Modelling fissile production in the Experimental Light Water Reactor (ELWR) of DPRK

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Abstract

Since North Korea, or the Democratic People's Republic of Korea (DPRK) left the Non-Proliferation Treaty (NPT) in 2003, the DPRK nuclear fuel cycle has continued operation as well as further development, without transparency to international inspectors. A recent addition to the DPRK fuel cycle is the Experimental Light Water Reactor (ELWR), a 100 MWth light water reactor in Yongbyon, which, as appears to be in operation since October 2023.

Considering the non-NPT-signatory status of DPRK, it is of concern that the ELWR may be used to produce plutonium for nuclear warheads, in addition to or instead of its use for electricity production. In this work we explore the possibility to model the fissile material production in the ELWR, by modelling the core with Serpent2, and integrating information from available remote monitoring, such as satellite imagery of cooling water outlets from the facility.

Little openly available and verified information exists on the details of the ELWR, such as nuclear fuel design and core geometry. Therefore, a base case based on available statements is used to create a core model similar to conventional international LWRs. Multiple scenarios for core load options are based on either assumptions on 1) uniform enrichment optimised for low burnup and production of weapons-grade plutonium, 2) heterogeneous core with drivers of enrichment fuel and targets of natural uranium for plutonium production or 3) uniform enrichment for high burnup and electricity production. Plutonium production made possible using the ELWR is estimated per MWd, as well as per year of operation. Special consideration is given to cycle length constraints from requirement of weapons-grade quality of the produced plutonium, and implications on availability and stoppage frequency, which might be monitored remotely, unless online refuelling is a possibility.

Possible implications on the DPRK Pu stockpile are discussed, as well as attempts to identify unknown parameters of importance (i.e. attempting to make unknown unknowns into known unknowns).

1. Introduction

North Korea, or the Democratic People's Republic of Korea (DPRK), proved its capability to manufacture nuclear weapons when they detonated their first nuclear device in 2006 and has become the ninth nuclear armed state.

The present North Korean regime, under the leadership of Kim Jong-Un, has made the ongoing development of nuclear weapons and their associated delivery systems high priority, and current estimates [1,2], point at a total number of nuclear devices in the order of 30-60 warheads. In the form of fissile material, it is estimated that North Korea has a highly enriched uranium (HEU) stockpile of 500-2100 kg [3,4] and a plutonium stockpile of 50-70 kg [3]. In this paper, we are investigating if the newly operational Experimental Light Water Reactor (ELWR) can be a way for North Korea to supplement its plutonium production.

2. North Korea’s plutonium production

The Yongbyon Nuclear Scientific Research Centre is located north of the capital Pyongyang, and contains all facilities known in open sources associated with plutonium production for the North Korean nuclear weapons programme. This is the location of the 5 MWe Magnox type reactor; a graphite-moderated gas-cooled reactor that runs on natural uranium. This reactor is loaded with 50 tons of metallic fuel, and it is estimated to produce 10-14 kg of plutonium per operational cycle (ca 2 years) [3]. The Yongbyon site also houses a fuel fabrication facility, a spent fuel storage and a reprocessing plant. Moreover, it is also the site of the IRT-2000 reactor; a research reactor supplied by the Soviet Union in the 1960s. This reactor ran out of Soviet-supplied fuel several years ago [5]. North Korea may have fabricated additional fuel for this reactor and it is still observed to be operational by the IAEA.

Hence, North Korea’s main source of plutonium has been the 5 MWe reactor, which was taken into operation in 1986. It is consequently an old reactor, and it is unknown for how much longer it can be operated. It has therefore been suggested that the newly finished Experimental Light Water Reactor, the ELWR, is at least partly intended for plutonium production, and that such a use could greatly increase North Korea’s plutonium production capability [6].

3. The ELWR - the Experimental Light Water Reactor

Very little is known for certain about the ELWR, and what is assumed is based on information given to an American delegation under Siegfried Hecker who visited North Korea and the Yongbyon site in 2004 and again in 2010 [7]. Some of the information they gathered about the ELWR, which was then just in the start-up phase of the building work is presented in Table 1. Only parameters that are of relevance for reactor simulations are included.

Table 1. Reactor parameters for the ELWR. All data is from [7]

Reactor type	Pressurised water reactor (PWR)
Thermal power	100 MW
Fuel type	UO_2
Fuel load size	4 tons of UO_2
Average enrichment	3.5%
Cladding	Unknown, likely stainless steel
Pressure-vessel material	High-strength steel
Average burnup	33000 MWd/tU

The parameters show a small reactor with a small fuel load but normal enrichment and burnup for a PWR. The only unusual feature is the cladding of stainless steel instead of zircaloy, but this is motivated in [7] with a discussion that North Korea might not have the raw materials necessary for producing zirconium alloys. It is interesting to note the mention of a pressure vessel; which is a common PWR design, but makes it difficult to exchange fuel during operation. Taking these figures at face value, there is nothing indicating that the reactor is designed for plutonium production. The burnup quoted (33000 MWd/tU) will place the fuel in the core for a ca 36 months and produce plutonium of reactor grade quality. However, as will be investigated in this paper, this design of a PWR can also be operated in a way that enables weapons-grade plutonium production. While it is known that non-weapons

grade plutonium can be used in nuclear weapons, using reactor-grade plutonium may increase complexity in weapons design and require additional nuclear tests.

4. Satellite imagery

The interest in the ELWR increased greatly at the end of 2023, as it was discovered by satellite imagery that the reactor released warm water from the secondary cooling loop, and it was interpreted to be in operation [8].

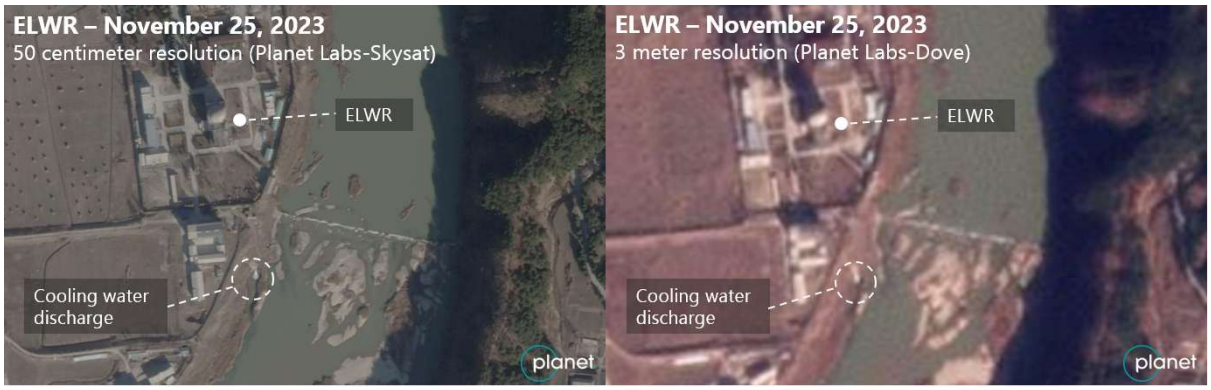

Figure 1. (Left) Planet Labs 50 centimetre Skysat satellite image of the ELWR and cooling loop water discharge on November 25th, 2023 / (Right) Planet Labs 3 metre Dove satellite image of the ELWR and cooling loop water discharge on November 25th, 2023

High resolution satellite images of the ELWR acquired by Maxar, Airbus, and Planet Labs, in conjunction with Planet Labs daily medium resolution imagery were used to identify early water discharge from the ELWR's secondary cooling loop on October 4th, 2023. The imagery signature of this activity, unlike that of North Korea's 5 MWe reactor, is visible at both high and medium resolutions, enabling great temporal coverage of the ELWR's operations, see Figure 1. Whereas in the past, operational periods could only be recorded with less frequent high-resolution images, the use of Planet Labs 3-metre resolution daily imagery enabled greater coverage with higher temporal accuracy for tracking when water discharge was occurring, weather permitting.

Figure *2. (Top) Google Earth image from March 28, 2013, showing the excavation for the secondary cooling loop water outflow pipe / (Bottom) Planet Labs SkySat image from April 29, 2024, showing the end of the secondary cooling loop water outflow pipe discharging water into the Kuryong river.*

To better assess possible operational signatures at the ELWR, a similar signature to that used for the operational status of the 5 MWe reactor was applied, which involves using archival satellite imagery of construction activity to identify piping construction leading to and out of the reactor. At the end of the pipe construction activity, downstream from the water intake location, water discharge is used to identify cooling loop activity, thus increasing the likelihood of the reactor's operational status, see Figure 2.

