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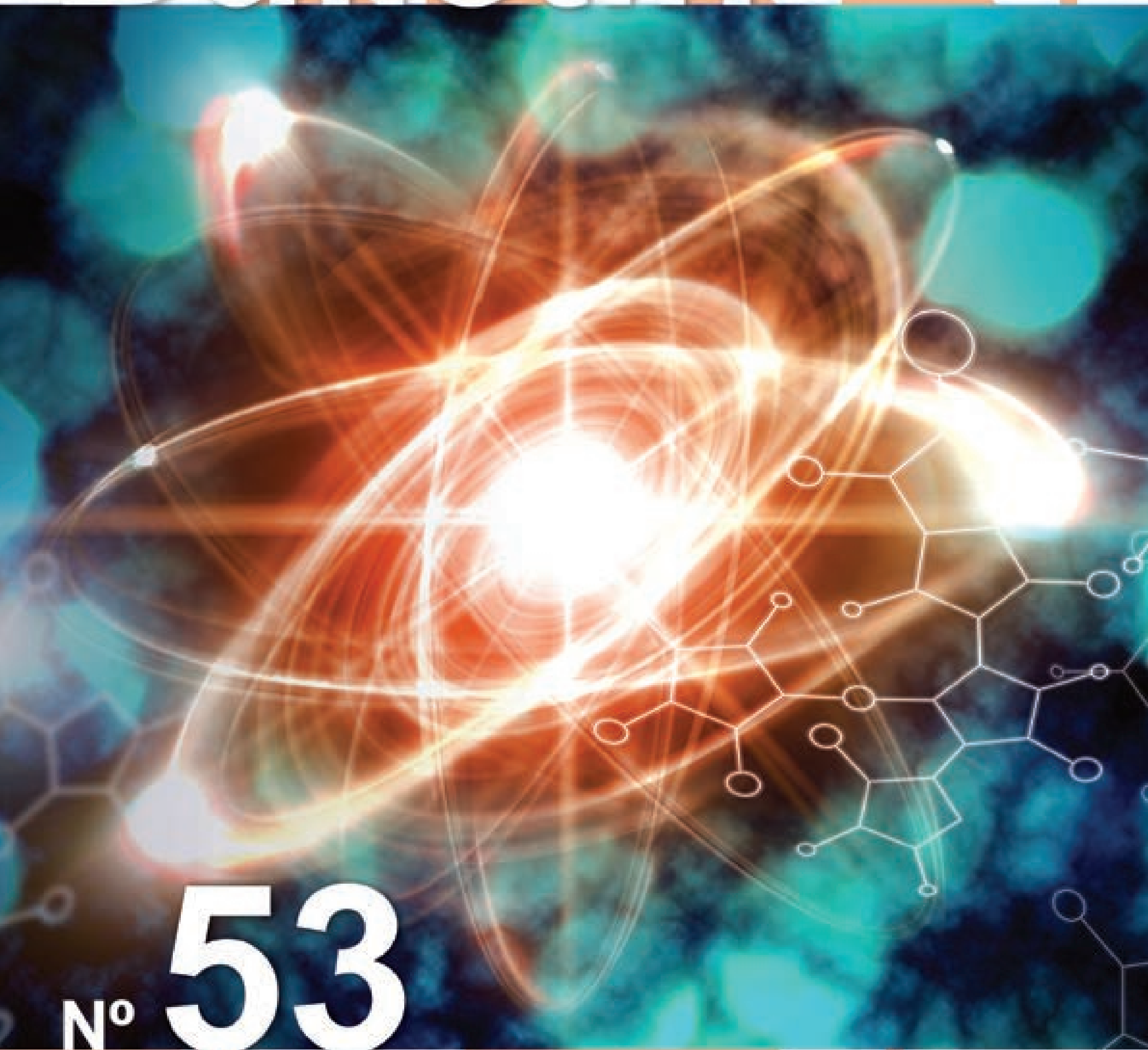

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Monitoring Uranium Mining and Milling using Commercial Observation Satellites

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Abstract:

All the states that have signed the Additional Protocol to their Safeguards Agreements with the International Atomic Energy Agency (IAEA) will need to submit description and information specifying the location of their nuclear fuel cycle activities, including their operational and shut down uranium mines. While satellite imagery is useful for monitoring changes in the declared nuclear facilities, there has not been much discussion of using this imagery to monitor the early part of the nuclear fuel cycle namely uranium mining and milling.

