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ARTICLE

Assessing Uranium Ore Processing Activities Using Satellite Imagery at Pyongsan in the Democratic People's Republic of Korea

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ABSTRACT
The Democratic People's Republic of Korea (DPRK)'s only confirmed uranium mill is within the Pyongsan uranium mining complex. The ore processing pathway and the production capacity for uranium concentrate is analyzed, based on comprehensive satellite imagery analysis of this facility. This assessment of the Pyongsan facility indicates an ore processing capacity of ∼750–1,200 tonnes per day. One year of maximum production at Pyongsan would yield enough processed ore to fuel one load of the 5 MWe reactor in Yongbyon as well as ∼3,000 kg of LEU or ∼100 kg of HEU. The analysis suggests that the ore processing capacity at Pyongsan is not a constraint on the DPRK's nuclear material production and that the available capacity at the Pyongsan milling facility strongly suggests that the DPRK has no need in another uranium milling facility of a comparable size. This report provides an improved understanding of the ore processing steps and production rates of the only confirmed uranium mill in the DPRK, enabling a more quantitative assessment of its nuclear materials production and inventories.

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Introduction

Given the DPRK's active nuclear program, it is of utmost importance to assess and understand its nuclear materials production capabilities. These capabilities govern the rate at which the DPRK might expand its nuclear arsenal, determine the magnitude of the threat to international security and the challenge of potential DPRK nuclear disarmament, and measure the DPRK's ability to provide fuels for its future nuclear energy program. The current and projected capacity for nuclear energy and weapons production in the DPRK depends primarily on the current and projected stocks of nuclear materials it possesses and can produce in the future.[1] The supply

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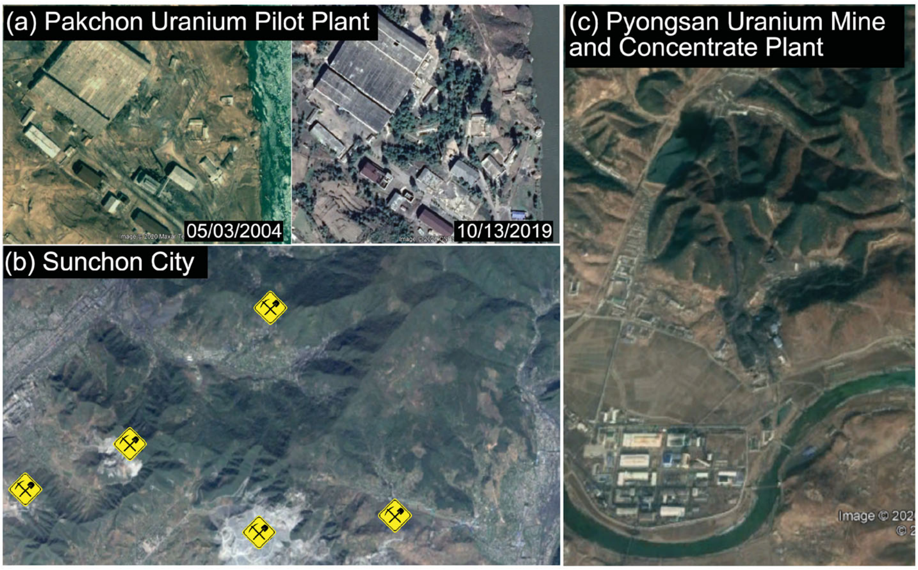

Figure 1. (a) Satellite images over Pakchon Uranium Pilot Plant. The plant was decommissioned in the 1990s and there is no obvious sign of nuclear activities since then. Location: 39°42′35.84″N 125°34′9.04″E. (b) Satellite image over Sunchon City with active mines, although whether these are uranium mines remains inconclusive. (c) Satellite image over the active and confirmed Pyongsan uranium mine and ore processing plant. Location, 38°18′57.1″N 126°25′49.2″E. *Source*: Google Earth.

of nuclear materials, in turn, depends on the mining and processing of domestic reserves of uranium.[2]

In May 1992, the DPRK declared two uranium mines to the International Atomic Energy Agency (IAEA): the Suncheon-Wolbisan Uranium Mine and the Pyongsan Uranium Mine. It also declared two uranium processing plants, in which uranium ore is processed through milling: the Pakchon Uranium Concentrate Pilot Plant and the Pyongsan Uranium Concentrate Plant (the latter also known as the January Industrial Mine).[3] There is remarkably little open-source information available on the Sunchon-Wolbisan mine, with no account of visits or specific coordinates of the location. While satellite images over Sunchon city reveal a few active mines (Figure 1b), it remains unclear whether these are uranium mines.[4] Among the two ore processing facilities, the Pakchon Uranium Concentrate Pilot Plant remains inactive, evidenced by satellite observations (Figure 1a). This leaves the Pyongsan mine and mill as the only declared and confirmed site for the first two steps of production of uranium (Figure 1c). Uranium can be further enriched to produce natural uranium fuel for a plutonium production reactor, or to low-enriched uranium (LEU: <20% uranium-235) for fueling light water reactors for commercial nuclear energy, or to high-enriched uranium (HEU: >20% uranium-235) that can be used in weapons.

With no reported accounts of outside inspector site access after the 1992 IAEA visits, the details of the Pyongsan uranium mine and mill remain highly uncertain. Based on one estimate, the facility may have produced roughly 300 tonnes of yellowcake annually from 30,000 tonnes of ore at its peak in the early 1990s.[5] This suggests an ore grade that is greater than 1 wt.% uranium, assuming an 80% recovery rate.[6] However, this estimated ore grade is an order of magnitude greater than those assumed in a 1979 telegram memo by the Hungarian embassy, which estimated an ore grade of 0.26 and 0.086% for the two uranium mines (believed to be the Pyongsan and Sunchon mines, respectively).[7] Other reports suggest the DPRK uranium ore grades range from 0.07 to 0.9%, and an estimated ore production capacity that range from 19,000 to 400,000 tonnes annually.[8] These figures highlight the uncertainty in estimates of the DPRK's uranium reserves and its capacity to build nuclear arsenals from domestic resources.

This study reports on the operation of the DPRK's uranium ore-to-yellowcake production processes and throughput at the Pyongsan uranium mill using satellite imagery. It illustrates the fact that satellite imagery can determine the overall size and characteristics of the plant, estimate mill equipment types and sizes, and estimate mill tailings volume, providing one means to quantitatively analyze the possible ore processing throughput at the Pyongsan plant.

The analysis here suggests that the Pyongsan mill facility has a processing capacity of ∼750–1,200 tonnes of ore per day (tpd). If the plant is operating optimally for 300 days per year, a maximum of 360,000 tonnes of ore input would generate ∼90 tonnes of natural uranium in yellowcake, assuming an average ore grade of 0.03 wt.% uranium and 20% resource conversion loss. This is enough supply to produce 50 tonnes of uranium metal for fueling one reactor load of the 5 MWe reactor, while leaving enough materials for making ∼3,000 kg of LEU or ∼100 kg of HEU. However, while such capacity is consistent with the characteristics of the Pyongsan plant and its mill equipment as observed today, observations of the overall tailings pile volume indicate that the actual throughput is likely much lower than the maximum capacity.

The analysis here provides a critical basis for assessment of nuclear materials production pathways and capabilities, which remain a key to understanding both the risks associated with the DPRK's capacity to expand its nuclear weapons program and the ability to produce fuels for its future nuclear energy program.

The DPRK's nuclear fuel cycle

The nuclear fuel cycle presents the progression of nuclear fuel from extraction to waste disposal. In the DPRK, the cycle begins with extracting

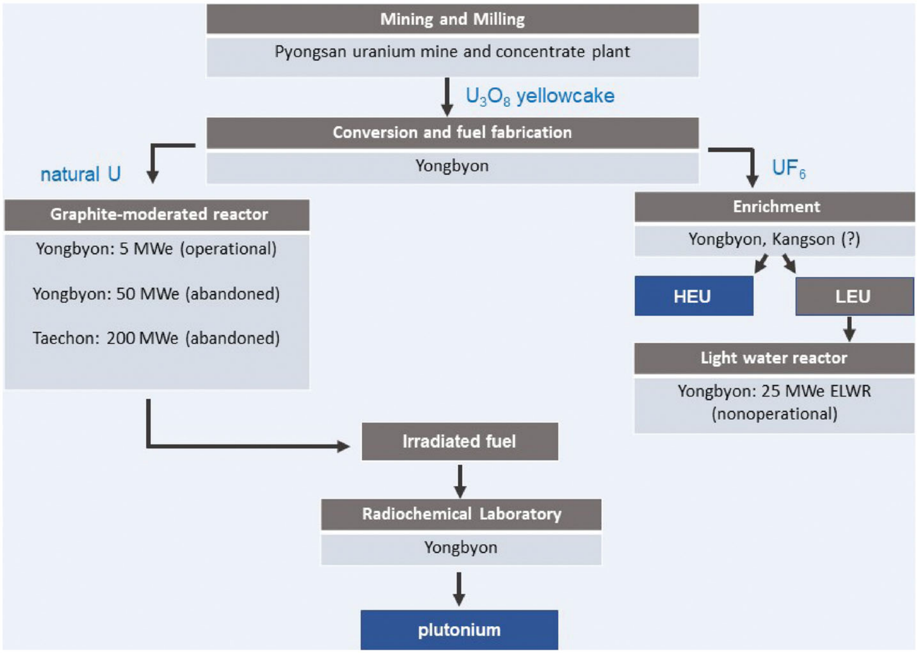

Figure 2. The DPRK's nuclear fuel pathways.

uranium from a mine in the form of uranium-bearing ore, which undergoes a series of physical and chemical treatments to produce triuranium octoxide (U_3O_8), colloquially called "yellowcake," at the Pyongsan uranium mill. The yellowcake is then further processed according to its final application (Figure 2).