Figure 3 Planet Labs Skysat satellite image of the ELWR and secondary cooling loop water discharge location on December 17th, 2023, false coloured with the Near Infrared band, showing steam above the cooling water discharge outflow point.

In December 2023, the Center for Nonproliferation Studies was able to see that the water opposite the ELWR cooling water discharge port hand not only not frozen over where as the rest of the Kuryong river had, but that there was steam appearing over the water discharge locations, indicating there was a noticeable temperature difference between the water coming out of the secondary cooling loop and the surrounding temperature, see Figure 3. This observation was later supported by research from another report which utilised thermal satellite imagery acquired by SatVu, which was not only able to detect warm water being discharged from ELWR, but also that the water was warmer than the discharge coming from the 5MWe reactor immediately to the north of the ELWR. Additionally, on December 23rd, 2023, The International Atomic Energy Agency issued a statement from the Director General which concluded the ELWR had reached criticality using similar signatures. [9]

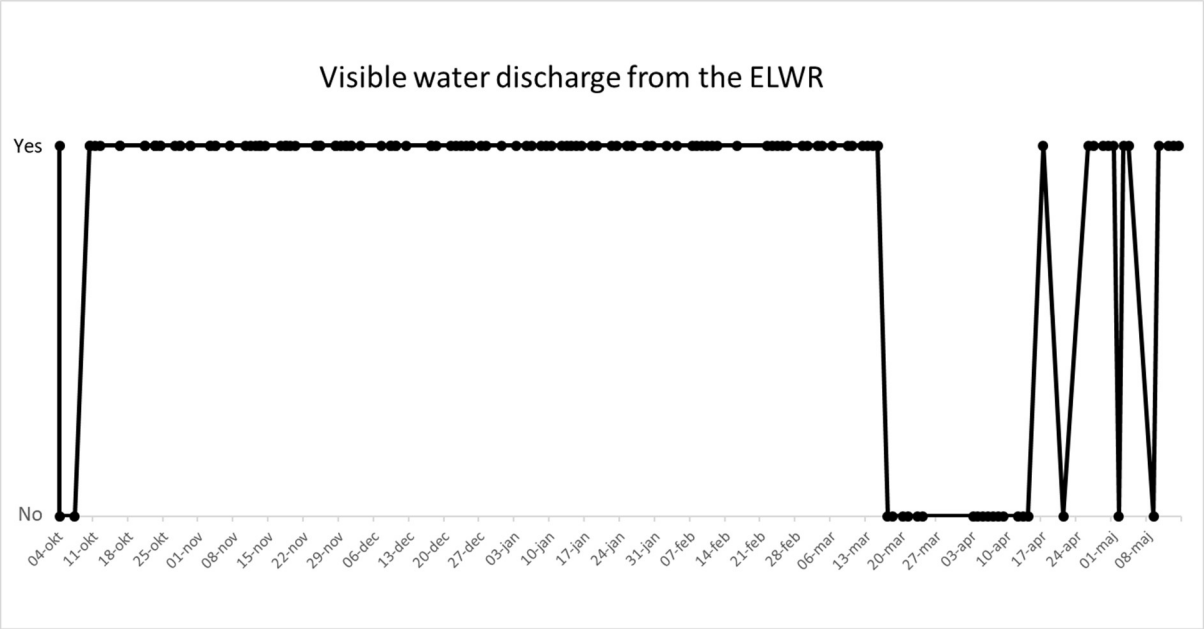

Figure 4. Observed water discharge from the ELWR. The dots indicate observations and the line ties together subsequent observations.

Utilising multiple satellite imagery providers and both high and medium resolutions, the centre was able to track the water discharge from the ELWR using 144 images from October 4th to May 14th, which resulted in roughly 5 months of active cooling water discharge from October 10th 2023 till March 15th 2024, which was follow by an absence of discharge identifiable activity from March 17th till April 14th, with discharge activity occurring visibly again on April 17th, which was then followed by intermittent periods of activity through till May 14th. The observed periods of visible water discharge is plotted in Figure 4.

5. Investigated cases

Starting from the data and constraints given in Table 1, a number of interesting cases to investigate were identified:

- ***Case 1 – homogenous core and varying the enrichment***
  It is well-known that plutonium-producing reactors usually discharge the fuel at low burnup and that a high enrichment is neither needed nor desired. Optimally, the reactor should be critical until the suitable plutonium composition has been reached, but not longer, since the latter can be seen as a waste of costly uranium enrichment. It is of course possible to reprocess and reuse the uranium of the spent fuel after it has been discharged, but there is no obvious benefit in using excessive enrichment. Case 1

is an investigation of a simple homogeneous core and simultaneous discharge of the entire core once the plutonium has reached suitable quality. We investigate case 1 with enrichments from 1% to 3.5%. North Korea has previously been observed to perform fuel exchanges in the 5 MWe reactor that has lasted between 1 and 2 months [10]. The ELWR core is approximately 10 times smaller than the 5 MWe core, so in this work we have evaluated the annual plutonium production for the cases of adding 7, 30 and 60 days of inoperation between core batches to allow for fuel exchanges. For each enrichment, the total amount of weapons-grade plutonium that can be created in one year is reported, together with the consumption of UO_2-fuel.

- ***Case 2 – heterogenous assemblies throughout the core***
  Another way of building a reactor core for plutonium production is to organise separate zones for drivers (where most of the fission event takes place) and targets (where most of the plutonium is produced). In this case, drivers are enriched to 3.5% and produce the fission events for the reactor operation and the neutrons for plutonium production. Targets consist of natural uranium and absorb neutrons to create plutonium. In our case 2; we have chosen to investigate an assembly design with an outer region of driver pins and an inner region of target pins. These assemblies are repeated through the reactor core.
- ***Case 3 – the normal PWR***
  Reactors continue to produce plutonium during operation, hence, for comparison, we include a simulation for the normal case PWR, i.e. running the reactor to full burnup (33000 MWD/tU) and investigate the quality and amount of plutonium that is produced.

Many more cases and also many variations of the chosen cases can be imagined, so this is by no means a complete investigation of all possibilities. We believe however, that the chosen cases can demonstrate some of the aspects that are of relevance for analysing possible strategies for using the ELWR.

6. Simulation methodology

To allow for comparison between the different cases described, a simulation methodology, depicted in Figures 5-6 has been developed.

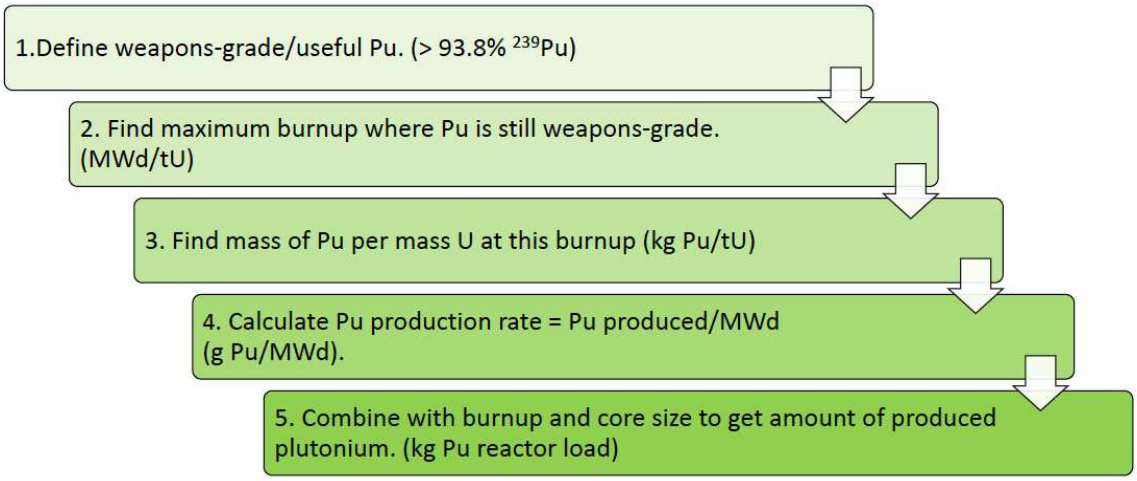

Figure 5. Structure of the simulations.

