In this reactor physics study, we attempt to design a soluble-boron-free (SBF) PWR civil marine reactor core that can operate over a 20 effective-full-power-years life at 333 MWth using mixed D$_2$O-H$_2$O coolant. We use WIMS to develop subassembly designs and PANTHER to examine whole-core arrangements, optimizing: subassembly and core geometry; fuel enrichment; burnable and moveable poison design; and whole-core loading patterns. In this study, we use 15% U-235 enriched UO$_2$ and 18% enriched micro-heterogeneous ThO$_2$-UO$_2$ duplex fuel arranged in a simple checkerboard configuration. Comparisons are made between the homogeneously mixed 15% U-235 enriched all-UO$_2$ case and the checkerboard configuration with high thickness ZrB$_2$ integral fuel burnable absorber pins for reactivity control. Taking advantage of self-shielding effects, the checkerboard option shows greater promise in the final burnable poison design while maintaining low, stable reactivity with minimal burnup penalty. For the final poison design with ZrB$_2$, the checkerboard contributes 2.5% more initial reactivity suppression, although the all-UO$_2$ design exhibits lower reactivity swing. All the candidate materials show greater rod worth for the checkerboard design. For both fuels, B$_4$C has the highest reactivity worth, providing 3% higher control rod worth for checkerboard fuel than all-UO$_2$. Finally, optimized assemblies were loaded into a 3D reactor model in PANTHER. The PANTHER results show that the designed cores can achieve the target core lifetime of 20 years, confirming the fissile loading is well-designed.

I. INTRODUCTION

In an effort to de-carbonise commercial freight shipping, a great deal of interest is presently being shown in the possible application of nuclear energy in marine propulsion. A nuclear-powered ship, be it a surface ship or submarine, receives its propulsive energy from a nuclear power plant on board, which does not consume hydrocarbon-based fuel and oxygen like conventional fossil power plants and produces no exhaust gas. Nuclear reactors are also reliable and compact sources of energy that can last for years between refuelings, and therefore do not need to be accompanied by vulnerable supply tankers. There is considerable experience in operating nuclear power plants in nuclear naval propulsion, particularly submarines. This accumulated experience may become the basis of a proposed new generation of compact nuclear power plant designs.

Reactor cores for commercial freight shipping would need to be fundamentally different from land-based power generation systems, which require regular refueling, and from reactors used in military vessels, as the fuel used could not conceivably be as...
highly enriched. Nuclear-powered propulsion could allow ships to operate with low fuel costs, long refueling intervals, and minimal emissions. Despite a proven track record in military service, nuclear propulsion has never played a significant role in the civil maritime sector due to the political barriers, the reluctance of shipyards and ports to accommodate nuclear vessels, legal and regulatory uncertainty surrounding nuclear propulsion, and the upfront costs needed to implement this technology. Nuclear marine propulsion also faces considerable technical and engineering challenges, including: non-proliferation concerns, the need for flexibility and high availability, high levels of passive safety, security, and engineering simplicity with limited support capability. The engineering solutions to these problems are further constrained by the demands of the harsh ocean weather, including pitching and rolling, space/weight limitations, and safety/shielding concerns. If these political and technical issues could be resolved, this could potentially open the door to significant cost savings and environmental benefits.

This study examines the feasibility of a mixed 80% D$_2$O-H$_2$O cooled 333 MWth soluble-boron-free (SBF) marine PWR using 15% U-235 enriched UO$_2$ and 18% enriched micro-heterogeneous ThO$_2$-UO$_2$ duplex fuel arranged in a simple checkerboard configuration. The aim is to achieve long refueling intervals of (at least) 20 effective full power years by taking advantage of the very small neutron capture cross-section and large moderating power of the mixed D$_2$O-H$_2$O coolant while maintaining the neutronic safety parameters. Fissile loading, neutronic analysis of burnable poisons, control rods and whole-core loading patterns have been investigated.

