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Preliminary Estimates of Nuclear Weapon Potential in North Korea's New ELWR

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Introduction

- **2016년 – 2017년 (핵보유 시도)**
  - 4차 핵실험 (16.1월)
  - 5차 핵실험 (16.9월)
  - 6차 핵실험 및 ICBM 발사 (17.9월)

- **2018년 (북핵 일부 합의)**
  - 판문점 선언 (4.27)
  - 싱가포르, 북미정상회담 공동성명 (6.12)
  - 평양공동선언 (9.19)

- **2019년**
  - 하노이, 제2차 북미정상회담 (2.27-28) -> 결렬

- **2021년 이후**, 영변 핵시설 재가동

북미협상: 북미 비핵화 실무협상에 엇갈린 양국 입장

2019년 10월 6일

북한대표단을 태운 차량이 미국과 회담장소인 스톡홀름 인근 리딩고 섬으로 향하고 있다

베트남 하노이 2차 정상회담 이후 약 7개월여 만에 열린 스웨덴 북-미 비핵화 실무협상이 사실상 결렬됐다.

앞서 북한 김명길 외무성 순회대사와 미국 스티븐 비건 국무부 대북특별대표가 각각 이끄는 북-미 협상단은 5일(현지 시간) 스웨덴 스톡홀름 북동쪽 리딩고 섬에서 비핵화 협상을 벌였다.

Figure 1. 북미협상 결렬[1]

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[1] BBC KOREA (Oct. 6, 2019). "북미협상: 북미 비핵화 실무협상에 엇갈린 양국 입장". https://www.bbc.com/korean/news-49949678

Introduction

- **The Nyongbyon nuclear scientific research center has the IRT-2000 research reactor, a 5 MWe reactor, and a 100 MWth reactor.**

Figure 2. 북, 영변 주요 핵시설[2]

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[2] 김지은 (Sep. 19, 2019). "“영구 폐기 뜻” 영변 핵시설, 북 핵개발의 심장”. 한겨레. https://www.hani.co.kr/arti/politics/defense/862869.html

Introduction

- **The Experimental Light Water Reactor (ELWR) was recently constructed at the Nyongbyon site in the 2010s.**

Figure 3. Development of pipelines at the ELWR from 2010 to 2013[3]

[3] Sulgiye Park and Allison Puccioni (Jan. 24, 2024). "North Korea's Pursuit of an ELWR: Potential Power in Nuclear Ambitions?". 38NORTH. https://www.38north.org/2024/01/north-koreas-pursuit-of-an-elwr-potential-power-in-nuclear-ambitions/

