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Impact of Fuel Enrichment on Key Naval Reactor Characteristics and Non-Proliferation Concerns

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ABSTRACT

This work reports on a notional compact naval reactor core running at 50 MWt full power—designed to investigate core life, reactivity margins and plutonium inventory for different levels of enrichment. A simplified computer model was constructed with the OpenMC neutron transport code and coupled to ONIX to calculate depletion of the initial fuel load—uranium dioxide mixed with gadolinia. It is shown that a notional low enriched uranium naval core could sustain criticality for 5–7 years at full-power and overcome xenon poison transients. Self-shielding of the burnable poison has been found to be significant in the radial direction and should be considered in such core design. Negative Doppler and moderator coefficients have been found for the low enriched cores. The plutonium inventory of the spent fuel produced at the end of life as a function of enrichment is also investigated. This study bears direct implications for the nonproliferation regime by suggesting that it may be possible to reduce the technical incentives for the use of highly enriched uranium on naval reactors.

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Introduction

Compact reactor cores have applications in the domain of marine propulsion—both civilian and military. Over the last seven decades, all the navies of countries classified as nuclear weapon states under the Treaty on the Nonproliferation of Nuclear Weapons (NPT) have heavily invested in the development of compact reactor cores to power their naval fleets, including aircraft carriers and nuclear-powered submarines.[1] By dispensing with the need for oxygen for combustion of oil, nuclear-powered submarines can move at fast (≈50 km/h) speeds for long time periods deep underwater without detection.[2] This gives these vessels unparalleled tactical and strategic advantages over their diesel-powered counterparts and Air

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Independent Propulsion (AIP) vessels for missions that require transit to distant locations.[3]

In the context of the Information Circular (INFCIRC)/153, paragraph 14, entitled "Non-Application of Safeguards to Nuclear Materials to be used in Non-Peaceful Nuclear Activities," countries that are parties to the agreement are allowed to withdraw nuclear materials from IAEA safeguards for nuclear propulsion activities.[4,5] A state which is party to the NPT could therefore invoke article 14 of INFCIRC/153 and assert, at any time, its intention to lawfully use either Low Enriched Uranium (LEU $<$20% of uranium-235) or Highly Enriched Uranium (HEU $\geq$20% of uranium-235) in activities related to naval propulsion.

As more countries proceed with their indigenous nuclear powered submarines programs, including NPT non-nuclear weapon states,[6] it is important to investigate what the proliferation paths associated with such programs could be and develop technical and policy approaches to safeguard them.[7]

Reducing the incentives to produce HEU for naval propulsion is relevant to any efforts to curb the production of nuclear-weapons usable fissile material. Three out of five NPT nuclear weapon states use HEU to power their submarine fleets, and one country which is not a signatory of the NPT—and has nuclear weapons—has been developing an HEU core for its burgeoning submarine fleet.[8] In fact, countries that use HEU to power their submarines could lead the reduction in use of HEU by converting their cores to LEU, or redesigning their cores to be used in the next generation of their nuclear fleets.

Because of their sensitive nature, there is a relative paucity of information in the open literature about the design of naval cores and fuel elements. An independent study undertaken by the JASON advisory panel, which was partially unclassified in 2016, concluded that the US decision to convert naval cores from HEU to LEU is possible but would require some combination of increased reactor core volume, reduced core lifetime and increased fuel densities.[9]

There is a growing body of knowledge that has, slowly but steadily, been accumulated in the open literature that give support to this claim. In 1990, Ippolito investigated some tradeoffs between the use of LEU and HEU fuel for submarine naval cores.[10] Based on the model he developed, he concluded that, using uranium dioxide fuel, with density of 9.1 g/cm^3 in a "caramel configuration," a 20% enriched core could be designed to have the same core lifetime as one that used 97.3% uranium-235. A similar conclusion was reached later by Diakov et al. in the context of converting a Russian icebreaker reactor from HEU to LEU.[11] Contemporary research in the field of kilowatt-class space reactors and on civil nuclear marine

propulsion present conclusions that yielded similar results with these early works.[12] On the other hand, the Virginia Tech Transport Theory Group, in its 2014 report, was reluctant to advocate for the conversion of naval cores from HEU to LEU, and stated that the development and certification of an LEU core design able to reliably handle the xenon poison transients immediately after shut down remain an unresolved issue.[13]

As far as fuel materials and density are concerned, a recent report by the Idaho National Laboratory on the evaluation of fuel reactor concepts for advanced LEU fuel developments compiled several fuel candidates with densities equal to or greater than uranium dioxide ($\geq$9.7 g/cm^3), such as U_xMo alloys and uranium carbide, and recommended further investigation of these alternative fuels. The authors recognize, however, that despite the potential, most of these candidate materials are not proven, with very limited demonstration worldwide.[14]

