Status on North Korea's Fissile Material Production

Sulgiye Park

Union of Concerned Scientists

North Korea's Nuclear Activities

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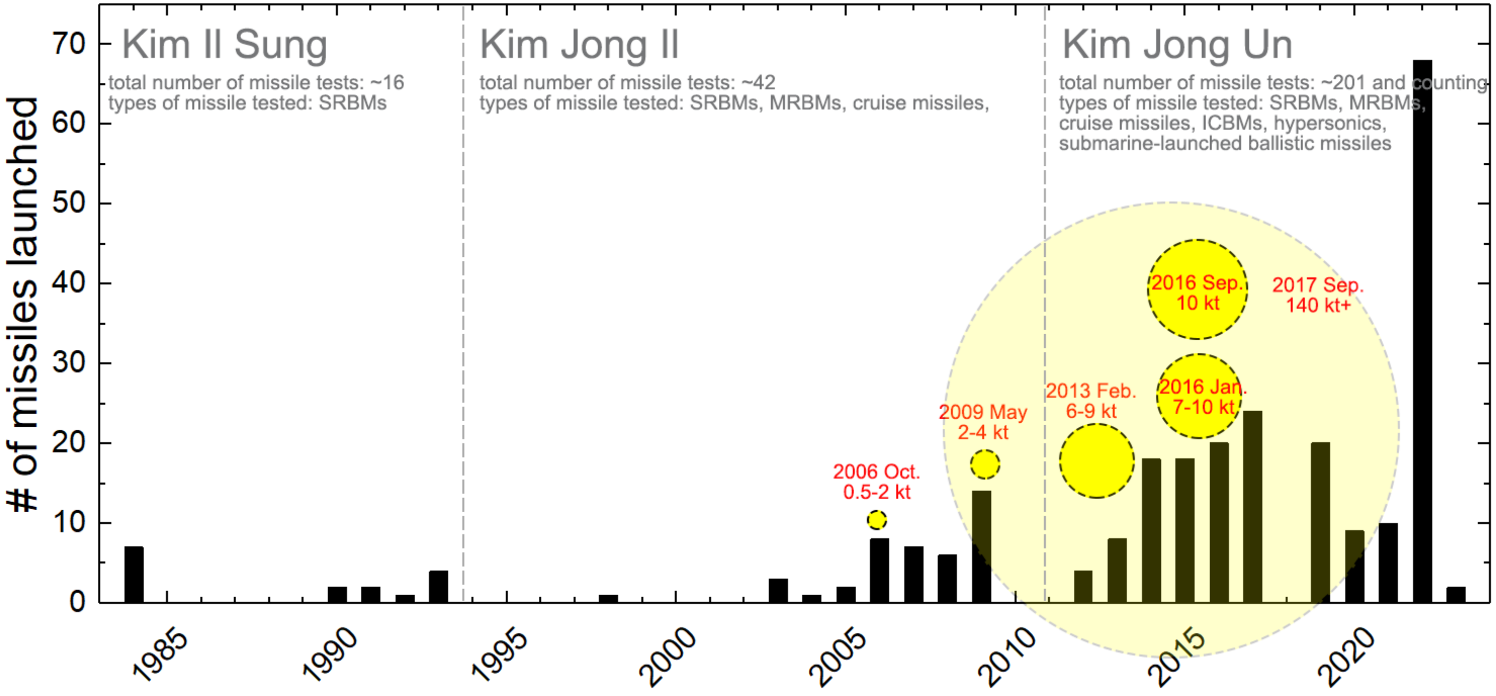

1) How many **nuclear arsenals** does it have? And how many more can it make?
2) How much **fissile materials** (U and Pu) does it have (stockpiled and capacity)?

Fissile Materials and Nuclear Weapons

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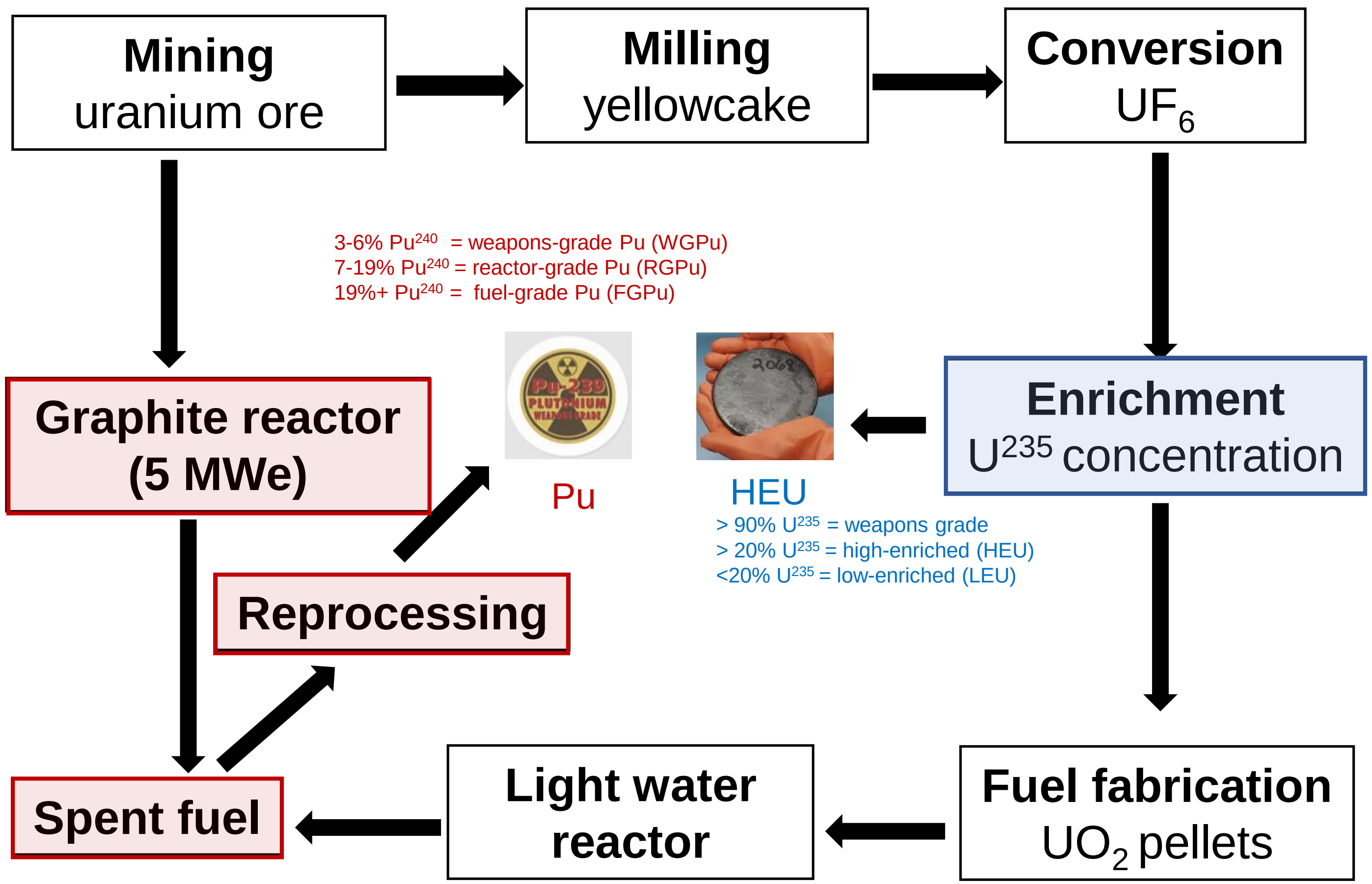
North Korea's nuclear warhead estimates

