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OCCASIONAL PAPER

#34 · DECEMBER 2017

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Cover image: May 2, 2017, optical image of Pyongsan uranium mine, Democratic People's Republic of Korea. Image copyright 2017 DigitalGlobe, Google Earth.

Open-Source Monitoring of Uranium Mining and Milling for Nuclear Nonproliferation Applications

by Jeffrey Lewis, Melissa Hanham, Joshua Pollack, Catherine Dill, Raymond Wang[1]

Uranium mines and mills represent the front end of the nuclear fuel cycle—where nuclear material originates. Uranium ore is brought out of mines and processed into uranium oxide, also called "yellowcake," at mills. Mines and mills are therefore important chokepoints for monitoring nuclear activity in states of proliferation concern. Because of their size and distinctive surface features, they are more readily identifiable in satellite imagery than uranium conversion or enrichment facilities.

Although mines and mills are not typically safeguarded by the International Atomic Energy Agency (IAEA), the challenge posed by unmonitored sources of uranium is obvious. When the existence of a new uranium mine and mill near Gchine, Iran, was revealed in the mid-2000s, the international community immediately understood that an undeclared new source of uranium represented a potential first step along a pathway running through covert enrichment sites and, possibly, to a nuclear weapon.[2] One of the main safeguards innovations in the 2015 Joint Comprehensive Plan of Action was the imposition of a 25-year monitoring requirement on all of Iran's uranium mines and mills to guard against a flow of unsafeguarded uranium into covert pathways toward a bomb.

Similarly, the amounts of yellowcake uranium produced from mines and mills in North Korea, China, India, and Pakistan are of great importance to analysts trying to assess the scale of uranium-enrichment activities in these countries.

At the moment, nonproliferation analysts are attempting to assess the state of production at uranium mines and mills for nonproliferation purposes using open-source information, including high- and medium-resolution satellite images. Additionally, researchers can aggregate publicly available geographic information about mining and milling to enhance their understanding.

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[1] *This is the first of a series of monographs funded by the MacArthur Foundation. It deals primarily with how researchers can use open-source information to monitor uranium mining and milling in the service of arms control, disarmament, and nonproliferation goals. Additional monographs will provide regional cases studies in North Korea, China, India, and Pakistan to demonstrate what these methods can reveal – and what they cannot. The final monographs look at the emerging, and potentially revolutionary, role of remote sensing for this application and gives policy recommendations.*

[2] For additional context on the Gchine mine, see Jeffrey Lewis, "Gchine (Gehine)," *Arms Control Wonk*, September 4, 2005, available at https://www.armscontrolwonk.com/archive/200756/gchine-gehine/.

Locating Uranium Production

In many cases, the location of uranium mines and mills is a matter of public record. Corporations usually publicize their exploration and production activities. Countries that produce significant amounts of uranium ore typically provide estimates of their national uranium resources and production to the International Atomic Energy Agency (IAEA) and the Nuclear Energy Agency (NEA) of the Organisation for Economic Co-operation and Development (OECD), which jointly publish this information every two years in a new edition of the "Red Book."[3] The latest edition includes official reports from 37 countries. Information on known uranium deposits is also available online in UDEPO, an IAEA database.[4]

Naturally, the information in these public sources cannot be presumed to be perfectly accurate or comprehensive. Even if all the national reports in the Red Book were beyond reproach, not all states submit information on uranium deposits and production in the first place. In some cases, states do not submit because they lack significant known uranium resources. In other cases, states consider information on their uranium resources and exploitation to be sensitive information, impinging on national security. States in the latter category prefer to operate mines and mills with minimal transparency and accountability to the outside world.

Still, it is possible to create baseline information for states that treat their uranium resources and production as sensitive. In some countries, exploitation activity is reported unsystematically, in occasional public statements or news reports. Based on public descriptions and even a small number of images, it is usually possible to geolocate uranium mines and mills. For example, researchers have mapped the uranium-production infrastructure of both North Korea and Pakistan, despite efforts made by both countries to keep this information out of the public domain.[5]

Assessing Uranium Production

Once a uranium mine or mill is located, there are several ways analysts might assess the scale of production.

For underground mines, the most straightforward approach is to monitor piles of spoil, the dirt from excavation, which is usually dumped in front of a mine. The size of these piles directly correlates with the amount of mining, although the volume is often difficult to

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[3] NEA and IAEA, *Uranium 2016: Resources, Production and Demand* (Paris: OECD, 2016).
[4] IAEA, *World Distribution of Uranium Deposits (UDEPO) with Uranium Deposit Classification,* IAEA-TECDOC-1629 (Vienna: IAEA, 2009). Online, see the UDEPO database: https://infcis.iaea.org/UDEPO/Deposits.
[5] For North Korea, see: Jeffrey Lewis, "Recent Imagery Suggests Increased Uranium Production in North Korea, Probably for Expanding Nuclear Weapons Stockpile and Reactor Fuel," *38 North*, August 12, 2015. For Pakistan, see: Zia Mian, A. H. Nayyar, and R. Rajaraman, "Exploring Uranium Resource Constraints on Fissile Material Production in Pakistan," *Science and Global Security,* (2009), 17:77–108.

estimate because the piles are not uniform shapes and are often dumped onto sloping ground. In general, analysts use changes in spoil piles to determine whether a mine is active while using other methods to estimate its production.