If novel core designs and advances in fuel development technology could allow LEU cores to have long lifetimes and performance equivalent to HEU, then this would be a major step toward the elimination of an important driver for the demand of HEU. This paper tries to contribute to this ongoing discussion by modeling three notional cores that differ by enrichment and uranium density. It relies on open-source information and software to compare the performance of LEU and HEU fuels in terms of core life and reactivity margins. In addition, the work investigated the plutonium inventory produced by these cores at the end of life (EOL). In doing this, this work has a two-fold objective: first, for those countries with plans to develop naval reactors, provide some leads on possible core designs that would dispense of the need of HEU for naval propulsion, and, second, for countries that already use HEU for naval propulsion, identify some pathways to use LEU fuel instead.

If LEU cores eventually become the standard for the navies of countries that have traditionally been operating with HEU cores, that could make a good starting point for the creation of an arrangement in which all parties involved could eventually forego the use of HEU for naval propulsion.

The notional core model—geometry and simulation

Pressurized water reactor (PWR) technology has been favored by countries that developed naval reactors for submarine propulsion, since it is mature—in part due to early use in submarines—and is deployed by many countries around the world.[15] While the core and fuel design information of naval reactors are militarily sensitive, the general physics of PWRs is in the public domain, and a good deal can be learned from the civilian designs.

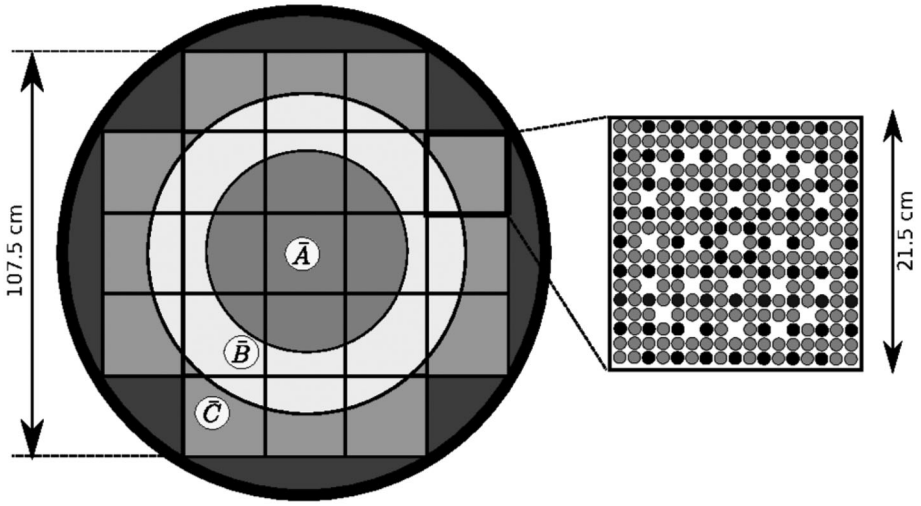

Figure 1. Core layout and pin cell distribution for the model discussed in this work. For the fuel depletion calculations, the pins in the core (left) were assigned to the radial zones as indicated. The pins cells shown in black (right) have the neutron poison gadolinia mixed into the enriched uranium. The exact fractions are discussed in the text. The geometry of the fuel assemblies and the fuel pins in this plane are based on typical PWR specifications, but the core height is only 1 m.

The cores of PWRs are typically loaded with a supercritical configuration of fuel. Control rods and burnable neutron poisons are then used to offset the excess reactivity at beginning of fuel life and with reduced effect as the uranium-235 in the fuel is consumed and the excess reactivity of the fuel declines. Since the details of naval cores design are not known some assumptions must be made in building the model.

The model presented here is based on a hypothetical PWR design adapted for the small volumes required for compact naval cores. This notional core comprises $3+5+5+5+3=21$ power-reactor fuel assemblies, each composed of a standard 17×17 fuel array, with spaces for control rods (Figure 1). Uranium dioxide and pure zirconium have been used as the fuel and cladding material. Dimensions and details of the pin cells can be found, for example, in Glaser et al.[16] This basic geometry has been fixed for the purpose of this study. It is also assumed that the power of the reactor will be either zero or 50 MWt. This is indeed an oversimplification, as it is known that one of the main design requirements for naval cores is the ability to vary power outputs. Table 1 summarizes the basic parameters used for the simulation.

To get maximum power out of a given size core, it is important to reduce radial power density gradients across the core and flatten the neutron flux. Techniques to flatten the flux include the addition of neutron reflectors in the baffle barrel region, increasing the effective radius;[17]

Table 1. Basic parameters used in the simulation of the notional core. See text for details.