Introduction

- **This new ELWR reportedly began operations in October 2023.**

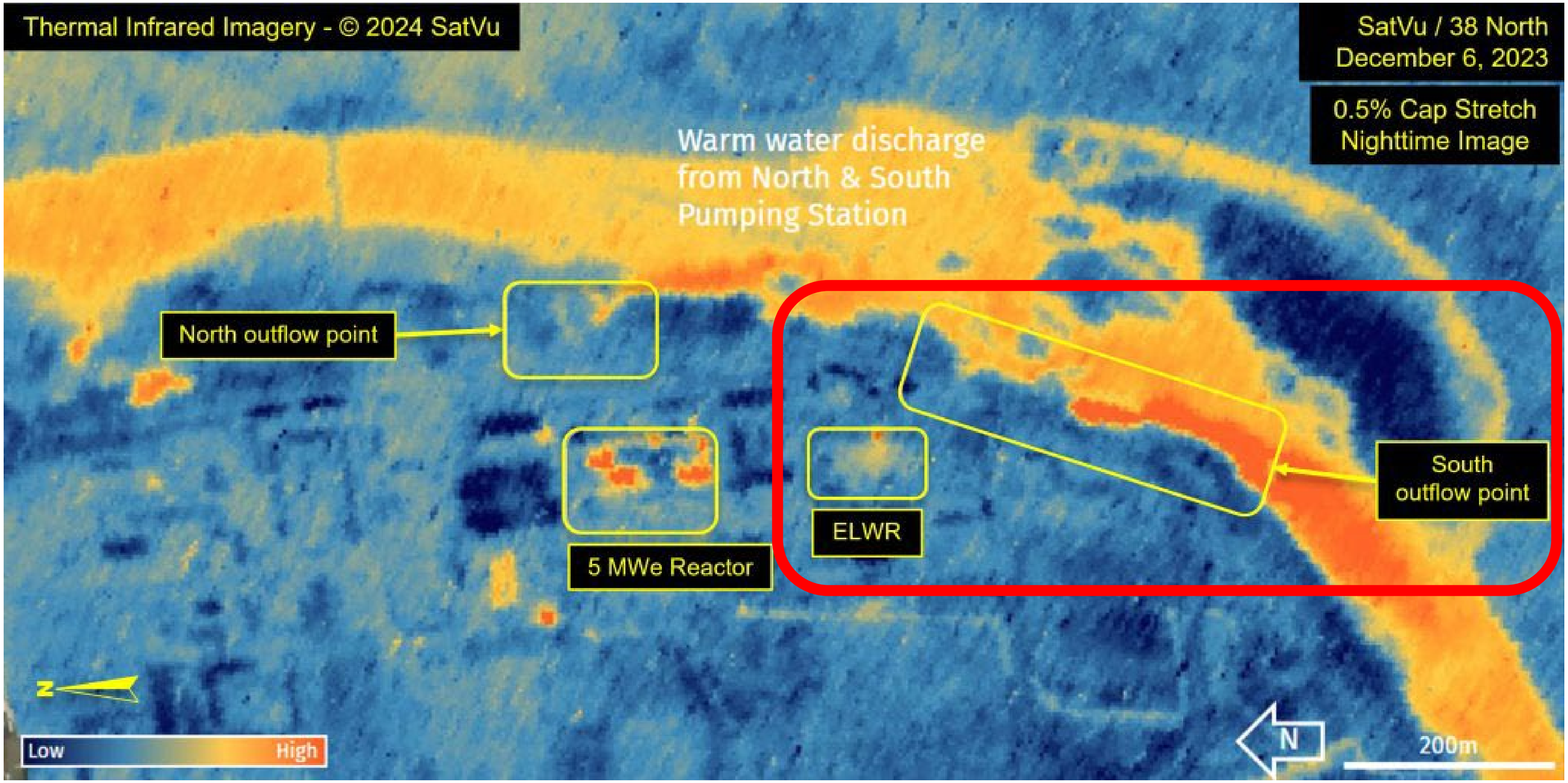

Figure 3. Thermal image over Yongbyon Nuclear Scientific Research Center from October, 2023.
Blue (lower heat) -> Red (higher heat)[3]

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[3] Sulgiye Park and Allison Puccioni (Jan. 24, 2024). "North Korea's Pursuit of an ELWR: Potential Power in Nuclear Ambitions?". 38NORTH. https://www.38north.org/2024/01/north-koreas-pursuit-of-an-elwr-potential-power-in-nuclear-ambitions/

Reactor Modeling

- **The 5 Megawatt-electric Reactor**
  - Power: 25 MWth
  - Type: Magnox (Graphite-moderated gas-cooled reactor)
  - Fuel: 50 tons, metallic natural-uranium (^{235}U 0.72 wt%)
  - From 1986, producing Weapon-Grade Plutonium

Table I: Operation history of 5 MWe Reactor and WG-Pu production estimations[4]

Operation and shutdown	Residence; avg. burnup	Amount.Spent fuel Removed	Reprocess Duration	Separated WG-Pu
Op. 1986–1989 Shutdown 1989 (70–100 days)	3 years (Unknown)	Unknown	Unknown	Less than or equal to 2 kg
Op. 1989–1994 Shutdown 1994	Unknown (~650 MWd/t)	Full core: 50 tons U	2003.01–06	20–30 kg
Op. 2003–2005 Shutdown 2005 (~70 days)	2 years (330 MWd/t)	Full core	2005.06–12	10–14 kg
Op. 2005–2007 Shutdown July 2007	1+ year (Less than 200 MWd/t)	Full core	2009	~8 kg
Op. 2013–2015 Shutdown 2015	2 years (intermittent: Uncertain burnup)	Likely full core	2016	5.5–8 kg
Op. 2016	In Reactor			

total 45 ~ 62 kg

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[4] Hecker S.S., Braun C., Lawrence C. (2016). "North Korea's Stockpiles of Fissile Material". Korea Oberver 47 (4), 721-749

Reactor Modeling

- **The new Experimental Light-Water Reactor**
  - Power: 100 MWth
  - Type: VVER-440 (Russia’s PWR using hexagonal fuel bundles)
  - Fuel: 4 tons, 3.5 wt% enriched UO_2[5]
  - Constructed since 2010 & Tested the cooling water system (July 2022)
  - Begun operating since October 2023

Figure 4. A significant amount of water discharge from the ELWR (Left: October 4, 2023 / Right: December 10, 2023)[6]

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[5] Hecker S.S. (Dec. 20, 2010). “Redefining denuclearization in North Korea”. Bulletin of the Atomic Scientists. https://thebulletin.org/2010/12/redefining-denuclearization-in-north-korea-2/

[6] David Albright (Jan, 2024). North Korea’s ELWR: Finally Operational After a Long Delay. ISIS report

Computational Method

- **Oak Ridge Isotope GENeration (ORIGEN) module in SCALE code**
  - Point-depletion (0-D) code that calculate time-dependent concentrations, activities, and radiation source terms for a large number of isotopes simultaneously generated or depleted by neutron transmutation, fission, and radioactive decay

  - Neutron spectrum-dependent libraries are created from interpolation of existing reactor libraries in SCALE code, using Automated Rapid Processing (ARP) module.

  - Depletion calculations are used the Chebyshev Rational Approximation Method (CRAM) in solving the Bateman equation.

  - For post-processing, OPUS module shows calculated isotopics and spectra to be sorted, ranked, and converted to other units.

Results

- Weapon-Grade Plutonium (WG-Pu) estimation
- WG-Pu is defined as plutonium with a high content of the fissile isotope (^{239}Pu)
- **Pu quality** $= \dfrac{\text{fissile Pu isotopes mass } (^{239}\text{Pu})}{\text{total Pu isotopes mass (total Pu)}} \geq 93\ \text{wt\%}$
- The Pu quality monotonically decreases due to the preferential fission reactions of ^{239}Pu.

