Simulating submarine reactor fuel in light of the AUKUS deal

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Abstract:

This work investigates fuel properties of submarine reactor fuel from a non-proliferation and safeguards perspective in light of the deal involving Australia, the United Kingdom and United States known as AUKUS. This study investigates the isotopic composition of the spent fuel at the end of intended reactor life. The fuel in the proposed AUKUS submarine is modelled after a Virginia Class fast attack submarine, discussed as an option for Australia.

The vast majority of civil experience with plutonium production is with fuel starting at low enrichments for shorter burnups. The AUKUS fuel at the start of irradiation campaign is assumed to contain uranium enriched to between 93% and 97,3%. It is burned at high power for about 33 years before retirement. Because the fuel is mostly uranium-235 initially, there are very few thermal captures leading to production of plutonium-239. In the submarine, the majority of non-fissile captures lead to the production of uranium-236 with other capture chains that do not lead to the production of weapons grade plutonium or weapons usable uranium.

This study concludes that the final isotopic composition of the AUKUS spent fuel is no longer VHEU, but a low grade of HEU diluted largely by uranium-236 instead of uranium-238. Several kilograms of plutonium are produced but it is composed of several different plutonium isotopes with a large fraction of plutonium-238. There is little likelihood that spent AUKUS fuel will be reprocessed by any of the countries involved. But if it were reprocessed, the resulting uranium and plutonium will have very unusual isotope compositions. Resulting materials would be subject to safeguards but would not, in fact, be well-suited as fissile material for weapons purposes.

Keywords: AUKUS, non-proliferation, safeguards, submarine, reactor fuel.

1. Introduction and objective

Nuclear-powered submarines are operated by six countries in the world: the US, Russia, Britain, France, China and India. The first five countries are NWSs under the Treaty on the Non-Proliferation of Nuclear Weapons (NPT), while India has never signed the NPT but is in possession of nuclear weapons. Nuclear-powered submarines have also to varying extent been considered by a number of non-nuclear weapon state parties to the NPT. These countries are Australia, Brazil, Canada, Iran and South Korea [1], as well as, potentially, Argentina and Japan [2]. A comprehensive overview of submarine nuclear reactors used for propulsion can be found in [3]. This work focuses solely on Australia in light of the recent AUKUS deal, but the implications are valuable in the context of other countries as well.

The United States and the United Kingdom have proposed supplying Australia with nuclear powered submarines under the so-called AUKUS security pact. These submarines are not designed to carry nuclear weapons. However, there are two nuclear safeguards issues associated with them. First, very highly enriched uranium (VHEU) in the form of reactor fuel would be in the custody of a non-nuclear weapon state (NNWS) and the fuel would probably be provided to Australia by a nuclear weapon state (NWS). Second, normal IAEA safeguards would not be in force on VHEU fuel in the submarine reactor core. These two facts have been interpreted in the literature as proliferation risks (or even loopholes in the legal frameworks) associated with the AUKUS deal. This paper's objective is to investigate those potential risks by assessing proliferation attractiveness of nuclear material in the AUKUS reactor fuel during its lifetime.

2. The AUKUS security pact and non-proliferation concerns

AUKUS is a trilateral security pact between Australia, the UK and the US. All three countries are parties to the NPT, a treaty aimed to prevent the spread of nuclear weapons by regulating, among other issues, how fissile materials can be used by states. Non-nuclear weapon states (NNWS) such as Australia, are explicitly forbidden to develop or acquire nuclear weapons, and must place their nuclear material intended for peaceful nuclear activities under nuclear safeguards. In 2021, it was announced that the pact would

cooperate on a range of topics, including nuclear-powered submarines as mentioned in references [4] and [5]. This announcement raised multiple questions, some of which were practical in nature and concerned how such a cooperation could be arranged and facilitated. It also raised a number of non-proliferation concerns [4], [5], [6] and it is argued in reference [7] that Australia "will have to become the first non-nuclear-weapon state to exercise a loophole that allows it to remove nuclear material from the inspection system of the International Atomic Energy Agency (IAEA)". Indeed, paragraph 14 of the safeguards agreement INFCIRC/153/Corr. allows for the "Non-Application of Safeguards to Nuclear Material to be used in Non-Peaceful Activities", which is often interpreted to include nuclear-powered ships and submarines, military space vehicles, nuclear reactors and radio-thermal generators (RTGs) for military bases or isolated radar stations [8]. A comprehensive overview of the paragraph 14 provisions can be found, describing the challenges for the IAEA safeguards system associated with states showing interest in nuclear-powered submarines and ships and in exempting nuclear material for safeguards [2]. A number of non-proliferation concerns are raised reference [7], and reference [9] states that the above-mentioned paragraph about non-application of safeguards could be considered a loophole in the NPT where removing nuclear material from nuclear safeguards could become a precedent for future proliferators to use naval reactor programs as a cover to develop nuclear explosive devices (NEDs). Already, Iran has been pointed out as one country that may be benefiting from the AUKUS deal, by being able to use the arguments put forward by Australia to support their own expanded nuclear ambitions [10], [11].