To start, a definition of weapons-grade plutonium has been decided upon; we have chosen the limit of ^{239}Pu > 93.8%, in agreement with e.g [11]. A depletion calculation is then run, and the maximum burnup where the plutonium is still regarded as weapons-grade is found. Using the isotopic composition of the core at the found burnup (the target burnup), the production rate of plutonium can be found. Finally, combining the production rate with the total size of the reactor core, an absolute value of produced plutonium by one full core load can be calculated, see Figure 5. At the same time, the amount of consumed UO_2 at the particular enrichment is calculated. The second step in the simulations is to take the power and operation of the reactor into account, see Figure 6.

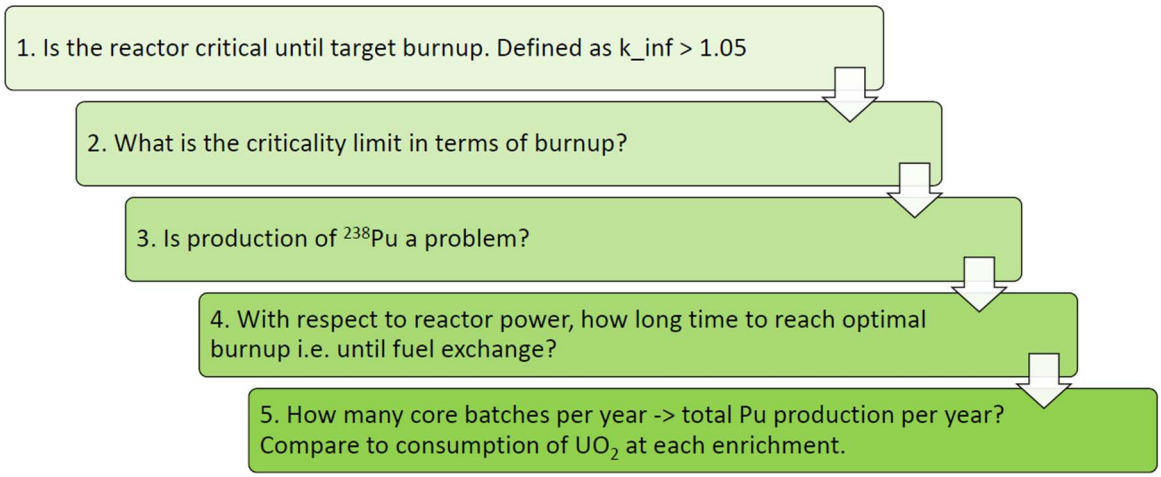

Figure 6. Taking the power and operation of the reactor into account.

We first investigate if the reactor is critical until the target burnup is reached, and also for how long the core is critical in total. Since an infinite core has been modelled, the criticality limit has been set to $k_{inf} = 1.05$, to account for that a real reactor has a loss factor for neutrons of a few percent.

As ^{238}Pu is an isotope that is created from ^{235}U, the amount of created ^{238}Pu is investigated. This isotope has a large alpha decay rate making it highly undesirable in a nuclear weapon. It was found, however, that at these low burnups, production of ^{238}Pu was always less than 0.1% of the total plutonium production, and therefore not a problem considered further. The final check is to combine the simulated data with the reactor power to get the time it takes to reach target burnup. As this is usually less than a year, several core batches are possible each year, and the number of batches give the final figure of how much weapons-grade plutonium can be produced in the reactor per year. This has been calculated for the cases of 7 days, 30 days and 60 days of down-time for unloading and reloading of the core.

7. Simulations in Serpent2

The reactor simulations have been performed with the Monte Carlo code Serpent2 [12]. In this code, an input file is used to define the geometry and material compositions as well as specify the depletion calculation with power level and burnup steps in a depletion calculation. The output files will contain the isotopic composition of the irradiated fuel, the k_{eff} at different steps and the various plutonium isotopes as well as their relative abundances.

Case 1 – homogenous core and varying the enrichment

For case 1; the geometry model chosen is an infinite 2-dimensional pincell model. This means that only the fuel pins are modelled and distributed in an infinite lattice, see Figure 7.

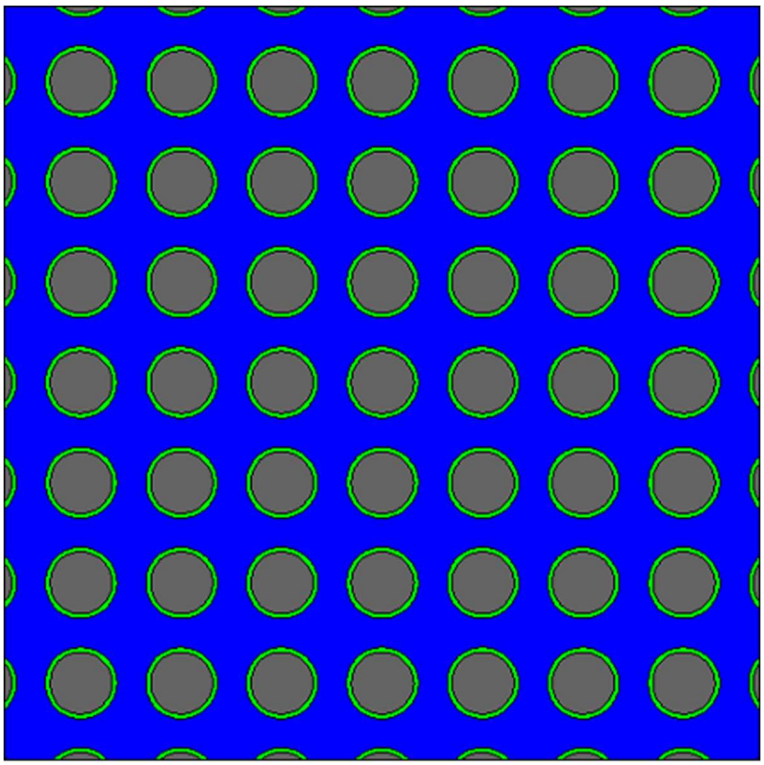

Figure 7. A part of the infinite two-dimensional pincell lattice.

The dimensions chosen for the pin lattice are:

- Pellet diameter: 0.82 cm
- Pin diameter 0.95 cm
- 1.33 cm between pin centres

These are standard dimensions for PWRs and similar values can be found in e.g. [13]. In this work, zircaloy was used as pin cladding, even though it is uncertain (according to [7]) if North Korea can manufacture this material. Using stainless steel instead, would slightly increase neutron absorption in the pins, and therefore lower the amount of plutonium produced per year. When looking at the worst-case scenario, or the upper limit of possible production, this would correspond to assuming that North Korea can use zircaloy as cladding material, and therefore this choice has been made. The simulations for case 1 are performed for initial enrichments of 1% to 3.5% in steps of 0.25%. Furthermore, the influence of changing the pin pitch and the water density was investigated, since these factors affect the neutron spectrum, and thereby the capture rate in ^{238}U which leads to plutonium production.

Case 2 – heterogenous assemblies throughout the core

For the heterogenous assemblies, the Westinghouse 17x17 assembly was chosen as a model. This fuel type is described extensively in the literature, and the design dimension can be easily obtained, see e.g [14]. It was considered to use the Russian design for PWR-fuel; the hexagonal fuel used in VVER, but a quick simulation showed that the difference between the two assembly types with respect to neutronics and fuel volume compared to moderator volume is very small, and the assembly model makes a very little difference to the end result. The standard 17x17 assembly contains 25 water channels/guide tubes for better moderation and for control rod insertion. In our simulation, we chose to omit the water channels and place the natural uranium target fuel in the centre of the assembly. The driver rods (3.5% enrichment) are situated along the edges and are moderated by water channels separating the assemblies, see Figure 8. In the simulations, the 17x17 assemblies were repeated in an infinite 2D assembly lattice.