The availability of satellite data cost free on the Google Earth web site and commercially from various imagery providers makes it possible for analysts to make assessments concerning the nuclear fuel cycle activities of various countries of interest. The mining of uranium and its conversion through a milling process into U_3O_8 (yellowcake) is the first step of a complex conversion cycle that determines how the mined material will be used.

Our study discusses the use of satellite imagery for identifying and monitoring uranium mining and milling activities. In the study an attempt is made to answer the following questions:

1. Can we identify uranium mines using openly available satellite imagery?

2. Can we use various steps in uranium milling operations to identify such mills across the world?

3. Are there other extraction processes that share similar features with those for uranium? If so, then are there any special features present or absent in the sequence of operations for their extraction that helps an analyst separate a uranium operation from other operations that share some or all of the features present in the extraction of uranium?

Based on empirically derived observables and signatures from satellite imagery for typical uranium extraction operations we have derived a decision making algorithm for determining whether a particular facility can be categorized as a uranium mill or whether it should be categorized as some other facility.

The method has been used to look at some copper mills across several locations and have shown that the decision making algorithm does help us to separate out a uranium mill from a copper mill.

Keywords: Uranium mills, Fuel cycle, Spatial features, Uranium mines, International Safeguards, Satellite Images.

1. Introduction

The need to prevent nuclear weapons proliferation has been of serious concern for the last several decades. These concerns resulted in a number of bi-lateral and international arms control treaties. The treaty on the Non-Proliferation on Nuclear Weapons (NPT) was one such international agreement under which the parties undertook to limit the spread of nuclear weapons and related technologies by a series of measures while encouraging the peaceful uses of nuclear energy under international safeguards system implemented by the International Atomic Energy Agency (IAEA).

The safeguards system is used to verify compliance with the NPT through inspections conducted by the IAEA. While this system worked well for the declared nuclear activities of a party to the NPT, it became apparent that it was difficult for the Agency to detect undeclared nuclear activities. Thus, the Director General's Standing Advisory Group on Safeguards Implementation (SAGSI) recommended that, as one measure "assessment of the usefulness, technical feasibility, associated costs and acceptability of the Agency obtaining satellite photographs from commercial sources" should be carried out (SAR-17, Report to the Director General on the 38th Series of SAGSI meeting, 21-22 March1994). Eventually in 1997, the new safeguards Model Protocol Additional to the Agreement(s) between State(s) and the International Atomic Energy Agency for the Application of Safeguards, INFCIRC/540, was established. The implementation of this provides the Agency with the capability to detect undeclared materials and activities in a state. The use of open sources, commercial satellite imagery, further additional information and extended access to nuclear facilities and other locations gave the Agency credible assurance on the absence of undeclared nuclear materials and activities.

The IAEA gathers and analyses safeguards relevant information about a State from: (a) information provided by the State party to the safeguards agreement, (b) safeguards activities conducted by the Agency on the ground and (c) from open sources and third parties [1]. The IAEA's analyses consist of validation of information provided by the States against information collected by the Agency under (b) and (c) including that obtained from commercial satellite imagery. Information may differ depending on whether it is acquired under a comprehensive safeguards agreement (CSA), under a CSA together with the Additional Protocol Agreement (APA) or that obtained on a voluntary basis.

Under the Additional Protocol, the Signatory States have to provide "Information specifying the location, operational status and the estimated annual production capacity of uranium mines…" [2]. This has increased the amount and type of information that states will have to provide to the IAEA. At the same time, the verification workload of the IAEA inspectorate has also increased commensurately. Keeping in mind the security, or the lack of it, in the world in recent years, the IAEA is bound to find itself in a situation where physical verification of the declared nuclear facilities will become increasingly difficult, which will also include the expanded list of declarable facilities, including those that form the early part of the nuclear fuel cycle, e.g., uranium mining and milling facilities. Newer remote monitoring methods and technologies, such as non-intrusive commercial satellite-based imaging, can strengthen nuclear safeguards by making the IAEA's verification process more efficient [3].

In 2001, the IAEA's Satellite Imagery Analysis Laboratory (SIAL) became fully operational [4] and the Agency has been using commercial satellite images as a tool for safeguard purposes routinely and it has become one of the most important information sources that the IAEA's Department of Safeguards has for remotely monitoring nuclear sites and activities [5, 6]. With the Additional Protocol, that monitoring now also applies to the early part of the nuclear fuel cycle which includes uranium mining and milling. However, satellite imagery has not been used in a major way by the IAEA for looking at existing or newly created mining or milling operations and assessing whether they are used for the production of uranium.