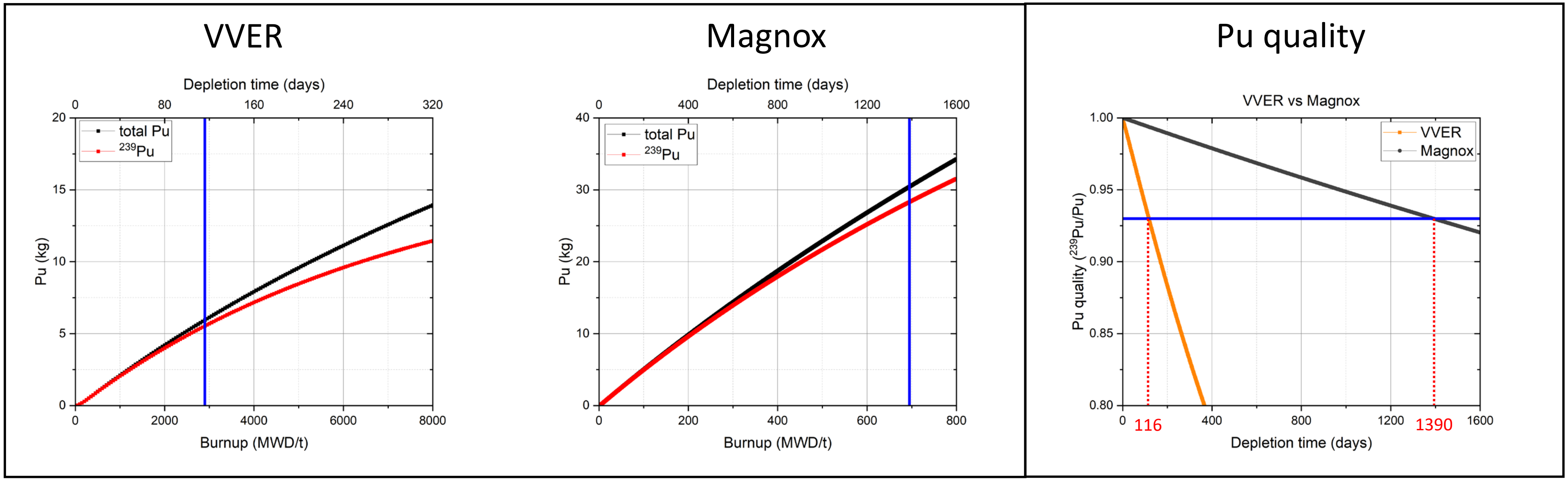

Figure 5. Comarison of plutonium production and quality over depletion by reactor types
(Left: VVER / Middle: Magnox / Right: Pu quality)

Results

- **Depletion time**
  - VVER: 116 days
  - Magnox: 1390 days
- **Burnup**
  - VVER: 2900 MWd/tU
  - Magnox: 695 MWd/tU
- **Pu production**
  - VVER: 5.94 kg
  - Magnox: 30.4 kg
- **Grams of WG-Pu per MWd**
  - VVER: 0.512 g/MWd
  - Magnox: 0.876 g/MWd

Table II: Plutonium Production and Weapon Potential

	VVER	Magnox
Thermal power (MWt)	100	25
Initial mass of uranium (tons)	4	50
Depletion time at which Pu quality becomes 93 wt% (days)	116	1390
Burnup (MWd/tU)	2900	695
WG-Pu production (kg)	5.94	30.4
Grams of WG-Pu per MWd (gPu/MWd)	0.512	0.876
Separated WG-Pu (kg)	3.74 ~ 4.28	19.2 ~ 21.9
Annual WG-Pu production (kg/year)	11.8 ~ 13.5	5.04 ~ 5.75
Number of nuclear weapon potentials (number/year)	2.95 ~ 4.49	1.26 ~ 1.92