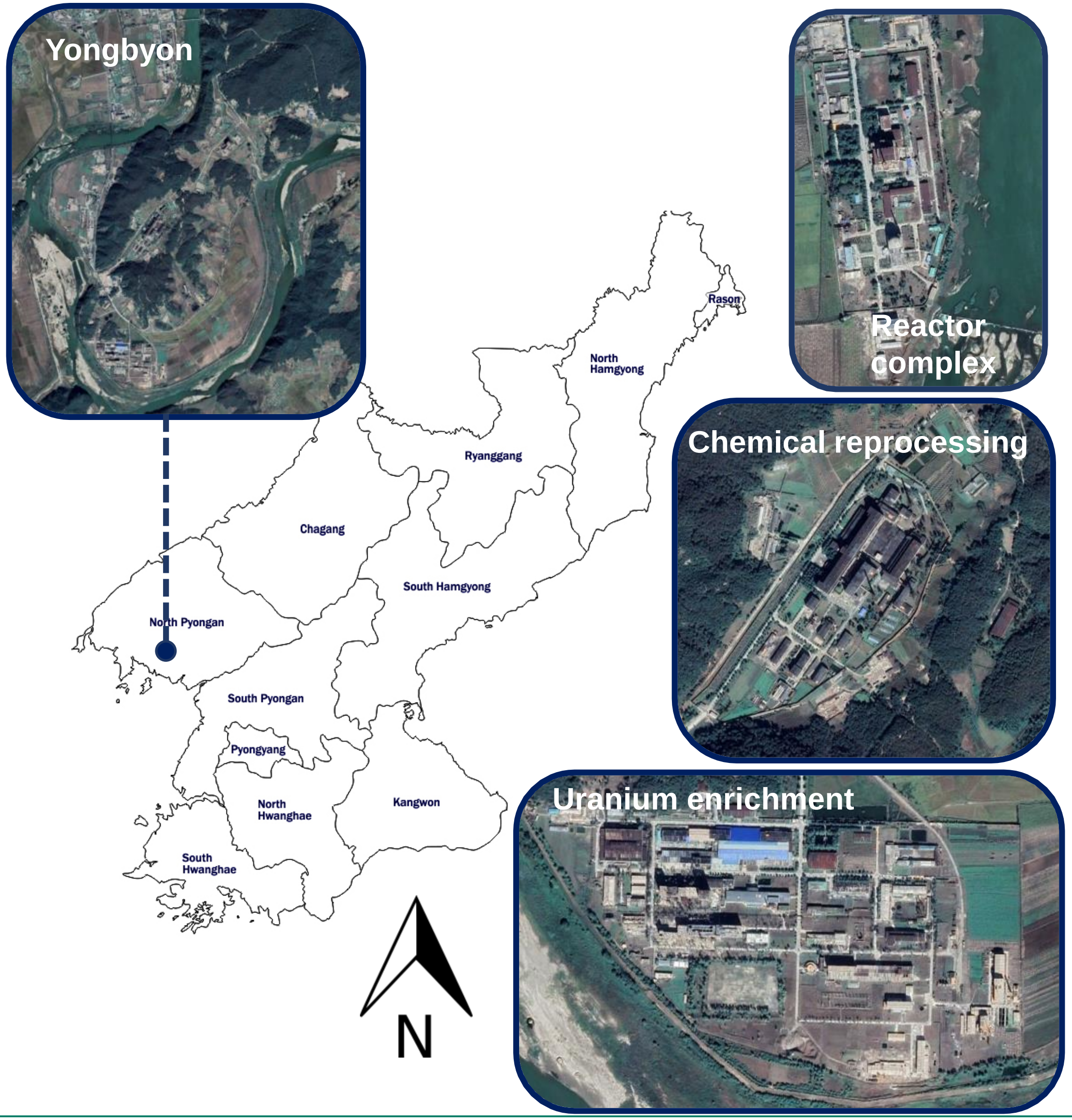
Lit. Review	warheads
D. Kimball (2022)	40-50
D. Albright (2023)	35-63 (46)
U.S. DIA (2020)	20-60
H. Kristensen & M. Korda (2022)	45-55
Fedchenko and Kelley (2020)	10-20 (thermonuclear bomb)
Hecker (2020, 2021, 2023)	20-60, average 45 (2021) & 65 (by 2024)
ICAN (2023)	40-50
Y.H. Park & S.K. Lee (2023)	80-90 (2023) & 166 (2030)
Stockholm International Research Institute (2023)	Enough to build 50-70 (likely assembled ~30)
H.J. Kim (2018)	20-60
B.M. Kim (2021)	10-60

"South Korea has become our undoubted enemy"
"**Exponential increase** in country's nuclear arsenal in 2023"
"…180 total nuclear weapons"

Small nuclear warheads that can be fitted on to short-range missiles

North Korea’s Fissile Materials Pathway





5 MWe Nuclear Reactor and Pu

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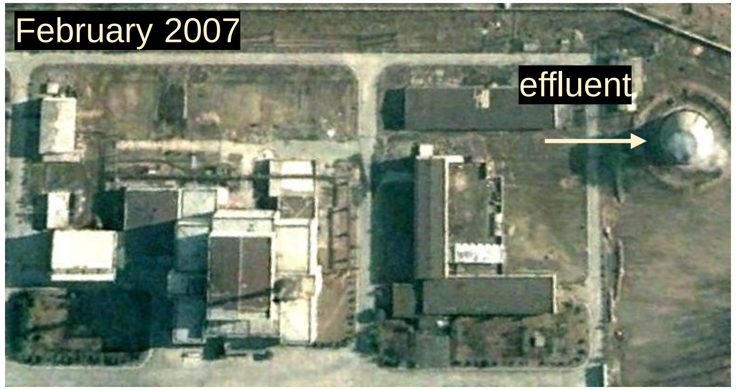
Cooling tower blew off
2008

1980	**1986**	**1989**	**1991**	**1994**	**2003-5**	**2006-7**	**2013-16**	**2016-18**	**2021-3**
Started construction	operational		operational		operational	operational	operational	operational	operational



Pu stockpile estimates

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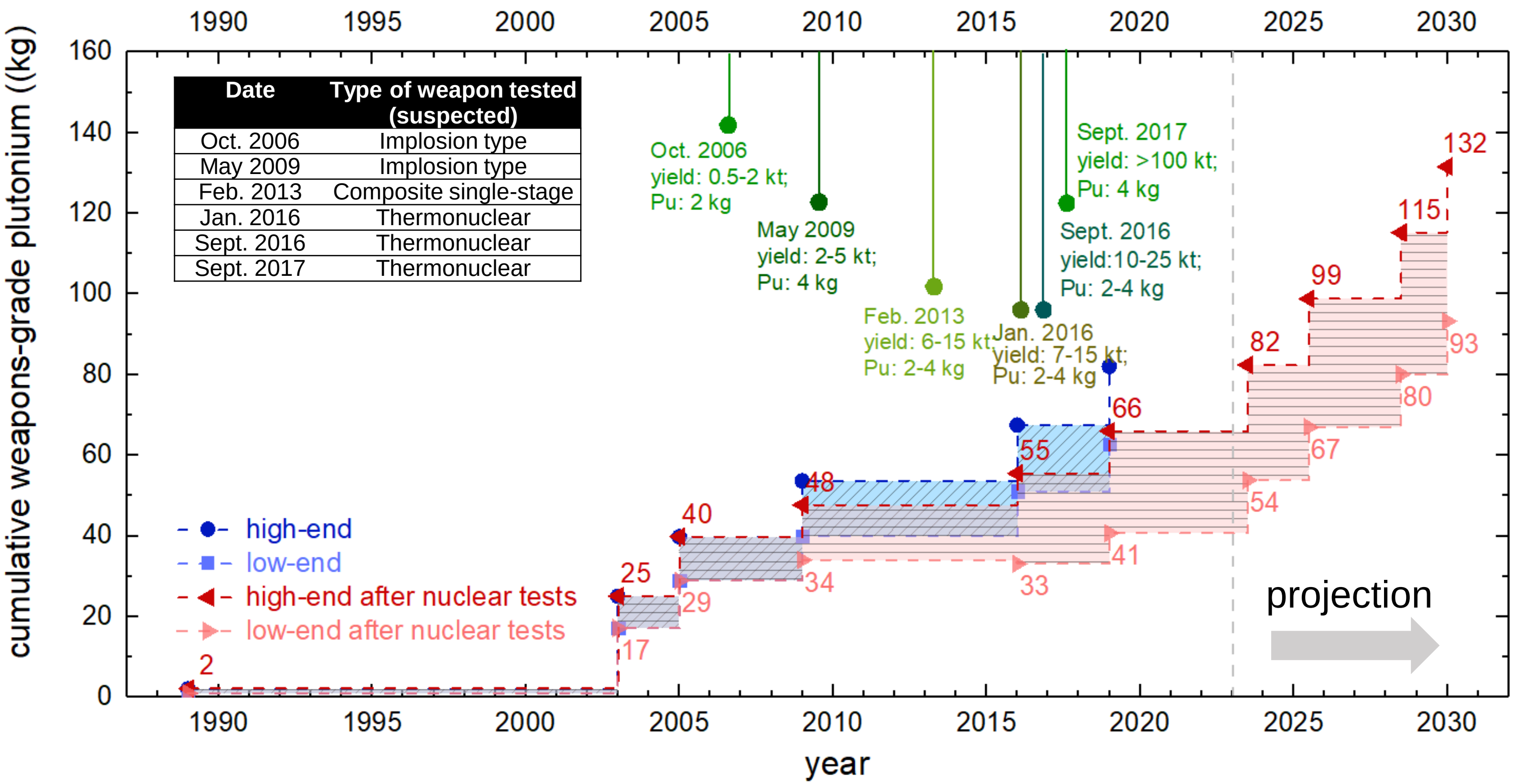
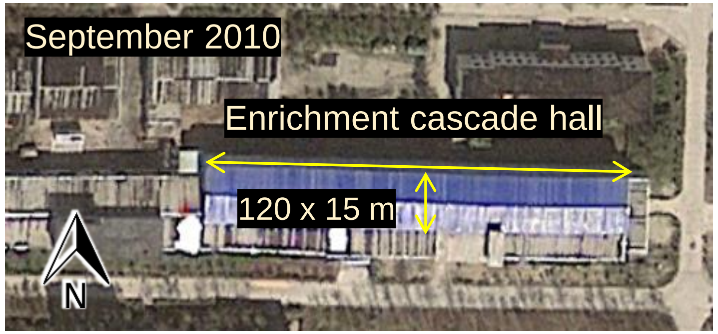