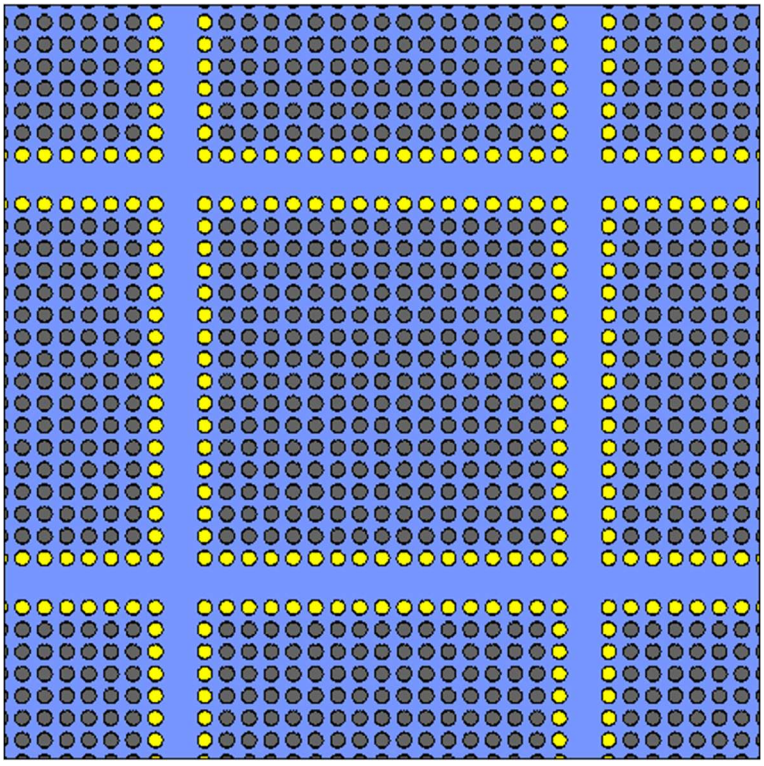

Figure 8. A part of the infinite assembly lattice. The yellow rods are the enriched drivers (3.5%) and the grey rods are targets of natural uranium

The dimensions for the assembly were taken from [14] and are:

- Pellet diameter: 0.78 cm
- Pin diameter 0.89 cm

- 1.26 cm between pin centres
- 21.6 cm between assembly centres

Case 3 – the normal PWR

The limit chosen for weapons-grade plutonium in this work (93.8% ^{239}Pu) is not an absolute figure for when plutonium is usable in a nuclear weapon. It has been stated that nuclear weapons can be produced with all mixtures of plutonium isotopes (except possibly ^{238}Pu), even if a high fraction of ^{239}Pu is regarded as desirable [15]. Is therefore interesting to investigate how much plutonium could be produced by the ELWR when running to full burnup. For the normal PWR case, we have used the pincell model from case 1 and the values from Table 1, i.e. enrichment 3.5% and an end burnup of 33000 MWd/tU. No variations with respect to pin pitch and water density were studied.

8. Results

Case 1 – homogenous core and varying the enrichment

For case 1, the depletion calculation was run for initial enrichments from 1% to 3.5% with increments of 0.25%. For each case, the plutonium production was calculated following the method in Figures 5-6. The results of the plutonium production rates can be seen in Figure 9. The plutonium production is given in the unit of grams/MWd at the target burnup, defining the limit for weapons-grade plutonium. In Figure 9, the simulated cases are compared to a similar calculation made by Glaser et al. [11] for Canadian heavy water reactor NRX – the National Research Experimental running on natural uranium, and data given by [11] for a (typical) PWR. The heavy water reactor in the figure represents the plutonium output from a reactor running on natural uranium and the figure would be similar for e.g a graphite-moderated reactor like the 5MWe reactor.

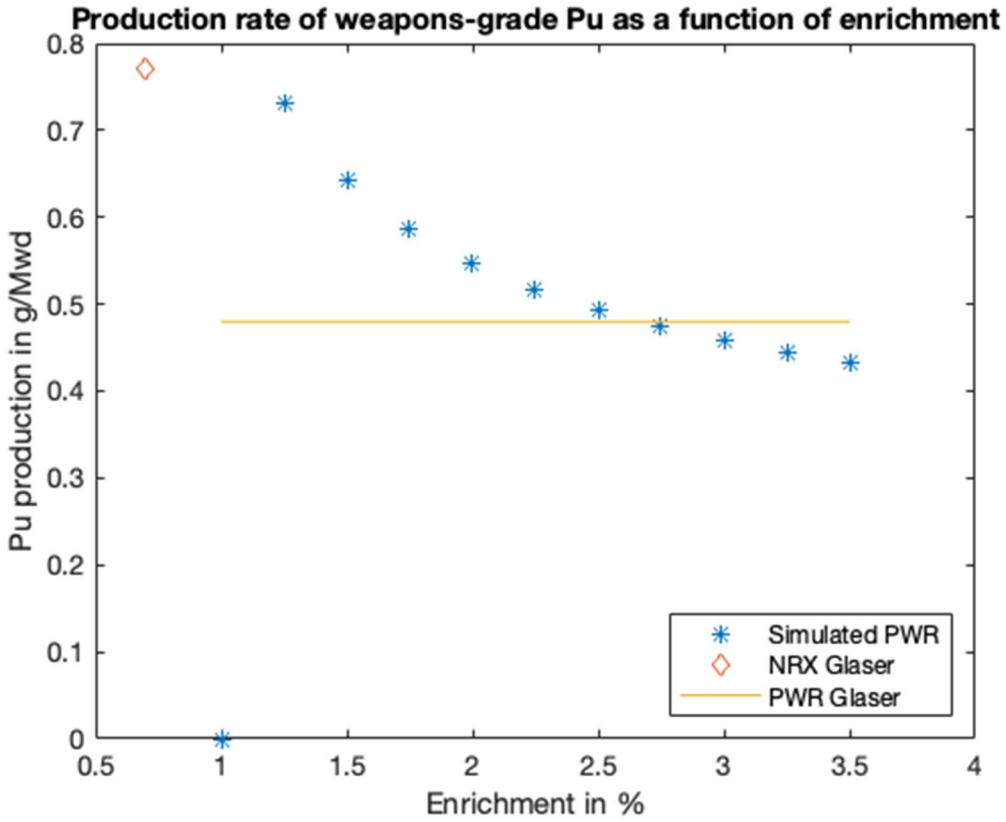

Figure 9. Plutonium production rates as a function of initial enrichment, See text for details.

From this figure it can be noted that the lower the enrichment, the larger the plutonium production rate. This is due to the fact that plutonium is created from ^{238}U which is present at a larger amount in low-enriched fuel. The Glaser article [11] does not specify the enrichment used for the typical PWR, but comparing with our simulated data, we see that the present simulation matches the plutonium production rate simulated in [11] for an initial enrichment of 2.5-3%; a reasonable enrichment for a PWR. From our simulations, we conclude that a PWR running on 1% enriched uranium fuel will not be critical, and therefore no plutonium is produced.

Taking the reactor power into account, the target burnup for the different enrichment cases will be reached at different times, i.e. the time the core needs to be irradiated to reach weapons-grade plutonium varies. This is shown in Figure 10, where we can note that at 2% enrichment, around 2 months of irradiation is needed, while at 3 % enrichment circa 3 months in the core is needed. This leads to a varying amount of core batches per year depending on the fuel enrichment level.

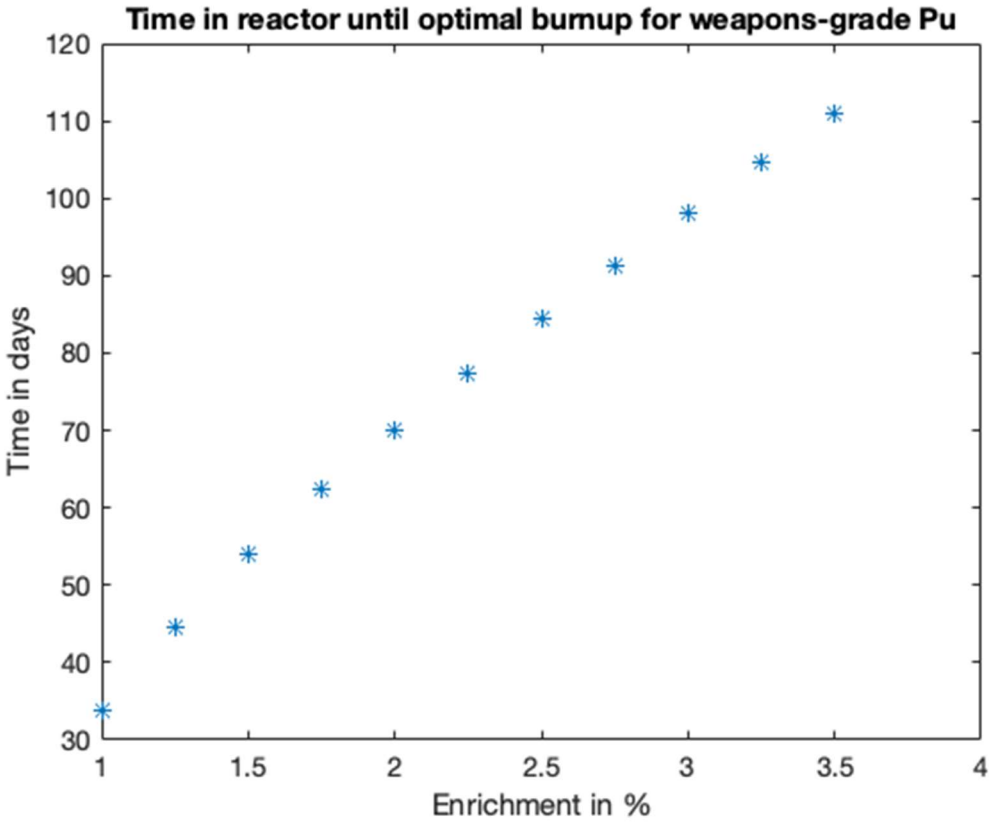

Figure 10. The time it takes to reach the target burnup for weapons-grade plutonium as a function of initial enrichment.