Parameter	Value
Thermal power output (MWt)	50
Capacity factor	100% (full power)
Fuel type	Uranium dioxide
Reactor pressure vessel diameter (cm)	152
Active core height (cm)	100
Core volume (m^3)	1.81
Power density (kW/l)	22.75

increasing enrichment with increased radius for radial power shaping; and utilization of burnable neutron poisons for reactivity control early in the core life.[18] This work applies these three different techniques simultaneously and is illustrated schematically in Figure 1.

Standard stainless steel was assumed for the pressure vessel walls and radial reflectors. Unborated water was chosen as the moderator and coolant; a burnable neutron poison was introduced into the fuel elements to lower the reactivity of the fresh fuel load. Gadolinia (Gd_2O_3), with pure gadolinium-155 has been chosen as the neutron poison mixed into 76 pins in a similar pattern to that described by Peakman et al.[19] In this model, however, gadolinia concentration and fuel enrichment of individual pins has been combined with the differentially enriched radial zones denoted as $\bar{A} = A + A', \bar{B} = B + B'$ and $\bar{C} = C + C'$, where the letters represent zones with the same level of enrichment and the prime symbol stands for pins that contain burnable poisons. The result is that, approximately 40% of the pins contain zoned burnable poisons, reducing spatial self-shielding and power peaks across the core.

The input file for the notional core geometry has been coded with the Python Application Programing Interface (API) for OpenMC,[20] an open-source software that relies on Monte Carlo methods to solve the neutron transport equation and compute a reactor's effective multiplication factor k_{eff}. OpenMC was fed with cross section data from the Nuclear Reaction Data Library—ENDF/B–VIII.0.[21] In order to compute the time-dependent fuel depletion, governed by Bateman equation, OpenMC was coupled with the recently-developed open-source fuel depletion code ONIX,[22] which implements the Chebyshev Rational Approximation Method (CRAM) for matrix exponentials.[23]

Three different configurations with different patterns of fuel enrichment were used in this study. In configuration I, the inner zone *A* was loaded with uranium-235 enriched to 4%, while the outermost zone *C* was loaded with uranium-235 enriched to 10%. The other two enrichment configurations are obtained by doubling and redoubling levels of enrichment (while halving the fuel densities). An empirical multidimensional

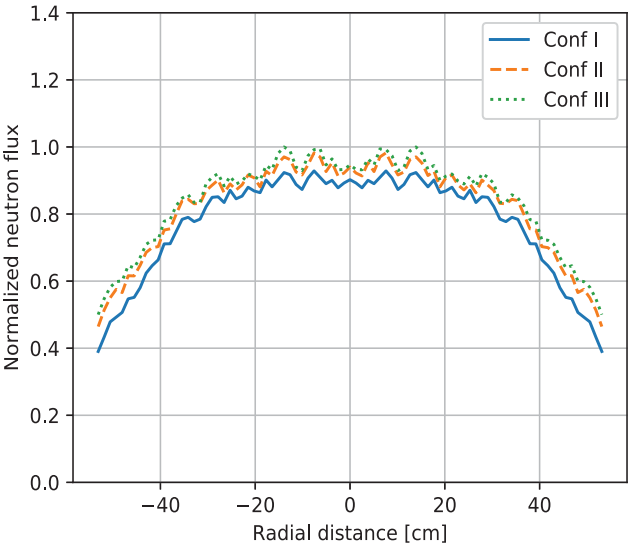

Figure 2. Normalized radial neutron flux profiles for the three Configurations. Normalization was done by dividing the radial flux of all configurations by the highest radial value found in Configuration III. See text for details.

criticality search was performed to find the optimal gadolinia concentrations in each configuration. The parameters were set by imposing $k_{eff} \approx 1$ at the beginning of life (BOL) without control rods inserted, plus a sufficient margin of reactivity to override the neutron poisoning effect of the fission product xenon-135 while keeping the initial radial neutron flux as flat as possible, as can be seen in Figure 2. In this way, a relatively flat power distribution can be maintained throughout core life, as prescribed by Radkowsky.[24]

This notional core is also segmented along the vertical axis into three identical axial layers equally spaced ($z1$, $z2$, $z3$), with a core height of 1 m. The total number of independent burnup zones is therefore $3 \times 3 \times 2 = 18$, where the last factor of 2 reflects that each zone contains poisoned and unpoisoned fuel rods. The simulation was run with the control rods fully out. Complete insertion of rods containing unenriched boron (1 g/cm^3) in Configuration I at a Cold Zero Power state with no xenon would produce a drop in the effective multiplication factor $\Delta k_{eff} = 0.42$, which gives enough margin for criticality control, as the burnable poison is depleted starting at the BOL and the multiplication factor increases up to a maximum, in all cases studied.