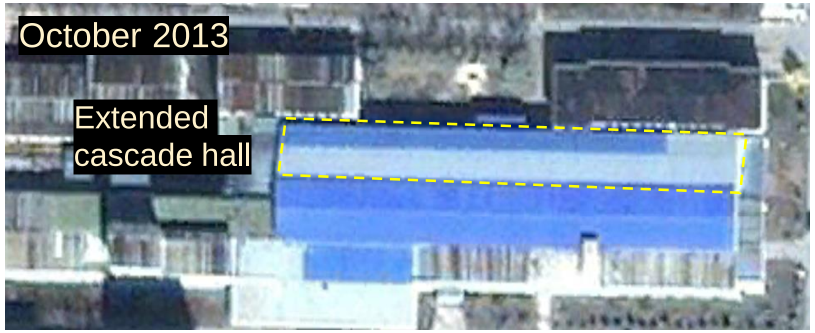
	Total produced	Pu used	balance	**Fission weapons:** 4-6 kg/weapon **Pu pits (small – large)**
< Oct. 2023	63-82 kg	19 (±3) kg	44-63 (±3) kg	9-12 (±2)
< 2030	102-131 kg	19 (±3) kg	83-112 (±3) kg	17-22 (±2)

Enrichment Program and HEU

Union of Concerned Scientists

Centrifuges	**2,000 – 14,500**
Enrichment capacity	8,000 – 58,000 kg SWU/yr
Type	P-2* type 250 grade maraging steel
Enrichment rate/centrifuge	4 kg SWU/year



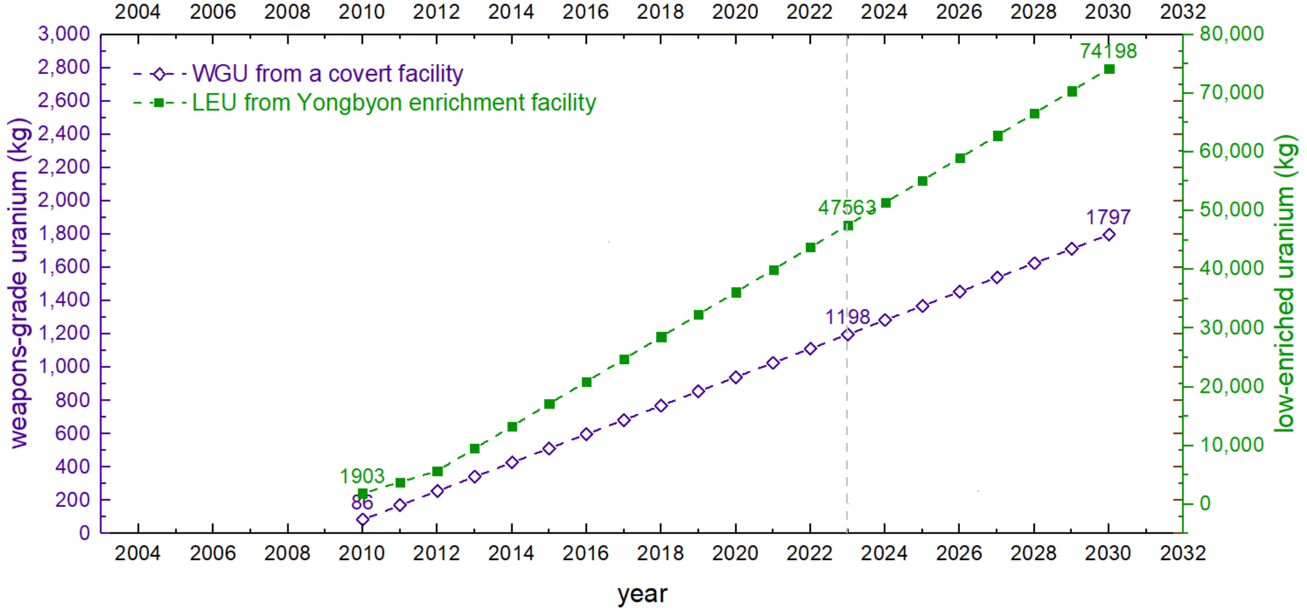


2005 — Pilot plant, 660 centrifuges

2010 — First known to the outside world, ~2000 centrifuges

Clandestine? (~4000 centrifuges)