The results of what can be learnt about uranium mining and milling using satellite imagery have been published in the open literature. For example spatial features associated with uranium extraction process are described in the Photo Interpretation Handbook [7]. During the Cold War period, the CIA monitored the uranium mining and milling activities in the USSR and Eastern European countries. Even as early as 1959, the CIA attempted to estimate production of uranium oxide in the Pyatigorsk Mill, USSR based on the ore grade and the size of the tailings pond as seen on aerial photography [8]. With the launch of the CORONA satellite in 1960, low resolution satellite images became available for intelligence gathering. Estimates of uranium production of the Steiu Plant in Rumania was however, not possible with this image based on the size of the tailings pond, because of the low resolution [9].

A few studies have been carried out to assess the effectiveness of high resolution satellite images as a tool for verification of safeguards agreements between the IAEA and various countries [10, 11, 12, 13, 14, 15, 16]. Some of these efforts try to define key features of a nuclear facility and seek to uniquely identify them in a satellite image. Evaluation of specific spectral and temporal characteristics of newer satellite sensors is also being carried out. Use of high resolution SAR and optical data for 3D analysis in the context of Safeguards has been of interest more recently [12]. Automated object based image analysis methods (involving the spectral signature, size, shape, proximity aspects of facility components) have been found to be particularly useful as demonstrated by Nussbaum and Menz [17].

The present paper is an effort to demonstrate the applicable aspects of commonly available satellite imagery for identifying and monitoring uranium mining and milling activities. Towards this it seeks to answer the following questions:

- Can we use the various steps in uranium milling operations to identify such mills across the world using commercially available satellite imagery?
- Are there other extraction processes that share similar features with uranium extraction processes? If so, how do we distinguish uranium mills from these mills in a satellite image?
- Is it possible to make an assessment of the uranium production capacity of a mill identified in a satellite image?

2. Past Work

A number of studies have reported the difficulties in uniquely identifying uranium mining and milling activities since the concentration of uranium is rather low at most places and does not show spectral characteristics that will help to uniquely identify it in a satellite image [18, 19, 20, 21]. The steps involved in the conversion of uranium ore to yellow cake were used to develop a set of keys to identify a uranium mill in a high resolution hyper-spectral satellite image. These studies demonstrated that the potential observables which are present in the uranium mining and milling operation, but not in copper mining and milling, include the discriminator station, pyrolusite (manganese dioxide) which is used as an oxidant in leaching, the pregnant uranium leach liquor produced in the sulfuric acid leaching process, the concentrated uranium strip solution generated from solvent extraction, and finally the yellowcake produced from the precipitation and drying steps. Most of these features do not have unique spectral signatures and their identification is further complicated by their small spatial extents. The Discriminator station or the Radiometric sorters perhaps could be identified with high spatial resolution data available these days.

Using the Ranger mine and mill as an example, researchers at the Sandia National Laboratory analysed the potential use of multi-spectral as well as hyper spectral data from a number of remote sensing satellites to separate out any unique features of a typical Uranium mining and milling operation [22]. Apart from magnesium chlorite the only other identifiable signature came from the Sulphur heaps at the Ranger site which is used to manufacture sulphuric acid for the acid leaching process at Ranger. The study concluded that hyperspectral data could not distinguish between uranium processes from other milling processes such as that of copper, zinc, vanadium, phosphorous and Rare Earths. Further the study pointed out that while high spatial resolution satellite systems such as Quickbird lack sufficient spectral resolution to uniquely identify many materials, spatial information provided by these systems could complement information obtained from high spectral resolution systems such as Hyperion. A unique aspect of this study however, was the creation of a decision tree that linked each step in the milling operation at Ranger to similar processes used in the extraction of other materials of commercial and strategic importance.

An important conclusion that emerges from these studies is that it is difficult to identify a uranium mill using only spectral signatures be it multi spectral or hyper-spectral satellite images. Perhaps in the future, with higher spatial resolution hyper-spectral imagery, such discrimination of sulphur heaps and uranium ore piles might be possible. It is also recognized that a combination of the hyper spectral images along with radar images are definitely useful to monitor the activities of a milling site and record changes that may be happening for various purposes, clandestine or otherwise [23].

3. Our Approach

As the commercial satellite images are expensive, we have largely relied on the images published cost free on the Google Earth (GE) web site.

While it is recognized that the IAEA would require the latest data, it could use GE images to study the historical development of a particular site.

In our approach a set of keys for identification of a uranium mill is developed based on the spatial features of the equipment used in the milling operations instead of looking for spectral signatures.

This is achieved by interpreting the GE images of a large number of commercial uranium mills across the world.

