0.0011	1.0301	0.0016
520	1.0031	0.0012	1.0046	0.0013	1.0008	0.0017	1.0270	0.0014	1.0290	0.0013	1.0303	0.0016
551	1.0007	0.0016	0.9983	0.0013	0.9985	0.0016	1.0272	0.0011	1.0294	0.0013	1.0302	0.0014
582	0.9983	0.0014	0.9989	0.0011	0.9996	0.0013	1.0275	0.0013	1.0283	0.0015	1.0266	0.0012
613	0.9982	0.0016	0.9964	0.0012	0.9997	0.0014	1.0239	0.0013	1.0233	0.0010	1.0225	0.0014
644	0.9954	0.0010	0.9962	0.0021	0.9933	0.0016	1.0237	0.0012	1.0240	0.0017	1.0215	0.0018
675	0.9941	0.0010	0.9938	0.0015	0.9925	0.0015	1.0219	0.0017	1.0203	0.0011	1.0193	0.0015
706	0.9941	0.0011	0.9927	0.0012	0.9913	0.0013	1.0187	0.0016	1.0160	0.0013	1.0167	0.0015
737	0.9888	0.0012	0.9890	0.0013	0.9910	0.0013	1.0168	0.0012	1.0153	0.0015	1.0155	0.0011
768							1.0155	0.0015	1.0175	0.0013	1.0164	0.0010
799							1.0142	0.0012	1.0146	0.0011	1.0145	0.0018
830							1.0135	0.0013	1.0124	0.0012	1.0106	0.0010
861							1.0104	0.0012	1.0115	0.0010	1.0091	0.0013
892							1.0068	0.0014	1.0076	0.0014	1.0113	0.0015
923							1.0085	0.0014	1.0068	0.0017	1.0071	0.0011
954							1.0044	0.0022	1.0072	0.0013	1.0051	0.0011
985							1.0054	0.0013	1.0048	0.0017	1.0033	0.0016
1016							1.0006	0.0014	1.0013	0.0009	1.0010	0.0019
1047							1.0011	0.0012	0.9967	0.0012	1.0005	0.0011
1078							0.9972	0.0016	0.9974	0.0017	1.0003	0.0010
1109							0.9971	0.0022	0.9974	0.0010	0.9975	0.0014
1140							0.9963	0.0014	0.9934	0.0015	0.9960	0.0010
1171							0.9954	0.0014	0.9944	0.0011	0.9943	0.0016