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Results

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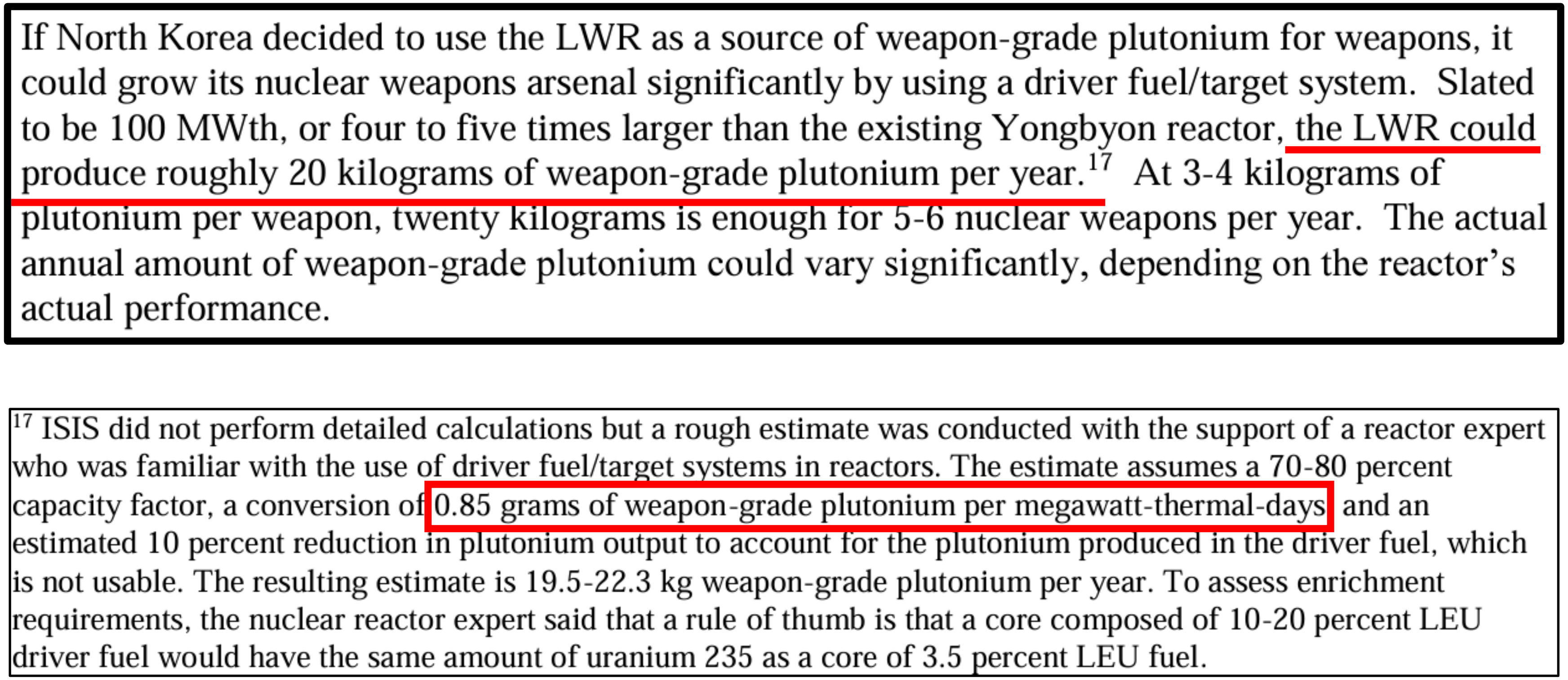
  - Magnox: 0.876 g/MWd



If North Korea decided to use the LWR as a source of weapon-grade plutonium for weapons, it could grow its nuclear weapons arsenal significantly by using a driver fuel/target system. Slated to be 100 MWth, or four to five times larger than the existing Yongbyon reactor, the LWR could produce roughly 20 kilograms of weapon-grade plutonium per year.[17] At 3-4 kilograms of plutonium per weapon, twenty kilograms is enough for 5-6 nuclear weapons per year. The actual annual amount of weapon-grade plutonium could vary significantly, depending on the reactor's actual performance.

[17] ISIS did not perform detailed calculations but a rough estimate was conducted with the support of a reactor expert who was familiar with the use of driver fuel/target systems in reactors. The estimate assumes a 70-80 percent capacity factor, a conversion of 0.85 grams of weapon-grade plutonium per megawatt-thermal-days and an estimated 10 percent reduction in plutonium output to account for the plutonium produced in the driver fuel, which is not usable. The resulting estimate is 19.5-22.3 kg weapon-grade plutonium per year. To assess enrichment requirements, the nuclear reactor expert said that a rule of thumb is that a core composed of 10-20 percent LEU driver fuel would have the same amount of uranium 235 as a core of 3.5 percent LEU fuel.

Figure 6. Institute for Science and International Security report[7]

[7] David Albright (Oct 7, 2015). North Korean Plutonium and Weapon-Grade Uranium Inventories. ISIS report

Results

- *Seperated Pu
    - VVER: 3.74 ~ 4.28 kg
    - Magnox: 19.2 ~ 21.9 kg
- **Annular Pu production
    - VVER: 11.8 ~ 13.5 kg/year
    - Magnox: 5.04 ~ 5.75 kg/year
- ***Number of nuclear weapon potentials
    - VVER: 2.95 ~ 4.49 #/year
    - Magnox: 1.26 ~ 1.92 #/year

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* Pu production × Capacity factor (70 ~ 80 %) × Reduction in output (10 %)
** Separated Pu × 365 days ÷ Depletion time
*** Annular Pu ÷ (3~4 kg Pu per weapon)

Results

- **Plutonium production vs depletion time**
    - At one operation, the Magnox has a more Pu production than the VVER.
    - During the same operation time, the VVER has a higher Pu production rate than the Magnox. (~130 % higher)