A number of diversion scenarios associated with the naval fuel programs have been identified in reference [9]. Diversion scenarios specifically associated with the AUKUS submarine deal were identified to include:

- diversion of low enriched uranium (LEU) and HEU from the enrichment facility;
- diversion of enriched stockpiled product intended for fuel fabrication;
- diversion of nuclear material from a fuel fabrication plant;
- the establishment of undeclared enrichment plant; and
- diversion of spent fuel from storage, followed by reprocessing.

In this work, we are interested in investigating non-proliferation concerns of the AUKUS deal from a technical perspective, focusing specifically on the last one of the potential diversion scenarios listed above. We will, using openly available information, model submarine reactor fuel and its irradiation to estimate how the isotopic composition changes as a function of irradiation. The objective of the work is to, from a technical perspective, analyse the usability of the fuel material (beginning-of-life, middle and end-of-life) for use in a NED. Of specific interest is the spent fuel at the end-of-life, as indicated in the list above, but as a complement to that we will also investigate fresh and partially irradiated fuel material as such results will become available as well. We will also make assessments of technical non-proliferation concerns related to the AUKUS deal that could have an impact on the nuclear safeguards community. Note that this work does not consider other parts of the fuel cycle except the operation of the submarines, as we assume that Australia will only operate the reactors and then return them to the host state which is a NWS in control of all military fuel cycle activities leading up to the production of nuclear weapons. However, if Australia were to use the AUKUS deal to motivate a need to control the front- and back-end fuel cycle including uranium enrichment facilities, fuel fabrication facilities, additional stockpiles or reprocessing facilities, the associated proliferation concerns would look very different.

3. Submarine reactor cores

The UK and US submarines under consideration in AUKUS are the British Astute-class submarines and the American Virginia-class submarines [9]. The intent is for Australia to operate the submarine reactors throughout their lifetime of 33 years, meaning that Australia will not produce the reactor fuel and that refuelling is not needed [12]. After having reached their end-of-life, the reactors will be returned to the supplier, meaning the US or UK [13].

All nuclear-powered submarines in the world, except the Russian ones, are equipped with one nuclear reactor, with the British and American nuclear-powered submarines are using pressurized water reactor (PWR) cores, fuelled with HEU having a starting enrichment level of at least 93% uranium-235 (Ma, 2008). The core is typically very compact and designed to give a high heat transfer area per fuel volume [12]. The power of the reactor core depends on the design. The power of the Virginia class submarines is believed to be slightly higher than that of the Los Angeles submarine, known to be 130 MWth, because the Virginia reactor core is slightly larger [14]. This also agrees with other estimates stating that the power is 150 MW_{th} [15].

3.1 Earlier works on submarine reactor models

The design information about a submarine reactor core is in general difficult to obtain because it is sensitive, but some information is openly available. A Virginia class attack submarine can be assumed to have a core of about 0.4 tons of weapons-grade uranium [14]. More details on submarine reactor cores are provided on the French Rubis-class submarines [16]. While details about the actual reactor operation are unavailable, existing models assume that the HEU fuelled submarines spend 240 days per year at sea and that they operate at 25% of maximum capacity,

corresponding to 60 full power days (FPD) per year [16]. The total reactor lifetime is up to 20 years, corresponding to 1200 full power days in total. This may not be a completely accurate information, but with limited data available on the operation of HEU-fuelled submarines, it is a reasonable estimate, and we will assume a similar history to allow for benchmarking. In the same work, a number of different fuel materials and submarine cores of 50 MW were modelled with the EPRI-Cell code, and depletion calculations were performed with the CINDER code. UO_2 fuel with Gd_2O_3 burnable absorbers, configured in a fuel plate geometry to ensure efficient cooling of the fuel, was considered. A number of different fuel geometries were modelled and three different HEU fuel designs were implemented. It was shown that the material composition of the core was dependent on the initial enrichment of the fuel as well as on the core geometry. Research was also published on the possibility of replacing HEU cores in submarines with LEU cores using the modern Monte Carlo code Serpent 2 [15]. In that work, a more realistic operation of the submarine reactor is employed, together with an HEU fuel plate geometry and burnable poison in the form of Gd_2O_3 .

3.2 Submarine reactor models used in this work

In this work, we have chosen to study multiple reactor cores. There are several reasons for this. Obviously, the main interest is in studying a Virginia-like reactor core, but there is no openly available information on it. The most detailed information about submarine reactor cores available to the authors was found in reference [16]. One core design from that work is here referred to as Model 1 and used as a benchmark, although another design (here known as Model 2) was more Virginia-like. Results on the isotopic composition of the spent nuclear fuel were however obtained using a completely different simulation framework available 30 years ago, which did not facilitate as comprehensive simulations that can be made today. We thus decided to make simulations of both models to more accurately study the composition of the end-of-life core, complementing the results published earlier.