In order to illustrate the effect of introducing burnable poison in the fuel mix, the Monte Carlo solution for the neutron transport equation in Configuration I produced $k_{eff} = 1.07$ and 1.35 with and without the introduction of gadolinia in the fuel. The details of the enrichment zoning and poisons setup are summarized in Table 2.

Table 2. Summary of uranium enrichment and poison fraction information for the three different configurations used in the simulation.

	Zone $\bar{A}$			Zone $\bar{B}$			Zone $\bar{C}$		
Configuration	*NV*	*PF*	*EE*	*NV*	*PF*	*EE*	*NV*	*PF*	*EE*
I	4%	0.1%	3.9%	7%	0.3%	6.9%	10%	0.7%	9.9%
II	8%	0.4%	7.9%	14%	1.2%	13.8%	20%	2.8%	19.4%
III	16%	1.6%	15.7%	28%	4.8%	26.6%	40%	11.2%	35.5%

Here *NV* is the nominal value of uranium enrichment for pin cells without poison in atom percent, *PF* and *EE* are the poison fraction and the effective uranium enrichment for the pin cells with gadolinia poison, respectively. The fuel densities for Configurations I, II, and III were set to 10, 5, and 2.5 g/cm^3, respectively, – and the corresponding mean uranium enrichment for each configuration are 7.4%, 14.8% and 29.6%, respectively.

Table 3. Volume and initial heavy metal (IHM) content in one axial layer(z1) for each of the radial zones, considering only the uranium in the fuel meat.

		IHM [kg]		
Zone	Volume [cm^3]	Configuration I	Configuration II	Configuration III
A	19,918	175.58	87.78	43.88
A′ (poison)	7.892	69.47	34.59	17.02
B	40,354	355.69	177.83	88.89
B′ (poison)	16,019	140.64	69.47	33.07
C	32,955	290.46	145.21	72.58
C′ (poison)	13,083	114.24	55.52	24.67
Total	131,225	1,146.11	570.42	280.13

Since there are pin cells with and without burnable poison, they comprised separate burnup zones. See text for details.

Table 4. Initial masses of uranium-235 and gadolinium-155 for the Zone C′ in one axial layer (z1) for different configurations.

Zone C′ (poison)	Configuration I	Configuration II	Configuration III
Uranium-235 [kg]	11.3	11	9.6
Gadolinium-155 [kg]	1.04	2.08	4.07

The increased amount of gadolinium-155 for the higher enriched configuration is required to offset the decreased amount of neutron absorption caused by the reduction of uranium-238. See text for details.

In the pin cells without burnable poison, the uranium-235 enrichment level corresponded to its nominal value (*NV*) in atom percent; for the pin cells with a gadolinia poison fraction (*PF*),[25] the effective uranium enrichment (*EE*) in each zone for a given configuration has been modeled to be $EE = (1 - PF(\%)) \times NV(\%)$, so when $PF = 0$, then the effective enrichment is unchanged. Table 3 shows the initial heavy metal (IHM) content (uranium-235 and uranium-238) for each of the radial zones in one axial layer (1/3 of the core height) for each configuration.

The fraction taken by the gadolinium-155 atoms in the outermost zone of the core (where, in this model, one finds the highest concentrations of uranium-235) rapidly reaches a limit as a function of enrichment. For a fixed amount of uranium-235 across the different configurations (≈33 kg), it would be necessary to pack increasingly more gadolinium-155 at the expense of the former. The breakdown is shown on Table 4.

Results and discussion

Core life

A full core calculation has been performed to investigate for how long each configuration could sustain criticality. In this exercise, the three configurations have been simulated at $T = 591$ K. Core life is limited by the amount of fuel in the core. For the three configurations presented, the core life exceeded 2,000 days (5.5 years) at full power maintaining criticality and therefore dispensing the need of refueling during that time. It should be mentioned that, with all cores containing the same amount of uranium-235, the longer core lives for lower enrichment are due to the production and fissioning of more plutonium.

The actual period of operation would be significantly longer if one considers the capacity factor. Operating at 20% capacity factor, rather than the 100% factor used in the model, could extend the life of configuration II core to over 35 years—practically dispensing the need of refueling for the life of the vessel. Figure 3 summarizes the results of the simulation for 50 MWt at full power, and Figure 4 shows the neutron spectra plotted for the BOL and EOL in the three configurations. One can see that toward EOL, the more enriched configurations produce significantly higher neutron fluxes near thermal energies.