Days extended	Two years: 180 degrees	Standard relative error	Anticlockwise	Standard relative error	Clockwise	Standard relative error
0	1.0763	0.0016	1.0769	0.0011	1.0764	0.0010
1	1.0805	0.0013	1.0801	0.0009	1.0803	0.0015
183	1.0731	0.0010	1.0755	0.0011	1.0732	0.0010
365	1.0641	0.0014	1.0631	0.0012	1.0621	0.0016
396	1.0598	0.0014	1.0606	0.0011	1.0598	0.0016
427	1.0580	0.0011	1.0591	0.0010	1.0574	0.0013
458	1.0577	0.0011	1.0571	0.0010	1.0572	0.0015
489	1.0544	0.0016	1.0567	0.0012	1.0543	0.0014
520	1.0527	0.0014	1.0516	0.0014	1.0536	0.0012
551	1.0514	0.0017	1.0547	0.0010	1.0509	0.0018
582	1.0501	0.0016	1.0521	0.0014	1.0501	0.0012
613	1.0462	0.0014	1.0469	0.0012	1.0464	0.0012
644	1.0470	0.0007	1.0478	0.0015	1.0491	0.0011
675	1.0436	0.0012	1.0435	0.0008	1.0446	0.0010
706	1.0425	0.0014	1.0415	0.0011	1.0429	0.0014
737	1.0419	0.0013	1.0386	0.0013	1.0416	0.0010
768	1.0403	0.0015	1.0408	0.0014	1.0385	0.0011
799	1.0371	0.0015	1.0363	0.0014	1.0352	0.0018
830	1.0349	0.0016	1.0347	0.0015	1.0381	0.0012
861	1.0323	0.0017	1.0366	0.0011	1.0351	0.0015
892	1.0327	0.0012	1.0324	0.0010	1.0315	0.0010
923	1.0293	0.0011	1.0304	0.0016	1.0292	0.0013
954	1.0292	0.0013	1.0297	0.0016	1.0314	0.0011
985	1.0259	0.0012	1.0283	0.0014	1.0276	0.0017
1016	1.0278	0.0017	1.0251	0.0011	1.0247	0.0008
1047	1.0230	0.0014	1.0248	0.0012	1.0272	0.0018
1078	1.0261	0.0015	1.0204	0.0017	1.0204	0.0015
1109	1.0224	0.0012	1.0217	0.0014	1.0225	0.0015
1140	1.0207	0.0013	1.0213	0.0011	1.0170	0.0016
1171	1.0168	0.0014	1.0161	0.0010	1.0174	0.0012
1202	1.0149	0.0017	1.0154	0.0013	1.0147	0.0015
1233	1.0122	0.0012	1.0154	0.0015	1.0149	0.0009
1264	1.0142	0.0017	1.0098	0.0016	1.0120	0.0010
1295	1.0091	0.0015	1.0096	0.0015	1.0121	0.0013
1326	1.0097	0.0017	1.0088	0.0014	1.0111	0.0014
1357	1.0079	0.0013	1.0078	0.0012	1.0081	0.0012
1388	1.0070	0.0015	1.0045	0.0013	1.0044	0.0016
1419	1.0022	0.0015	1.0036	0.0016	1.0010	0.0016
1450	1.0030	0.0013	1.0036	0.0010	1.0023	0.0015
1481	1.0005	0.0010	1.0035	0.0013	1.0008	0.0017
1512	0.9969	0.0015	0.9993	0.0017	0.9995	0.0014
1543	0.9987	0.0013	0.9971	0.0012	0.9990	0.0014
1544	0.9947	0.0014	0.9977	0.0012	0.9963	0.0012