More recent work did study operational and safety aspects of a Virginia-like core with higher power and slightly lower initial enrichment compared to research in [16], using modern Monte Carlo codes [15]. The isotopic composition of the spent nuclear fuel was however not investigated nor reported in that work. For this reason, it was decided to update the core designs with information about the core geometry and irradiation based on published data [15], here known as Model 3 and 4, and make new simulations focusing on non-proliferation aspects of the fuel.

4. Methodology

In this work, a number of different reactor cores are studied and different designs are implemented in Serpent 2 [18]. The operation of the reactor cores is modelled, and the depletion calculations show how the nuclide inventory changes over time. After having reached its end-of-life, the isotopic composition of the fuel is evaluated, with special attention paid to the uranium and plutonium vectors.

4.1 The submarine core model and its irradiation

All cores modelled in this work assume that the fuel is made of HEU that is dispersed in the form of UO_2 in a metal alloy containing both uranium and zirconium as

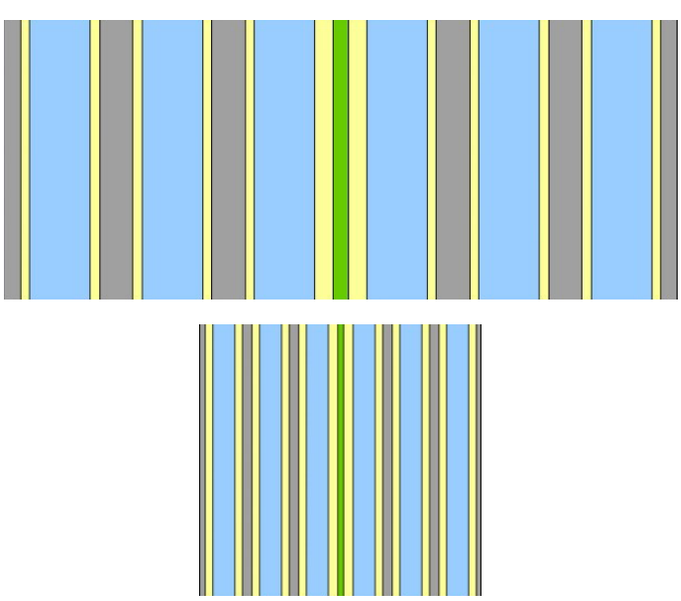

Figure 1: The Model 1 (upper) and Model 2 (lower) geometries implemented Serpent2. The Gd2O3 plate is shown centrally in green, the zirconium cladding in yellow, the fuel (or fissile) material in grey and water in blue. Dimensions are provided in table 1.

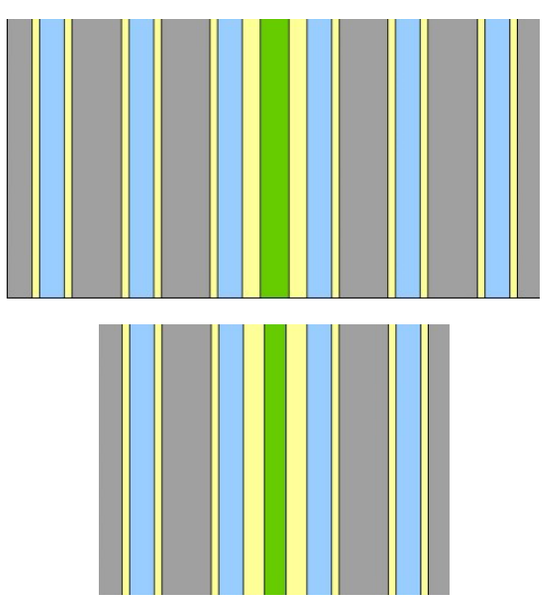

Figure 2: The Model 3 (upper) and Model 4 (lower) unit cell design implemented in Serpent 2. Both unit cells are infinitely reflected in two dimensions. Gd2O3 is shown centrally in green, the zirconium cladding in yellow, the fuel material in grey and water in blue. Dimensions are provided in table 1.

described in references [15] and [16]. The fuel material is located in fuel plates, with water channels surrounding the plates on both sides. This design is chosen because of the extremely high burnups (compared to light-water reactor fuel where the typical discharge burnup is around one-tenth of the studied submarine cores) and the need to ensure sufficient cooling of the fuel during operation. Gadolinium is also present to control the reactivity throughout the reactor lifetime.

In this work, the objective is to study the fuel composition evolution over time. For such analyses, it is not necessary to model support structures or the core in its full geometry. We have thus implemented a number of geometries consisting of a unit cell comprising fuel plates, gadolinium plates and water channels. The details of the geometries are provided in table 1. The implementation of Model 1 and 2 are also shown in figure 1, and Model 3 and 4 in figure 2. Numerical values relating to the submarine reactor cores either come from references [15] and [16], or result from scaling the Model 1 and 2 parameters to the size of the Model 3 and 4 core.