Although the number of uranium-235 nuclei has been kept constant between the three configurations, there is relatively less uranium-238 in the fuel to absorb thermal neutrons at higher enrichments, which would, on

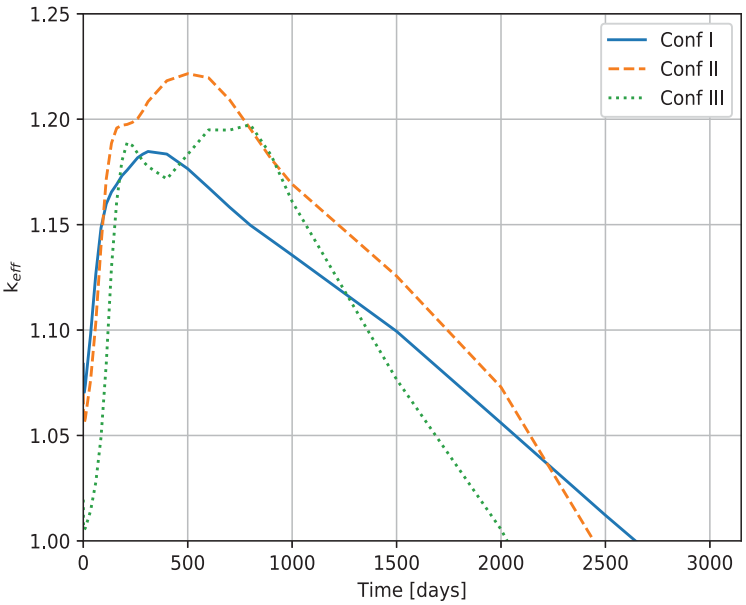

Figure 3. k_{eff} time-evolution for different configurations. See text for details.

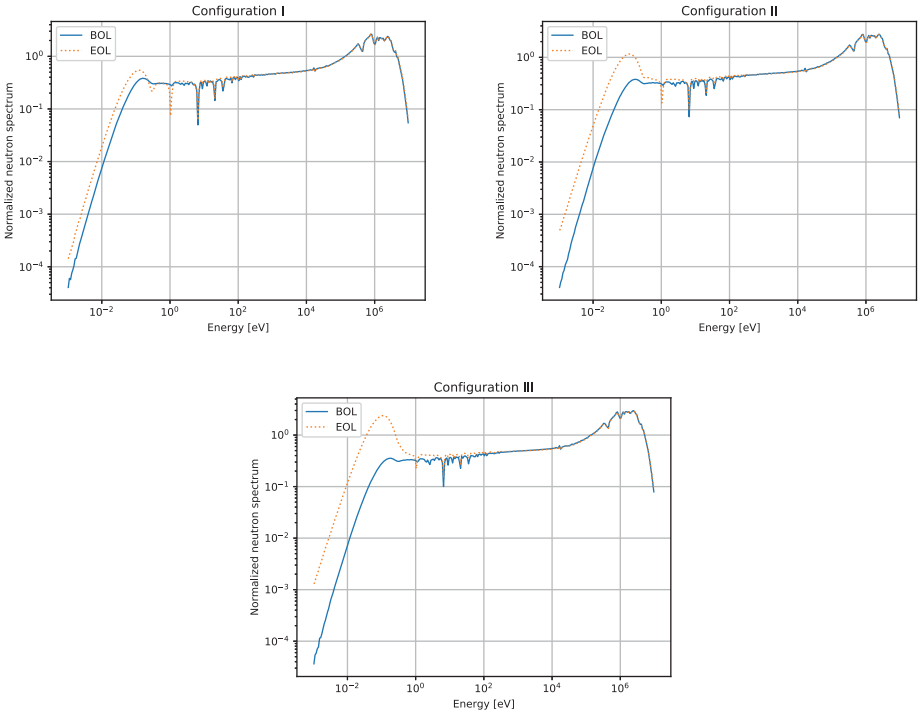

Figure 4. Neutron spectra for all the three configurations at the BOL and EOL. See text for details.

the one hand, increase core life; on the other hand, in order to keep k_{eff} at BOL ≈ 1, the poison fraction also had to be increased (as shown in Table 2), which significantly contributed to the reduction of core life. In a more realistic design, this could be balanced, for instance, by an increase in fuel density, compensated with the insertion of control rods, in order to maintain the criticality within bounds.