II. DESIGN METHODS

II.A. Determination of Subassembly and Core Size

In PWR assembly-loading patterns, there is the geometric issue of fitting square assemblies into a cylindrical reactor vessel. For a given fuel mass, smaller assemblies provide greater granularity, allowing arrangements that better approximate a circle; hence less space is wasted along the periphery of the reactor vessel. The Sizewell B reactor has assemblies with a 17×17 array of pins and a total fueled core area of 9 m$^2$, whereas we have calculated that our proposed marine core should have a fueled area of 3.03 m$^2$. This leads to a 66.33% reduction in fueled core area. If we use 112 assemblies with 169 (13×13) pins, we can achieve a 42.4% reduction in pins per assembly and a 41.96% reduction in assemblies per core. Since 112 is a magic number, it can be formed into the approximate shape of a circle. A circular core experiences the least leakage compared to other axisymmetric shapes. Thus, we select 112 assemblies with a 13×13 subassembly arrangement for our design, as shown in Fig. 1.

II.B. Fuel and Coolant Selection

This study focuses on homogeneously mixed UO$_2$ fuel and micro-heterogeneous ThO$_2$-UO$_2$ duplex fuel arranged in a simple checkerboard configuration in a 13×13 assembly, as shown in Fig. 2. In the duplex fuel, an individual fuel pin is composed of a UO$_2$ centre surrounded by an annulus of ThO$_2$, as shown in Fig. 3. We use the term “checkerboard” or “CHK” to refer to this fuel. Homogeneously mixed all-UO$_2$ fuel is also considered in comparison to the checkerboard configuration.

For our study, the subassembly design analysis used the WIMS-10 reactor physics software package with nuclear data derived from the JEF2.2 database.
available from the IAEA. For each burnup step, WIMS completes a fine 172-group solution to the transport equation in a smeared geometry. It then refines this solution using a few-group calculation in a precise geometry. PANTHER\(^5\) is used for whole-core design. This imports few-group nuclear data from WIMS. The process by which the fuel lattice and coolant composition were determined is described in a companion paper.\(^6\) The design parameters of the proposed marine core are shown in Table I.\(^7\)

### III. BURNABLE POISON DESIGN

Due to the high fissile loading and 80% \( \text{D}_2\text{O} + 20\% \text{H}_2\text{O} \) coolant used, the beginning-of-life (BOL) reactivity is very high. It is essential to suppress this reactivity and have sufficient control measures in place that the reactor can be shut down safely in an emergency. For operational reasons the use of soluble boron is not an option, so this places increased reliance on burnable poisons (BPs). In a previous paper,\(^7\) it was observed that integral fuel burnable absorber (IFBA) exhibits superior performance in terms of initial reactivity suppression, reactivity swing and residual burnup penalty compared to a gadolinia (Gd\(_2\)O\(_3\)) BP loading scheme. Therefore, this section will focus on IFBA in the form of ZrB\(_2\).

#### III.A. High-Thickness IFBA Coating

We have considered IFBA designs adapted for checkerboard and all-UO\(_2\) fuels with 29 to 45 high-thickness IFBA rods in our assembly. Many sources cite a standard thickness of 590 nm (1 g/cm) for a ZrB\(_2\) layer.\(^8\) Here, we use boron 95% enriched in B-10 throughout our IFBA designs in order to increase the neutronic effectiveness. We have considered a high-thickness ZrB\(_2\) coating in order to achieve the crucial self-shielding effect, investigating a coating of 150 \( \mu \text{m} \) as a reference from our previous study.\(^7\) A 150 \( \mu \text{m} \) coating has poison layers with thicknesses greater than 4\( \lambda \), where \( \lambda \) is the neutron mean free path of \( \sim 34 \mu\text{m} \). This high-thickness poison layer can therefore intercept at least 95% of incident neutrons.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal power (MWth)</td>
<td>333.33</td>
</tr>
<tr>
<td>Desired lifetime (years)</td>
<td>20</td>
</tr>
<tr>
<td>Assembly size</td>
<td>13×13</td>
</tr>
<tr>
<td>Control rods per assembly</td>
<td>16</td>
</tr>
<tr>
<td>Pin pitch (mm)</td>
<td>12.65</td>
</tr>
<tr>
<td>Fuel pellet diameter (mm)</td>
<td>8.19</td>
</tr>
<tr>
<td>Cladding thickness (mm)</td>
<td>0.605</td>
</tr>
<tr>
<td>Gap thickness (mm)</td>
<td>0.0498</td>
</tr>
<tr>
<td>Number of assemblies</td>
<td>112</td>
</tr>
<tr>
<td>Fuel height (m)</td>
<td>1.79</td>
</tr>
<tr>
<td>Core diameter (m)</td>
<td>1.97</td>
</tr>
<tr>
<td>Power density (MW/m(^3))</td>
<td>61.6</td>
</tr>
<tr>
<td>Average linear rating (kW/m)</td>
<td>9.90</td>
</tr>
</tbody>
</table>