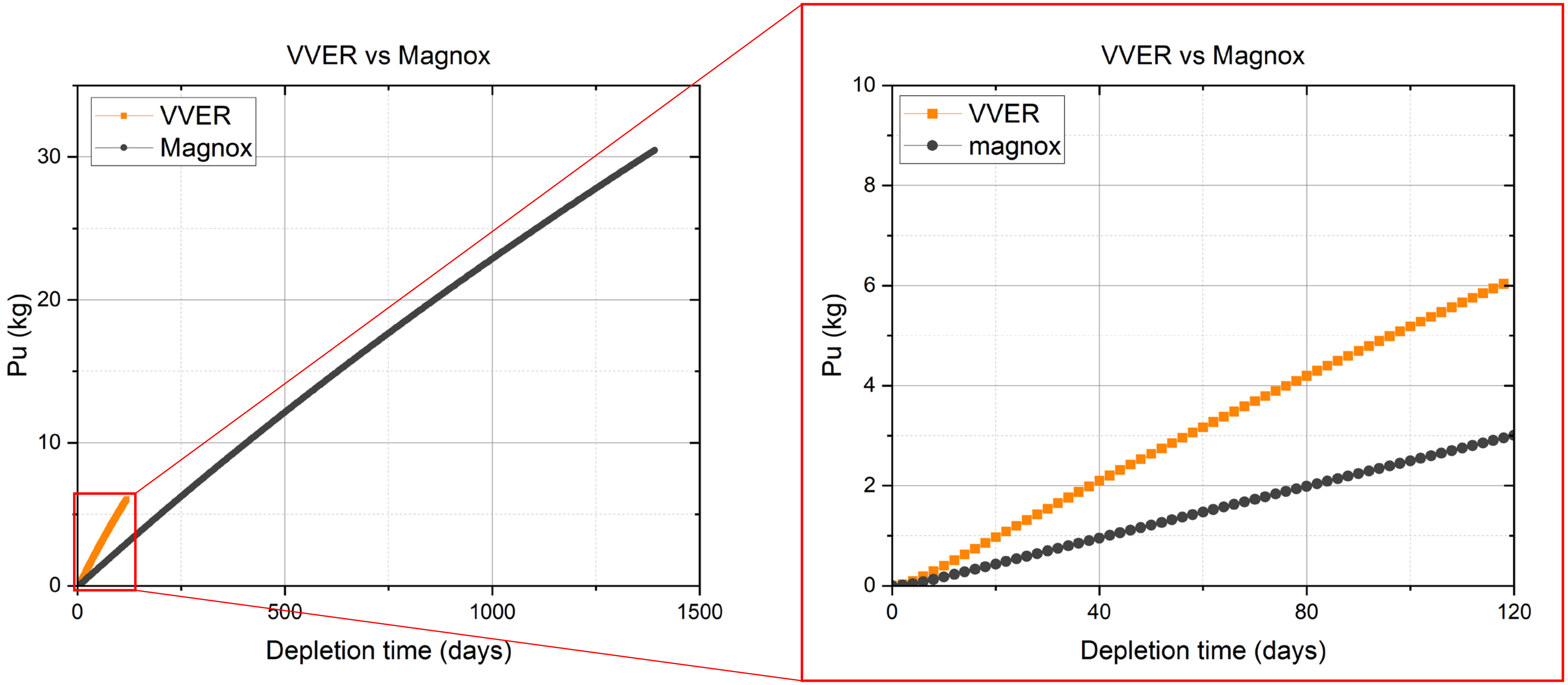
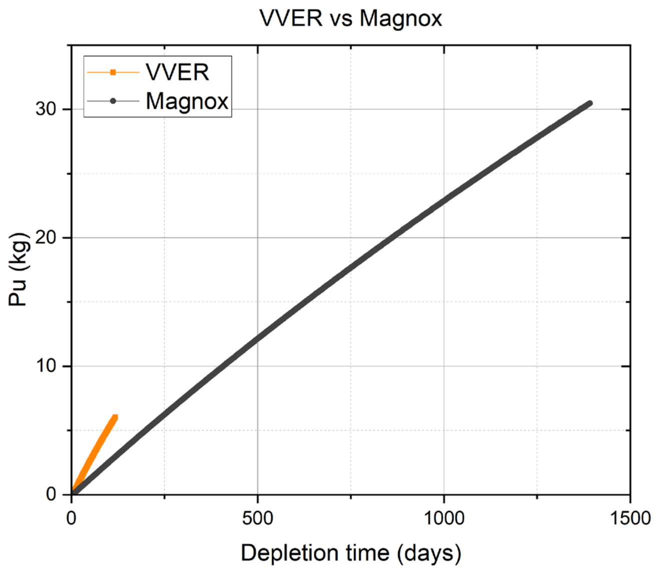


Figure 7. Comarison of plutonium production over depletion time by reactor types

Conclusions

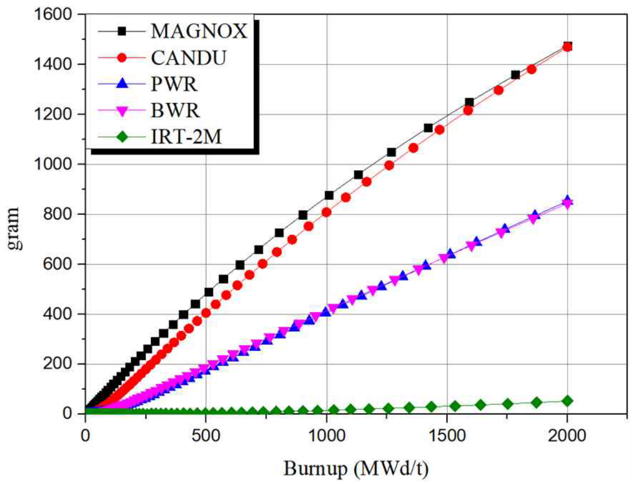
- The construction of a new Experimental Light Water Reactor (ELWR) by North Korea continues to pose a significant nuclear proliferation threat.
- In this work, the plutonium production capacity for this ELWR was estimated, assuming it is based on the Russian VVER reactor design.
- It was estimated that North Korea's existing Magnox-type reactor can produce 1.26 to 1.92 nuclear weapons per year, while the ELWR can produce 2.95 to 4.49 nuclear weapons per year.
- This result undervalues from the estimation provided in the ISIS report.