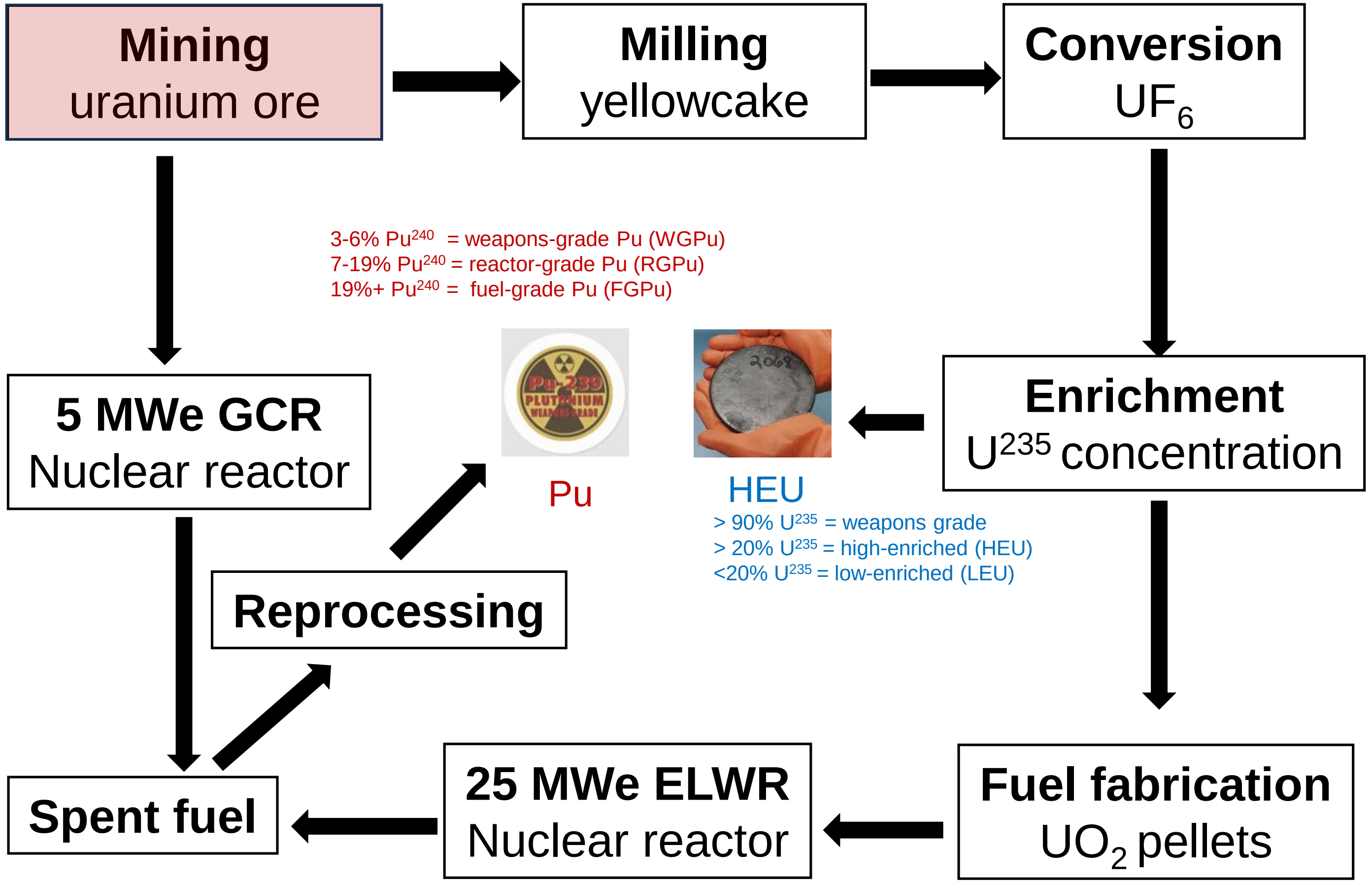
2013 — expansion, ~2000 centrifuges

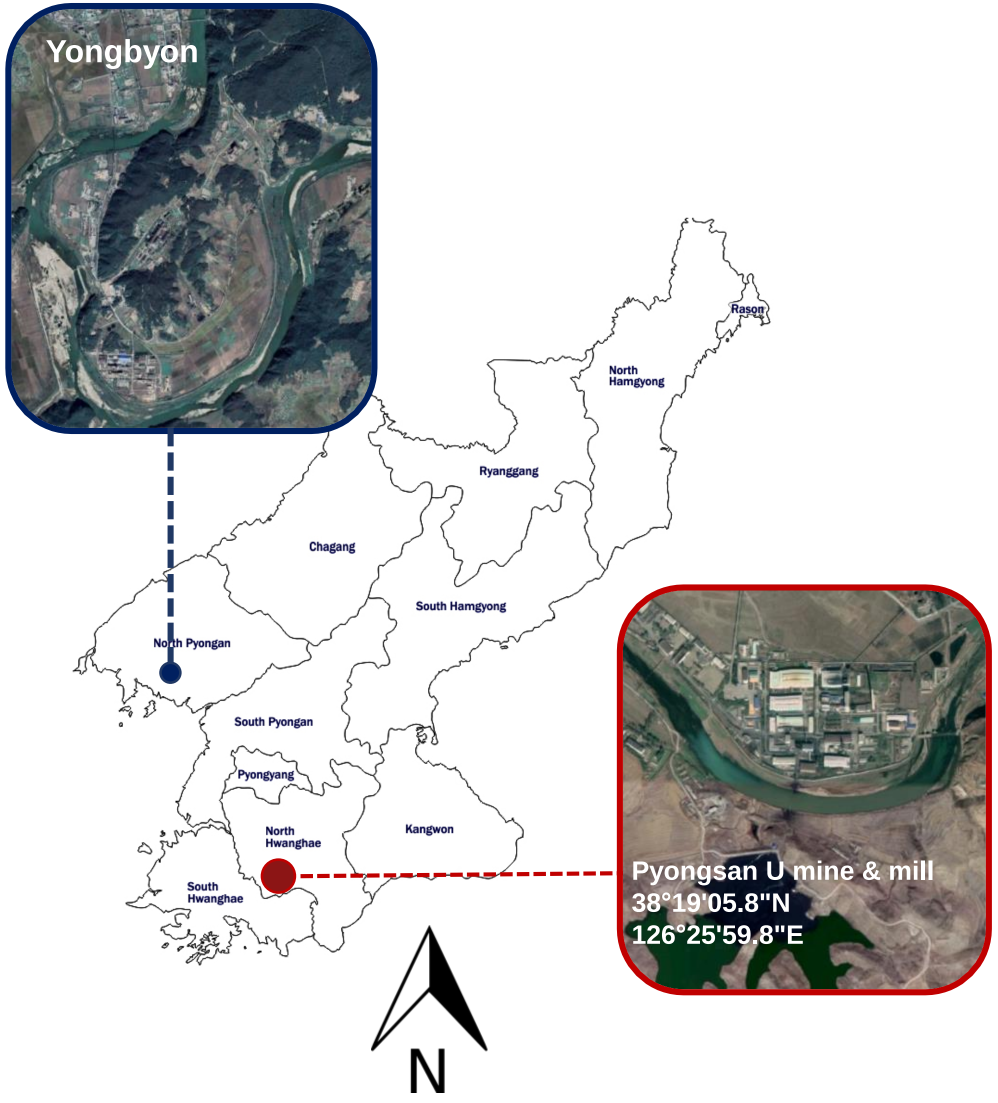


- 50 kg used from tests
- First generation: 20 kg/weapon

Year	HEU	LEU (3.5 wt.%)
2023	**1,200 kg** 1st generation bomb: 60	47 MT
2030	**1,800 kg** 1st generation bomb: 90	74 MT

Front-end of North Korea's Nuclear Program





Front-end of North Korea's Nuclear Program

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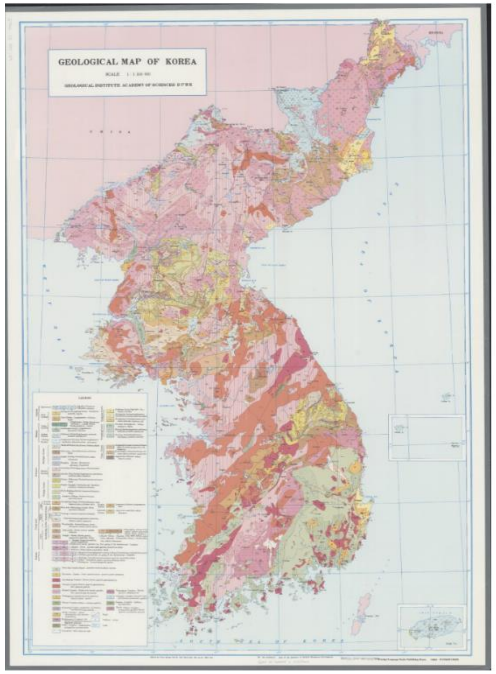
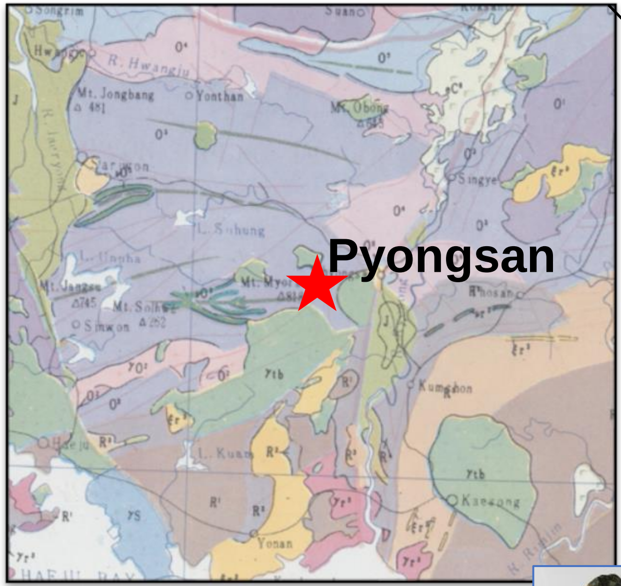
- **Geology plays a significant role in the uranium production pathway**
  - Exploration and exploitation
  - Design of mines, mining techniques
  - Commissioning, operating, decommissioning

Evidence-based analysis of what could be on the ground

- geological maps of North Korea explanatory texts
  - multiple institutions
  - 1940s – 2022
- geochemical literature, peer-reviewed field geology reports (1950s-2021)
- primary documents
- field collection/analysis of analogous rock samples