Self-shielding effect of the gadolinia poison

Since this notional core has been divided into three radial zones (Figure 1), it has been possible to simulate the material depletion independently for each burnup zone, which permitted an investigation of the self-shielding effect of the gadolinia poison. For example, Figure 5 illustrates the time evolution of the effective cross sections for neutron capture of gadolinium-155 for the three radial zones with burnable poison in the first axial layer ($Az1'$, $Bz1'$, and $Cz1'$) of the notional core. The results clearly show the self-shielding effect—per gadolinium atom, the neutrons in the core have a higher probability of being captured in the inner radial rings than in the outer radial rings. This effect becomes more pronounced for the more enriched configurations, since they required a higher poison load to control

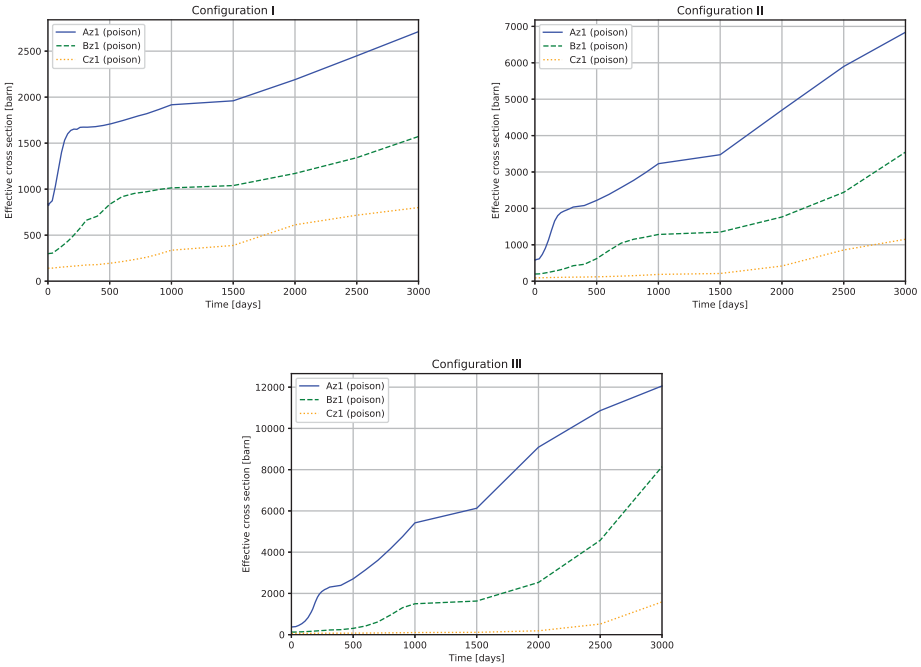

Figure 5. Effective cross sections for neutron capture (n, gamma) for gadolinium-155 in the three configurations. See text for details.

the initial excess reactivity. In the case of Configuration III, for instance, the neutron absorption probability of the gadolinia poison located in the outer ring only increases toward the end of the core life.

Reactivity dependence on poisoning by transient xenon-135

A key featureof the dynamics of fission products in PWR fuel during operation is the buildup after shutdown of xenon-135, the decay product of iodine-135. Because of its high cross section for the absorption of thermal neutrons, the build-up of xenon-135 works as a transient neutron poison that lowers the reactivity of the core during a period after shutdown. This period is determined by the half-lives of iodine-135 and xenon-135, 6.6 hours and 9.1 hours, respectively. Civilian reactors can allow time for these products to decay away before restarting the reactor, or they can reduce the boron concentration in the cooling water. Boron dilution is a slower process, however, compared to the withdrawal of control rods to offset the transients.

Naval reactors must be able to produce power quickly after shutdown. For instance, under stringent operational demand to produce power for evasion or attack maneuvers, a naval core must be able to produce enough excess reactivity in order to overcome the absorption of neutrons due to

the build up of xenon-135 poison caused by shutdown. This extra reactivity can be provided by pulling out the control rods to compensate for that loss until the populations of iodine-135 and xenon-135 reestablish equilibrium. The xenon-135 poison transient after shutdown is given by Equation (1):[26]

$$X(t_s) = \frac{\lambda_I}{\lambda_X - \lambda_I} I_0 (e^{-\lambda_I t_s} - e^{-\lambda_X t_s}) + X_0 e^{-\lambda_X t_s}, \quad (1)$$

where $X(t_s)$ is the xenon-135 concentration at a time t_s after shutdown, λ_I and λ_X are the decay constants for iodine-135 and xenon-135, and I_0 and X_0 are respectively the equilibrium values of iodine-135 and xenon-135 at full power before shutdown.