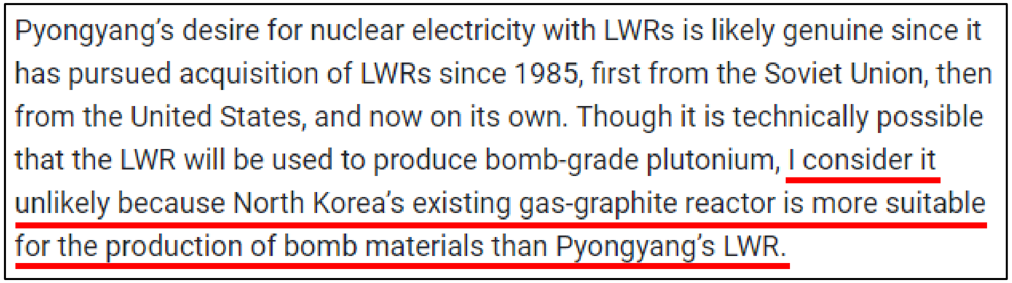
	ELWR	5 MWe reactor
Reactor power (MWth)	100	25
Initial uranium mass (tons)	4	50
Grams of WG-Pu per MWd (gPu/MWd)	0.512	0.876
Number of nuclear weapon potentials (number/year)	2.95 ~ 4.49	1.26 ~ 1.92
ISIS's estimation (number/year)	5 ~ 6	

Conclusions

- **Limitations**
  - Light Water Reactors (LWRs) are generally not well-suited for plutonium production.



Figrue 8. Pu production over burnup per initial uranium ton by reactor types[8]



Pyongyang's desire for nuclear electricity with LWRs is likely genuine since it has pursued acquisition of LWRs since 1985, first from the Soviet Union, then from the United States, and now on its own. Though it is technically possible that the LWR will be used to produce bomb-grade plutonium, I consider it unlikely because North Korea's existing gas-graphite reactor is more suitable for the production of bomb materials than Pyongyang's LWR.

<Siegfried S. Hecker. (December 20, 2010). "Redefining denuclearization in North Korea", Bulletin of the Atomic Scientists>

- **Future works**
  - This work focused on point-depletion calculations and did not consider neutron leakage and operational periods.
  - Incorporating 3D modeling will be needed to attain more accurate results, which may lower the estimated WG-plutonium production capacity.
  - Accounting for reactor cooling periods will also be necessary.

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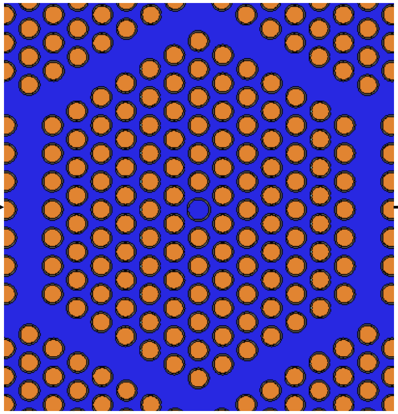
[8] G.H.Park (2022). "Evaluation of Potential Weapon-Grade Plutonium Production for Scenarios of Varying Uranium Enrichment for the MAGNOX Type Reactor". Master's Thesis, Hanyang University

Future work (Doing)

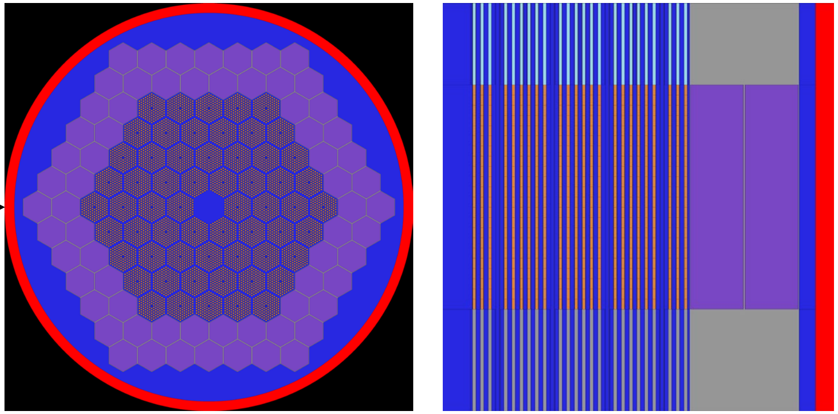
- **3D Modeling**
  - We are using Monte-Carlo code Serpent2 for full-core 3D analysis.