5 MWe gas-graphite reactor at Yongbyon

The 5 Megawatt-electric (MWe) unit is a gas-cooled, graphite-moderated reactor, which is based on the same design concept as the UK's Calder Hall plutonium production reactor.[9] The reactor uses MAGNOX-clad, natural-uranium fuel elements, and requires 50 tonnes of natural uranium metal in a full core load every two-to-three years if operated continuously.[10] Yellowcake from the milling facility is first converted to uranium dioxide (UO_2), which is hydro-fluorinated into uranium tetrafluoride (UF_4) and reduced with magnesium, to make the uranium metal. Operation of a nuclear reactor generates irradiated fuel. Because this MAGNOX fuel is susceptible to corrosion and cannot be stored for long periods in spent fuel pools, the irradiated fuel from this reactor must be reprocessed.[11] The DPRK has an industrial-scale reprocessing plant, the Radiochemical Laboratory at Yongbyon, which separates plutonium from irradiated fuel.

During optimal operation, the 5 MWe reactor is believed to generate enough irradiated fuel for 6 kg of plutonium annually.[12]

Experimental light water reactor (ELWR) at Yongbyon

The DPRK began construction of the ELWR, a 25–30 MWe unit at Yongbyon in July 2010, with a stated purpose of electricity generation.[13] For operating the ELWR, treated uranium first needs to be converted into UF_4, fluorinated into uranium hexafluoride (UF_6), which is fed into an enrichment facility to increase the proportion of the fissile uranium-235. Once enriched to ~3.5% uranium-235, the uranium is converted into oxide suitable for fuel for the ELWR. A full load of fuel of this reactor would require ~4 tonnes of enriched uranium.[14] Once operational, the reactor would consume that amount every 1.5 years.[15] However, the reactor has not become operational as of early 2021.

IRT-2000 research reactor

The DPRK also houses an IRT-2000 nuclear research reactor, a pool-type reactor that utilizes light water as a moderator and coolant. The reactor initially used LEU and was gradually upgraded to 80% HEU with fuel rods supplied by the Soviet Union.[16] When the supply of fuel halted in 1991 with the dissolution of the Soviet Union, the reactor turned its use for research purposes.[17]

Pyongsan uranium mine

The Pyongsan uranium mine is an underground mine located 45 km north of the Korean demilitarized zone near the 38th parallel north, in Pyongsan-gun, North Hwanghae Province. The mine is situated in a geological basin known as the Phyongnam basin. Based on the comparable geological formation of the Phyongnam basin with that of the Okchon Metamorphic Belt of South Korea, a recent geological study suggests that the Pyongsan uranium deposit is a metamorphosed organic shale.[18] Combined analysis of geological maps and extensive geochemical research conducted by Soviet geologists suggest that uranium ore grade in the metamorphosed organic shale is low, with an average ore grade of 0.01–0.03 wt.% U.[19] The low ore grade of the shale deposit at the Pyongsan uranium mine is further corroborated by comparison with black shale uranium deposits of comparable geologic settings in South China's Niutitang Formation of the Guizhou Province (ore grade = 0.002–0.06% U),[20] or the Alum Shale Formation in the lower unit of the Peltura zone of the Narke region, Sweden (ore grade = 0.01–0.03% U).[21] While there will be spatial variations in ore grade, it is hypothesized that any ore grade higher than 0.2% U is depleted, given the long history of uranium mining at Pyongsan. Peer-reviewed field geology reports, combined with historical archives, including geological maps, provide a relatively well-constrained range of ore quality at the Pyongsan uranium mine.[22] However, the available uranium ore quantity at the time the mine was first exploited, how much has been exploited until today, and how much remains, are difficult to trace.

Estimating mine wastes expansion

Mine wastes expansion can be broadly estimated by area and land-use change detection of mine waste rock volume in satellite images (Figure 3a). Mine wastes include byproducts and waste rocks produced during ore extraction, including uranium-bearing ore that is not concentrated enough

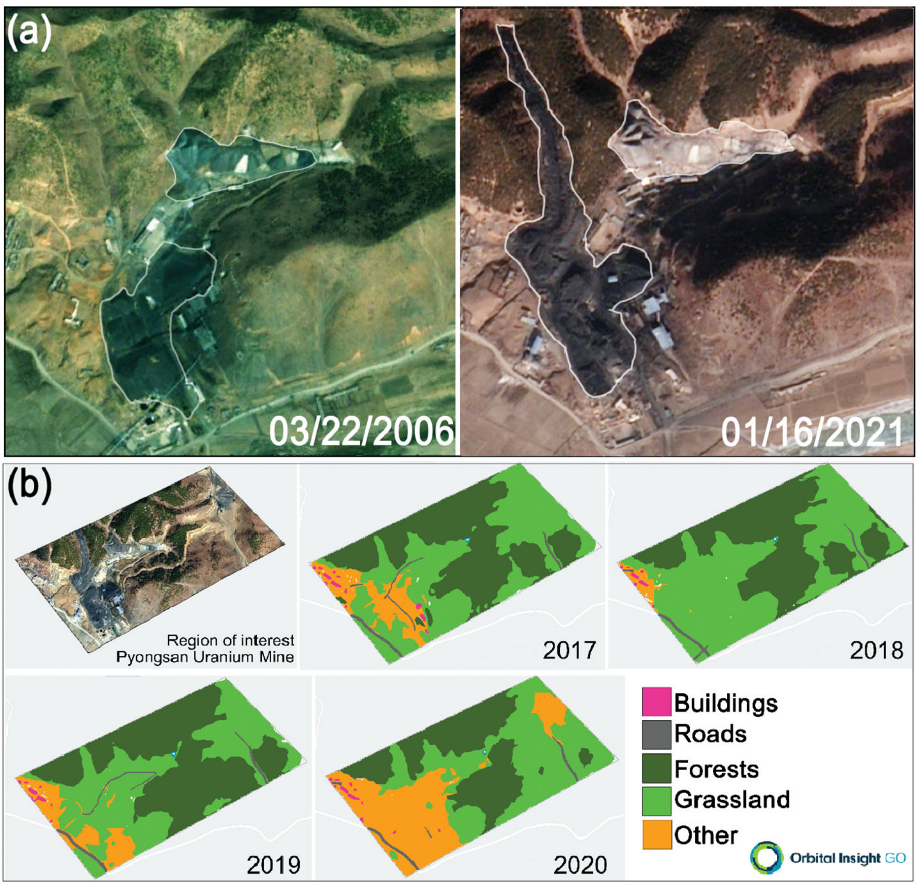

Figure 3. (a) Electro-optical satellite imagery of mine wastes expansion over time at the Pyongsan uranium mine. *Source*: Google Earth (left), Blacksky (right). (b) Machine learning-driven analysis of multispectral satellite imagery of the mine expansion at Pyongsan. Algorithm was developed by Orbital Insight.[86]

to be processed at a mill. These appear as large piles of dark, crushed rock. As seen in Figure 3a, the mine wastes volume increased from the year 2006–2021, indicating a continuing production at the mine. Mine wastes expansion was observed even during the global pandemic and typhoons in 2020.[23]

Currently, there are too few commercial satellite images to accurately detect the volume of mine wastes at Pyongsan, which would enable a better estimate of yellowcake production capacity. However, increasing access to commercial satellite imagery and vastly emerging analytics are enhancing the ability to better visualize and quantify ongoing mining production. For example, machine-learning driven analytics in land-use change detection over the Pyongsan uranium mine is illustrated in Figure 3b. An analytical algorithm to track land-use in satellite imagery was applied to a set of 1.5 m resolution satellite images collected over the months of March–May from 2017 to 2020. A reduction of vegetation, including forests and grasslands, by 20% from 2017 to 2020, concurrent to an almost four times increase in "others" is likely a result of mine and wastes expansion over time.[24] A major advantage of the application of machine learning to satellite images is efficiency. However, caution is needed to interpret such results, as vegetation change may not always indicate a mine expansion.