Table 5 - Criticality of none axially rotated systems

	End of life						Three years							Two years					
Days extended	180 degrees	Standard relative error	Anticlockwise	Standard relative error	Clockwise	Standard relative error	180 degrees	Standard relative error	Anticlockwise	Standard relative error	Clockwise	Standard relative error	Days extended	180 degrees	Standard relative error	Anticlockwise	Standard relative error	Clockwise	Standard relative error
0	1.0280	0.0011	1.0269	0.0012	1.0282	0.0013	1.0481	0.0011	1.0523	0.0016	1.0506	0.0017	0	1.0898	0.0011	1.0907	0.0012	1.0890	0.0017
1	1.0245	0.0012	1.0247	0.0012	1.0248	0.0020	1.0495	0.0016	1.0482	0.0017	1.0488	0.0018	1	1.0882	0.0013	1.0878	0.0009	1.0872	0.0016
32	1.0204	0.0019	1.0231	0.0015	1.0226	0.0014	1.0460	0.0012	1.0393	0.0015	1.0433	0.0013	183	1.0645	0.0011	1.0607	0.0013	1.0662	0.0013
63	1.0188	0.0013	1.0192	0.0015	1.0192	0.0016	1.0410	0.0013	1.0390	0.0011	1.0428	0.0013	365	1.0409	0.0015	1.0414	0.0013	1.0408	0.0009
94	1.0150	0.0015	1.0151	0.0010	1.0126	0.0017	1.0360	0.0014	1.0376	0.0012	1.0341	0.0018	396	1.0368	0.0012	1.0366	0.0018	1.0370	0.0012
125	1.0091	0.0011	1.0102	0.0015	1.0114	0.0011	1.0308	0.0010	1.0321	0.0013	1.0315	0.0018	427	1.0356	0.0017	1.0306	0.0015	1.0330	0.0016
156	1.0056	0.0016	1.0052	0.0015	1.0061	0.0014	1.0274	0.0015	1.0308	0.0014	1.0272	0.0013	458	1.0302	0.0006	1.0267	0.0015	1.0281	0.0012
187	1.0002	0.0013	1.0008	0.0014	1.0043	0.0017	1.0240	0.0008	1.0265	0.0016	1.0253	0.0012	489	1.0277	0.0009	1.0272	0.0015	1.0261	0.0015
218	0.9991	0.0015	0.9987	0.0013	1.0002	0.0010	1.0208	0.0013	1.0227	0.0011	1.0184	0.0016	520	1.0201	0.0016	1.0197	0.0011	1.0233	0.0014
249	0.9940	0.0018	0.9958	0.0014	0.9931	0.0010	1.0174	0.0014	1.0152	0.0020	1.0162	0.0014	551	1.0196	0.0015	1.0171	0.0013	1.0196	0.0017
280	0.9906	0.0012	0.9912	0.0010	0.9873	0.0014	1.0119	0.0012	1.0116	0.0011	1.0112	0.0016	582	1.0157	0.0016	1.0153	0.0013	1.0161	0.0012
311	0.9860	0.0010	0.9872	0.0012	0.9874	0.0013	1.0087	0.0016	1.0088	0.0014	1.0097	0.0012	613	1.0106	0.0010	1.0100	0.0010	1.0104	0.0014
342	0.9838	0.0012	0.9835	0.0014	0.9839	0.0011	1.0050	0.0013	1.0063	0.0015	1.0054	0.0016	644	1.0073	0.0010	1.0062	0.0018	1.0072	0.0011
373	0.9772	0.0011	0.9803	0.0012	0.9800	0.0014	1.0024	0.0017	1.0006	0.0013	1.0027	0.0015	675	1.0039	0.0015	1.0025	0.0017	1.0034	0.0012
404	0.9774	0.0010	0.9767	0.0012	0.9769	0.0015	0.9970	0.0014	0.9984	0.0012	0.9959	0.0011	706	1.0005	0.0012	1.0012	0.0014	0.9998	0.0014
435	0.9701	0.0014	0.9703	0.0014	0.9733	0.0012	0.9945	0.0012	0.9937	0.0010			737	0.9973	0.0011	0.9958	0.0011	0.9981	0.0015
466	0.9671	0.0014	0.9687	0.0016	0.9667	0.0015	0.9917	0.0015	0.9901	0.0013									

Table 6 – Life time extensions of the axially rotated options

None axial rotation		Days before first interaction	Days extended through rotation	Total lifetime	Total lifetime years	Total fuel costs per day (€)	Amount of refuels	Total cost of fuel	Amount of reshuffles	Total cost of reshuffels	Total cost
2 years	180 degrees	746	1481	2227	6.10	1454.79	9.83	€31.9M	19.67	€9.8M	€41.7M
	anticlockwise	746	1481	2227	6.10	1454.79	9.83	€31.9M	19.67	€9.8M	€41.7M
	clockwise	746	1481	2227	6.10	1454.79	9.83	€31.9M	19.67	€9.8M	€41.7M
3 years	180 degrees	1111	745	1856	5.08	1745.59	11.80	€38.2M	23.60	€11.8M	€50.0M
	anticlockwise	1111	714	1825	5.00	1775.24	12.00	€38.9M	24.00	€12.0M	€50.9M
	clockwise	1111	652	1763	4.83	1837.67	12.42	€40.2M	24.84	€12.4M	€52.7M
End of life	180 degrees	1328	249	1577	4.32	2054.42	13.89	€45.0M	27.77	€13.9M	€58.9M
	anticlockwise	1328	218	1546	4.24	2095.61	14.17	€45.9M	28.33	€14.2M	€60.1M
	clockwise	1328	218	1546	4.24	2095.61	14.17	€45.9M	28.33	€14.2M	€60.1M
Direct refuel	no rotation	1328	0	1328	3.64	2439.62	16.49	€53.4M	32.98	€16.5M	€69.9M