0-D
ORIGEN

2-D Fuel bundle



3-D Whole core



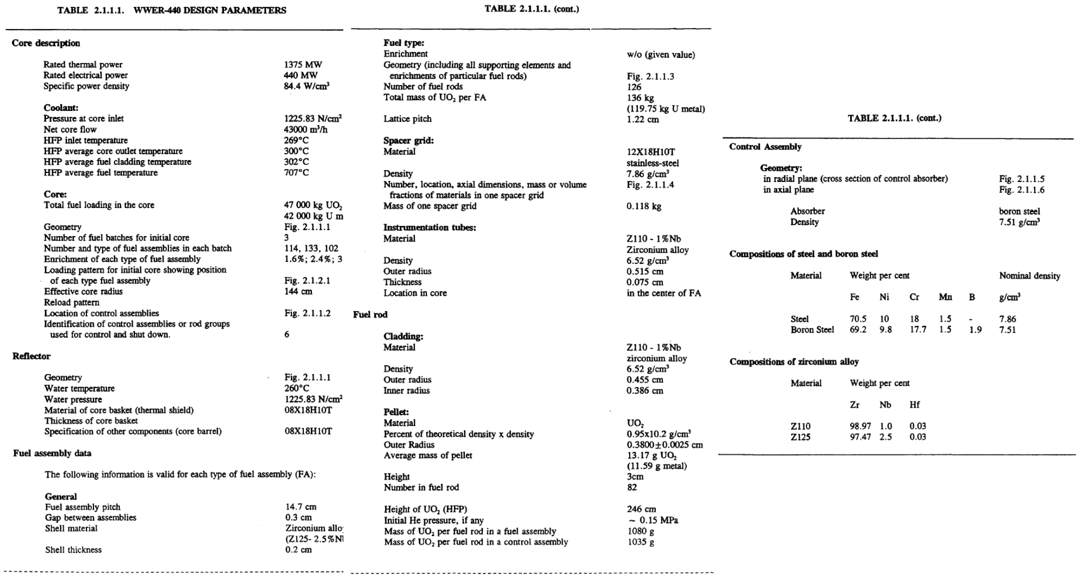


TABLE 2.1.1.1. WWER-440 DESIGN PARAMETERS

Core description	
Rated thermal power	1375 MW
Rated electrical power	440 MW
Specific power density	84.4 W/cm³
Coolant:	
Pressure at core inlet	1225.83 N/cm²
Net core flow	43000 m³/h
HFP inlet temperature	269°C
HFP average core outlet temperature	300°C
HFP average fuel cladding temperature	302°C
HFP average fuel temperature	707°C
Core:	
Total fuel loading in the core	47 000 kg UO_2 42 000 kg U m
Geometry	Fig. 2.1.1.1
Number of fuel batches for initial core	3
Number and type of fuel assemblies in each batch	114, 133, 102
Enrichment of each type of fuel assembly	1.6%; 2.4%; 3
Loading pattern for initial core showing position of each type fuel assembly	Fig. 2.1.2.1
Effective core radius	144 cm
Reload pattern	
Location of control assemblies	Fig. 2.1.1.2
Identification of control assemblies or rod groups used for control and shut down.	6
Reflector	
Geometry	Fig. 2.1.1.1
Water temperature	260°C
Water pressure	1225.83 N/cm²
Material of core basket (thermal shield)	08X18H10T
Thickness of core basket	
Specification of other components (core barrel)	08X18H10T
Fuel assembly data	
The following information is valid for each type of fuel assembly (FA):	
General	
Fuel assembly pitch	14.7 cm
Gap between assemblies	0.3 cm
Shell material	Zirconium allo (Z125- 2.5%N
Shell thickness	0.2 cm

TABLE 2.1.1.1. (cont.)

Fuel type:	
Enrichment	w/o (given value)
Geometry (including all supporting elements and enrichments of particular fuel rods)	Fig. 2.1.1.3
Number of fuel rods	126
Total mass of UO_2 per FA	136 kg (119.75 kg U metal)
Lattice pitch	1.22 cm
Spacer grid:	
Material	12X18H10T stainless-steel
Density	7.86 g/cm³
Number, location, axial dimensions, mass or volume fractions of materials in one spacer grid	Fig. 2.1.1.4
Mass of one spacer grid	0.118 kg
Instrumentation tubes:	
Material	Z110 - 1%Nb Zirconium alloy
Density	6.52 g/cm³
Outer radius	0.515 cm
Thickness	0.075 cm
Location in core	in the center of FA
Fuel rod	
Cladding:	
Material	Z110 - 1%Nb zirconium alloy
Density	6.52 g/cm³
Outer radius	0.455 cm
Inner radius	0.386 cm
Pellet:	
Material	UO_2
Percent of theoretical density x density	0.95x10.2 g/cm³
Outer Radius	0.3800±0.0025 cm
Average mass of pellet	13.17 g UO_2 (11.59 g metal)
Height	3cm
Number in fuel rod	82
Height of UO_2 (HFP)	246 cm
Initial He pressure, if any	~ 0.15 MPa
Mass of UO_2 per fuel rod in a fuel assembly	1080 g
Mass of UO_2 per fuel rod in a control assembly	1035 g

TABLE 2.1.1.1. (cont.)