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**Table I. Design Parameters of Proposed Marine Core**

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![Fig. 2. 13×13 assembly geometry layout for the checkerboard fuel with micro-heterogeneous duplex ThO\(_2\)-UO\(_2\) and UO\(_2\) fuels.](image)

![Fig. 3. Configuration of the micro-heterogeneous duplex ThO\(_2\)-UO\(_2\) fuel.](image)
It can be observed in Figs. 4 and 5 that an increase in the number of high-thickness IFBA pins leads to higher poison longevity and initial reactivity suppression for both the checkerboard and all-UO\textsubscript{2} fuels. However, we observe almost no residual burnup penalty for IFBA designs. To compare the reactivity swing and initial reactivity suppression performance, we considered various numbers of IFBA pins with 150 \( \mu \)m coating for both fuels. The reactivity swing results are mixed depending on the thickness and loading. It is clear from Figs. 6 and 7 that the checkerboard fuel exhibits smaller (by \( \sim 5\% \)) swings than the all-UO\textsubscript{2} fuel for BP loadings less than 37 IFBA pins. The fissile content of the checkerboard fuel reduces more slowly due to the enhanced breeding of fissile material (U-233 in the case of checkerboard fuel vs. Pu-239 in the case of UO\textsubscript{2}). This effect accounts for the reduction in reactivity swing. On the other hand, with BP loadings greater than 37 IFBA pins, the checkerboard fuel exhibits worse reactivity swing performance than UO\textsubscript{2}. Due to the effectiveness of the very high-thickness ZrB\textsubscript{2} coating in absorbing neutrons the beneficial build-up of U-233 is delayed in comparison to the lower IFBA loading cases. Fig. 6 also shows that checkerboard fuel outperforms UO\textsubscript{2} in terms of BOL reactivity hold-down
for the same thickness and number of IFBA pins. This is due to the higher neutron absorption cross-section of the fertile component of the checkerboard fuel, which leads to greater reactivity suppression.

III.B. Final Poison Design

From our BP study it can be observed that high-thickness IFBA is effective as a BP in terms of reactivity swing, initial reactivity suppression and residual burnup penalty performance for both fuels with the mixed D$_2$O-H$_2$O coolant. However, since the initial reactivity of the fuel with this coolant is very high due to its higher moderating power, the BP design requires further optimization in order to suppress more reactivity and reduce reactivity swing.

It has been observed that increasing the number of BP pins (> 33 IFBA pins) for the same (150 μm) thickness exacerbates the reactivity swing (Fig. 7). Therefore, we vary the IFBA thickness and number of BP pins in order to achieve the minimum possible BOL $k_{\infty}$ and reactivity swing while maintaining $k_{\infty} \geq 1$ over the burnup cycle. Figs. 8 and 9 show that for both fuels 41 IFBA pins with 205 μm coating satisfy our BP design criteria. ZrB$_2$ IFBA of higher thickness exhibits better BP performance due to the fact that a poison layer with a thickness of 3λ absorbs ~95% of incident neutrons. Therefore, early in life, the fuel in these pins sees only a severely attenuated neutron flux, and is gradually brought up to power as the poison burns off. This results in a power-sharing arrangement: the pins that were coated in poison have higher fissile content and power late in life, allowing the assembly to stay critical even longer than if it had no poison at all. For both checkerboard and UO$_2$ fuel, a BP design using 41 pins poisoned with a 205 μm thick layer of ZrB$_2$ will be used in our control rod design and whole-core analyses.

IV. CONTROL ROD DESIGN

Using IFBA 41 pins coated with a 205 μm layer of ZrB$_2$ poison, we have seen in Section III that in full-power operation $k_{\infty}$(checkerboard) < 1.136 \[ \rho_{\text{checkerboard}} < 0.120 \] and $k_{\infty}$(UO$_2$) < 1.128 \[ \rho_{\text{UO}_2} < 0.113 \] throughout the entire core lifetime. We aim for a shutdown margin $\rho_{\text{SM}} \geq 0.14$ at any point in life, even if one control rod fails to insert. To determine the necessary control rod worth, we must first evaluate the core’s reactivity in a variety of temperature and power conditions. Then we must determine how many control rods and what control materials are necessary to satisfy the shutdown margin requirement.