Considering the time the fuels need to spend in the reactor and the number of batches possible per year (see data in Table 2), as well as the core load size of uranium we arrive at Figure 11, where the three data sets correspond to different amounts of time between core batches. This figure shows how much plutonium could potentially be produced in the ELWR with different initial enrichment levels when exchanging and reprocessing the whole core several times a year. Except for the lost irradiation time during core unloading and reloading, the reactor has been assumed to run smoothly at full power (100 MWt).

Table 2. Data for the simulated total plutonium production

Enrich-ment	WG-Pu per batch (kg)	Days until target burnup	Batches per year (7 days between)	Pu per year (7 days between)	Batches per year (30 days between)	Pu per year (30 days between)	Batches per year (60 days between)	Pu per year (60 days between)
1	0	34		0		0		0.0
1.25	3.27	44	7.2	23.4	4.9	16.1	3.5	11.5
1.5	3.46	54	6.0	20.7	4.3	15.0	3.2	11.1
1.75	3.65	62	5.3	19.3	4.0	14.5	3.0	10.9
2	3.83	70	4.7	18.2	3.7	14.0	2.8	10.8
2.25	4.01	77	4.3	17.4	3.4	13.7	2.7	10.7
2.5	4.16	84	4.0	16.7	3.2	13.3	2.5	10.5
2.75	4.32	91	3.7	16.1	3.0	13.0	2.4	10.4
3	4.49	98	3.5	15.6	2.9	12.8	2.3	10.4
3.25	4.65	105	3.3	15.2	2.7	12.6	2.2	10.3
3.5	4.81	111	3.1	14.9	2.6	12.5	2.1	10.3

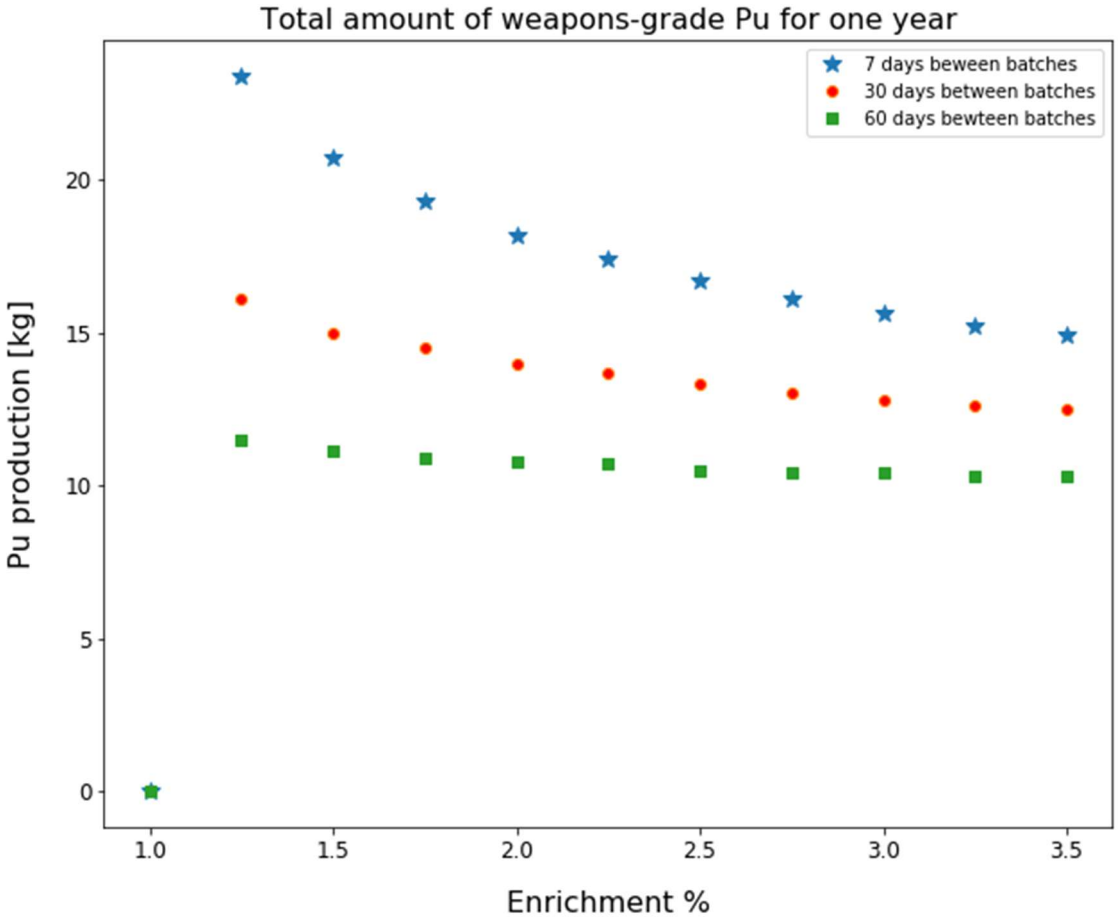

Figure 11. The total amount of weapons-grade plutonium that can be produced per year as a function of initial enrichment. Three different data sets presented corresponding to 7, 30 and 60 days between batches.

It was also investigated how far from maximum burnup the cores are at the time of discharge in the scenarios above. Figure 12 gives an indication by showing the target burnup for weapons-grade plutonium production together with the burnup limit for a critical reactor. Note that the real maximum burnup is slightly larger than what is indicated, since the figure shows the highest depletion step where the reactor is still critical (defined as a k_eff > 1.05, to allow for neutron losses). The overall result shown in Figure 12 is, however, that the difference between the target burnup for weapons-grade plutonium and the burnup limit increases with initial enrichment. Also, note again that the reactor is never critical for 1% enrichment, and barely critical until target burnup for 1.25%.

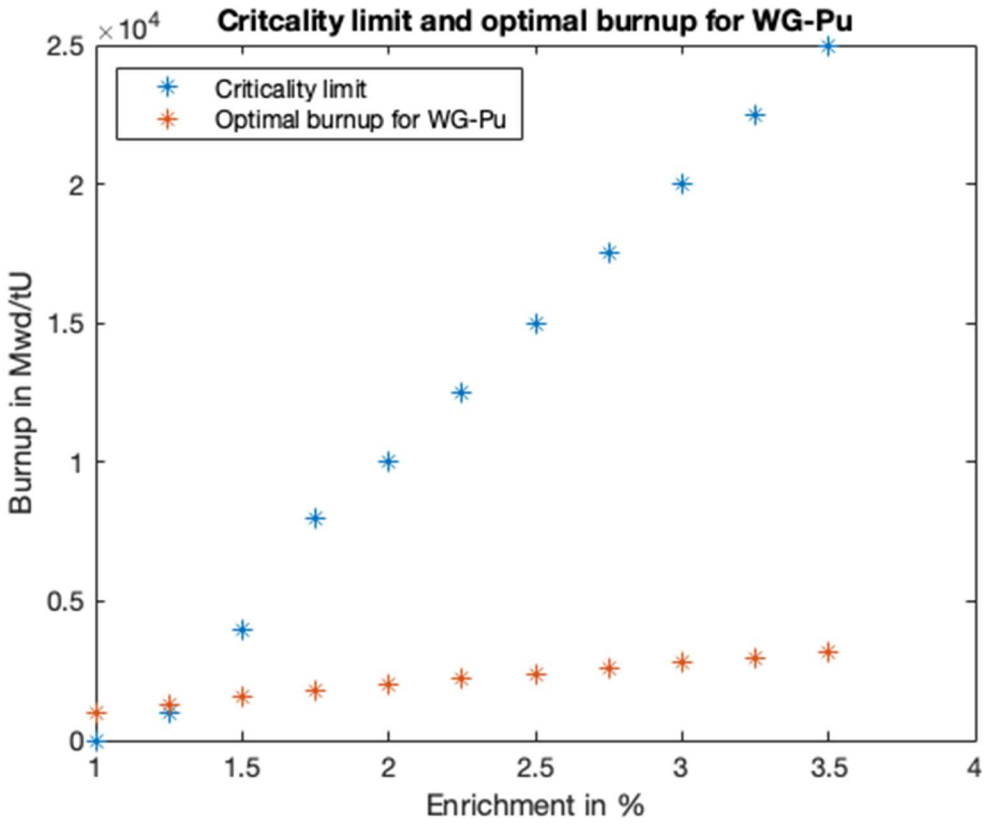

Figure 12. The target burnup for weapons-grade plutonium production together with the burnup limit for a critical reactor.