While satellite images provide qualitative information on the ongoing production and corresponding mine expansion, there are drawbacks in using this method over the mine as a sole source of estimating ore production. For example, the stripping ratio (overburden thickness-to-ore thickness ratio) of a mine depends on many variables, including the type of deposit, ore thickness, orebody shape, or value of the desired resources, and many of these factors are unknown for the Pyongsan mine.[25] This necessitates a set of complementary analyses for a more refined determination of the DPRK's fissile material production capabilities. Some of the insights can come from looking at the features at the mine portal and the ore processing plant.

Ore crushing and sorting at the mine

Satellite images over the Pyongsan uranium mine exhibit features associated with the initial stages of uranium ore processing. Notably, there are stepped buildings at the mine, which were identified as primary and secondary ore crusher houses and an ore preparation building (Figure 4).[26] When ore is mined from underground, the coarse ores are crushed and ground in a series of operations to produce ore of desired mesh size. Uranium mines commonly have a crusher and a conveyor belt with air jets and radiometric scanners, which can sort the crushed ore based on the level of radioactivity.

Figure 4. Slurry pipeline that runs from the Pyongsan uranium mine to the Pyongsan Uranium Concentrate Plant. Copyright MAXAR 2021; *Image credit*: Apollo Mapping.

The method is attractive for a low-grade deposit, as its ore factor (usable ore quantity) can be upgraded by a factor of up to three as compared with the case without scanners.[27]

Ore conveyance to the mill

Crushed and sorted ore is then transported to the mine portal through either a conveyor belt or a slurry pipeline depending on the size of the crushed rocks. The multiple shafts and building structures, including the water tanks, at the mine suggest that the ore is crushed and mixed with water to be carried in the form of slurry through a ~530 m long above-ground slurry pipeline (Figure 4).

The slurry pipeline structure observed in Figure 4 is ~1.6–2 m wide based on satellite imagery. The structure is most likely a walkway on which the slurry pipeline is located, which allows personnel to inspect and maintain the pipeline. A slurry pipeline itself is relatively small, with the actual size and design depending on the interplay between minimizing pumping power and pipe erosion while maximizing slurry transport efficiency. Typically, a slurry pipeline cannot convey ore that has a particle size distribution (PSD) greater than ~0.7–1 mm to reduce particle degradation and to prevent settling of solids in the pipeline.[28] Although the current resolution of satellite imagery does not help reveal the actual size of the pipeline, the diameter of this slurry pipeline at Pyongsan can imply the rate and capacity of ore carried to the milling complex, which has important implications on the rate of yellowcake production.

Pyongsan uranium concentrate plant

Once transported to the ore processing plant, the slurry is processed in the following steps at a conventional uranium mill (Figure 5):[29]

1. Ore preparation for further grinding
2. Slurry pumped into leach tanks
3. Extraction with leaching to dissolve uranium (acid or alkaline)
4. Solid-liquid separation to separate uranium solution from the leached tailings
5. Purification and concentration to remove impurities
6. Precipitation to separate uranium
7. Drying to remove moisture and volatiles
8. Packaging of yellowcake for dispatch
9. Tailings disposal or impoundment

These processes take place at the Pyongsan Uranium Concentrate Plant, located half a kilometer southwest of the Pyongsan uranium mine. The facility encompasses approximately 0.21 km^2. The overall size and characteristic of this facility suggests a rough capacity of ~750–1,200 dry tonnes of ore per day (tpd). Constructed during the mid- to late- 1980s, the Pyongsan uranium mill has regularly been renovated and developed.[30] Activities and overview of the Pyongsan ore processing complex have been extensively discussed in recent publications such as those by Schmerler (2020),[31] Bermudez et al. (2020; 2021),[32] and Makowsky et al. (2020),[33] which provide exemplary details on the uranium pathway from the mine portal to mill tailings as well as its ongoing activities. The independent study conducted here discusses a possible pathway of uranium processing at Pyongsan, which corroborates the bulk of previous reports while providing new technical details.

Figure 5. A satellite image of the Pyongsan Uranium Concentrate Plant. Labels 1–8 are buildings and structures directly involved in the uranium to yellowcake pathway. Labels A–E are features that are assumed to be support buildings. *Source*: Google Earth.

Ore preparation and grinding at the mill

The slurry in the form of mixed liquid and solids is transported to a three-story tall building (Figure 6). The building is presumably used for regrinding the slurry from the pipeline to smaller PSD to increase surface area for leaching efficiency. The black discoloration of the roof (see electronic copy for colored image), resembling dust accumulation from ore grinding, qualitatively corroborates the assumption. A circular basin-type settler tank is connected immediately east to this building. This tank is 17 m wide and ~3.5 m tall, which is typical for a circular settling tank that is used to separate water from crushed ores. There is a lot of variability in the settling area requirement for uranium ore slurries, which depends on the size of the ground

Figure 6. A probable grinding facility. This is the first building to which slurry is transported to. *Source*: Google Earth.

product, clay content, as well as the desired settling rate.[34] But at nominally 17 m diameter, the capacity ranges from 370 to 1,500 tpd, largely consistent with the ore processing capacity estimate of ∼750 ∼ 1,200 tpd.[35]

Uranium extraction with leaching

When ground to the size of fine sand particles, the uranium ore is leached, and the uranium is extracted by reacting with either an acid agent, such as sulfuric acid (H_2SO_4) or an alkaline agent, such as sodium carbonate (Na_2CO_3).[36] In either case, oxidation of insoluble tetravalent uranium to the soluble hexavalent species is required. For acidic leaching, the common oxidants are sodium chlorate, $NaClO_3$, and manganese dioxide, MnO_2. In addition to extracting uranium, this process is also used to extract other elements, such as vanadium, iron, selenium, lead, or arsenic from the processed slurry. Based on the rusting on the roof, a three-story building labeled 2 (Figure 7a), connected to the grinding facility (building 1) with a ∼1.5 m diameter pipeline structure, was identified by Schmerler as a leaching tank house.[37] Schmerler identified a natural draft-type building design for the type of rust and localized damage on the roof ventilation system, which is likely caused by reactions from gas or vapor generated during the leaching process, including hydrogen sulfide (H_2S), sulfur dioxide (SO_2), carbon dioxide (CO_2), and acidic mist if the leaching agent is H_2SO_4.[38] Building 2 likely contains propeller-type agitated tanks for acid leaching of uranium ore for subsequent extraction and purification.

North of the leaching tank house, there is a set of eight 16 m wide × 12 m long open-air rectangular sedimentation tanks or ponds, in addition

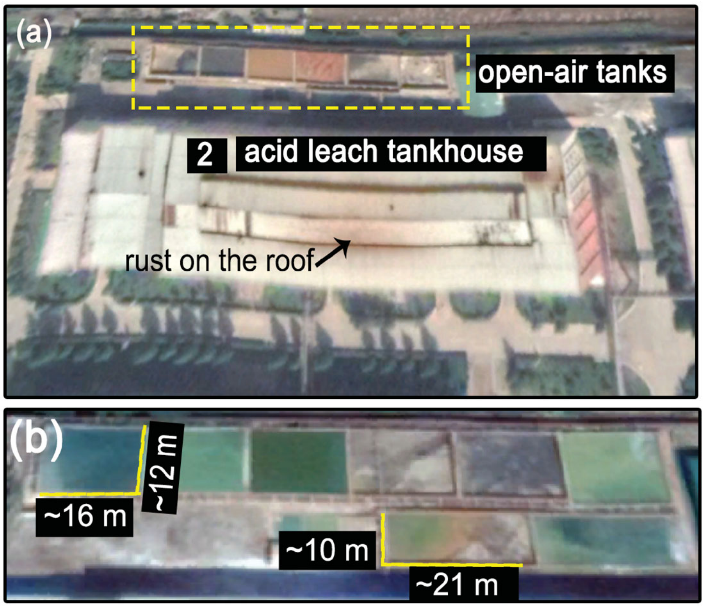

Figure 7. (a) Probable acid leach tank house at Pyongsan. Source: Google Earth. (b) Ten rectangular open-air tanks north of the facility. *Source*: Google Earth.

to two larger 21 m wide × 10 m long tanks (Figure 7b).[39] These sedimentation tanks function to separate solids from water. The green color of the tanks indicates a possible uranium and/or vanadium-rich liquid.[40] In the scenario in which the DPRK processes vanadium, as mentioned by a defector, Kim Tae-Ho, who worked at the wastewater treatment facility at the Pyongsan plant, H_2SO_4 could be used to dissolve vanadium in addition to uranium.[41] Typically, vanadium extraction requires a salt roasting process to solubilize vanadium for subsequent leaching.[42] This process likely occurs in a rotary kiln in building 5.[43] An alternative to salt roasting is a combination of stronger oxidation and a higher free acid concentration than required for uranium alone.