A comprehensive understanding of the spatial signatures of the uranium operations at each site is built up using the process flow sheets of the mill along with publicly available information about the mill.

Together with the Google Earth (GE) image of the mill, the keys for identification are developed.

The most commonly occurring features in the sample sets along with their signatures are then used to decide whether a mill seen on a satellite image is a uranium mill or not.

4. Uranium Milling Process

The process of uranium extraction is very well known [24]. However, to integrate it with our study, a schematic of a typical process for the extraction of uranium from its ore is shown in Figure 1.

The associated equipment / reagents with each of these steps are also shown in the figure.

Our objective is to determine which of the equipment are unique to a uranium milling operation and visible and identifiable in a satellite image.

For the purpose of this study we have not considered those mills that use heap leaching as the only method for leaching.

The reason for this omission is that the process steps involved in this case will differ slightly and it may not be possible to uniquely identify such mills in a satellite image.

We selected 11 uranium milling operations and our sample set is shown in Table 1.

The imagery available on GE for each of these mills was studied in detail along with other publicly available information.

The set of observables that we could identify from these images formed the basis for identifying the key observables needed to identify a uranium mill.

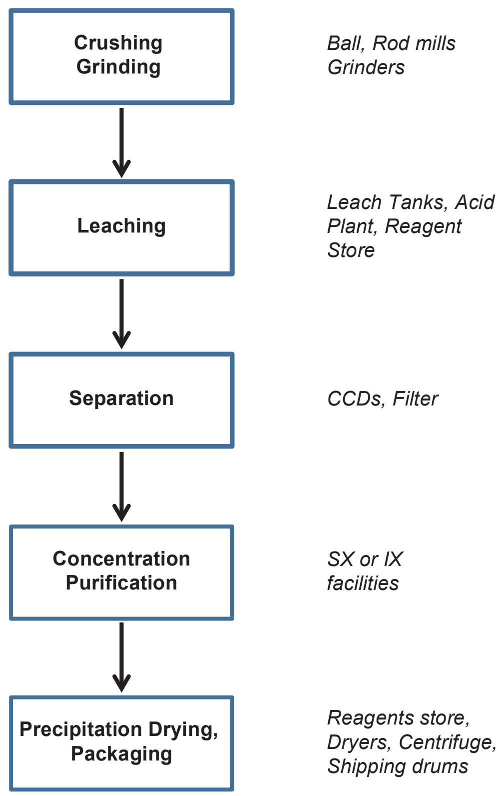

Figure 1: Simplified Overview of the Steps involved in Uranium Milling Process

Country	Mill Name	Location (Lat / Long)	Owner	Start Year
USA	Sweet Water	42 03 N 107 54 W	Shut Down	1981
Canada	Rabbit Lake	58 15 N 103 40 W	CAMECO	1975
Australia	Ranger	12 41 S 132 55 E	ERA	1981
Canada	Mclean Lake	58 21 N 103 50 W	Areva	1999
Canada	Key Lake	57 13 N 105 40 W	CAMECO	1983
Niger	Arlit	18 47 N 7 21 E	Areva	1970
Namibia	Rossing	22 28 S 15 03 E	Rio Tinto	1976
Namibia	Langer	22 49 S 15 20 E	Paladin	2006
Russia	Krasnokamensk	50 06 N 118 11 E	Argun	1968
Czech Republic	Rozna	49 30 N 16 14 E	DIAMO	1958
Romania	Feldiora	45 50 N 25 30E	State Owned	1978

Table 1: Sample set of Uranium Mills

5. Observations from Satellite Images of a Uranium Mill

The uranium mill features observable in a satellite image for the sample sites are summarised in Table 2

Though crushing, grinding and slurry preparation facilities are identifiable in most of the images they do not offer any special features associated with only a Uranium Milling operation.

Radiometric sorters are used in many Uranium mills to improve the ore quality. While they can be identified in the satellite images of some of the mill or mine sites, we could not identify them in all the mills or mines of our sample set.

The most commonly visible feature in the satellite image is the Counter Current Decantation (CCD) unit, used in the solid / liquid separation process. Figure 2 shows some typical CCDs of some of the mills. In all the cases except the Sweet Water mill, this feature is easily identifiable. The Sweet Water mill was closed down in 1984 and according to published reports the CCD is housed inside a building.

There are several features associated with the leaching process. Some feature or the other is seen in all the mills.