Table 7 – CBA of not axially fuel rotated

Axial rotation		Days before first interaction	Days extended through rotation	Total lifetime	Total lifetime years	Total fuel costs per day (€)	Amount of refuels	Total cost of fuel	Amount of reshuffles	Total cost of reshuffles	Total cost
2 years	180 degrees	746	706	1452	3.98	2231.28	15.08	€48.9M	30.17	€15.1M	€63.9M
	anticlockwise	746	675	1421	3.89	2279.95	15.41	€49.9M	30.82	€15.4M	€65.3M
	clockwise	746	706	1452	3.98	2231.28	15.08	€48.9M	30.17	€15.1M	€63.9M
3 years	180 degrees	1111	373	1484	4.07	2183.16	14.76	€47.8M	29.51	€14.8M	€62.6M
	anticlockwise	1111	373	1484	4.07	2183.16	14.76	€47.8M	29.51	€14.8M	€62.6M
	clockwise	1111	404	1515	4.15	2138.49	14.46	€46.8M	28.91	€14.5M	€61.3M
End of life	180 degrees	1328	187	1515	4.15	2138.49	14.46	€46.8M	28.91	€14.5M	€61.3M
	anticlockwise	1328	187	1515	4.15	2138.49	14.46	€46.8M	28.91	€14.5M	€61.3M
	clockwise	1328	187	1515	4.15	2138.49	14.46	€46.8M	28.91	€14.5M	€61.3M
Direct refuel	Direct refuel	1328	0	1328	3.64	2439.62	16.49	€53.4M	32.98	€16.5M	€69.9M

Table 8 – CBA of the axially rotated fuel reshuffling

With axial rotation however, there was observed a significantly reduced life extension, contradicting the initial hypothesis. One potential cause could be from a reduced neutron contribution during operation, from the U235 being depleted, thus reducing the axial contribution when rotated. To test this hypothesis the flux was monitored after the rotation at both the bottom of the core and the centre of the 180 degree rotations. This would then identify the main cause for difference in the two rotation models.