In order to obtain I_0 and X_0, OpenMC was coupled with ONIX to solve the fuel depletion equation. By using Equation 1, it was possible to obtain the maximum xenon-135 build up for each burn up zone hours after shutdown. The values for I_0 and X_0 were then retrofitted into OpenMC to compute the new value of the effective multiplication factor k'_{eff}, compared to k_{eff} obtained immediately before shutdown. The comparisons have been made at $T = 293$, since the reactivity of the xenon unpoisoned core can be expected to be at its maximum at the lowest temperature. The difference $\Delta\rho = \rho' - \rho$, where $\rho = (k_{eff} - 1)/k_{eff}$, expresses the loss of reactivity in the system and, conversely, the reactivity that would need to be introduced in the core to overcome the reduction in the neutron flux due to the buildup the of xenon-135 transient poison.

The time evolution of the fuel depletion was simulated with finer time-steps for the first 30 days. The xenon-135 and iodine-135 concentrations reached equilibrium at $t \approx 5$ days for the three configurations. The change in reactivity caused by the xenon-135 peak for the three different configurations tested is given in Table 5.

These results compare well with literature values (see the work of Fribourg on naval reactors)[27] and are similar in the three configurations, which suggests that xenon transient is weakly dependent on the enrichment used. While changes in reactivity tend to be reduced as one moves toward higher levels of enrichment, the reactivity changes could be tolerated in the core designs utilizing LEU fuel. As the core gets closer to its EOL, however, the ability to compensate for the xenon reactivity transients by pulling out

Table 5. Change in reactivity caused by xenon-135 peak for different configurations at $T = 293$ K. See text for details.

Configuration	Xenon-135 peak [atom/barn*cm]	$\Delta\rho$ [pcm]
I	2.31×10^{-7}	−700
II	2.28×10^{-7}	−613
III	2.22×10^{-7}	−420

the control rods will be reduced. This effect must be considered during both design and operation.

Reactivity control by thermal feedback

The transient effects on k_{eff} of changes in temperature is of relevance to this study, because in a PWR system, when the power output increases, the temperature of the water coming back from the steam generator decreases, and if the temperature coefficient ($\Delta\rho/\Delta T$) is negative, the reactor power will increase in response to the power demand. Conversely, if the temperature of the core increases, its reactivity should decrease, which is important to keep k_{eff} under control.

Generally speaking, an increase of fuel temperature Doppler-broadens the neutron absorption cross sections. In addition, there is also a moderator temperature effect that influences how far the neutrons are being slowed down before eventually getting absorbed by the fuel. These effects influence the competition between the neutron capture of uranium-235 and uranium-238 (as well as other neutron absorbers), and thereby the effective neutron multiplication factor, k_{eff}. In order to check these effects, the temperature coefficients of the three configurations have been estimated.

The cross section library used for this study lacked data for $293\,\mathrm{K} \leq \mathrm{T} \leq 591\,\mathrm{K}$, so the simulations have been undertaken with the information available for these two temperatures only. In addition, the temperatures of moderator and fuel have been assumed to be the same. The results obtained are therefore a combination the fuel (Doppler) and moderator coefficients. Figure 6 shows the changes in reactivity $\Delta\rho$ between $T = 293\,\mathrm{K}$ and $T = 591\,\mathrm{K}$ for the entire core lifetime for the different configurations. Based on these crude results obtained by the full core simulation with these

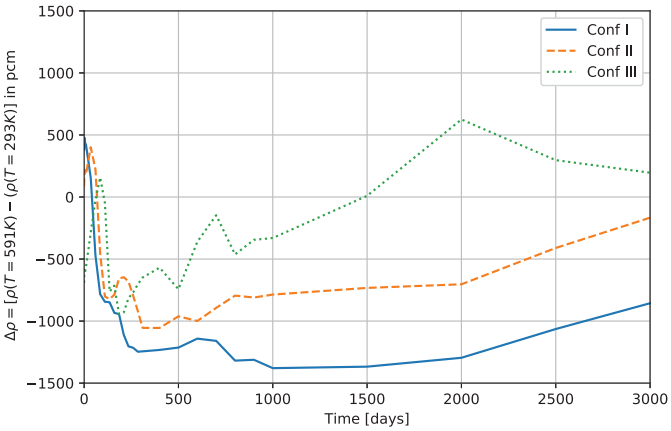

Figure 6. Changes in reactivity $\Delta\rho$ between $T = 293\,\mathrm{K}$ and $T = 591\,\mathrm{K}$ for the entire core lifetime for different configurations. See text for details.

two temperature data points, Configurations I and II would produce combined negative Doppler/moderator coefficients, -5 pcm/K $\lesssim(\Delta\rho/\Delta T)_I \lesssim -3$ pcm/K and -3 pcm/K $\lesssim(\Delta\rho/\Delta T)_{II} \lesssim -1.5$ pcm/K, respectively, until the very end of their useful life (5.5 years), which is somewhat consistent with the values reported by Peakman et al.[28] It should be noted that under more realistic conditions, the temperature inside the uranium-oxide fuel would be higher than the temperature of the moderator because the heat is being generated in the fuel and uranium-oxide has a low conductivity, therefore the effect of Doppler feedback in the simulation may be underestimated. It should be mentioned that the Configuration III core would start producing positive temperature reactivity coefficients after approximately 4 years of operation, which would make it unstable and thus unsafe to operate.