Solid-liquid separation with thickeners

Leached uranium ore usually undergoes a solid-liquid separation. The primary purpose of this process is to separate out the uranium-bearing solution, called "pregnant solution," from the leached ore through a series of thickeners. These thickeners, often called continuous countercurrent decantation (CCD) units, are a series of cylindrical tanks with a cone-shaped bottom and revolving rakes. The leached ore slurry containing depleted solids and a solution that is "pregnant" with uranium is fed into the first of a string of thickeners with a flocculant (e.g. a polysaccharide) to form large agglomerations of thickened slurry solids that gravitationally settle to the bottom of the cone. The thickened slurry is then removed through the underflow pipe and advanced to the next countercurrent unit to stage-wash the solids and separate them from the pregnant solution. The thickened slurry leaving each stage has a density of 35–60% solids by weight (density can depend on the size distribution of the solids, as well as the ore mineralogy), and the final thickened slurry is removed through the last thickener's underflow pipe. Meanwhile, clean pregnant solution rises to the top of the thickener and overflows into a peripheral collection launder—and effluent collecting trough. The collected solution is often stored in tanks or ponds for recycle or downstream treatment.[44]

There are several assessments of CCD tanks at the Pyongsan mill.

Outdoor CCD tanks

One assessment is that the CCD tanks are located outdoors. If placed outdoors, a feature labeled 3 in Figure 8 captures the probable CCD tanks at the Pyongsan mill. The number and size of these tanks indicate the possibility for their being multiple CCDs. The recovery of dissolved uranium increases exponentially as the number of countercurrent tanks for washing the residue increases. Six CCD tanks is an optimal number to maximize recovery of the uranium solution and meet the economic objective for the typical CCDs at a medium-sized mill.

Until 2003, a total of six CCD tanks were observed. A satellite image from March 2011 shows an additional tank of comparable size, and one more tank was added in year 2015. While it is reasonable to assume that the newly added

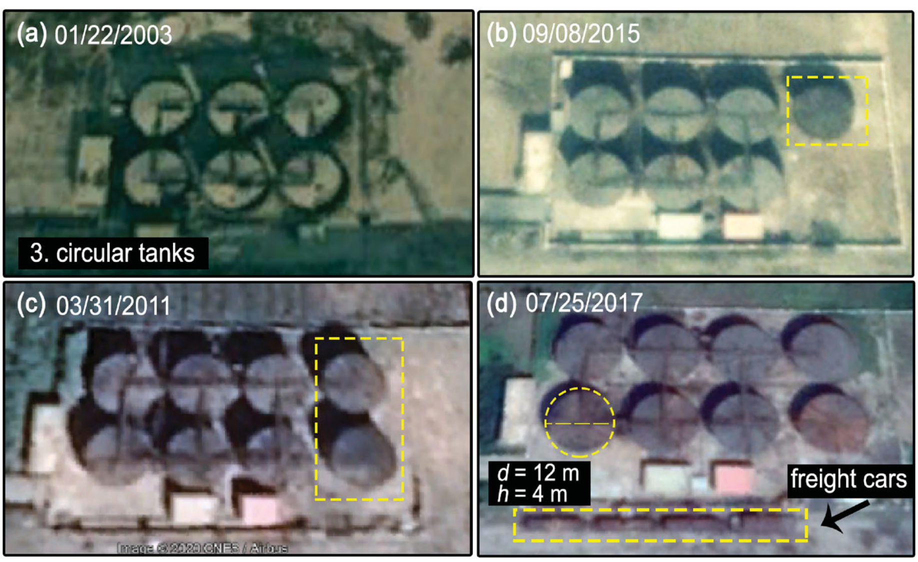

Figure 8. (a–d) Circular tanks at Pyongsan in 2003. Two additional tanks of comparable size were added between 2003 and 2015. *Source*: Google Earth.

tanks could be built to increase the recovery of dissolved uranium, the absence of bridge and walkway on top of the two additional tanks suggest that they more likely serve the purpose of a clarifier for CCD overflow solution and a storage tank for clarified solutions. The assumed clarifier and CCD thickener appear similar in the image and are both used to separate liquids and solids. Yet, the primary purpose of thickeners is to concentrate solids by providing a high-density underflow, whereas clarifiers purify liquids (i.e. to recover processed water and extract fine particles for treatment or disposal).

While there are different types of CCD units, high-rate thickeners with an on-ground, flat-bottom design are consistent with the observations from the satellite imagery. Many factors influence the choice and size of thickeners. Commonly, the area of a thickener is dependent on the density ratio of pregnant solution and settled solids, as well as settling rate.[45] A typical CCD unit of the comparable size has a capacity up to ~1800 tpd.[46] This is largely consistent with the capacity of the settler tank in building 1 and corroborates the estimate of the ore processing capacity based on the characteristics and size of the plant.

For the purpose of this analysis, these circular tanks are considered as CCD tanks. However, typical CCDs commonly exhibit signs of liquid overflow, which are absent in Figures 8a–d. The lack of overflow signature could be due to covers on the CCD tanks, commonly used for sensible heat retainment. However, these covers are typically made from lightweight materials, such as fiberglass-reinforced polymer, and the satellite imagery analyses indicate that the covers are made of heavier material. This suggests a possibility that the CCD tanks could be kept indoors.[47]

Indoor CCD tanks

The CCD tanks in Pyongsan could be indoors, possibly for concealment and/or to prevent freezing during winter. If kept indoors deep cone CCDs with small diameters are likely used to minimize the building size.[48] If this is the case, the feature labeled 3 in Figure 8 more likely serves as storage tanks for reagents rather than as CCDs.[49] The proximity of these tanks to a railroad with frequently observed closed-top railcars suggest that reagents are being transported directly to these tanks.[50]

In a uranium mill, a typical reagent used in substantial quantities is H_2SO_4. However, a large volume of concentrated H_2SO_4 is usually stored in long horizontal cylinders due to the high specific gravity (1.8) that makes conventional tanks too expensive to construct. Furthermore, the tanks in Figure 8 are ~12 m wide and ~5 m tall, and eight of these tanks would hold a maximum of ~4400 m^3 of solution, implying an excessive volume of acid for a mill of this size. Typically, an ore suitable for acid leaching would require >30 kg of concentrated acid per tonne of ore, whereas an ore containing over ∼1.5% calcium carbonate and requiring more acid would be leached with an alkaline solution in pressurized autoclaves.[51] For a medium-sized plant, such as the Pyongsan mill, one or two vertical tanks would be adequate for storing one-two months' supply of H_2SO_4.[52] Other likely reagents would be an oxidant, such as sodium chlorate or manganese dioxide, and coagulants, all of which are powders and would not be stored in such tanks or in such large quantities. It is also possible that these tanks store coal as a slurry for firing the on-site boiler. Lastly, it cannot be ruled out that other chemical products are likely processed and used at Pyongsan.

Absence of CCD tanks

Finally, it is also possible that the Pyongsan mill does not use CCD thickeners to separate uranium from solution from the leached tailings. Purification of uranium solution can also be done without a series of thickener tanks if the resin-in-pulp method is utilized. This is discussed below.

(a) Purification and concentration

Once the solution is clarified, the following step nominally includes purification and concentration to remove impurities. Based on the pipeline connection and the building size, the building labeled 4 in Figure 9 is likely an extraction facility, hosting the equipment to purify and concentrate uranium.[53] Uranium purification can be conducted on (1) clear solutions, after CCD removes leached solids from the pregnant leach solution, or (2) a resin-in-pulp configuration, where baskets of resin beads are suspended and vertically agitated in tanks, through which the leached slurry, or pulp, is flowing.[54]

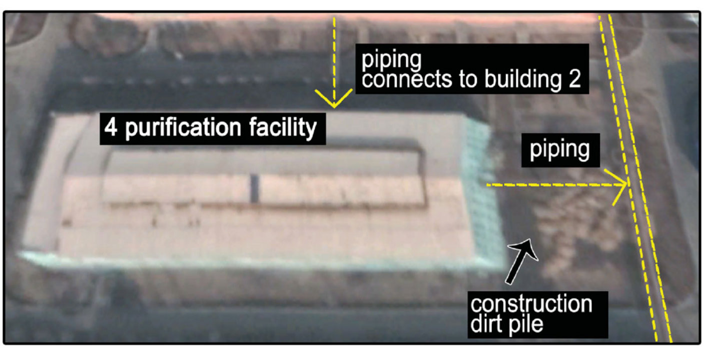

Figure 9. A probable purification facility. The facility has piping connected to the acid leaching tank house (top), as well as to the main pipeline that is connected to the thermal steam plant (right). *Source*: Google Earth.