Both Model 1 and 2 consists of a unit cell centred around a Gd_2O_3 plate surrounded by 2.5 fuel plates on each side, infinitely reflected. Model 2 has reduced plate thickness compared to Model 1 and also reduced water channels, found to result in a higher inventory of uranium-235 at the end-of-life (and thus a potentially more attractive material for use in a NED) [16]. The water density was unrealistically

	Model 1	Model 2	Model 3 & 4
Power [MW]	50	50	150
UO_2 enrichment [%]	97.3	97.3	93
UO_2 volume% in fuel [%]	20	33	24.1
Zr volume% in fuel	80	67	75.9
Start-up uranium composition [%]	U235: 97 U238: 3.0	U235: 97 U238: 3.0	U234: 0.739 U235: 93.0 U238: 6.27
Beginning-of-life composition [kg]	U235: 106	U235: 152.5 U238: 4.3	U234: 5.1 U235: 638.7 U238: 43.1
Temperatures			
Fuel temperature [°C]	927 (1200 K)	927	400
Cladding temperature [°C]	927	927	400
Water temperature [°C]	327	327	327
Gd_2O_3 temperature [°C]	327	327	327
Densities			
UO_2 density [g/cm3]	10.3	10.3	10.97
Zr density [g/cm3]	6.56	6.56	6.56
UO2Zr density [g/cm3]	6.56	6.56	6.56
Gd_2O_3 density [g/cm3]	7.64	7.64	7.64
H_2O density [g/cm3]	7.64	7.64	7.64
Dimensions			
Fuel material thickness [mm]	1.45	0.5	2.5
Zr cladding thickness [mm]	0.385	0.385	0.4
Fuel plate thickness [mm]	2.22	1.27	3.3
Gd_2O_3 thickness [mm]	0.0665	0.0285	0.1425
Water channel [mm]	2.63	1.12	1.25
Cell thickness [mm]	29.1	14.32	27.27
Irradiation conditions			
Irradiation scenario	1200 full-power days	1200 full-power days	Duty cycle of 6 months/year (183 days). Operation at 25% of full power during that time.
Power density [kW/g]	0.457142	0.31892	0.05525
Discharge burnup [MWd/kgU]	548.57	382.70	333.65

Table 1: Properties of the submarine reactor cores modelled here.

high at 1 g/cm3, and results on core volume and reactivity was later corrected for this in order to ensure more realistic results. In this work, the same (unrealistic) water density was used to allow benchmarking with previously published results [16].

Two other models describing a more Virginia-like core were also implemented; they are referred to as Model 3 and 4. The two designs were largely taken from published research [15]. One exception is the gadolinium plates, which were not included in the previous work (the atomic density of the fuel was simply increased by adding gadolinium atoms in varying amounts throughout the core, noted as being an unphysical manner) [15]. In this work, two different Virginia-like designs are investigated. In Model 3, a gadolinium plate was again surrounded by 2.5 fuel plates on each side, and the ratio of gadolinium volume over fuel volume in the unit cell was identical to that in Model 2. In Model 4, this ratio was changed as 1.5 fuel plates surrounded the gadolinium plate on each side. The unit cells of Model 3 and 4 are shown in figure 2. The UO_2 density in this work was chosen as the theoretical maximum density to allow for comparison of results with previous works [15].

5. Analysis and discussion

5.1 Results of Model 1 and 2

The results of the simulations show that the inventory of uranium-235 and uranium-238 are, as expected, reduced over time, while uranium-236 and various plutonium isotopes build up. The results from Model 1 and 2 are on a general level in accordance with previous results [16], with a few exceptions. Earlier works [16] did not include any other heavy isotopes than uranium-235, uranium-236, uranium-238 and plutonium-239 to plutonium-242, and the results here show that including additional isotopes is essential for a proper evaluation of the end-of-life core properties. The inclusion of plutonium-238 is found to be especially important, as it is dominating the plutonium vector for the end-of-life core in Model 1 and 2. Excluding this isotope from the analysis shows that the results of this work are in good agreement with already published results [16], on a relative scale. As Model 1 was intended as a benchmark of this work against such earlier results, this finding supports the conclusion that the modelling done here is sufficiently good.

The evolution of the plutonium in Model 1 and 2 can be seen in figure 3. It is seen that the production of plutonium-239 increases sharply in the beginning, while production of plutonium-238 and plutonium-240 to plutonium-242 sets in after 400 full power days (FPDs). Of the total amount of plutonium at the end-of-life of the core, about 64% is plutonium-238 in Model 1, and 51% in Model 2. In all cases the relative content of plutonium-238 is below 80%, a value defined in the nuclear safeguards community, at which point the plutonium is considered to be of such quality that it is exempted from safeguards. This means that if the nuclear material used for naval propulsion purposes were to be returned to the civil fuel cycle, it would have to be placed under safeguards. It can be noted that the relative content of plutonium-240 in Model 1 and 2 is around 5%, which is lower than the “impurity” level of 7% limit, defined by the US Department of Energy (U.S. Department of Energy, 2009), below which plutonium is classified as weapon-grade. This classification is however a result of how plutonium has been produced historically, and where plutonium-239 would make up 93% of the plutonium isotopes. The amount of plutonium-240 found in the plutonium produced in this work should thus not be interpreted to indicate that the material is suitable for weapons manufacture, as other impurities (such as plutonium-238) are also present and the fraction of plutonium-239 is far below 93%.