Plutonium inventory

Figure 7 shows the buildup of the ratio of plutonium-239 plus plutonium-241 build-up to uranium-235 for the three configurations from BOL until EOL.[29] The initial mass of uranium-235 $\approx$ 250 kg. It turns out, as could be expected, that the LEU cores (Configurations I and II) will have a higher plutonium inventory toward the EOL than their HEU counterpart because they contain more uranium-238. For instance, after 5.5 years of operation (2,000 days), the amount of plutonium produced with Configuration I (62 kg) is a factor of three higher than with Configuration III (20 kg). This helps explain the longer core life of the less enriched configuration as due to the larger amount of fissile plutonium at the end of core life.

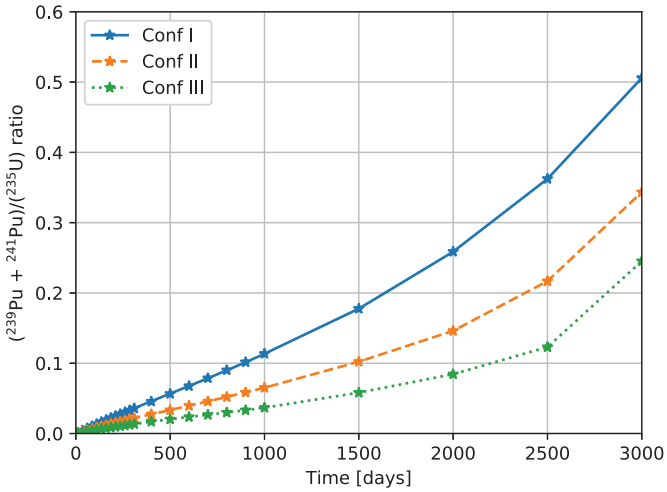

Figure 7. The ratios of (plutonium-239 + plutonium-241)/uranium-235 over time for different configurations. See text for details.

Operational performance is one of the key elements to be considered in the discussions about the adequate level of enrichment of the fuel deployed on nuclear powered submarines. In addition, the choice of LEU could imply more frequent refueling and thus not compatible with specific military constraints. Higher levels of uranium enrichment at the same uranium density allows for operation of the reactor core for longer periods, sometimes dispensing with the need for refueling. On the other hand, production of HEU is considered to be very sensitive and poses a great proliferation concern because it involves the production of weapons-grade uranium. If one assumed that LEU is an option, some proliferation concern would be shifted from the front end to the back end of the naval fuel cycle, because of the larger plutonium inventory increasing the importance of safeguards measures to ensure it would not be extracted from the spent fuel.

In deciding on the use either LEU or HEU, an assessment of the resulting plutonium inventory would need to be taken into account, because standard (civilian) safeguards measures for the spent fuel may not be completely applicable for the case of naval fuel.

Conclusion and future work

This work presented three notional compact PWR cores, differing in enrichment. By choosing a particular combination of enrichment zoning together with burnable poisons to radially flatten the power, it was shown that, from purely neutronics considerations, for a fixed amount of uranium-235 in a core, an LEU option could sustain criticality competitively. The reactivity changes caused by the accumulation of xenon-135 during shutdown decrease somewhat for increasing enrichment. In terms of thermal feedback, the LEU core configurations have negative temperature coefficients and thus are stable. Finally, for a constant inventory of uranium-235, the plutonium inventory is inversely proportional to the enrichment of uranium-235 in the fuel meat. Taken together, these results suggest that an LEU core is feasible under the specific set of assumptions and constraints presented.

However, naval cores must be designed to sustain shocks and to rapidly provide power for critical maneuvers. This “ruggedness” requirement has not been fully considered in this model. The work presented has only considered the neutronics aspects of the design of a notional naval core. The author recognizes that the validity of the conclusions presented would have to be tested against other requirements such as thermo hydraulics, structural and mechanical stability, radiation shielding and protection of the crew.

In any case, the challenge of maximizing the efficiency of naval cores utilizing LEU fuel is facilitated enormously by the great potential offered by the ongoing developments in the domain of core and fuel design.

The study of safeguarding the nuclear cycle for naval cores with a focus on spent fuel verification is of special importance and will be the subject of a separate work.

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Notes and References

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