(b) Solvent extraction (SX) or ion exchange (IX)
The SX process begins with a mass transfer between the clarified uranium-containing solutions and organic solvents.[55] The solution and solvent are mixed, and the desired uranium constituent is extracted from the pregnant aqueous phase into the organic phase. The clear pregnant leached solution is most typically treated by SX. Previous reports have also identified the building as a "solvent extraction facility,"[56] which is a common interpretation, since SX process is a preferred method at many conventional mills due to its efficiency and flexibility regarding the reagent type used to strip uranium.[57] However, there are also reasons to assume otherwise, mainly economic considerations.

Compared with SX, the IX process is more economically viable on lower-grade solutions as it allows for a higher uranium recovery from a comparable ore grade.[58] In addition to the advantages the IX process offers in processing low grade uranium ores, there is another reason to presume that the DPRK is using IX process on clear pregnant leach solution if it adapted some of the milling technologies from the Soviet Union. Prior to the 1990s, the Soviets preferred IX over the SX process for purifying metals.[59] The reason may have been as simple as the unavailability or shortage of high-quality reagents, such as a tertiary amine extractant.

(c) Resin-in-pulp
In a resin-in-pulp method, leached uranium is removed by passing through columns of ion exchange resins, which remove complexed uranium ions.[60] The method eliminates the solid-liquid separation process, and hence the need for the CCD tanks. If the Pyongsan mill does not have CCD tanks, this method explains the residue removal process. The resin-in-pulp method was initially used for low-grade uranium ores, and can be a lower capital-cost alternative, while requiring less space for the same uranium capacity. However, the advent of effective flocculants in the mid-1950s essentially eliminated the resin-in-pulp method alternative in favor of CCDs and SX.

Though an assumption can be made on the building's probable function, lack of granular data precludes full assessment of which type of technique is used to conduct uranium purification (*i.e.* whether solvent extraction (SX), ion exchange (IX), or resin-in-pulp is used to purify uranium cannot be fully determined).

Precipitation and rotary kiln for drying and calcination

After uranium is purified and concentrated, it is precipitated by various methods to yield yellowcake, which is then dried to remove impurities and

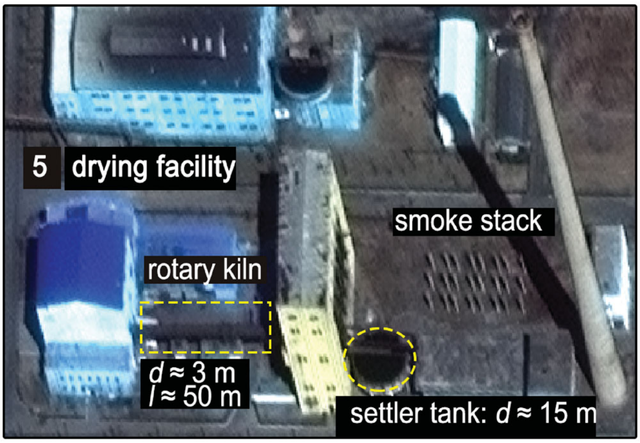

Figure 10. A probable drying facility, featuring a rotary kiln, a settler tank, and a smokestack. Copyright MAXAR 2021; Image credit: Apollo Mapping.

volatiles. The drying process is done in a rotary kiln in a separate drying building (Figure 10). A rotary kiln serves several purposes. Schmerler proposed that the use of a rotary kiln in roasting ore is to reduce carbon content prior to leaching of uranium, supposing the ore mined is an anthracite coal.[61] The process would take place earlier during the slurry-to-yellowcake production. Roasting of uranium-bearing coal is a plausible scenario for the anthracite coal ore type. However, if the ore is in a metamorphosed shale, the rotary kiln is mostly used to dry and calcine (densify at elevated temperature and eliminate volatile impurities) the uranium prior to filling drums. For shale, roasting is unnecessary due to a metamorphism-induced reduction of carbon-content during shale formation.

Analysis of satellite images concludes that the rotary kiln at Pyongsan has an outer diameter of ∼3 m and runs between the two buildings that are 50 m apart (Figure 10). A typical rotary kiln of a comparable size with the sole purpose for drying uranium yellowcake has a capacity in the range of ∼16–18 tonnes/h, although the maximum capacity depends on the process variables unique to each application. For the overall size of the Pyongsan milling facility, the capacity of ∼16–18 tonnes/h is on a very high-end for a site like Pyongsan. Most likely, the kiln is used for both drying and calcining processes at temperature as high as 650 °C. Part of the length of the building could be used for cooling by convective heat transfer from the hot kiln shell.

Rotary kiln for vanadium

Additionally, a rotary kiln could be employed for vanadium processing. The roasting process removes impurities from the uranium ore.[62] Extraction and recovery of vanadium frequently occurs as a byproduct of processing ores. This is especially true for ores in which the mineral is carnotite, a potassium-uranium vanadate. This option requires leaching with a higher free acid concentration and more oxidants, such as $NaClO_3$ or MnO_2 for a higher oxidation potential than required for uranium recovery alone. Naturally, this increases the acid consumption per tonne of ore since more gangue minerals are dissolved along with the vanadium.[63]

Packaging and dispatch

The solid dry yellowcake is then ready for packaging and dispatch. Observations of packages and proximity to the railyards suggest that packaging and shipping occur in the building labeled 6 in Figure 11a. The building has two rail thruways, one of which was constructed in the summer of 2017 (Figure 11b).

Typically, yellowcake is packaged in a standard reinforced steel drum with a lid and a locking attachment clamp.[64] The standard drum is ~0.57 m wide and 0.8 m tall, with a total volume of 0.2 m^3 (~55 gallons).[65] Each drum can hold ~300–400 kg of yellowcake. If the plant processes 360,000 tonnes of ore with an average grade of 0.03 wt.% U, at 80% recovery, this produces a maximum of ~7,000 kg of yellowcake per month. If each rail car stores 20–50 drums on a well-maintained track, one load would carry ~7,000–17,500 kg of yellowcake, equivalent to 1–2 months of production.[66]

At the Pyongsan mill, the main rail node splits into two (Figure 12). The first rail node (a–d) goes through the center of the milling complex and the second one connects to the south (e, f) of the complex. The types and sizes of freight cars observed on the rail roads are varied. Analysis of the satellite images suggests the presence of three main types of railcars at the site: (1) gondola-type railcars; (2) closed-top boxcars; and (3) tank cars. Although no definitive conclusions about functions served by these specialized railcars can be made at this time, the yellowcake drums are typically carried in boxcars sealed for security purposes.[67] With careful monitoring

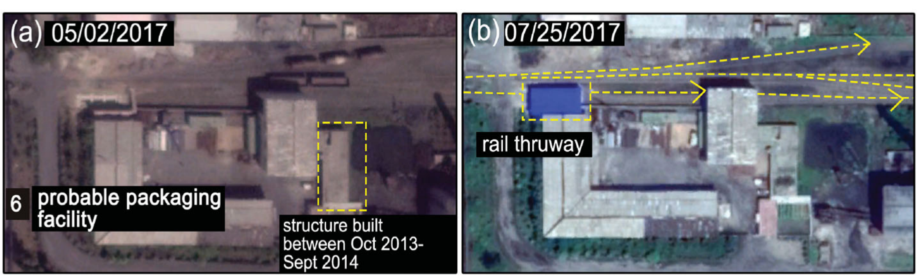

Figure 11. (a) A building that is presumably a yellowcake packaging and shipping station. (b) The building has a recent rail thruway that was completed in 2017. *Source*: Google Earth.

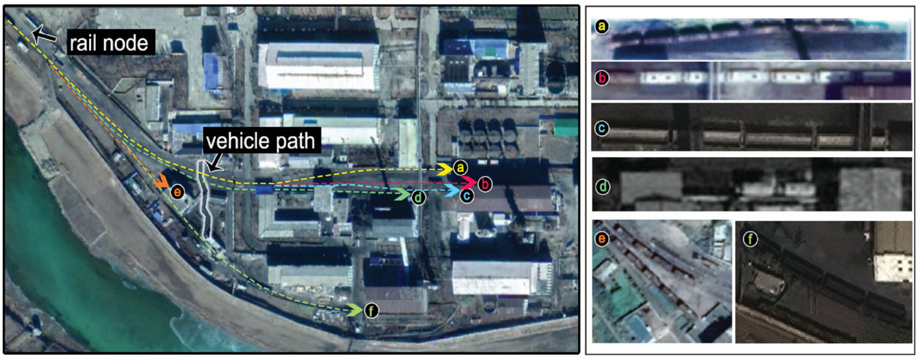

Figure 12. Rail node and railroads at the Pyongsan Uranium Concentrate Plant. *Source* Google Earth.

of the frequency and number of such railcars, a complementary estimate on the frequency of yellowcake shipments could be made.