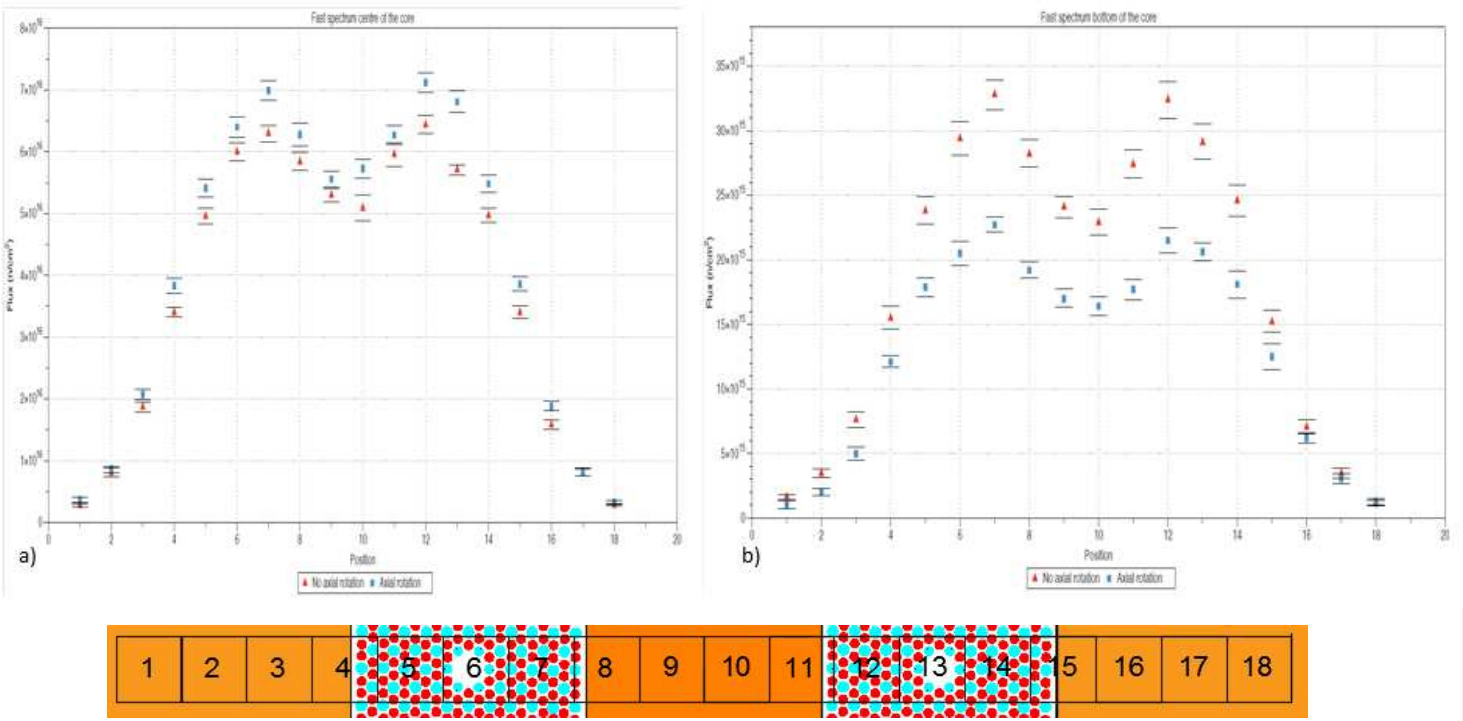

Figure 11 – a) fast flux from the centre of the core, b) fast flux at the bottom of the core at 0.4µ – 20 MeV

The longest life extension would be expected to arise from a balanced burn up of fuel through fuel rotation, as shown in Table 5. This would then create an effective fuel lifetime of six years, which exceeds that required in the initial design brief. However, the initial hypothesis regarding the axial rotation providing the highest life extension has been shown to be incorrect.

Examination of expected fluxes, shown in figure 11, provides insight into why when the centre of the cores fast flux, representing U235 undergoing fission, is examined. The axial rotation gains a slightly higher flux at the centre of the core due to the freshest fuel being placed. However, such fluxes at the bottom of the core highlight the impact of axial rotation which significantly lowers the burn which identifies that rotation is reducing fission rate. This reduction in fission rate dramatically impacts criticality as the axial lengths of the core no longer play a role feeding neutrons back into, helping to keep fission going, thus the core now has a lower concentration of fission which in turn causes the lower life extension of the axial rotation method.

Placing more fuel at the edges of the core would provide a higher effect of neutrons being passed back into the centre of the core axially. This then implies that increasing the packing factor of the top and bottom core, will in turn enable an extended lifetime extension and potentially higher burn up in all sectors.

Due to the small size of the design such rotational options of fuel blocks is limited which gives rise to the symmetrical burnup seen in in figure 9. This benefit might not be found if the active core was wider due to the impact of the side reflectors now being less. As seen in figures 9 the axial increased burnup from reflectors, contributes up to 30cm into the core, thus covering just over half of the radial fuel block dimensions hence, giving rise to symmetrical burnup.

From a rotational point of view, where the earlier the rotation the longer the fuel life cycle, is problematic, as the core now requires a FM to be required more frequently. From an operational perspective the cost of a FM would need to be considered.

Financially the most economical approach is a simple rotation after two years, which is also the least technically challenging. The initial lifetime cost of the fuel in the core was estimated to to be €70mn but, by rotating the fuel as required this could be reduced to €42mn. This cost saving could then allow an additional €1mn per fuel reload to be allocated to help offset any risk with the procedure and still save €10mn over the lifetime of the reactor. From these finding, it does seem that the additional cost could be overcome through fuel rotation. There are situations where this might be too difficult, for example military applications where access after two years would be problematic.

Conclusion

Several different rotational techniques have been examined through variation in operational time and rotation within the core. Through this the most beneficial was a zero rotation model after two years, which was modelled to increase the core lifetime by 42%. This increase could lead to a fuel cost reduction of up to €30M over the lifetime of the reactor. However, the full economic risks involved in this process have not been covered, but are the focus of a further paper.

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