Many mines are co-located with milling infrastructure, which can be assessed to determine the scale of activity at the mine. Scholars at the National Institute of Advanced Studies (NIAS) in Bangalore, India, have developed an empirical methodology for identifying uranium mining and milling activities and estimating this capacity from satellite images.[6]

These scholars propose to conduct identification and monitoring based on focusing on the visual features of the uranium mines and mills in commercial satellite images. This approach starts by cataloging the specific and identifiable signatures shapes and features associated with known uranium-mills and then correlating them with material flow at a site of interest.

Uranium milling uses various processes, which are associated with equipment that might be observed in satellite imagery: crushing and grinding utilizes grinders; leaching utilizes leach tanks, acid plants, and reagent storage; solid–liquid separation utilizes counter-current decantation and filters; concentration/purification utilizes solvent extraction; precipitation is then filtered; and drying utilizes centrifuge dryers. In addition to being useful for identifying uranium mills, the authors posit that the volumetric capacity of much of this equipment can provide estimates for the volume of uranium ore processed at the mills. One limitation of this approach is that the associated equipment is not always visible, or the spectral resolution of a satellite image is not high enough to measure with sufficient accuracy.

Similarly, this approach attempts to understand how to distinguish uranium mills from other types of mills which contain similar processes, most notably copper mills. (Zinc and vanadium mills also are similar.) The authors identify one key spatial feature of the uranium milling process to accomplish this: the sequence of acid or alkaline leaching. Additionally, they identify processes that would not be present at uranium mills but might be at copper, zinc, or vanadium mills, such as smelting facilities.

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[6] S. Chandrashekar, Lalitha Sundaresan, and Bhupendra Jasani, "Estimating Uranium Mill Capacity Using Satellite Pictures," NIAS Report R35-2015, December 2015; S. Chandrashekar, Lalitha Sundaresan, and Bhupendra Jasani, "Identification of Uranium Mill Sites from Open Source Satellite Images," NIAS Report R34-2015, September 2015; Lalitha Sundaresan, Chandrashekar Srinivasan, and Bhupendra Jasani, "Monitoring Uranium Mining and Milling using Commercial Observation Satellites," ESARDA Bulletin, December 2015; and, Lalitha Sundaresan, S. Chandrashekar, and Bhupendra Jasani, "Discriminating Uranium and Copper Mills Using Satellite Imagery," *Remote Sensing Applications: Society and Environment*, January 2017. For additional background, see also Christopher L. Stork, Heidi A. Smartt, Dianna S. Blair, and Jody L. Smith, "Systematic Evaluation of Satellite Remote Sensing for Identifying Uranium Mines and Mills," Sandia Report SAND2005-7791, Sandia National Laboratories, January 2006.

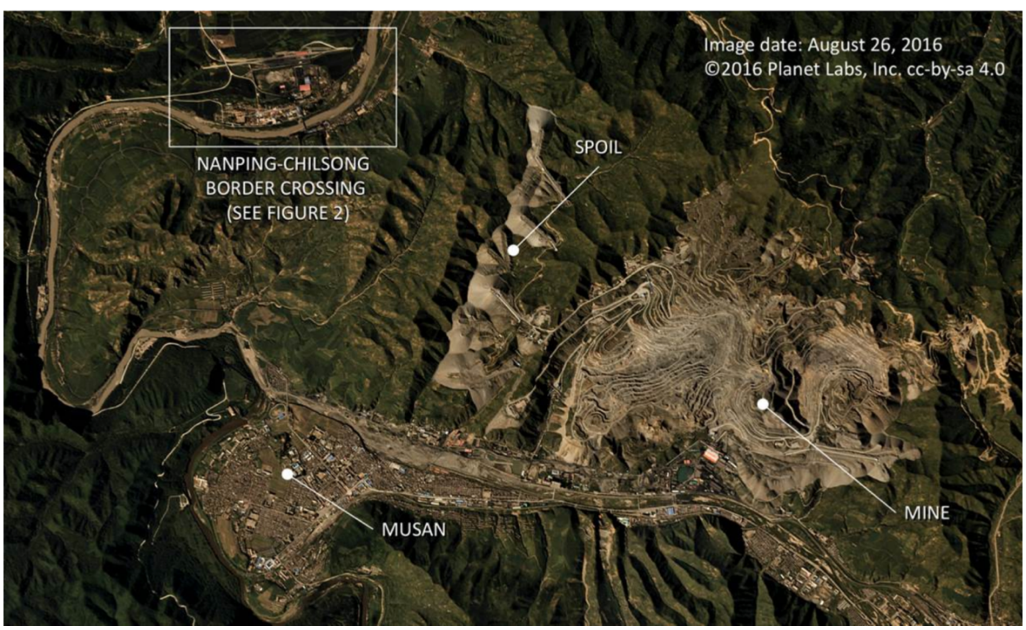
As a final step, the volume of tailings ponds at mills can also be measured in the same manner as spoil piles outside underground mines, although this type of analysis suffers from some of the same limitations with limited datasets and resolution.