The results also show that the end-of-life cores in Model 1 and 2 have a uranium-235 enrichment of 61.3% and 76.8%, respectively, which is slightly below those published earlier in [16]. Similarly, the results show a somewhat higher absolute content of uranium-238. The explanation for the lower

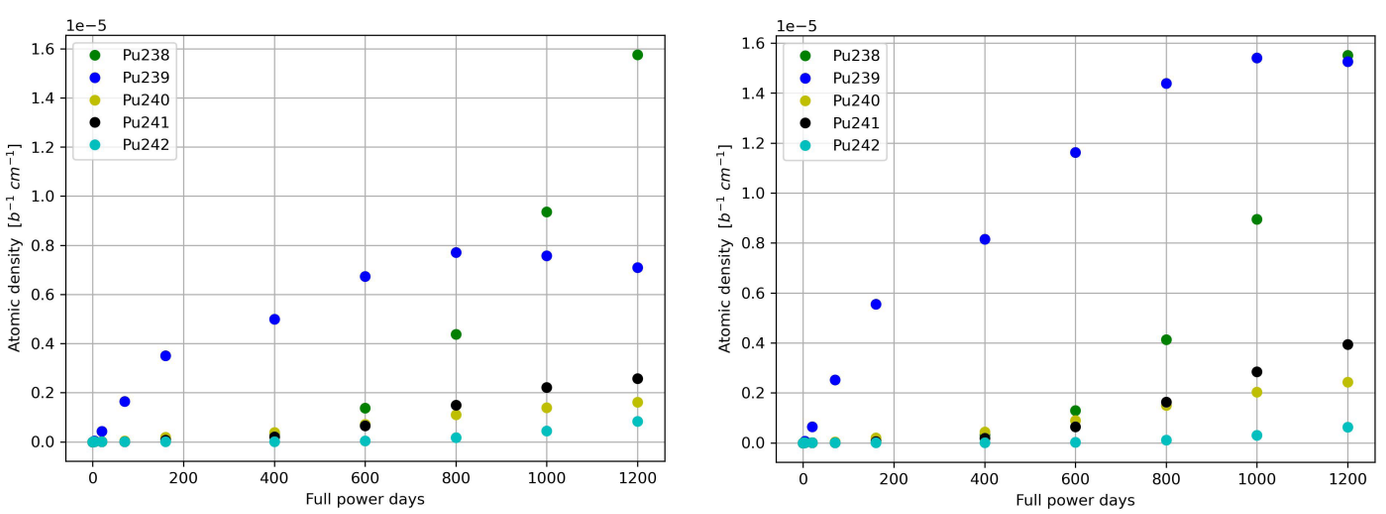

Figure 3: The plutonium composition in Model 1 (left) and 2 (right) as a function of operation time of the submarine.

enrichment is the fact that the gadolinium in the absorber plates did not last throughout the entire lifetime of the reactor (it is depleted after about 1000 FPDs), despite the importance of balancing the fuel volume against the need for Gd_2O_3 to ensure reactivity control [16]. After full depletion of the gadolinium, the neutron spectrum will be more thermalized, leading to relatively less fast fission and neutron resonance capture in uranium-238, consistent with the findings here of more uranium-238. It will also lead to less plutonium-239 than in previous works [16]. The findings can also be explained by the inclusion of the complete inventory of heavy nuclides in the simulations, which in turn results in less neutron absorption in uranium-238 and more absorption in other nuclei. The depletion calculations also reveal that the end-of-life core in Model 1 consists of 1.38 kg of neptunium (1.54 kg in Model 2), which can be compared with the total plutonium mass of 906 g. The vast majority of that neptunium, over 99%, is neptunium-237.

Compared to the results of Model 1, Model 2 has a slightly higher relative content of uranium-235 and a plutonium vector slightly less dominated by plutonium-238. More notably, the relative amount of plutonium-239 is almost 60% higher in Model 2 than Model 1. All the results are however essentially an effect of the lower discharge burnup in combination of a different start-up fuel, as the volume fraction of UO_2 is 33% in Model 2 instead of 20% as in Model 1, rather than an effect of the modified geometry. Table 2 and 3 show the relative and absolute content of major uranium and plutonium isotopes in the end-of-life core for Model 1 and 2.

	Relative content [%]			
Model	1	1 [16]	2	2 [16]
U234	0.0252	-	0.0167	
U235	61.3	68.1	76.8	81.8
U236	33.8	28.4	19.6	-
U237	0.0655	-	0.0303	-
U238	4.83	3.55	3.55	-
Pu238	64.4	-	50.8	-
Pu239	19.6	52.3	31.2	-
Pu240	5.04	14.0	5.72	-
Pu241	7.30	24.4	10.1	-
Pu242	3.70	9.30	2.25	-

Table 2: Results from the simulations of Model 1 and 2 corresponding results published in [16]. Isotopes with a relative content below 0.01% have been excluded.