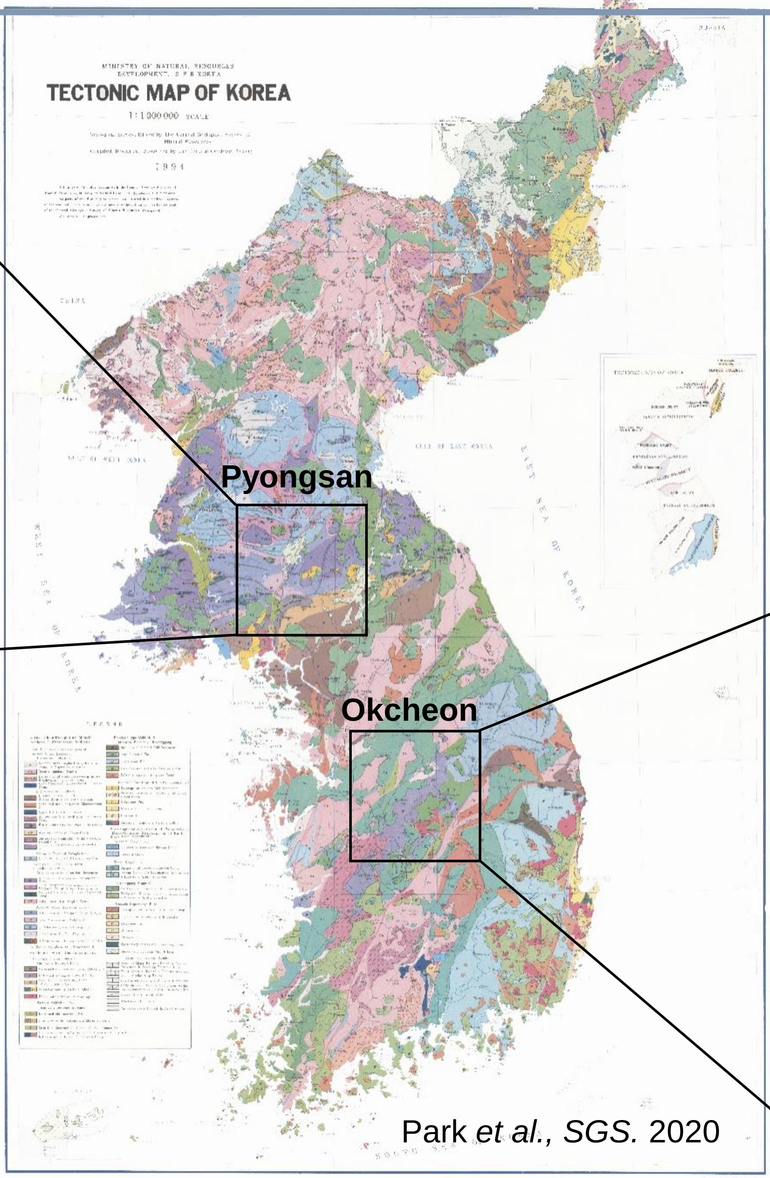


Geological Analysis of North Korea’s U Deposit



Pyongsan mine

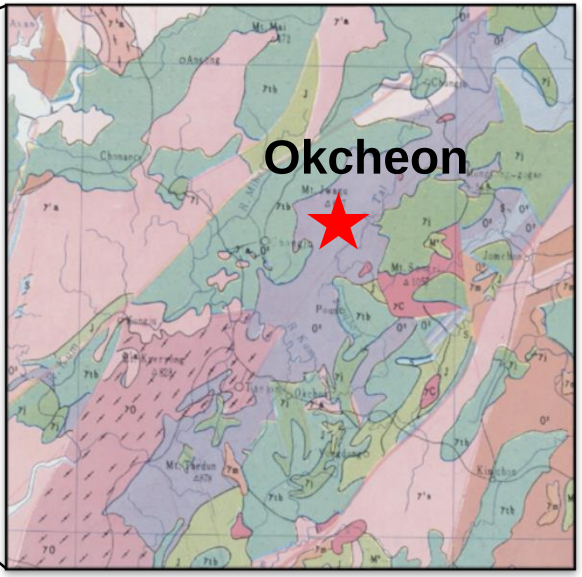
- Meta-sedimentary rocks
- MesoProterozoic eon
- Common minerals: coffinite, uraninite
- Sulfide minerals
- Trace elements
- Ore quality and quantity?



Park *et al.*, *SGS.* 2020

Okcheon metamorphic belt (OMB)

- Metamorphosed sedimentary rocks
- Late Proterozoic – Proterozoic age
- Common uranium minerals
- Sulfide minerals
- Trace elements
- Low grade: 0.026-0.036% U
- Volume: ~15,000 tons
- Metalliferous black shale



Geochemical Analysis and Ore Quality

Union of Concerned Scientists

- Comparable geological settings, host rock age, mineralogical details with OMB
- Deposit type: **metamorphosed organic shale**
- Average grade: **0.01-0.03 wt.% U** (*vs*. ~1.00 wt.% U)
  - Soviet geologists: 21.8 – 323.9 ppm (~0.002-0.03% U) for carbon shales
  - Sweden peltura zone: 0.02% U on average
  - Black shale deposits in China: 0.06% U maximum

Gapsin & Sozinov 1991: North Korean Shale

원소	I(6)	II(2)	III(4)	IV(6)	V(7)	VI(2)
Li	33±13	228	119±26	41±40	42±13	22
Na	0,12±0,07	0,05	0.06±0,06	0,02±0,01	0,03±0,02	0,03
K	1,98±0,59	0,16	4.60±1,49	0,88±0,63	2,39±0,71	1,00
Rb	123±39	4	188±90	33±13	123±36	61
Cs	15±5	1,1	18.4±15,7	3,4±2.2	15±3	6,3
Be	2.5±0,6	1,9	6.2±3,7	1.8±1,1	6,3±1,5	1.9
Ca	0,73±1.63	2,20	0.65±1.16	0.54±0,49	0,62±0,51	0,13
Mg	1,09±0.73	5,66	1.16±0.41	0.70±0.90	0,54±0,16	0,32
Sr	22±29	90	101±167	61±34	63±36	16
Ba	595±133	1130	892±237	335±109	914±255	525
Al	6,91±1,22	6,88	7.57±3,13	1,58±1.10	4,55±1,36	1.73
Sc	16.2±4.4	14	20±11	4±2	11±4	5.5
La	38±13	121	36±18	19±11	40±10	15
Ce	62±17	188	72±49	36±20	59±11	17
Nd	30±9	83	32±21	19±11	36±10	12.8
Sm	6.9±2,0	11,2	5.8±4,0	2.6±1,2	5,5±1,8	1,32
Eu	1,42±0.37	2,55	1.40±1.37	0.67±0,30	1,37±0,69	0.45
Gd	6.6±3,0	12,0	7.2±10,6	3.9±1,9	6,2±2,7	1,7
Tb	1,00±0,38	1,50	0.81±0.82	0.41±0,21	0,82±0,36	0,20
Yb	3,37±1,27	3,89	2.77±2.18	1.29±0,75	3,08±1,05	1,11
Lu	0,55±0.21	0.16	0.28±0.15	0.09±0.06	0.43±0.13	0.15
U	21.8±6.9	323.9	111±197	87±59	116±53	21.8
Th	12,9±3,9	12.3	12.6±6,2	3.3±2,0	7,6±1,9	3.2
Si	19,52±3,44	19.10	30.2±5.50	41.51±3,24	18,27±2,02	12,34
Ti	0,36±0.10	0,37	0.38±0,24	0.10±0,06	0.26±0,09	0.13

Schovsbo, *GFF*, 2002: Sweden Peltura Zone

Table 1. Summary of uranium and TOC variation.