New Technologies

These relatively straightforward methods can now be supplemented by three novel approaches that may allow more advanced monitoring of uranium-mining and milling infrastructure.

The first is to use algorithms that can detect changes or identify objects in satellite imagery. The San Francisco-based company Planet operates a constellation of satellites that photographs the entire Earth's surface of the earth every day. Most of these satellites produce medium-resolution imagery of about 3 meters of space per pixel. In many cases, this is enough to monitor changes to large features such as spoil piles and tailings ponds. This analysis may be strengthened with change-detection tools and pattern-detection algorithms.

Planet routinely monitors mines around the world, using daily imagery to detect mining operations: from revealing strip mining for coal in West Virginia to illegal gold mining near protected areas in Peru. CNS has worked with Planet to monitor the Musan iron mine in North Korea, which appeared to be exporting iron to China in violation of UN sanctions.



August 26, 2016, optical image of Musan iron ore mine, North Korea. Image © 2016 Planet, annotation by Jeffrey Lewis.

Planet is introducing a series of satellites that produce images up to 1 meter resolution. Additionally, its high-frequency imagery can be used to identify patterns of mining and milling facilities using deep convolutional neural networks. CNS is collaborating with open-source software companies to identify patterns in satellite imagery using pixel- and object-based detection algorithms by providing training data, human guidance, and verification of algorithms.

Researchers at the University of Missouri used similar techniques with high-resolution DigitalGlobe imagery to identify Chinese surface-to-air-missile sites. Not only could this software identify these sites many times faster than an unaided human, but it could also find sites not previously recorded in open sources.[7] It may be possible to create similar application for mining and milling sites, particularly because of the distinctive shadows and shapes associated with open-pit mining techniques.

Second, Synthetic Aperture Radar (SAR) creates radar images of locations with exceptional fidelity—a few tens of centimeters. Radar can penetrate thin roofs, which may allow analysts to assess the size of milling components *inside* buildings, depending on the roofing material. SAR also allows analysts to measure minute changes in surfaces, detect ground disturbances from vehicle traffic in arid climates, and even accurately measure changes in spoil and tailings.

Working with Airbus Space & Defense, CNS researchers analyzed subsidence of the mountains near North Korea's nuclear test site and detected changes in the height of the mountain using SAR.

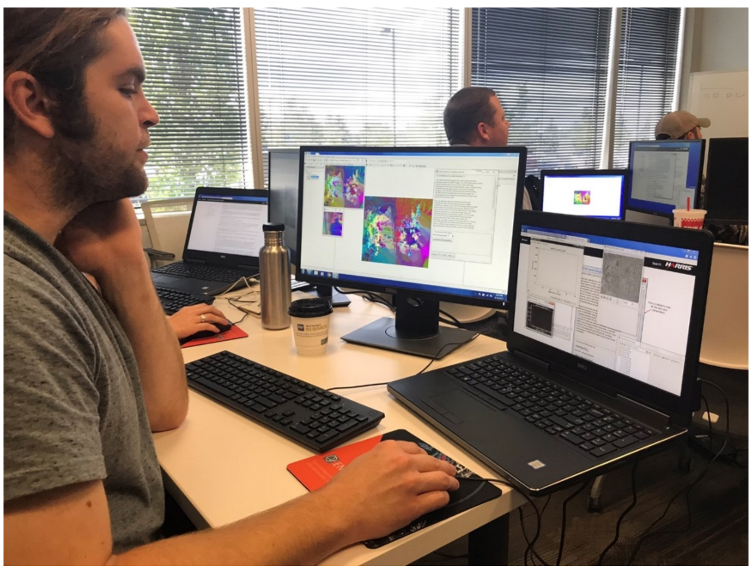
August 26, 2017, Synthetic Aperture Radar image of Punggye-ri nuclear-test site, North Korea.
Image © 2017 Airbus, software processing Radian software © DLR HR.