	Absolute content [g]			
Model	1	1 [16]	2	2 [16]
U234	11.2	-	15.3	
U235	27 400	33600	70500	74900
U236	15200	14000	18100	1670
U237	29.6	-	28.1	-
U238	2190	1750	3 300	3 300
Tot U	44 900	49 400	91 900	79 870
Pu238	582	-	497	-
Pu239	177	135	306	294
Pu240	45.9	36	56.4	56
Pu241	66.8	63	99.6	92
Pu242	34.0	24	22.4	16
Tot Pu	900	258	981	458

Table 3: Results from the simulations of Model 1 and 2 corresponding results from [16]. Isotopes with a relative content below 0.01% have been excluded.

It can be noted that the results of this work show a difference in total uranium content in the end-of-life cores when compared to previously published results [16]. Some of it can be explained by the increased plutonium production (of which the majority is plutonium-238), and some of it by the production of neptunium, not considered earlier. Remaining differences could be due to that the results here are obtained using more modern depletion code and fuel libraries.

5.2 Results of Model 3 and 4

Results from the simulations of the more Virginia-like cores Model 3 and 4 are shown in table 4. The first thing to note is that although the two models have a different frequency of absorber plates, the composition of the spent nuclear

	Model 3		Model 4	
	Relative cont. [%]	**Absolute**	**Relative**	**Absolute**
U234	0.764	cont. [g]	cont. [%]	cont. [g]
U235	73.3	3310	0.75	3260
U236	17.9	319000	73.2	318000
U238	7.98	78300	18.1	79200
Tot U		35200	7.94	35000
		436000		436000
Pu238	22.1			
Pu239	66.8	1520	22.6	1610
Pu240	7.16	4620	66.4	4750
Pu241	3.66	497	6.91	497
Pu242	0.289	255	3.85	278
Tot Pu		20.3	0.31	22.8
Pu241	3.66	6900		7200
Pu242	0.289	20.3	0.31	22.8
Tot Pu		6900		7200

Table 4: Results from the simulations of Model 3 and 4. Isotopes with a relative content below 0.01% have been excluded.

fuel is almost identical in the two designs because in both cases, the gadolinium amount is sufficient to last throughout the lifetime of the reactor.

A key goal of this study was to calculate the end-state enrichment of the uranium fuel. The high burn-up long-life submarine core is very different from most familiar power reactor fuel cycles. The breeding of uranium-236 is a significant feature of this fuel cycle. Uranium-236 is a non-fissile diluent in HEU. We argue that it behaves much like uranium-238 and increases the critical mass, and hence diminishes utility for weapons. The uranium enrichment of the end-of-life cores is around 73%, which is below weapons-grade (above 90%) but still a very high enrichment. On the absolute scale, the uranium content is considerably larger than in Model 1 and 2, because the Virginia-like reactors are larger.

It is not our intent to speculate on the utility of 73% enriched uranium for NED. There is little information about intermediate levels of uranium-235 enrichment, such as 70% in the literature, presumably because it is an unattractive composition. The “Little Boy” device had “most” of its HEU enriched to 89% uranium-235, “for an average enrichment of only about 80%” [19]. It can also be noted that the critical mass of 70% enriched uranium is about 60% higher than the critical mass of 93% enriched uranium-235 diluted with uranium-238 [20]. This larger critical mass would require a larger NED and the effect may be nonlinear considering high explosives and the necessary implosion energy required to reach explosive supercriticality. Nevertheless, it cannot be excluded that a crude NED could be manufactured using reprocessed uranium from the end of core life. This should however not be interpreted to indicate that a crude NED is something that can be easily manufactured. Also a crude weapon would require substantial efforts in a large number of weapon design and manufacturing areas to do anything but fizzle. If something more advanced that a crude NED is desired, it may also be attractive to try to enrich the 73% HEU to above 90%. However, the enriching will be more expensive compared to enrichment of natural uranium (where there is a mass difference of three atomic mass units between the isotopes in the feed), because the reprocessed uranium contains additional uranium isotopes making the mass difference between uranium-235 and other uranium isotopes (such as uranium-236 and heavier isotopes) as low as one atomic mass unit.

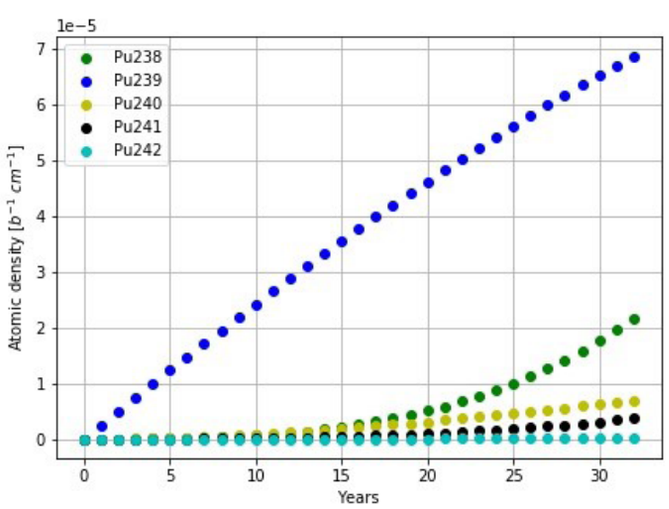

Figure 4: The plutonium composition in Model 3 as a function of operation time of the submarine.