The amount of UO_2 fuel consumed per year varies with the number of fuel batches per year (shown in Table 2) which is a function of enrichment and time between batches. If we assume that the full reactor fuel load (4 tons of UO_2) is discarded at each fuel exchange, the fuel consumption corresponds to the number of full core batches needed, see Figure 13.

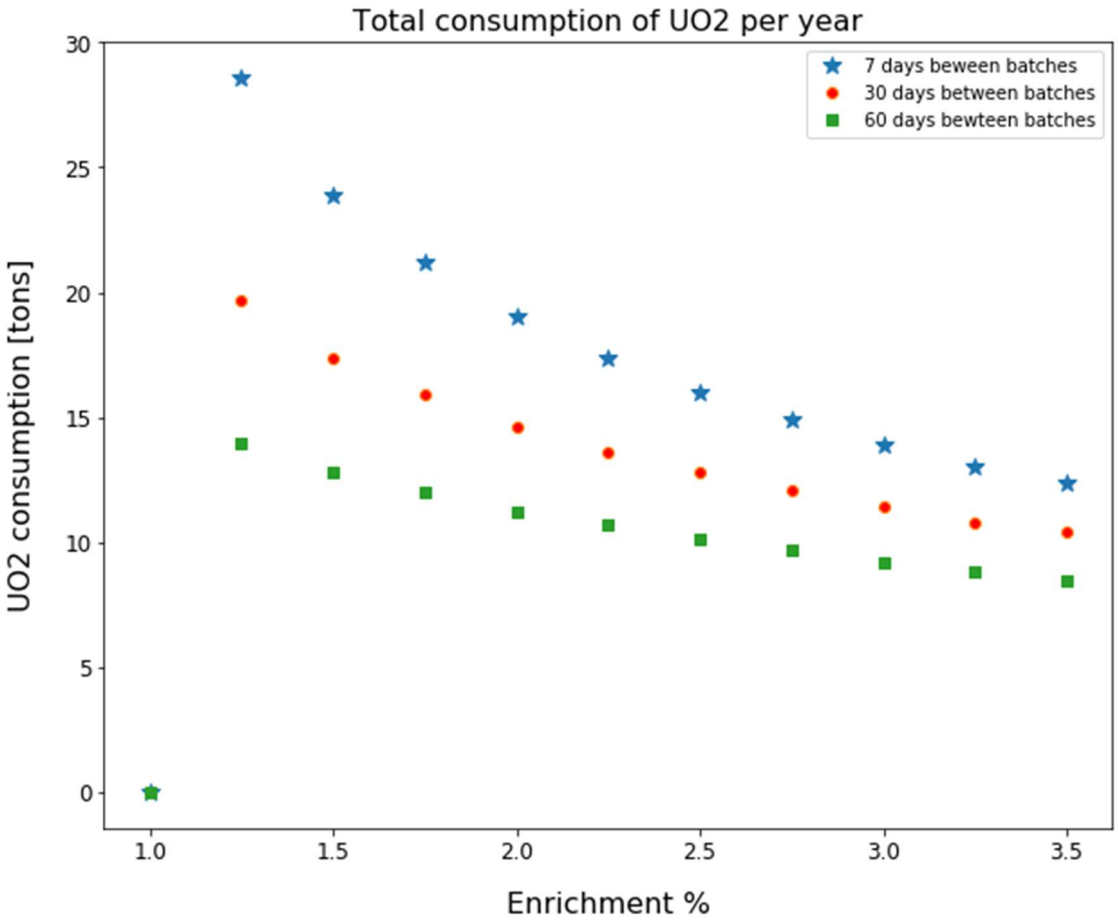

Figure 13. The total amount of fuel for all the irradiated core batches, assuming all of the fuel is regarded as spent after irradiation and no uranium is reprocessed.

Finally, for case 1, we investigated what influence the pin pitch (the distance between pins in the lattice) and the water density have. For these calculations a constant initial enrichment of 2% was chosen, and the case of 7 days between batches. In Figure 14, variations due to different distances between pins are shown. The pin pitch in the lattice is defined as the half the distance between the pin centres, and the default value is 0.665 cm. Since the pin radii is 0.475 cm (constant), this figure is the absolute minimum the pin pitch can be. In the simulations, the pitch varied between 0.5 cm and 0.85 cm. The default value (i.e. the same value as for enrichment 2% and 7 days between batches in Figure 11) is indicated with the ring.

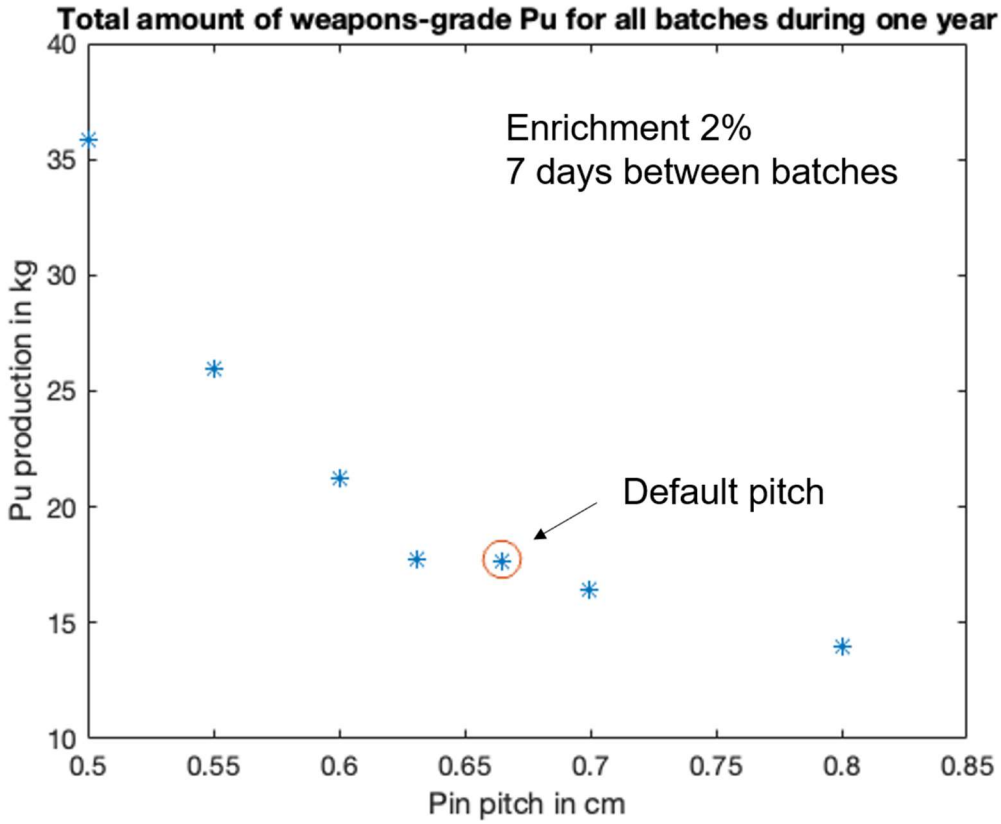

Figure 14. The influence on plutonium production of varying the pin pitch.

The water density was also varied, and since the density is a function of both the pressure and the temperature in a PWR; and both these are unknown, some assumptions have been made. We have assumed the default pressure to be 15 MPa and the water temperature to be 280 °C, corresponding to typical PWR values. This gives a default density of 0.75 g/cm^3. Assuming constant pressure, we find the boiling temperature at 15 MPa to correspond to a density of 0.6 g/cm^3, which is the minimum density possible in this PWR system. Thus, the water density is varied between 0.6 and 1.1 g/cm^3, and the results can be seen in Figure 15. Again, the default value also present in Figure 11 for 2% enrichment and 7 days between batches, is indicated with a ring.