Wastes and mill tailings

Each of the steps outlined above generates wastes. In an active mill, the remaining wastewater or materials are treated before being discarded as mill tailings. Mill tailings are a sand-like waste sludge consisting of slurries of sands and clay-like particles called slimes.[68] If the processed material is uranium ore, mill tailings could contain low concentrations of radioactive alpha-emitters.[69]

Due to the waste accumulation, effluent treatment is an integral part of the operations with barren liquor (liquid remnants from processing with little to no recovery value) being recycled to the mill or processed through a water treatment plant before being discarded into the mill tailings.[70] The characteristics of barren liquor depend on the type of leaching process used. The barren liquor and decanted water from the pond are transported to an effluent treatment building.[71] The building labeled 7 in Figure 13 has been identified as a wastewater treatment facility.[72] In agreement with previous reports, the present analysis notes the pipeline connecting the building across the river to the tailings pond, supporting the conclusion that wastes are transported to the impoundment with natural hills as side barriers.

At Pyongsan, the mill tailings pond is located south of the complex, across the Ryesong river (Figure 14a). A single pipeline structure, ~1.5 m in width, carries wastes and discharge from the waste treatment facility into the impoundment area. Waste diversion pipelines stretch southeast of the tailings pile (Figure 14a). The white color at the edges of pile is likely either evaporites formed by solution constituents or crystallized gypsum following acid neutralization of tailings. The expansion of these tailing piles

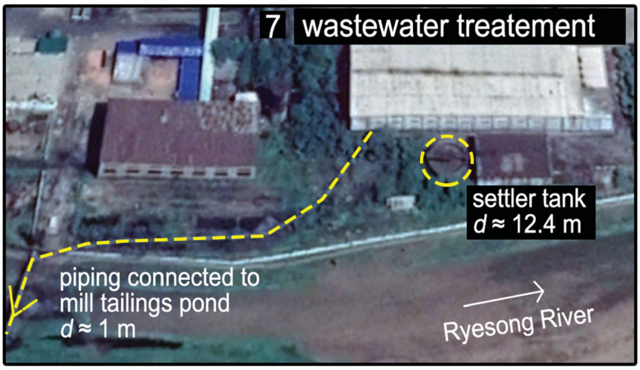

Figure 13. Wastewater treatment facility with piping that is connected to the mill tailings pond across the Ryesong river. *Source*: Google Earth.

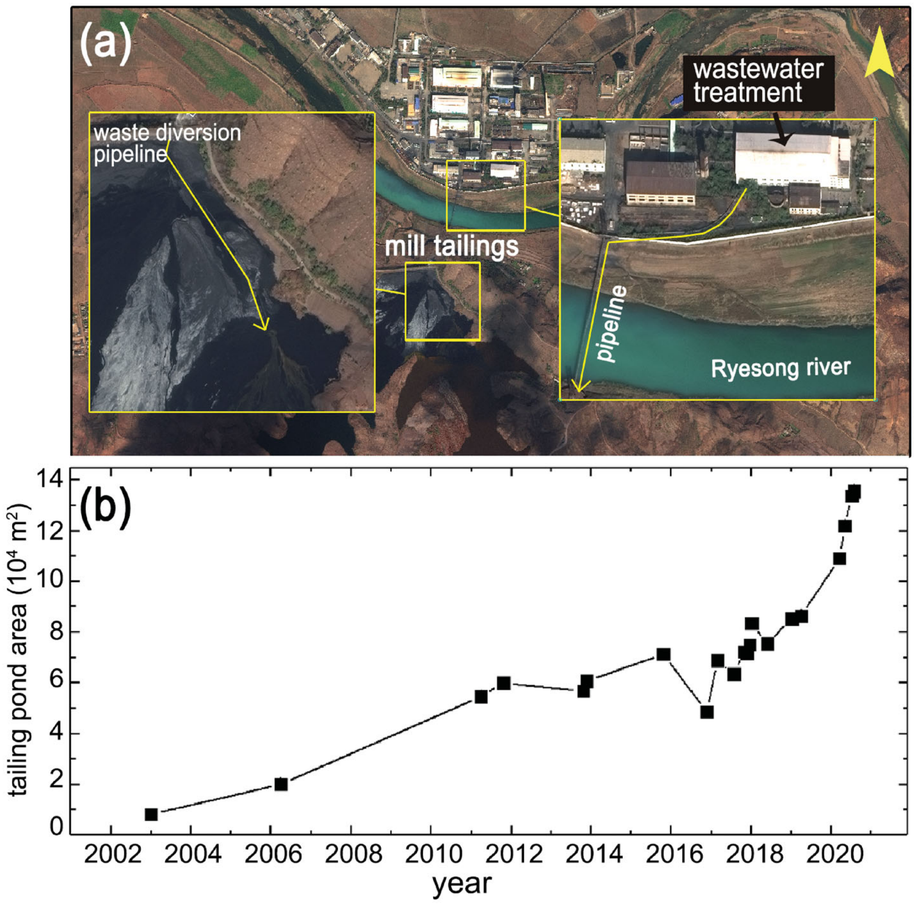

Figure 14. (a) Mill tailings pond south of the ore processing plant. A pipeline from the waste-water treatment facility transports wastes to the mill tailings pond. Copyright MAXAR 2021; *Image credit*: Apollo Mapping. (b) A graph of the tailing pile surface area increasing over time. The area measurement may be affected by seasonal fluctuations of water level; figure updated from Park et al., 2020.

has been observed by many researchers, suggesting the ongoing activity at the mill. A study by Park et al. (2020) for example, showed an increase in the tailing pond area since 2003 (Figure 14b).[73] By mid-2020, the surface area reached $\sim 13.8(0.1)\times 10^4$ m^2.

If the impoundment area stores mill tailings directly associated with processing uranium-ore (as opposed to, for example, coal refuse from the thermal power plants), the size of the pile can provide a key insight into the yellowcake production capacity. For example, assuming that the ore deposit is metamorphosed shale, solid particles have a specific gravity of about 2.6, a reliable number for a mixture of metamorphic rocks and clays.[74] Under a zero net evaporation assumption, the ultimate density of the fully settled tailings is about 70% by weight, implying ~1,800 kg of dry solids per cubic meters of tailings in the impoundment.

However, caution is needed when interpreting the geometry of the mill tailings. Observation of the mill tailings impoundment suggests a dam that is ~3–5 m high. The height of this dam is also corroborated by the apparent elevation difference between the upper surface of settled solids and the bottom of the ravine at the toe of the dam. If the surrounding low hills have constant slopes to the bottom of the ravine, a rough estimate of the enclosed impoundment volume is $\sim 250{,}000\,m^3$, which translates to <300,000 tonnes of settled solids. This translates to an average ore processing rate of ~16,500 tonnes of ore per year since the first satellite image over Pyongsan was available. The milling rate is highly suspicious given the size of the Pyongsan milling infrastructure, which for its size and observed mill equipment, can process 20 times that capacity. The volume estimate, however, remains speculative with the currently limited satellite imagery analysis capabilities. Increased resolution of imagery, combined with extensive analyses, including digital elevation model and bathymetry may help better estimate water depth and hence, volume of this mill tailings.

Support buildings and thermal plant

In addition to the facilities that are directly involved in uranium processing, there are support buildings that indirectly serve the complex. One type of support could be additional material production.

Material production

In agreement with Schmerler, the building labeled A in Figure 15 appears to serve such a purpose.[75] As seen in Figure 15, this support building has undergone multiple upgrades. The satellite image from 2003 shows two corrugated steel stacks. One of the stacks is seen absent in 2011 and 2013, and the image from 2017 once again shows two corrugated steel stacks.

Figure 15. (a–f) A facility that is presumably used for production of sulfuric acid (H_2SO_4) over time. Satellite images show construction of two tanks in 2017, in addition to disassembling of one steel stack. *Source for a–d, f*: Google Earth. *Source for e*: Copyright MAXAR 2021; *Image credit*: Apollo Mapping.