Area [1]	TOC (wt.%)	± [2] (wt.%)	n	U (ppm)	± [2] (ppm)
		Agnostus pisiformis Zone			
Rügen G14	4.7	4.0	3	27	n.d.
Bornholm	7.18	1.16	5	38	90
Scania	8.5	0.8	15	31	4
S. Öland	8.9	1.5	5	40	5
N. Öland	8.6	0.6	3	28	46
Gotland	11.2	n.d.	1	35	n.d.
Billingen	9.1	0.7	10	56	30
Östergötland	10.4	26.5	2	55	84
Kinnekulle	10.9	0.3	6	37	9
		Peltura zones[5] (*P. scarabaeoides* Zone)			
	TOC (wt.%)	± [2] (wt.%)	n	U (ppm)	± [2] (ppm)
Rügen G14	not cored			not cored	
Bornholm	11.1(11.7)	1.3(n.d.)	9(1)	113(100)	30(n.d.)
Scania	11.5(11.6)	0.5(0.6)	87(56)	99(97)	13(14)
S. Öland	14.5(15.3)	6.3(26.4)	3(2)	180(197)	86(205)
N. Öland	-			-	
Gotland	-			-	
Billingen	14.4(14.7)	0.6(0.6)	76(69)	315(309)	56(56)
Östergötland	14.8[6]	2.5	4	138[6]	137
Kinnekulle	17.6(15.2)	2.1(3.2)	20(7)	168(176)	67(63)
Närke	15.6(14.4)	1.5(4.2)	13(5)	192(211)	48(148)
Finngrundet	-			-	

Schovsbo, *GFF*, 2002: China Niutintang Deposit

Table 2

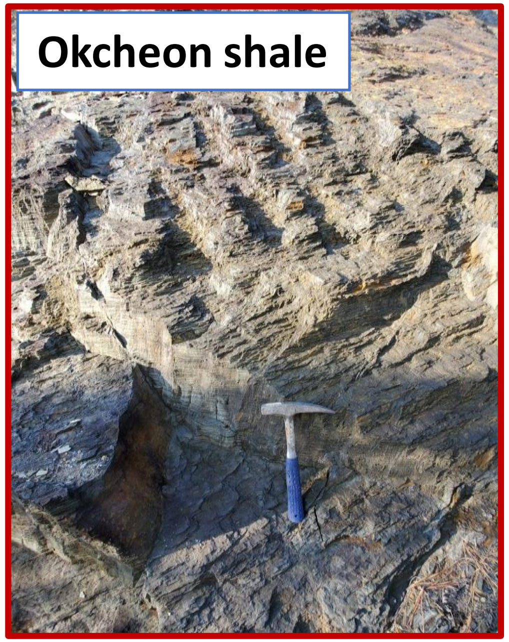
Mo isotope, iron speciation, sulfur isotope and geochemical data of the Dingtai profi: Dazhuliushui, Maluhe, and

Sample	Depth (m)[a]	Lithology	V ppm	Cr ppm	Co ppm	Ni ppm	Cu ppm	Mo ppm	Pb ppm	U ppm
Dingtai profile										
Interval 3										
PM-27	32.3	Black shale	265	108	7.10	42.5	74.6	15.1	17.7	12.3
PM-24	29.3	Black shale	1010	122	8.39	92.9	59.5	24.4	8.75	11.0
PM-23	28.3	Black shale	385	112	7.34	60.7	35.6	27.6	22.7	17.0
PM-22	27.3	Black shale	248	104	11.5	74.5	37.8	26.1	25.2	13.2
PM-21	26.3	Black shale	1430	119	9.98	81.4	30.4	19.0	16.9	17.3
PM-20	25.3	Black shale	314	108	7.40	49.7	36.3	27.7	22.9	13.0
PM-19	23.8	Black shale	899	106	8.01	75.0	51.9	38.4	19.0	17.4
PM-18	22.3	Black shale	926	102	12.4	106	42.3	73.0	17.3	19.3
PM-17	20.8	Black shale	1060	119	36.2	202	74.8	24.8	19.2	17.9
PM-16	19.3	Black shale	2110	141	12.4	135	32.1	56.9	8.40	18.3
PM-15	17.8	Black shale	1410	116	8.36	104	37.3	49.9	11.4	18.8
PM-14	16.3	Black shale	756	105	11.0	88.6	112	26.5	18.9	15.7
PM-13	14.8	Black shale	1510	145	19.0	203	30.3	70.8	10.0	16.6
PM-12	13.3	Black shale	1240	122	3.11	36.5	16.8	13.9	12.5	9.35
PM-11	11.8	Black shale	960	111	3.44	65.8	16.9	86.4	20.2	17.2
Interval 2										
PM-10	10.3	Black shale	1070	103	1.09	52.5	18.2	110	13.4	18.0
PM-9	8.8	Black shale	1750	110	4.29	215	24.9	394	13.1	23.3
PM-8	7.3	Black shale	1070	69.9	1.50	40.1	13.4	67.2	15.4	19.1
PM-7	5.8	Black shale	1160	96.3	3.24	120	21.6	374	20.2	26.9
PM-6	4.3	Black shale	4090	159	5.59	133	19.2	188	45.5	28.0
PM-5	2.8	Black shale	4400	1180	2.12	147	30.1	38.0	15.7	21.0
PM-4	1.3	Black shale	4270	2450	2.31	154	29.8	140	11.3	23.0
Interval 1										
Maluhe deposit										
MLH-4	0.7	Black shale	310	116	32.1	301	69.0	142	47.2	54.9
MLH-5	0.5	Sulfide ore	423	53.0	255	36,300	1970	70,900	156	112
MLH-2	0.5	Sulfide ore	480	64.0	254	37,700	1880	61,600	235	118
MLH-6	0.3	Phophorite	417	26.0	4.56	356	44.1	117	3.09	517
Dazhuliushui deposit										
DZLS-7	0.7	Black shale	409	93.0	22.5	332	71.4	65.2	15.3	30.6
DZLS-8	0.5	Sulfide ore	644	55.0	220	60,100	2740	62,800	117	114
DZLS-2	0.5	Sulfide ore	658	53.0	273	62,700	2450	73,100	183	125
DZLS-9	0.3	Black shale	320	85.1	18.5	249	52.8	90.6	15.4	24.5
Sancha deposit										
SC-11	0.5	Sulfide ore	37.80	149	111	29,900	1180	65,900	37.0	595
SC-2	0.5	Sulfide ore	1680	68.0	172	61,500	2080	56,400	180	408