	Acid Plant	Sulphur store	Acid/Alkali store	Hot Leach	Leach tanks	CCD	SX	IXColumn	NH_3 tanks
Sweet Water	NA	NA	S	NS	NS	NS	Building?	NA	S
Rabbit Lake	S	S	S	NS	S?	S	Building?	NA	S
Ranger	S	S	S	NS	S	S	Pattern seen	NA	S
Mclean Lake	S	S	NS	NS	NS	S	Building?	NA	S
Key Lake	S	S	S	Smoke	NS	S	Building?	NA	S
Arlit	S	S	S	NS	S	S	Pattern Seen	NA	S
Rossing	S	S	S	NS	S	S	Pattern Seen	S	NS
Langer Heinrich	NA	NA	S	Heat Exch.	S	S	NA	S	NA
Krasnokamensk	S	NS	S	Chimney Seen	Autoclave	S	NA	S	NS
Rozna	NA	NA	S	Smoke	NS	S	NA	NS	NS
Feldiora	NA	NA	S	Chimney seen	Autoclave	S	NA	S	NS

S – Seen, **NS** – Not Seen, **NA** – Not Applicable

Table 2: Uranium Mill Features Observable in a Satellite Image

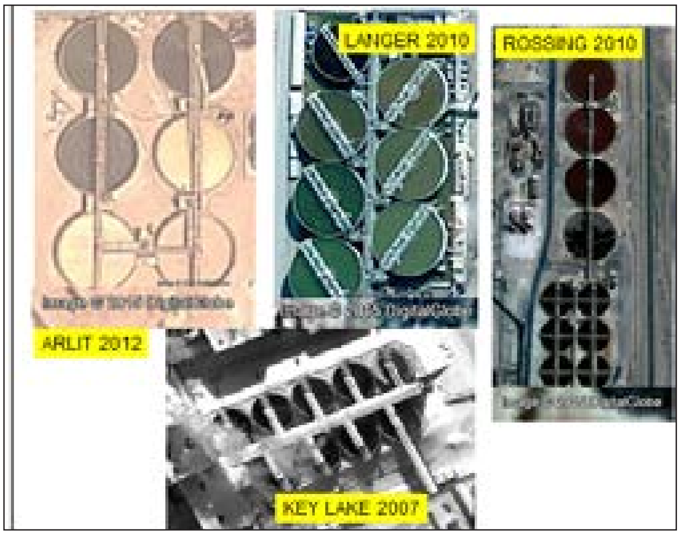

Figure 2: CCD units as seen in a Google Earth (GE) satellite image (Key Lake Image was obtained separately from DigitalGlobe)

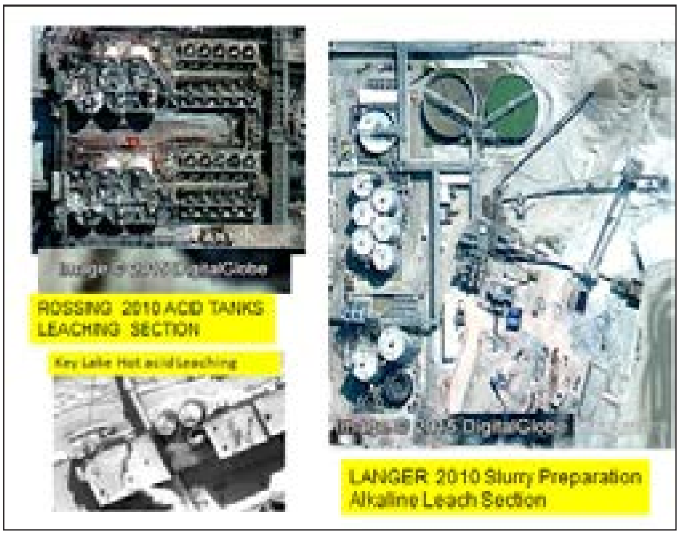

Figure 3: Leaching equipment as seen in Google Earth satellite image (Key Lake Image was obtained separately from DigitalGlobe)

Of the 11 mills Langer Heinrich, Rozna and Feldiora use alkaline leaching, while the other mills use acid leaching. Since alkaline leaching involves higher temperatures; one can look for evidence of chimney, heat exchangers or even smoke. Additionally in the case of acid leaching one can see either the acid plants or the leach tanks and sometimes the acid storage tanks close to the leaching facility.

Figure 3 shows typical leach tanks and leaching sections of some of the mills in our sample.

Unlike the CCDs, the leaching facility is difficult to identify and requires knowledge of the process being employed in the mill. However, we do know that the leaching operation follows the ore preparation step and is followed by separation and therefore the sequence of operation helps to identify some of the leaching features.

The next feature of interest is the equipment associated with the process of concentration and purification. In most mills this is done using either the solvent extraction (SX) columns or the ion exchange (IX) process. Occasionally a combination of both may be used.