The steel stack is estimated to be 7.5–8 m wide and ~30 m tall. The combination of the steel smokestacks and two heavy-duty tanks likely indicates the production of chemical reagent, most likely H_2SO_4 for leaching. The steel stacks for such a purpose are usually lined with firebricks and supported on angle-iron rings every 4–5 meters. These can corrode and disintegrate when exposed to gases from smelting-plant furnaces or from roasting sulfur or iron pyrite to produce H_2SO_4, so they may require periodic replacement. The absence of one stack in 2011 and 2013 images may be explained by the fact that the stack was reinstalled with a new lining. The two heavy-duty tanks may be used to store chemical reagent or water. Another clue to the reagent production onsite is the types of tank railcars that directly enter the building. There are various numbers and types of railcars (4–9 railcars) of 11 × 3 m or 14 × 3 m dimensions that are detected here. These tank-type railcars could be bringing in iron pyrite or molten sulfur needed to produce H_2SO_4. The building below the corrugated stack is connected to a probable wastewater treatment facility with a ~3.6 m wide bridge/walkway. The presence of a conveyor belt would be consistent with the hypothesis that this building is used for roasting of pyrite, as it would be used to move iron oxide residue (calcine) to the treatment facility for recovery of byproducts (e.g. nickel is often present in pyrite).

Thermal plant

Another support building would serve the purpose of power generation for the mill complex—the thermal energy plant, labeled B in Figure 16. The shed is connected to the building above through a conveyor structure or gallery that is ~4.8 m wide and 48 m long. The building likely contains

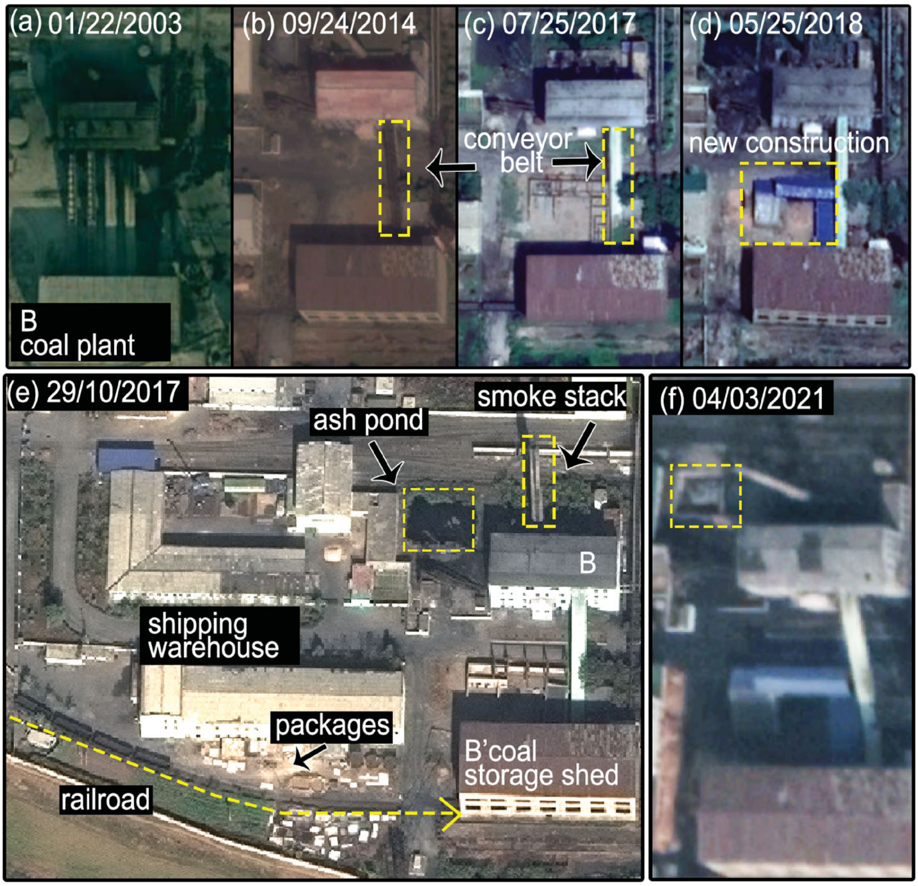

Figure 16. (a–d) Improvements made to the coal plant over time. *Source*: Google Earth. (e) Coal storage shed, thermal plant, and a railroad that is connected to the coal storage shed. Copyright MAXAR 2021; *Image credit*: Apollo Mapping. (f) new embankment around the ash pond. *Source*: Google Earth.

coal-fired boilers for steam and power generation with flue gases exiting through the adjacent smokestack. There is also an ash waste pond, also known as an ash basin, where ash from the coal plant is mixed with water to form a slurry. A satellite image from 2020 shows a structure around this ash pond, suggesting that the DPRK has built a ring embankment ($\sim 13 \times 13$ m) to enclose the disposal site (Figure 16f). Another observation is the construction of a blue-roofed L-shaped building that was completed in early 2018 (Figure 16d), again suggesting active renovation and development progress at the Pyongsan milling complex.

Additional support buildings

There are other less obvious support buildings. These are labeled C–G in Figure 5. The frequent observations of trucks and vehicles around building

Figure 17. Support buildings that are presumably related to administration, machine shop, warehouses, shipping and receiving facilities. *Source*: Google Earth.

C likely suggest that it is a machine shop or maintenance shop (Figure 17a). Buildings D–E could be administrative buildings or dormitories (Figure 17b). Buildings F and G are presumably shipping and receiving facilities or warehouses (Figure 17c–f). Ongoing activities are noted by the presence of effluent, packages, and vehicles outside the buildings (Figure 17c–f).

Discussion

The analysis reported here provides new insight into the characteristics of the Pyongsan ore processing facility and a quantitative analysis on its likely ore processing throughput. Most notably, the assessment of the facility and estimates of mill equipment types and sizes indicate an ore processing capacity of ∼750–1,200 tpd. If the Pyongsan plant operates at its full capacity 300 days per year, this corresponds to an annual input of

~225,000–360,000 tonnes of uranium ore and an output of 50–90 tonnes of natural uranium as yellowcake, assuming an average ore grade of 0.03 wt.% uranium and 20% loss of uranium in the conversion of ore to yellowcake during milling.

Because production of yellowcake is a critical step in the production of fissile material, ore processing rates provide for an improved quantitative assessment of the DPRK's nuclear materials production and inventories. Yellowcake produced by milling can be converted into metallic uranium fuels, U, for the 5 MWe reactor at Yongbyon, which is currently the only significant source of plutonium in the DPRK. Alternatively, yellowcake can be converted and enriched to ~3.5% uranium-235 LEU in UO_2 fuel for the as-yet-inactive ELWR.[76] Finally, the yellowcake is a source for HEU suitable for weapons.

5 MWe reactor

Fueling the 5 MWe reactor requires the reduction of yellowcake and conversion to UF_4, and subsequent production of uranium in metallic fuel, clad with a magnesium alloy.[77] The reactor does not require enriched uranium, but uses 50 tonnes of natural uranium metal per reactor load, with reloading every 2–3 years.[78] Assuming 80% recovery rate, and 10% loss from conversion to uranium metal, one fuel load at the reactor requires ~60 tonnes of natural uranium in yellowcake. This translates to ~250,000 tonnes of uranium ore, assuming an average ore grade of 0.03 wt.% U. Based on this analysis, a maximum one-year supply of yellowcake from the Pyongsan plant is enough to provide fuel for the 5 MWe reactor for slightly more than a single 2–3-year loading cycle.[79] Assuming an average burnup at the reactor to be ≈460 MWth-d/tU,[80] the uranium processed from a single year of operation at the Pyongsan plant is sufficient to produce an average of 11–17 kg of plutonium over 2.5 years of reactor operation. This suggests that the yellowcake production does not constrain plutonium production in the 5 MWe reactor.

ELWR

Fueling the ELWR requires the conversion of yellowcake to UF_6 and subsequent enrichment. The ELWR, once operational, would take 4 tonnes of uranium oxide enriched to ~3.5 wt.% uranium-235 every 1.5 years.[81] Assuming a tails assay of 0.27 wt.% uranium-235, 10% loss in the fuel fabrication process,[82] and no constraints on enrichment capacity, this will require ~30 tonnes of natural uranium feed. Assuming a 10% conversion loss from yellowcake and 20% extraction loss the ore processing, this would translate into ∼150,000 tonnes of uranium ore. At a maximum ore processing capacity of ∼1,200 tpd, one year of continuous operation at the Pyongsan plant can produce ∼10 tonnes of LEU, enough to support the ELWR for over three years.

HEU

Assuming that the DPRK's enrichment facilities are configured to produce 90 wt.% uranium-235 HEU,[83] a given quantity of uranium ore will generate ∼30 times less 90 wt.% uranium-235 HEU compared with 3.5 wt.% uranium-235 LEU. If there are no constraints on the enrichment capacity, this means that ∼200–350 kg of HEU can be produced from a milling capacity of ∼750–1,200 tpd.

LEU, HEU, and plutonium production as a function of milling rate and uranium ore grade are illustrated in Figure 18. The estimates assume a scenario in which all uranium processed is used for producing either LEU, HEU or plutonium.