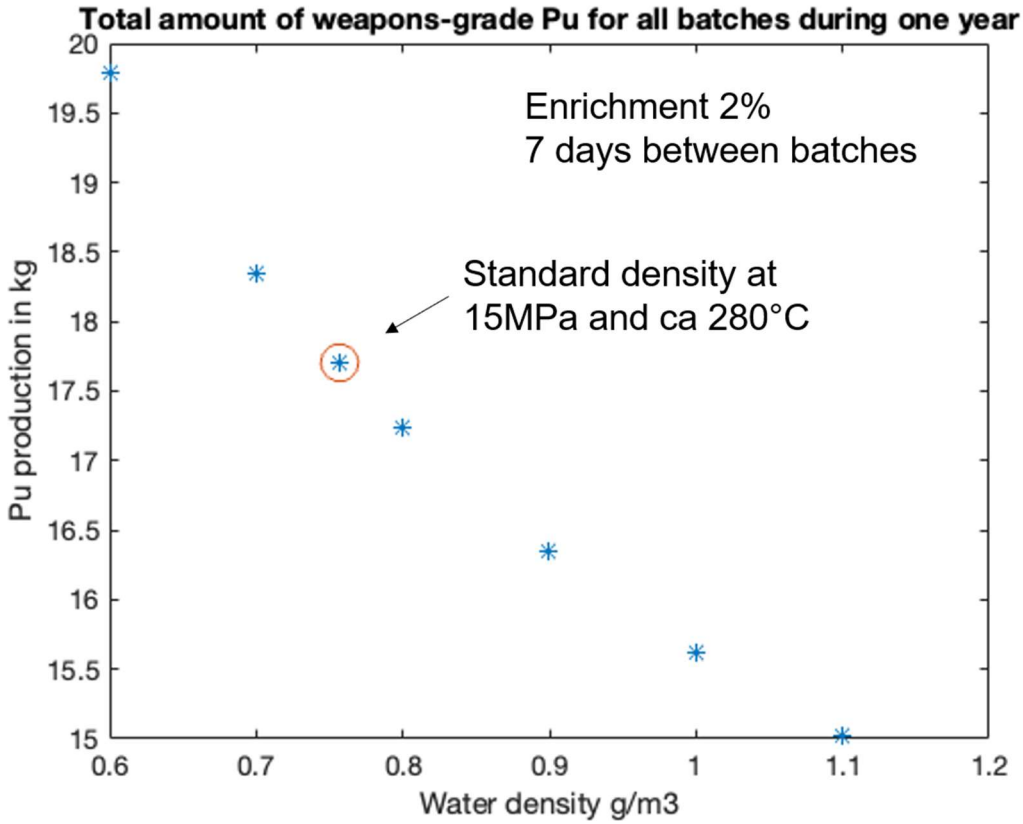

Figure 15. The influence on plutonium production of varying the water density.

Case 2 – heterogenous assemblies throughout the core

The heterogenous assembly design depicted in Figure 8 is just an example, and many other designs can be imagined. The simulated one showed there is potential in this kind of assemblies, but also challenges. Our calculation shows the results in Table 3, the total yearly production of plutonium valid for the case of 7 days between batches.

Table 3. The results from the heterogenous assembly simulation.

Plutonium production rate	0.64 g/MWd
Time in core until discharge	47 days
Total yearly production	19.8 kg
Criticality	Barely critical at target burnup

The design with parts of the assembly constituting drivers and parts constituting targets, will by default lead to uneven power distribution, see Figure 16.

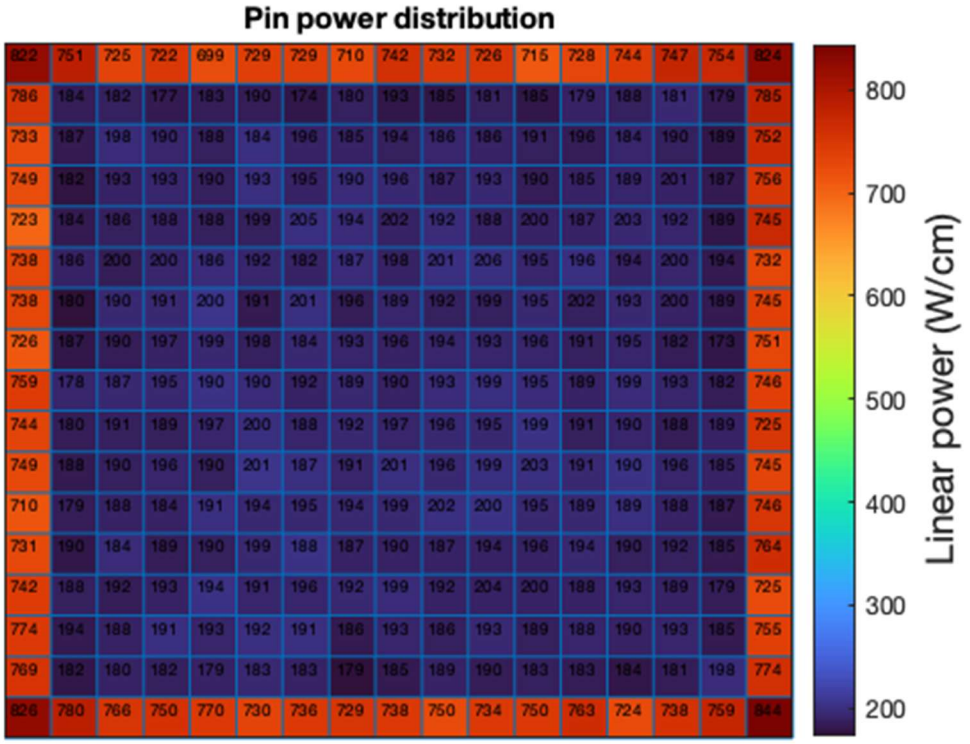

Figure 16. Pin power distribution in linear power/cm for the heterogenous assembly.

In general, the linear heat generation rate in nuclear fuel pins is limited by critical heat flux considerations. With a mixed target and driver core design, a strongly inhomogeneous power distribution may be expected, and thus the thermal power of the full core needs to be limited not to exceed the acceptable pin power in the most exposed pin of the core. Therefore, any gains in plutonium production per core load that is achieved by using a heterogeneous assembly using mixed target and driver pins, is likely to require compensation by lowering the full core thermal power. This in turn prolongs the time to reach the target burnup per core load, and reduces the overall plutonium production. While it is possible that driver and target zones might be optimised carefully to obtain high plutonium production while maintaining an acceptable pin power distribution, this has not been further examined in this work.

Case 3 – the normal PWR

A PWR will produce plutonium throughout its operation, and in fact, the total amount of plutonium grows with burnup, see Figure 17. The problem is that the quality of the plutonium

decreases, and at the burnup of 33000 MWd/tU, the plutonium composition can be seen in Table 4.