IV.A. Assembly Reactivity in Different Temperature and Power Conditions

In an under-moderated reactor, decreasing the moderator temperature leads to a better-thermalized neutron spectrum, lower resonance absorption in the fuel, and hence higher reactivity. Similarly, lower
fuel temperatures lead to a narrowing of the epithermal resonances in the fuel, increased resonance escape probability and higher reactivity. Thus, during times of lower fuel or moderator temperatures, the core will have higher reactivity than in its standard operating state. When determining the optimal control rod worth, it is essential that we have enough reactivity for a rapid shutdown even in these cold or low-power conditions. To evaluate these various scenarios, we measure the assembly reactivity in three temperature and power conditions: hot full power (HFP), hot zero power (HZP) and cold zero power (CZP). These conditions are defined in Table II.

Table II. Different Temperature and Power Conditions

<table>
<thead>
<tr>
<th>Condition</th>
<th>Fuel temperature</th>
<th>Coolant temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>HFP</td>
<td>900 K</td>
<td>580 K</td>
</tr>
<tr>
<td>HZP</td>
<td>580 K</td>
<td>580 K</td>
</tr>
<tr>
<td>CZP</td>
<td>295 K</td>
<td>295 K</td>
</tr>
</tbody>
</table>

Fig. 10 shows the variation in assembly reactivity with burnup at these three conditions for both the checkerboard and UO$_2$ fuels. Reviewing this figure, we note that the maximum lifetime reactivity of an assembly at CZP is $\rho_{\text{max}}$ (checkerboard) = 0.191 and $\rho_{\text{max}}$ (UO$_2$) = 0.182. Thus, with our desired $\rho_{\text{SM}}$ of 0.14, the required control bank must have a reactivity worth of $\rho_{\text{CR}}$(checkerboard) = 0.331 and $\rho_{\text{CR}}$(UO$_2$) = 0.323.

IV.B. Control Rod Material

We examine boron carbide (B$_4$C), hafnium (Hf) and an Ag-80% In-15% Cd-5% (Ag-In-Cd) alloy as candidate control rod materials. For each material, we evaluate the BOL control bank worth ($\Delta\rho$) of a 20-rod bank at full insertion. The results are shown in Table III.

Table III. Control Bank (20-rod) Worth for Various Rod Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>$\Delta\rho$(Checkerboard)</th>
<th>$\Delta\rho$(UO$_2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hafnium</td>
<td>0.208</td>
<td>0.203</td>
</tr>
<tr>
<td>B$_4$C</td>
<td>0.333</td>
<td>0.326</td>
</tr>
<tr>
<td>Ag-In-Cd</td>
<td>0.207</td>
<td>0.202</td>
</tr>
</tbody>
</table>

It can be seen that the control bank worth is $\sim$3% greater for all control materials in the checkerboard fuel than the UO$_2$ fuel. This is due to the harder spectrum experienced by the UO$_2$ fuel. It is also clear that the worth of the B$_4$C rods is $\sim$50% greater for both fuels, making it the natural choice of control rod material to take forward in this study.

IV.C. Number of Control Rods

It is essential to have enough rod worth for a quick shutdown even in cold or low-power conditions. For safety purposes, it is necessary that the reactor be able to shut down even if one control rod fails. However, we can see from Table III that the worths of our control bank, $\Delta\rho$(checkerboard) = 0.333 and $\Delta\rho$(UO$_2$) = 0.326, are almost equal to the required worth identified in Section IV.A.: $\rho_{\text{CR}}$(checkerboard) = 0.331 and $\rho_{\text{CR}}$(UO$_2$) = 0.323. We can see that a 20-rod control bank gives the required shutdown margins for both candidate fuels. Furthermore, a 20-rod control bank naturally provides octant symmetry, which has been identified as an essential feature for subassembly design.
V. WHOLE-CORE ANALYSIS

In Sections III and IV, we developed a subassembly design that was optimized for consistent and controllable reactivity over a long core life. We now load these assemblies into a whole-core model so we can assess the effects of neutron leakage and spatial flux dependence. Using PANTHER, we model the 112-assembly core and divide it into three radial zones (A, B and C, see Fig. 11). The two most obvious radial zoning pattern options are fissile-zoning and BP-zoning. Since we have observed that fissile-zoning is not an effective way of controlling the power peaking factor in our small marine PWR core in a previous study, we have investigated BP-zoning in this study.