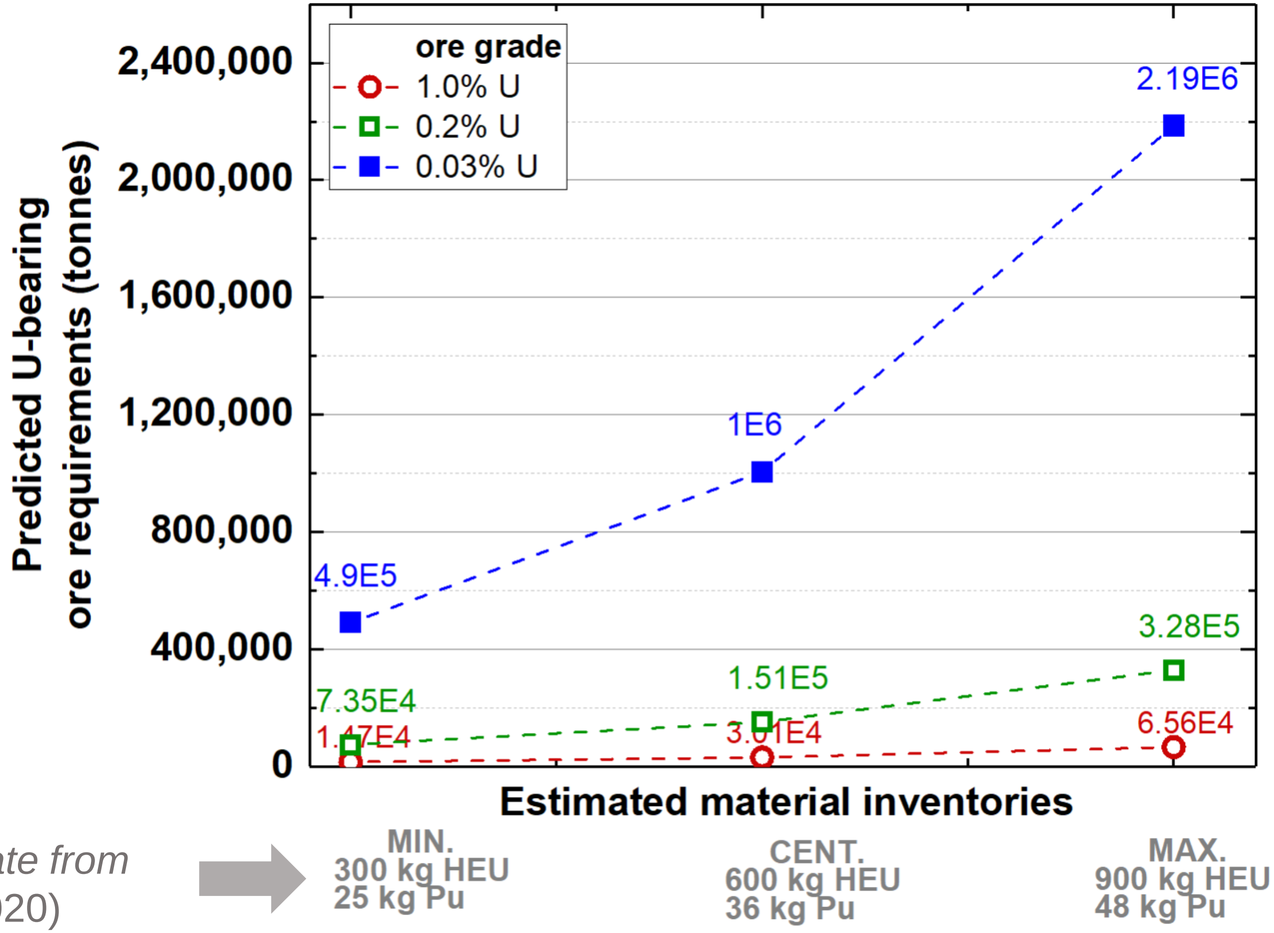
Geochemical Analysis and Ore Quality

- Comparable geological settings, host rock age, mineralogical details with Okcheon black shale
- Hypothesized deposit type: **metamorphosed organic shale**
- Average grade: **0.01-0.03 wt.% U** (*vs*. ~1.00 wt.% U)
  - *Sozinov et al*.: 21.8 – 323.9 ppm (~0.002-0.03% U) for carbon shales
  - Black shale deposits in China: 0.06% U maximum
  - Sweden peltura zone: 0.02% U on average

Park *et al*., *SGS*. 2020



Implications of Low Ore Quality



Pu, HEU estimate from S.S. Hecker (2020)

Park *et al., SGS.* 2020

- Estimates of current weapons-grade material inventory depends on accurate ore grade.

Looking Beyond Pyongsan

Name	Predicted deposit type	Predicted ore grade (%U metal)
Cholsan	Monazite from pegmatite deposit or granite related	*Av*. ~0.001%, with an upper bound of ~0.05%.
Hamhung	Possibly granite-related or metasomatite	*Av*.~0.001%, with an upper bound of ~0.05%.
Hyesan	Metamorphosed organic shale or anthracite coal mines	*Av*.~0.03%, with an upper bound of ~0.2%.
Kumchon	Metamorphosed organic shale	*Av*.~0.03%, with an upper bound of ~0.2%.
Kusong	Monazite from pegmatite deposit or granite related	*Av*.0.001%, with an upper bound of ~0.05%.
Pyongsan	Metamorphosed organic shale	*Av*.~0.03%, with an upper bound of ~0.2%.
Rajin	Granite related	*Av*.~0.001%, with an upper bound of ~0.05%.
Sinpo	Metamorphic terrane	*Av*.~0.005%, with an upper bound of ~0.01%.
Sunchŏn (Wolbisan)	Limestone	*Av*.~0.04%, with an upper bound of ~0.2%.
Wiwon	Limestone	*Av*.~0.04%, with an upper bound of ~0.2%.

Further studies are needed to verify other sources for uranium production.

Conclusions

Union of Concerned Scientists

- North Korea's nuclear program remains active, and it continues to expand its nuclear arsenal both quantitatively and qualitatively
- **To exponentially increase nuclear arsenals → drastically increase fissile materials output**
- **Indigenous uranium ore** is the first rate-limiting step in the fissile material production pathway
  - Pyongsan uranium ore grade is lower than previously reported
    - challenging for electricity generation, but not an impediment for arsenal purpose
    - quantity of ore?
- There remain **large** uncertainties in predicting North Korea's fissile material stocks and production capacity

→ Negotiations process and non-proliferation commitment
→ Decommissioning of once-operated reactor

How do we restart diplomacy with North Korea?