The SX columns are housed inside a building and thus not readily identifiable. In our sample mill sites we, however noted that the SX columns are housed inside a sequence of identical buildings and linked to these are the storage tanks containing the solvents used in the SX process (Figure 4).

The IX columns are usually left in the open and are visible in the satellite image (Figure 5).

The features associated with precipitation, drying and calcining are not uniquely identifiable in a satellite image. In most cases they have to be identified indirectly by the presence of containers holding solvents and reagents used for this purpose. Proximity to the SX or IX facilities of such features is another aspect that we can use to identify this facility. In some of the mills where ammonia is used, the ammonia cylinders are seen clearly in the satellite image.

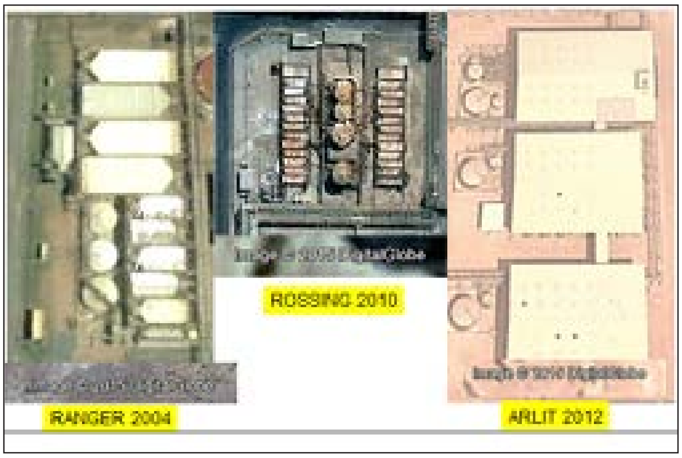

Figure 4: Solvent Extraction Buildings as seen in a Google Earth satellite image

To summarise the procedure for identifying a uranium mill from a GE image, we first identify the CCD circuit; then try to locate the leaching facility upstream. If the CCD process is followed by a SX or IX facility, we could conclude with high level of confidence that the facility is a uranium mill.

This approach has certain limitations because many other mineral extraction processes are very similar to the uranium extraction process. For instance the process steps of copper, zinc and vanadium are very similar to Uranium. Of these it is most difficult to discriminate copper and uranium extraction processes spectrally in a satellite image.

By identifying spatial features that are unique to copper mills, we will be able to differentiate a uranium mill from a copper mill.

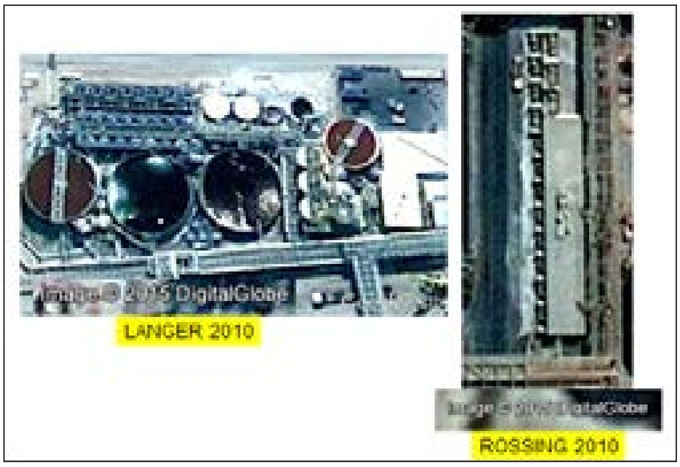

Figure 5: Ion Exchange columns as seen in a Google Earth satellite image

6. Copper Extraction Process and Observables in a Satellite Image

The major steps involved in a copper extraction process are shown schematically in Figure 6.

A major difference between copper and uranium is the scale of operation. Invariably due to economic considerations, the copper processing facility will be several times larger than the uranium operation.

Copper occurs mostly in the Sulphide or Oxide forms. While the crushing and grinding steps are common to all extraction processes, the process steps in the case of sulphide ore are different from that of the oxide ore. This is shown in the Figure 6.

The sulphide ore goes through a froth flotation process after the initial crushing and grinding which concentrates the copper part. The froth from the flotation process contains the bulk of the copper. The froth is dried and then sent directly to a smelter. The smelter may be located at the mill site or may be located elsewhere. The smelter converts the copper concentrate into blister copper which is further refined to produce anodic copper and finally goes through an electro winning step to produce high purity copper.