However, for both cases of LEU and HEU production, the enrichment capacity in the DPRK can be a limiting factor. While the full capacity of enrichment is unknown, a limited enrichment operation means that only a certain amount of natural uranium, and correspondingly, uranium ore, could be processed. For example, an estimated enrichment capacity in the DPRK by Braun et al., is ∼34,660 kg-SWU per year.[84] Assuming a continuous and steady LEU or HEU production, ∼35,000 kg-SWU means that only 56 tonnes of uranium from 260,000 tonnes of ore can be processed into ∼7 tonnes of LEU per year, or 35 tonnes of uranium from 165,000 tonnes of ore can be processed into ∼160 kg of HEU per year.

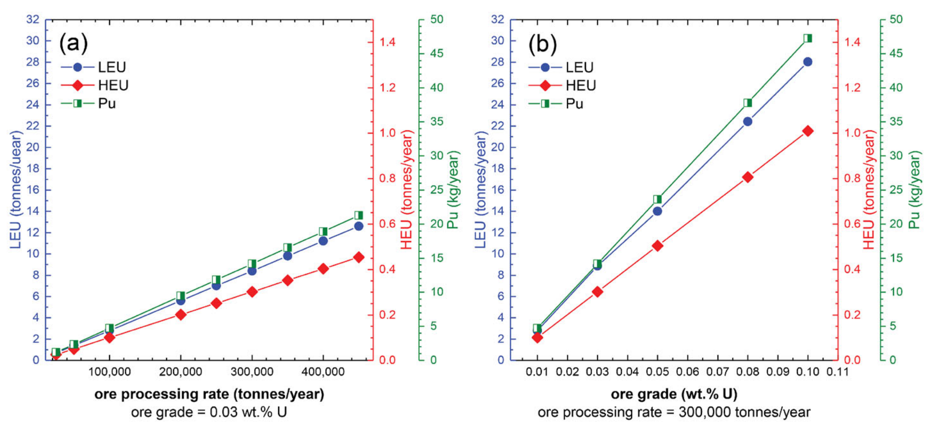

Figure 18. The maximum amount of LEU, HEU, or plutonium production as a function of (a) ore processing rate (when ore grade = 0.03 wt.% U) and (b) uranium ore grade (when ore processing rate = 300,000 tonnes per year), when all efforts are devoted to producing either LEU, HEU, or plutonum.

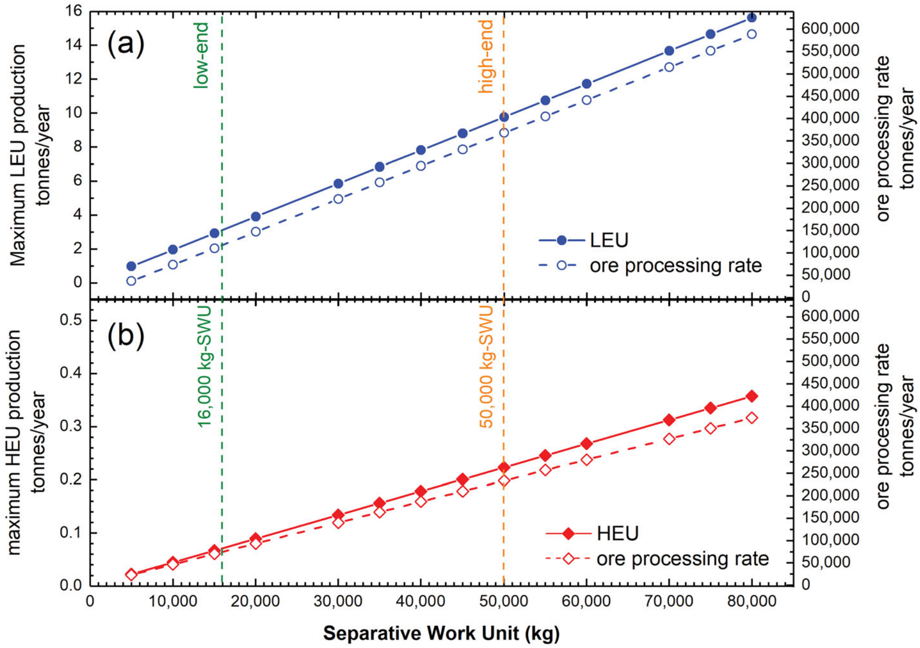

Figure 19. Annual production of (a) LEU or (b) HEU as a function of separative work unit. The maximum ore processing rates required for the corresponding (a) LEU or (b) HEU production are illustrated in dashed lines. This analysis assumes that all enrichment capacity is either devoted to the LEU or HEU production only.

The estimated enrichment capacity of the DPRK ranges from 16,000 to 50,000 kg-SWU per year.[85] The maximum amount of enriched uranium, and the corresponding yearly ore processing rate as a function of enrichment capacity is illustrated in Figure 19.

Conclusions

While technical characteristics of the Pyongsan facility and its mill equipment indicate that it could process, at maximum, ~360,000 tonnes of uranium ore yearly, this does not mean that the DPRK has been processing this quantity of ore. Indeed, analysis of mill tailings pile expansion rates suggests a much lower ore processing rate. While these are based on rough estimates of the tailings pile volume, it is clear that the DPRK appears to have substantially more milling capacity than it has been using to date. This means that the DPRK could produce much greater quantities of milled natural uranium if desired, and if enough uranium ore is available, enabling them to fuel their reactors while also expanding their HEU and plutonium inventory. Furthermore, the available capacity at the Pyongsan milling facility precludes the need for other uranium milling facility of comparable size, as all uranium needs are covered.

Analysis of satellite imagery may not provide a complete view into the operation of the DPRK's uranium ore processing and yellowcake production today. However, given the paucity of information on this activity, such work provides critical input as one attempts to estimate the DPRK's nuclear materials production capabilities. As imagery data with improved spatial and temporal resolution, or complementary data sources, become available, methods demonstrated in this study will allow for more refined determination of the DPRK's production of nuclear fuel and uranium.

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39. Schmerler, "A Satellite Imagery Review of the Pyongsan Uranium Mill"; Bermudez et al., "Pyongsan Uranium Concentrate Plant (Nam-chon Chemical Complex)"; Bermudez et al., "Recent activity at the Pyongsan Uranium Concentrate Plant (Nam-chon Chemical Complex) and January Industrial Mine."
40. U. S. Department of Energy, Office of Operational Safety, "Evaluation of the 1943-to-1946 liquid effluent discharge from the Linde Air Products company ceramics plant," Aerospace Report No. ATR-82 (7963-04)-2, Appendix B. Prepared by the Environment and Conservation Directorate, Eastern Technical Division, The Aerospace Corporation, December 1981.
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49. Pabian et al., “North Korea’s Uranium Mining and Milling Operations Continue at Pyongsan.”
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51. International Atomic Energy Agency, *Manual of acid in situ leach uranium mining technology* (Vienna: International Atomic Energy Agency, 2001).
52. One week supply of acid is typically considered adequate unless the supply chain is especially unreliable.
53. Schmerler, “A Satellite Imagery Review of the Pyongsan Uranium Mill”; Bermudez et al., “Pyongsan Uranium Concentrate Plant (Nam-chon Chemical Complex); Bermudez et al., “Recent activity at the Pyongsan Uranium Concentrate Plant (Nam-chon Chemical Complex) and January Industrial Mine.”
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63. For uranium processing, the oxidation reduction potential is approximately +525 mv while the pH is ∼1.5, whereas vanadium requires an oxidation reduction potential of approximately +650–700 mv, and a pH of 1. To increase the oxidation reduction potential, more oxidants are required, and to reduce the pH, additional acid is added. H_2SO_4 acid is normally stored at 98% concentration.
64. See for example, "Uranium Concentrates: Industry Good Practices for ISO Containers in Multimodal Transports," Revision 0, World Nuclear Transport Institute, 2008, https://web.archive.org/web/20160804115410/.
65. U.S. Nuclear Regulatory Commission, "Uranium Conversion" 2 December 2020, www.nrc.gov/materials/fuel-cycle-fac/ur-conversion.html.
66. Under the nuclear safety guidelines and on a well-maintained track by widely accepted industry standard, each boxcar can hold approximately 20 drums of yellowcake. The standard used in the DPRK may be different.
67. Gondola-type railcars likely bring in coal for the thermal plant, and tank-cars most likely carry chemical reagents.
68. Edward R. Landa, "Uranium Mill Tailings: Nuclear Waste and Natural Laboratory for Geochemical and Radioecological Investigations," *Journal of Environmental Radioactivity,* 77(2004): 1–27, https://doi.org/10.1016/j.jenvrad.2004.01.030.
69. The mill tailings are different from the mine tailings, in that mill tailings are generally reduced in size, processed through a chemical separation, and the remains generally do not contain uranium. Whereas the mine tailings refer to rocks that cannot be processed due to poor quality. A preferred industry convention of the term mine tailings is "mine waste."
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