The evolution of the plutonium composition in Model 3 can be seen in figure 4. The main difference between the Virginia-like designs and Model 1 and 2 with respect to material composition of the irradiated fuel, is found in the plutonium vector. In Model 3 and 4, the relative content of plutonium-238 is less than half of that in Model 2 and roughly a third of that in Model 1. At the same time, the plutonium-239 content is roughly a factor of two higher than for Model 2 and a factor of three higher than for Model 1. The relative content of plutonium-240 is also higher for Model 3 and 4 than for Model 1 and 2, and is around 7%. Depending on how plutonium is classified, this could mean that the material may reach a fuel-grade classification rather than weapon-grade, assuming that the classification considers only the fractions of plutonium-239 and plutonium-240. Should a more comprehensive classification of plutonium be available that takes into account also other plutonium isotopes, the classification could however be very different. It can also be seen in figure 4 that the relative contribution of plutonium-238 and plutonium-240 to plutonium-242 is considerably lower in the first 15 years of operation. In fact, during the first 14 years, the plutonium consists of over 90% plutonium-239 and less than 5% plutonium-238. For shorter irradiation times, the relative contribution of plutonium-239 increases, and that of plutonium-238 decreases. The amount of neptunium in the end-of-life core is 5795 g in Model 3 (5997 g in Model 4), which could possibly be another non-proliferation concern, should the irradiated core be reprocessed.

It has been investigated what the reason is for the dramatic change in plutonium composition for Model 3 and 4 compared to Model 1 and 2. It was found that the lower fuel temperature in Model 3 and 4 had a minimal effect on the uranium and plutonium composition, as did the actual fuel irradiation history. The slightly lower enrichment of the Virginia core (93% as opposed to 97.3%) had only a minor impact, as did the slightly different volume fractions of the fuel. In fact, the change in plutonium composition was found to be a result of the relatively thick plates of fissile material in combination of the thinner water channels and that there is enough gadolinium in the absorber plates to last through the entire lifetime of the reactor. Thicker plates of fissile material lead to more neutron captures in uranium-238, which produces more plutonium-239. At the same time, more Gd_2O_3 in the core means that more plutonium-239 (which would otherwise fission at thermal energies) remains at the end-of-life. An important production path of

plutonium-238 starts from uranium-235 (of which there is plenty in this fuel), which captures neutrons to form uranium-236 and uranium-237 before beta-decaying to neptunium-237. Neptunium-237 then absorbs another neutron and beta decays to plutonium-238. The Virginia-like core has less water and more fuel than the Model 1 and 2 cores, and neutron energies are thus higher. A higher neutron energy increases the probability that uranium-236, uranium-237 and neptunium-237 undergo fission, and decreases the probability that neptunium-237 absorb a neutron and decays to plutonium-238. All these effects lead to a lower plutonium-238 production.

Thus, the results here suggest that the details of the design may have a considerable effect on the composition of the plutonium that is produced, although it should be pointed out that on an absolute scale the plutonium amounts are relatively small (around 7 kg); just below the 8 kg defined by the International Atomic Energy Agency as a significant quantity (SQ). We have chosen to relate these values with the well-known SQs, despite knowing that it does not reflect the material needed in a NED since devices can be made with considerably less material. The reason for referring to SQs here is simply that it offers a way to relate results and numbers to a quantity that is commonly known in the safeguards community.

6. Conclusions and outlook

This work has been a study of non-proliferation aspects of the AUKUS deal, through studies of the submarine spent reactor fuel. Four main conclusions can be drawn from this work.

6.1 Technical non-proliferation concerns

Upon irradiation, the enrichment level decreases, and plutonium starts to be produced. The end-of-life core is still highly enriched to a level of around 70%, where the uranium could potentially be useful in certain weapon designs. [20] In total, the end-of-life core from each Virginia-like core contains about 436 kg HEU at an enrichment of 73%, which corresponds to more than 17 SQs according to the IAEA. The fresh fuel, however, contains almost 640 kg HEU enriched to 93% (more than 25 SQs).

The first conclusion is thus that the fresh, unirradiated HEU should be considered as a bigger proliferation threat than the irradiated HEU. However, given that this fuel is produced and supplied by a NWS already in possession of weapons material, we do not assess that the fabrication of the fuel and placement of it in a submarine increases the proliferation risk. However, if the core material was to be removed from the submarine in Australia, or if the operation of the submarine would be interrupted early on and require unplanned maintenance in Australia, this could be a source of concern.