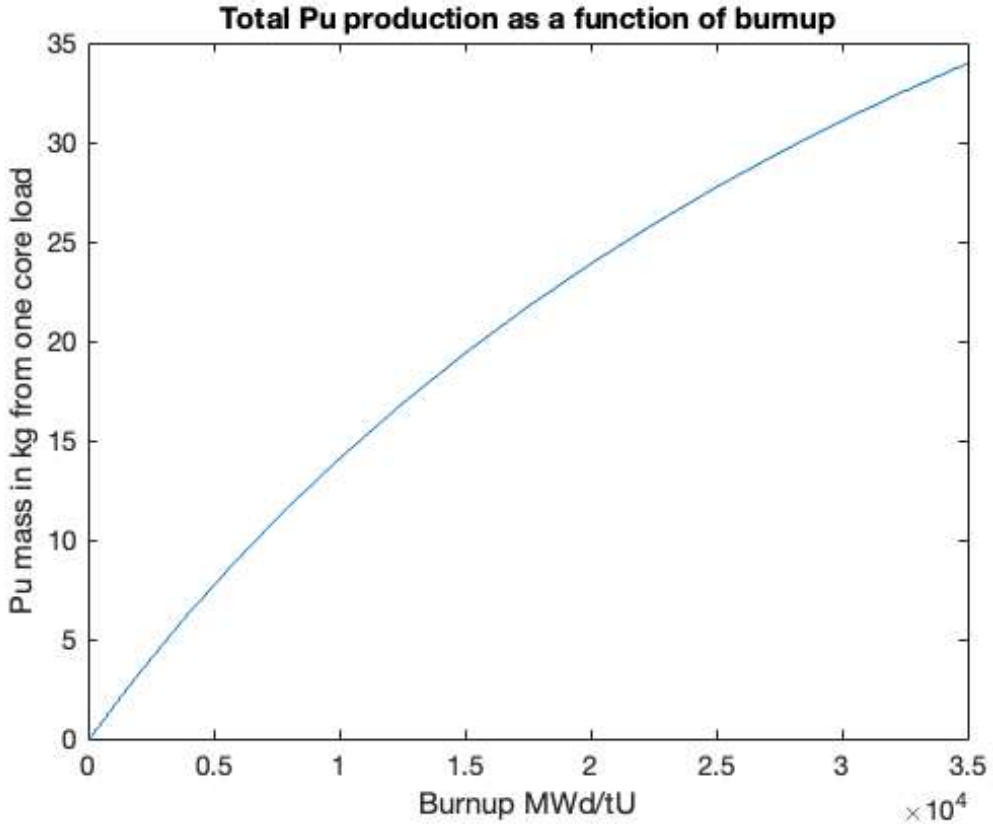

Figure 17. The total amount of plutonium (all isotopes) created in the ELWR core as a function of burnup at the operational parameters specified in Table 1.

Table 4. The isotopic composition of plutonium at burnup 33000 MWd/tU.

Isotope	**Fraction of all plutonium (%)**
^{238}Pu	1.31
^{239}Pu	56.6
^{240}Pu	24.0
^{241}Pu	13.2
^{242}Pu	4.85

The fuel will stay in the reactor for 3.2 years to reach a burnup of 33000 MWd/tU and during this time, a total amount of 33 kg of plutonium is produced, or 9.9 kg yearly.

9. Summary and discussion

A summary of the three investigated cases can be seen in Table 5. Discussions on each case follows.

Table 5. Summary of the simulated results in this work. See text for detailed discussion.

	WG-Pu production per year (kg)	**Considerations**	**Advantages**	**Disadvantages**
1. Homogeneous core	10-20	Low initial enrichment preferable	Large amounts of WG-Pu.	Frequent fuel exchanges, large fuel manufacturing and reprocessing capability needed.
2. Heterogeneous assembly	Up to 20	Very uneven power distribution.	Large amounts of WG-Pu theoretically possible.	Risk of fuel failure, complicated sorting for reprocessing.
3. Normal PWR	10 (not WG)	Normal operation	Optimised for electricity production.	Low Pu quality

Case 1 – homogenous core and varying the enrichment

Having a full core of homogeneous fuel and keeping it in the reactor until low burnup is one way of producing large amounts of weapons-grade plutonium. As can be seen from the results above, this set-up can produce up to 20 kg per year which would quadruple North Korea's plutonium yearly production. The yearly production can be slightly increased if the fuel is designed with dense pin lattices and low water density. Both these variables (pin pitch and moderator density) will affect the moderation of the neutrons, and since plutonium is mainly produced by resonance-energy neutrons being captured in ^{238}U, pins with less moderation will produce more plutonium.

The reactor operation in case 1 relies on frequent fuel changes as several core batches per year have to be irradiated. This puts large constraints on fuel fabrication, fuel handling and reprocessing. The question is whether North Korea has the fuel logistics and fuel fabrication

capability necessary. In Figure 13, the total amount of UO_2 fuel that is needed for the different enrichment cases can be seen, and even if the amount in tons goes down with higher enrichment, this fuel is more expensive to produce in terms of enrichment costs (SWUs) and ingoing natural uranium asset. The high requirement on uranium raw material together with the demand for enrichment will furthermore strongly compete with the production of highly enriched uranium, HEU. These aspects have to be considered in a full analysis of North Korea's nuclear fuel cycle.

Case 2 – heterogenous assemblies throughout the core

This case, and variations of it, have the potential of producing large amounts of weapons-grade plutonium. It is technically possible to create assemblies with pins of different enrichments and only send some of the pins (the targets) to reprocessing, even if the sorting process of the spent fuel will be complicated and sensitive to human errors. However, the largest problem with this design is the uneven power distribution, which might lead to fuel failure and fuel damages. Depending on the exact design on the fuel assemblies, it might be necessary to run the reactor at lower power than intended, and in that case, the plutonium production will decrease.

In case 2, there is still a need for rather frequent fuel exchanges (after ca 50 days) but, the need for enrichment capability and competition with the HEU programme is smaller compared to case 1, since a majority of the fuel pins are made of natural uranium.

Case 3 – the normal PWR

Case 3 applies to the operation of any PWR since plutonium is always produced during reactor operation, but will be of so-called reactor grade (i.e. >19% of ^{240}Pu) when the reactor is operated until high burnup. The reasons for the plutonium quality decrease are:

1. ^{239}Pu undergoes fission adding to the electricity generation.
2. ^{239}Pu captures neutrons and builds up heavier plutonium isotopes.

Note that the plutonium composition as given in Table 4 generates a lot of heat from the large fractions of ^{238}Pu and ^{241}Pu. This must be considered if reprocessing and handling the plutonium.

In the present scenario, with the core size and reactor power given in Table 1, 10 kg of plutonium of reactor-grade quality was produced per year while the reactor was running

continuously and producing electricity. Even if this plutonium could be used for weapons purposes, we note that less plutonium is produced per year compared to most of the variations of case 1. The advantage of case 3 is of course the low fuel consumption, steady operation and electricity production.

To summarise, North Korea has experience with a graphite-moderated plutonium producing reactor; the 5MWe reactor. Another similar reactor would be the obvious choice if the purpose was purely plutonium production, and it seems surprising if an PWR design would be favoured unless there were other boundary conditions to consider. Electricity production could be one such condition, and even if a graphite-moderated reactor also can produce electricity, the PWR design has become the dominating power reactor worldwide. North Korea is in demand of electricity, and even the nuclear weapons programme is a large consumer of electricity, especially the enrichment plants. One should also keep in mind that the operation of the ELWR could change over time, to sometimes favour plutonium production like in cases 1 or 2, and sometimes running the reactor as a normal PWR (case 3).

10. Outlook

Many things are unknown about North Korea's design and operation of the ELWR, it is in fact not even certainly established that the reactor is a PWR and we do not know the actual thermal power. However, here we have considered a small 100 MWt PWR with a common type of layout and fuel. Some of the questions that have arisen have to do with the time structure of the operation, and this is something where we hope and foresee that extended monitoring through satellite imagery analysis will help. If patterns can be observed in the operation periods and shut down periods of the reactor, this could potentially be fitted with a certain pattern for fuel exchanges in agreement with a particular mode of operation, i.e. one of the fuel exchange patterns for extraction of irradiated fuel for reprocessing. This rests on the assumption given in Table 1, that the ELWR has a pressure vessel and that the reactor needs to be stopped for fuel exchanges. Many reactors requiring frequent fuel exchanges, such as heavy water moderated reactors running on natural uranium, have pressure tube designs and can exchange fuel during operation with the use of a loading machine. Online refuelling is mentioned in [7] as having been done for the 5 MWe reactor in North Korea, and even if this is a different design compared to a water-moderated reactor, North Korea has had experience with changing fuel during operation.

If online refuelling were to be implemented in the ELWR, it might not be possible to detect fuel discharges by watching for reactor shut downs, so any information about a loading machine or pressure tubes would be valuable. If there are such instalments, they would strongly suggest frequent fuel exchanges, and could be an indication of plutonium production.

As an outlook to future work, we have considered a core design based on whole assemblies of targets and drivers. This is a design that could potentially have target assemblies of natural or even depleted uranium along the edge of the core, and driver assemblies of enriched uranium centrally. Such a design could even be imagined with metallic uranium targets, which would make it possible to facilitate the same fuel manufacturing and reprocessing infrastructure as for the 5 MWe reactor. Since only a part of the total core volume would produce plutonium in such a setup, a reactor like this would likely produce less plutonium annually than our case 1, but it would not demand as frequent fuel exchanges and could also produce power steadily. This case would consume less enrichment and fuel manufacturing resources than case 1, but given the fairly small total plutonium production North Korea has today from the 5 MWe, even a small yearly production in combination with electricity production could give a substantial contribution to the total plutonium inventory,

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