Control Assembly	
Geometry:	
in radial plane (cross section of control absorber)	Fig. 2.1.1.5
in axial plane	Fig. 2.1.1.6
Absorber	boron steel
Density	7.51 g/cm³

Compositions of steel and boron steel

Material	Weight per cent					Nominal density
	Fe	Ni	Cr	Mn	B	g/cm³
Steel	70.5	10	18	1.5	-	7.86
Boron Steel	69.2	9.8	17.7	1.5	1.9	7.51

Compositions of zirconium alloy

Material	Weight per cent		
	Zr	Nb	Hf
Z110	98.97	1.0	0.03
Z125	97.47	2.5	0.03

Figure 9. VVER-440 Design parameters[9]

[9 IAEA (Nov, 1995). “In-core fuel management code package validation for WWERs”. IAEA-TECDOC-847

Future work (Doing)

- **3D Modeling**
  - We aim for the similar R/H of the active core and linear heat densities.
  - Rod number per bundle, rod diameter, rod pitch, and bundle pitch are same.
  - To achieve the similar R/H, the number of fuel bundle is determined while the same number of fuel rods per bundle.
  - Considering the similar R/H and linear heat density simultaneously, the active core height are decided.

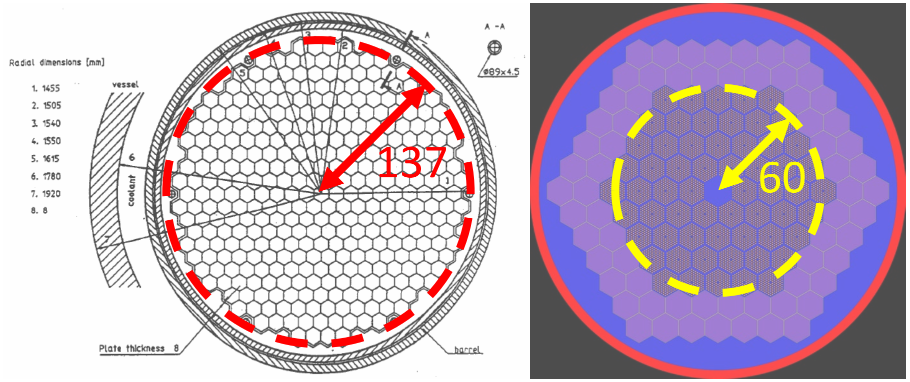


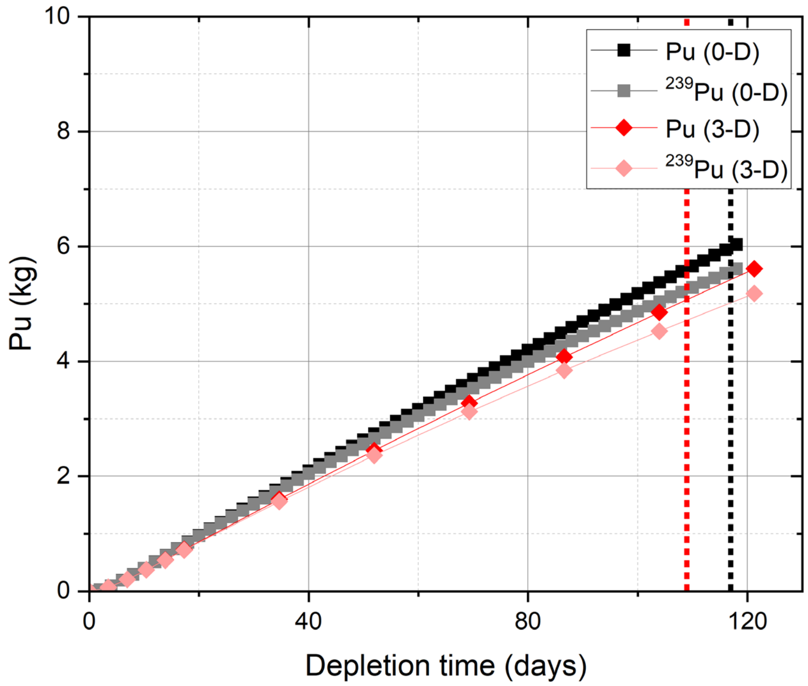
Figure 10. Core configurations of VVER-440[9] and ELWR
(Left: VVER-440 / Right: ELWR)

Table III: Design parameters of the VVER-440 and ELWR

	VVER-440	**ELWR**
Thermal power (MWt)	1375	100
Initial uranium mass (tons)	~ 37	3.93
Rod number per bundle	126	126
Number of fuel bundles	312	60
Active core radius (cm)	137	60
Active core height (cm)	246	110
Radius/Height of core	0.555	0.548
Linear heat density (W/cm)	142	120

Future work (Doing)

- **0-D vs 3-D calculations**
  - Due to the more computational cost of the 3-D calculation compared to 0-D depletion calculation, the 3-D calculation was performed with a longer depletion time step.
  - The 3-D calculations result in a smaller amount of plutonium (Pu) production, with approximately a 15.3% difference compared to the 0-D calculations.



Pu quality = 93 wt%	0-D ORIGEN	3-D Serpent
Depletion time (days)	117	109
Pu production (kg)	6.006	5.086
Number of nuclear weapon potentials (number/year)	2.95 ~ 4.49	2.68 ~ 4.08

Figure 11. Comarison of plutonium production over depletion time by calculation types

Thank you for listening