History of North Korea’s Nuclear Program

Union of Concerned Scientists

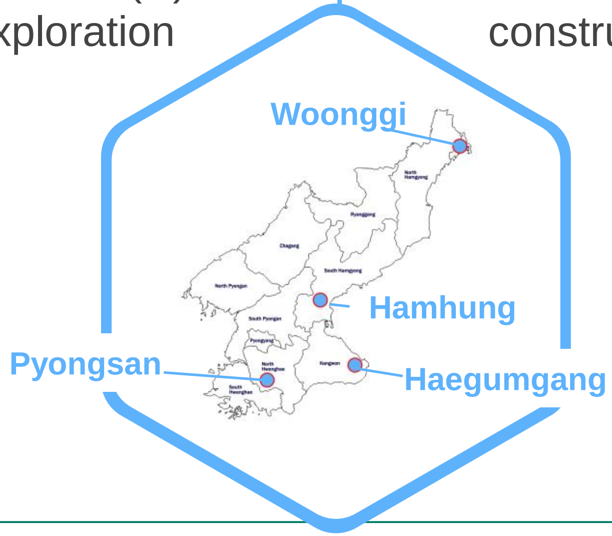
1940s

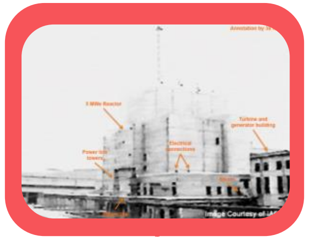
Uranium (U) exploration

1959

Nuclear Cooperation Agreement

U exploration expedited





1980

5MWe reactor construction

1985

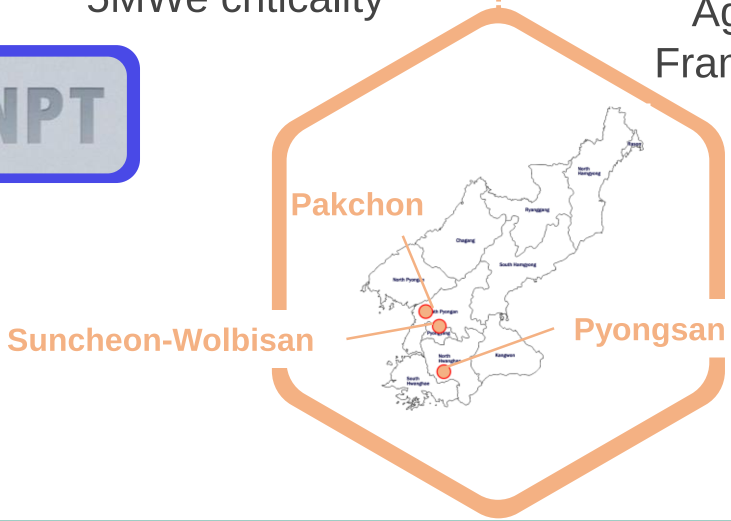
NPT

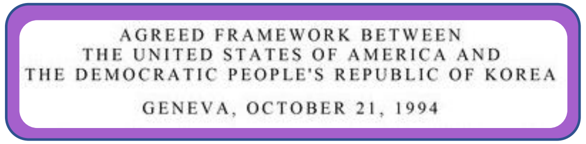
1986

5MWe criticality

1992

IAEA inspection
NK declares
2 mines, 2 mills





AGREED FRAMEWORK BETWEEN
THE UNITED STATES OF AMERICA AND
THE DEMOCRATIC PEOPLE'S REPUBLIC OF KOREA

GENEVA, OCTOBER 21, 1994

1994

U.S. – DPRK Agreed Framework

2002

NPT withdrawal

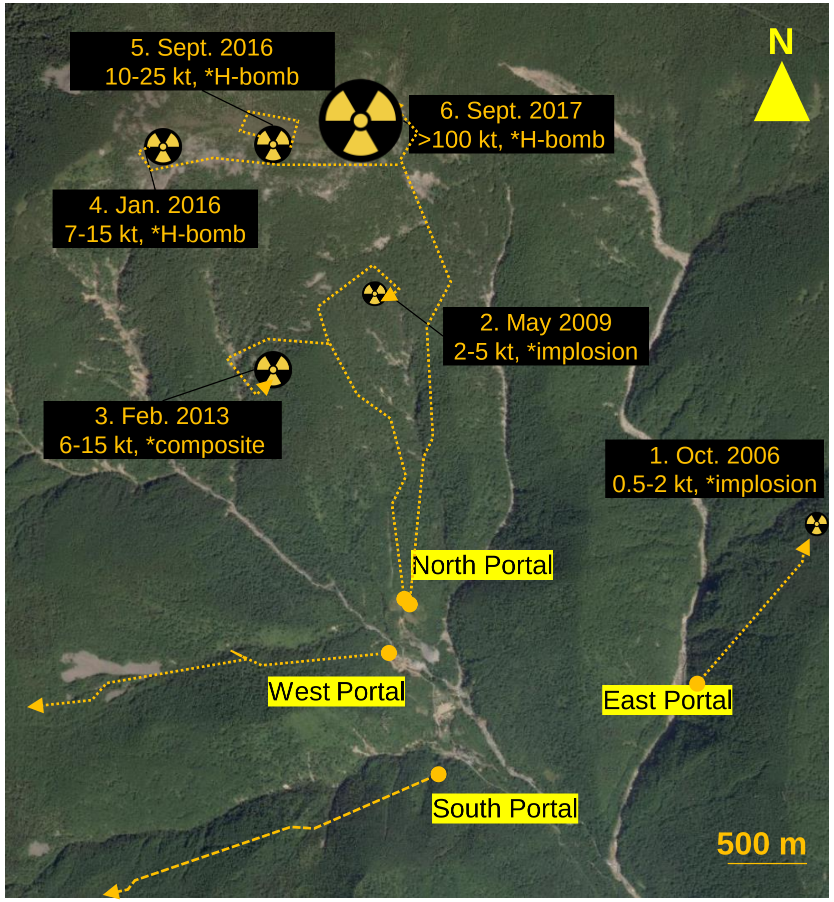
2003-today

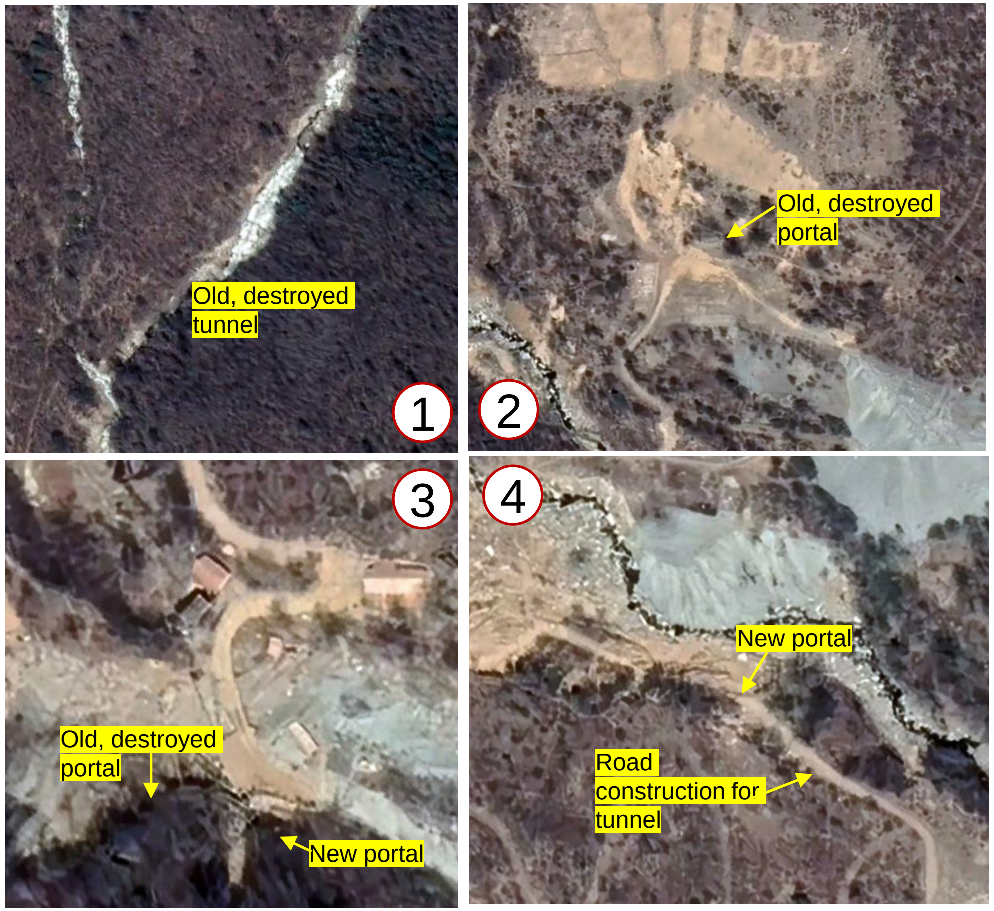
shutdown,
suspension
nuclear tests
Operation resumes

Activities at Punggye-ri

Union of Concerned Scientists

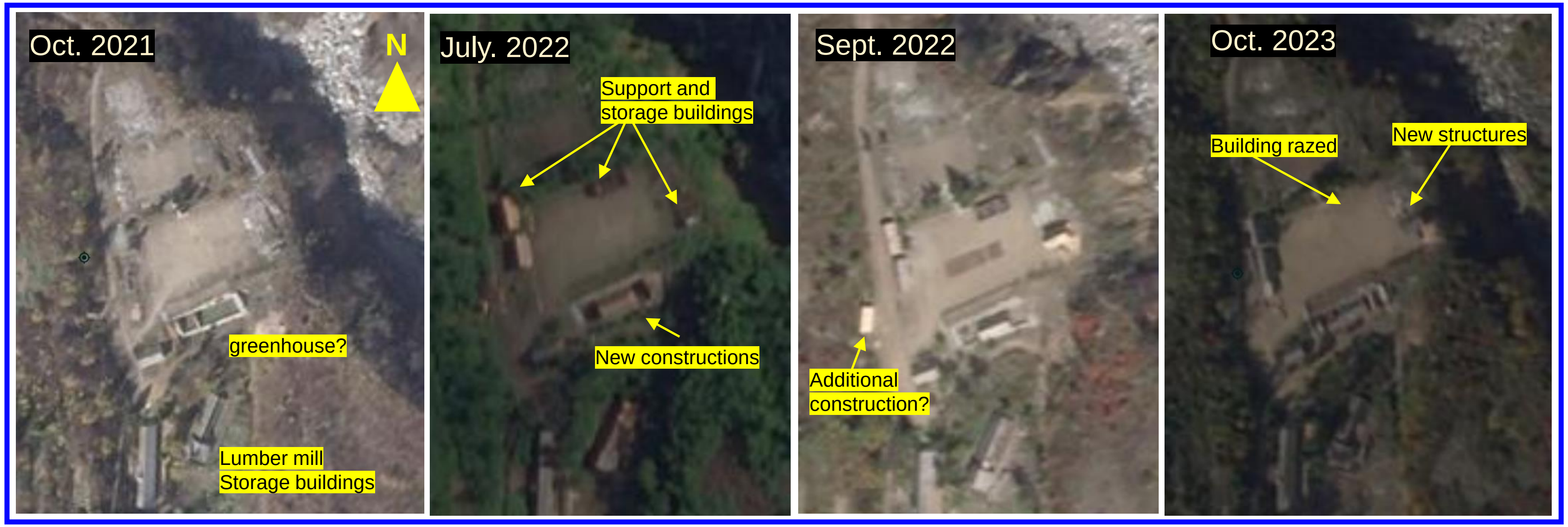
- Early 2022 → refurbishment work and preparations at tunnels → potential for future testing?





Activities at Punggye-ri

Union of Concerned Scientists



5 MWe Nuclear Reactor and Pu

Union of Concerned Scientists

Reactor type	Pressurized water reactor
Thermal power	20 MWth
Fuel type	U metal
Fuel load size	50 tons U
Average burnup	~300-800 MWth-d/ton
Spent fuel	8000 fuel rods
Electricity	2.18 MWe
Operation cycle	2-3 years
Spent fuel pond	25 feet deep
Spent fuel rest period	3 months before transported to the RCL
80 fuel	60 grams Pu

$$XPu\left(\frac{kg}{yr}\right) = CPth\ (MW)\beta\left(\frac{kg}{MWd}\right)365\left(\frac{d}{yr}\right)$$

C = capacity factor (0.4-1) *f*(refueling period)
$\mathbf{P}_{th}$ = thermal power
β = Pu/MWd → *f*(burnup)
3-6% Pu^{240}: 8.5-9.0 x 10^{-4} kg/MWd
1 gram/MWd

Sources of uncertainty: reactor power, operation days, capacity factor, and the fact that they can be modified.