On a higher level, proliferation risks related to additional states using the AUKUS deal as a precedent or inspiration for their own pursuit of nuclear-powered submarines would be more concerning if such activities were to be used to motivate the establishment of new facilities in the state. The state could then either choose to remove nuclear material originally part of the civil fuel cycle and placed under safeguards for naval propulsion purposes, or investigate ways to increase the amount of nuclear material available. Both alternatives would pose a challenge for the non-proliferation regime. In the former case, amounts of nuclear material outside international control would increase. On the latter case, additional nuclear facilities could be established to openly or covertly produce the fissile material needed for the reactor cores, or to manage the disposal or reprocessing/recycling of the fissile material after irradiation. The establishment would be associated with a non-zero risk of diversion of nuclear material from e.g., fuel fabrication plants or enriched stockpiled product intended for fuel fabrication (see Section 2 of this work). The nuclear facilities producing or processing the nuclear material would however not be exempted from safeguarded in signatory states to the NPT, which means that safeguards verification would come in at that point.

6.2 Fuel composition and NED usability

The results show that it is crucial to include heavy isotopes beyond uranium-235, uranium-236, uranium-238 and plutonium-239 to plutonium-242 in the analysis. Especially plutonium-238 is found to play a major role as it is produced in relatively large amounts, and significantly degrades the plutonium quality beyond what would be acceptable in a NED (although studies of the implications of varying fractions of plutonium-238 in a NED design can be found [21]). The quality of the plutonium produced depends on the irradiation conditions, and varies from being dominated by plutonium-238 to being dominated by plutonium-239 but with a significant contribution from plutonium-238. This contribution is however considerably lower in the first years of operation of the submarine, which in fact produces very small quantities of plutonium suitable for NEDs. In absolute terms, about 7 kg plutonium, just short of the 8 kg corresponding to an SQ, is produced at the end-of-life in the Virginia-like reactor cores studied here. Note however, that in order to obtain the plutonium, reprocessing activities are needed to separate it from the uranium and waste products. Typically, weapons-grade plutonium is used in NEDs, where the contribution from plutonium-238 is less than 0.05%. (Nuclear Weapons Archive, 1999) Practically all plutonium compositions with a plutonium-238 contribution < 80% (i.e. not only weapons-grade plutonium) can be used in a NED. [23] An evaluation of what the physics behind the 80% level is, is beyond the scope of this work, but it could be worth studying further whether this is truly a lower limit. How well the NEDs perform will vary depending on the plutonium composition, where those using a composition with

more plutonium-238, plutonium-240 and americium-241 are more likely to perform poorer than those with less.

The second conclusion is thus that plutonium suitable for use in a NED is produced at short irradiation times, but in small quantities. The plutonium produced at the end-of-life has significant contributions from (above all) plutonium-238 but also plutonium-240, which makes the material ill-suited for, but not impossible to, use in a NEDs. The reasons to why plutonium-238 is very undesirable in NEDs are that i) it emits so much thermal energy that it is very difficult to handle; that ii) plutonium-238 has a significant spontaneous neutron emission which may cause a nuclear explosive device to pre-initiate; and that iii) plutonium-238 has a very high alpha particle emission rate (short half-life) which contributes to alpha-neutron reactions with light impurities, again resulting in copious neutrons that may cause pre-initiation. Accordingly, we draw the conclusion that the use of this fuel material in submarines operated by a NNWS, does not automatically mean that material attractive for use in a NED will become available. However, large quantities of a nuclear material that could at least theoretically be used in a NED - neptunium - will be produced. Neptunium is also produced in civil reactors, but not in these quantities.

6.3 Material classification

The results show that the classification of plutonium in the nuclear safeguards community as weapons-grade, fuel grade or reactor grade based only on the plutonium-240 content appears inadequate here. In fact, one could see this study as an illustration of a situation where using definitions designed for nuclear safeguards thresholds are inappropriate for determining weapons applications. The universal safeguards definition of plutonium with a plutonium-238 content <80% was not intended to deal with discharged material from very high enriched fuel with ultra-high burnups, where specifications for minor isotopes and plutonium-238 content (responsible for producing heat from alpha decays) cannot be ignored from a NED-usability point of view.

A third conclusion from this work is thus that a more suitable definition of weapons-grade plutonium should be considered in the light of this work, stating limits on for instance plutonium-238 and plutonium-240, alternatively on plutonium-238, plutonium-239 and plutonium-240. This would better reflect the usability and proliferation concerns associated with plutonium, and also potentially direct safeguards resources to where they are best needed.

6.4 Civil reprocessing incentives

There are no indications that the irradiated nuclear fuel from the submarine reactor cores will be reprocessed. Nuclear fuelled submarines out-of-service are in many cases still awaiting dismantlement. In other cases the decommissioned nuclear submarine reactor cores are stored. The simulations in this work have however shown a relatively large production of plutonium-238, which could potentially make the irradiated reactor material attractive for applications in civil use, such as heat sources for spacecraft and motivate reprocessing of the fuel. This would require separation of both uranium and plutonium, and possibly neptunium. Such reprocessing activities potentially motivated by the recovery of plutonium-238, would constitute a considerable challenge for the non-proliferation regime.

A fourth conclusion is thus that a pressing challenge for the non-proliferation regime could be a future interest in reprocessing the irradiated submarine reactor fuel. Should this happen, the safeguards community and the IAEA must also be prepared to monitor and verify elements such as neptunium in a regular fashion, similarly to uranium and plutonium, and not just on a voluntary basis.

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