One of the main objectives of the whole-core analysis is to keep the radial form factor (RFF) below 1.55 throughout the core life. Therefore, two types of BP loading scheme (lower BP loading (LBL) and higher BP loading (HBL)) were employed to control RFF while obtaining the highest achievable core life.

We considered a LBL scheme in which assemblies in zones A, B and C have 33, 17 and 9 IFBA pins, respectively. In contrast, the HBL scheme considered used 41, 33 and 25 IFBA pins in zones A, B and C, respectively. In the figures in this section, we use “U” to denote the core with all-UO$_2$ fuel and “CHK” for the core with checkerboard fuel.

It can be seen in Fig. 12 that the reactor cores remain critical throughout the designated core lifetime of 20 years for all fuel configurations. The cores with lower BP loading can achieve $\sim$7% longer core life ($\sim$23 years) than the higher BP loading cores ($\sim$21.5 years). Both checkerboard cores, in fact, exhibit 2% longer core life compared to the UO$_2$ cores due to the higher thermal “fertile capture-to-fissile absorption ratio” (Fig. 13) of the checkerboard core over the entire energy range, which leads to the efficient breeding of fissile U-233 over the core lifetime.

Fig. 14 shows the RFF variation over time for the radially zoned reactor cores. For the LBL cores with both fuels, the RFF is well above the standard limit of 1.55 after $\sim$18 years. When the BP in these assemblies burns out after $\sim$18 years, the power share in the inner assemblies increases, causing very high power peaking. In contrast, the HBL scheme enables the
Fig. 14. Radial form factors over time for the radial-zoning core loading patterns.

RFF to be maintained below the 1.55 limit for both fuels throughout the core lifetimes. In both cases, the RFF increases gradually over life and peaks at 16 years but is still well below the limit.

Fig. 15 shows that the values of fuel temperature (reactivity) coefficient (FTC) are negative throughout the core life for both fuels. The FTC values of the checkerboard core are considerably more negative compared to the UO$_2$ cores due to the stronger Doppler effect of Th-232 that arises from increased Doppler broadening by the simultaneous presence of Th-232 and U-238 in the checkerboard fuel.

Fig. 15. FTC over time for the radial-zoning core loading patterns.

Fig. 16. MTC over time for the radial-zoning core loading patterns.

Fig. 16 shows that the moderator temperature coefficient (MTC) is more negative in the checkerboard cores than the UO$_2$ cores at BOL for both the LBL and HBL schemes due to the increased neutron absorption in the Th-232 resonances as the moderator temperature increases. MTC is higher at BOL for both fuel cores, and the value decreases (becomes more negative) with burnup due to the changes in isotopic composition and increased variety of isotopes present. MTC is slightly more negative in the UO$_2$ cores than the checkerboard cores after $\sim$20 years. As the burnup progresses, more plutonium (particularly Pu-239) is generated in the all-UO$_2$ fuel than the checkerboard fuel. Due to the strong thermal neutron absorption of plutonium, MTC is more negative in the all-UO$_2$ cores at EOL.

VI. CONCLUSIONS

One of the most important points that can be drawn from these studies is that a checkerboard fuel lattice needs less burnable absorber than uranium-only fuel to achieve the same poison performance. The higher initial reactivity suppression and relatively smaller reactivity swing of the checkerboard fuel make the task of reactivity control through BP design in a thorium-rich core easier. It is also apparent that control rods have greater worth in a checkerboard core, reducing the control material require-
ments and thus potentially the cost of the rods. In the whole-core analyses, we have observed that BP-zoning enables both candidate cores to achieve the required core lifetime while maintaining acceptable values for the neutronic safety parameters throughout. The checkerboard core, however, provides a longer core lifetime than the all-UO$_2$ core due to efficient breeding of U-233. For all these reasons, we plan to continue our analysis of thorium-based fuels for civil marine propulsion applications. Future work will include the consideration of alternative cladding materials (e.g. ODS-type steel and SiC) for very high burnup fuels and coupled neutronic-thermal-hydraulic studies.

REFERENCES