The tailings from the froth flotation may also contain copper which could be recovered. These tailings are leached with sulphuric acid, passed through a series of CCDs followed by a solvent extraction step. The copper solution that comes out of the solvent extraction step is then sent to an Electrowinning Facility for the extraction of copper.

Thus a mill which processes low grade copper ore or a part of a copper mill which processes the tailings from a froth flotation process will look similar to a uranium mill. It will have the features such as CCD circuits, SX units in addition to the acid leach facilities that we have seen in a uranium mill.

However, the differentiating factor for the extraction of copper from flotation tailings is that after solvent extraction it goes to an electro winning facility instead of a precipitation facility. Since such an electro winning facility has a typical signature evidence of this step in a satellite image can be used to separate out a Uranium mill from a copper mill.

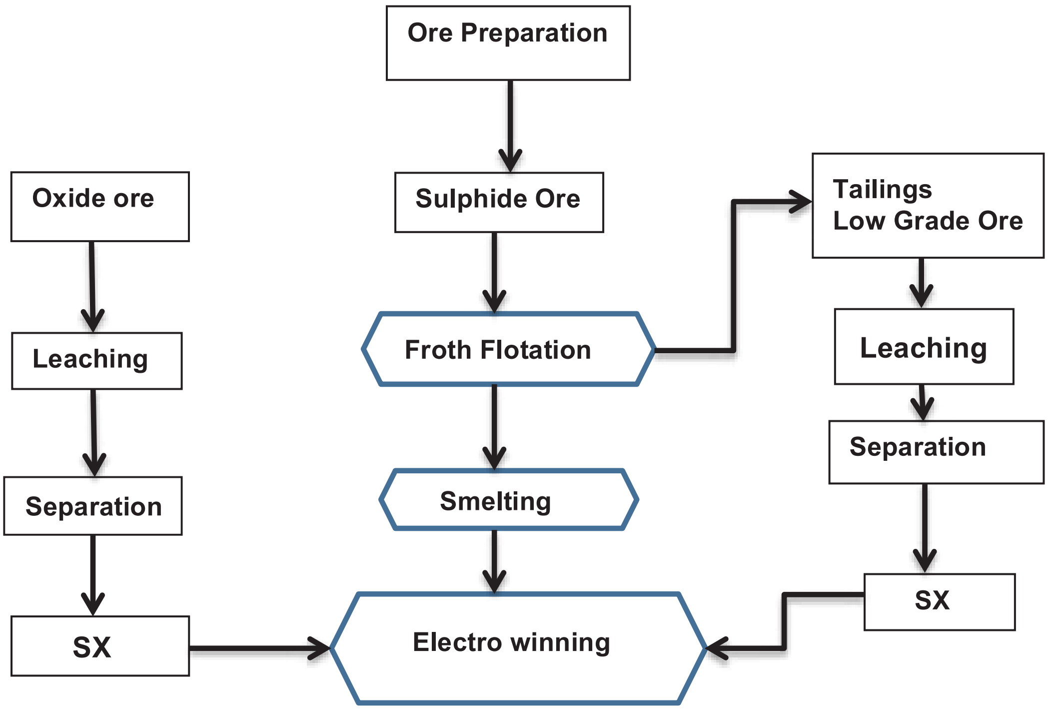

Figure 6: A Simplified Diagram showing the Copper Extraction Process Steps

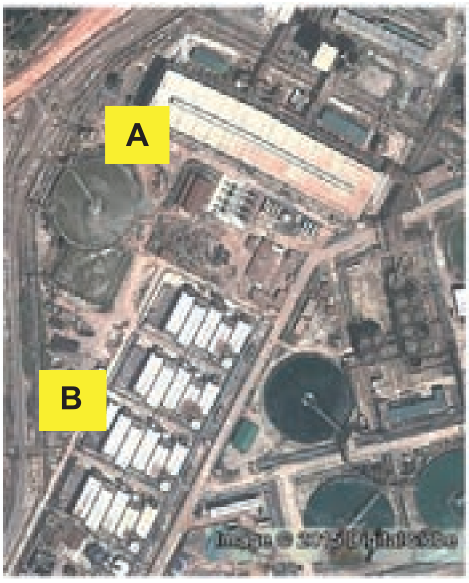

Figure 7: Google Earth image of Nchanga Copper mill (A – Electrowinning, B – SX)

Figure 7 shows a typical electro-winning facility as seen in a satellite image.

In the figure the long building (A) is an electro winning facility which can be easily identified and this is co- located with the solvent extraction facility in the foreground (B).