Third, hyperspectral sensors may allow analysts to assess the mineral content of mines and tailing ponds. Hyperspectral sensors capture light reflecting off objects much like traditional optical sensors. However, unlike traditional optical imagery, comprised of blue, green, red, and possibly near-

[7] Richard A. Marcum, Curt H. Davis, Grant J. Scott, and Tyler W. Nivin, "Rapid Broad Area Search and Detection of Chinese Surface-to-air Missile Sites Using Deep Convolutional Neural Networks," *Journal of Applied Remote Sensing,* (October, 2017), vol. 11, no. 4, https://www.spiedigitallibrary.org/journals/journal-of-applied-remote-sensing/volume-11/issue-04?SSO=1.

infrared wavelengths of light, hyperspectral imagery collects large—ideally contiguous—swaths of visible and non-visible light for the purpose of identifying the composition of the materials in the image. These spectral signatures can give important insights into land cover and are already being used to analyze environmental changes, agriculture production, availability or water, the oil and gas industry, and mining activity.

Researchers at CNS have trained on a software called ENVI, which provides the tools to process large blocks of data in the form of dozens or hundreds of spectral bands. ENVI also provides thousands of spectral signatures in a library that can be used to classify land. Researchers import data into the program, remove data that are effects of atmospheric reflectance, and classify minerals or other material based on the unique spectral signature in each pixel. Researchers false-color these images in order to produce geo-referenced maps classifying the ground.



September 13, 201,7 image of David Schmerler training on ENVI software to processes hyperspectral imagery at Harris Geospatial in Lousiville, Colorado, USA. Image © 2017 Melissa Hanham.

Using this technology to monitor uranium mining and milling is an obvious application of this technology. Hyperspectral imaging is now being used to assess uranium deposits.[8] The technology also has obvious implications for safeguards.[9]

To date, however, hyperspectral images have typically been collected by sensors aboard aircraft, not from space. A need to fly an aircraft or drone over the area of interest represents a significant limitation of this technology for arms control, disarmament and nonproliferation applications. To date, the only easily available source of hyperspectral data was collected by NASA's Hyperion orbital sensor, which was in orbit from 2000 until 2017.

The main challenge to developing commercially viable, high-resolution, space-based hyperspectral imaging is transferring the massive amounts of data collected by space-

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[8] For a recent example, see: Rodrigo dos Reis Salles *et al.*, "Hyperspectral remote sensing applied to uranium exploration: A case study at the Mary Kathleen metamorphic-hydrothermal U-REE deposit, NW, Queensland, Australia," *Journal of Geochemical Exploration* 179, August 2017, pp. 36-50.
[9] Q.S. Bob Truong *et al.*, "Hyperspectral and Multispectral Remote
Sensing at Uranium Processing Facilities," Proceedings. 25. Annual Meeting. Symposium on Safeguards and Nuclear Materials Management.

based sensors to ground-stations on Earth. Currently, a number of companies are attempting to solve this problem, including:

- Satellogic, which has offices in San Francisco as well as in South America, has raised $27 million in a second round of funding. It has six satellites in orbit, offering 30-meter spatial resolution.

- Planetary Resources, which was founded to take pictures of asteroids in search of space-based resources, raised $21.1 million to start an Earth-observation business called Ceres, taking advantage of their existing space-based assets.

- Hypercubes is a company that is early in development, but is focused on a novel solution involving on-board processing of data.

Other firms operating in this space include HySpecIQ and NorthStar.

Conclusions

Uranium mines and mills offer an important focus for the analysis of fissile-material production. It is possible to combine traditional research techniques with new tools and technologies to estimate the production of yellowcake uranium; such estimates can, in turn, be used to roughly estimate the throughput of a country's nuclear fuel cycle. In some cases, this may help researchers to determine whether undeclared fuel cycle facilities exist and to estimate their capacity.

These tools are evolving rapidly. First, constellations of small satellites with moderate resolution but high "cadence" (revisit rates) can be used to provide routine monitoring of mining activities, especially when combined with automated or semi-automated object- and change-detection tools. Second, SAR images allow for the detection of minute changes that can reveal traffic patterns at mining and milling sites, assess structures inside buildings not otherwise visible from space, and detect changes in the volume of spoil piles and tailings ponds. Third, hyperspectral imagery, if it becomes practical to collect and transmit it from space, may represent a breakthrough, allowing space-based spectral analysis of geologic deposits, spoil, and tailings.

These technologies, both extant and anticipated, allow outside analysts to confirm information declared by governments and detect omissions that might well be part of a cover nuclear weapons program. This information can be useful to outside analysts attempting to assess the size of a country's nuclear-weapon, nuclear-propulsion, and nuclear-energy programs. It can also be integrated into existing and future international safeguards and monitoring approaches. At a time where the availability of data is exploding, artificial intelligence and semi-automated techniques can offset some of the redundant and time-consuming tasks for imagery analysts and allow them to focus their energy on higher-level tasks instead.

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