Copper occurring in the oxide form is typically leached using sulphuric acid after suitable crushing and grinding. Following concentration through a solvent extraction process the solution containing copper is sent to an electro-winning facility. Depending on the concentration of the ore the leaching step may also be followed by a CCD sequence prior to solvent extraction and electro-winning.

Again the differentiating step between copper and uranium is the electrowinning facility.

7. Key Differentiators for a Uranium Mill

The sequence of Acid or Alkaline leaching – CCD – solvent extraction – precipitation is typical of all Uranium mills.

The CCD unit of these mills is the most amenable to observation from satellite. Though its absence does not completely rule out Uranium, its presence is a robust indicator of a potential Uranium milling operation.

The leaching step is the next most visible feature in a satellite image. Both direct and indirect signatures are available to make inferences about this step. The absence of a leaching process rules out a Uranium mill.

Thus the sequence of CCD preceded by a leaching step provides a baseline signature for a possible Uranium Mill.

In many cases solvent extraction facilities have features such as repetitive identical buildings close to the CCDs that can be identified through satellite imagery.

Ion exchange facilities can be seen in a satellite image unless in rare cases they are housed inside buildings.

In the case of precipitation, storage tanks for the various chemicals and their location in the flow of material provide some indications. Ammonia tanks used in many cases for the precipitation of Uranium are often identifiable in a satellite image. Along with a CCD and a leaching step Ammonia tanks provide a firm indication of a Uranium extraction operation.

Since the solvent extraction or ion exchange or even the precipitation steps in a Uranium mill do not provide very robust signatures one way to enhance the reliability of our classification is to eliminate other materials that share the Leaching - CCD - Solvent Extraction sequence.

Copper extraction mills that may in some cases share a similar Leaching – CCD – Solvent extraction sequence can be eliminated by the presence of Electro-winning, Smelting and froth flotation facilities in such extraction processes. All of these have clear signatures and can be identified easily in a satellite image. Through such elimination of various alternatives that share the leaching step and in some cases the CCDs as well as solvent extraction steps, we can increase the probability that the mill we are seeing is indeed a Uranium Mill.

8. Assessment of Production Capacity

Using the observables from the satellite image such as the number of CCD circuits, the diameter of the CCD in a mill along with the average ore grade, we have been able to arrive at an empirical equation to estimate the production capacity of the mill.

The equation was derived linking the nominal production capacity data of the sample mills in our study with the measurements made on the satellite images of these mills.

The equation is in exponential form:

$$P = k * G^a * N^b * A^c$$

Expressed in log form and estimating the coefficients k, a, b and c using the sample data gives,

$$\text{Ln } P = 3.112976 + 0.457613 * \text{Ln}G + 0.956309 * \text{Ln } N + 0.561587 * \text{Ln } A$$

Where,

k = Constant
G = Ore grade in percentage U_3O_8
N = Number of CCDs
A = Area of the CCD in meter square.

The data used for this purpose is shown in Table 3.

The nominal capacity for the mills is taken from the Red Book.

The estimated production values for the mills from the empirical equation are also shown in the table for comparison.

The results are reasonably good except for the Russian Mill.

Agencies such as IAEA having access to more accurate data will be able to improve upon these estimates.

Country	Mill Name	Ore Grade (% U_3O_8) G	CCD Nos. N	CCD Diameter (meters) D	Nominal Production Capacity (tonnes) P	Predicted Capacity (Tonnes)
USA	Sweet Water	0.048	6	9.752782825	350	401.41
Canada	Rabbit Lake	0.79	4	30.00530739	4615	3467.43
Australia	Ranger	0.13	8	34.65020841	4660	3463.12
Canada	Mclean Lake	1.22	8	12.85019021	3077	3166.65
Canada	Key Lake	3.40	8	20.00353826	7200	8320.77
Niger	Arlit	0.30	6	23.00650697	2330	2434.56
Namibia	Rossing	0.03	10	56.32028518	4000	3781.54
Namibia	Langer	0.05	7	23.15041609	1425	1251.39
Russia	Krasnokamensk	0.18	6	52.01257401	3000	4817.18
Czech Republic	Rozna	0.378	5	24.98407136	3200	2493.75
Romania	Feldiora	0.12	4	28.00705098	1120	1354.75

Table 3: Data from the Sampled Mills (All data taken from Uranium 2009: Resources, Production and Demand, A joint Report by OECD NE Agency and IAEA, 2010, commonly called the Red Book)

This estimation process is applied to an Indian mill at Turamdih, Jharkhand.

This mill uses acid leaching and ion exchange. (See Figure 8).

The mill processes uranium ore of grade 0.034%. In the satellite image we can identify 3 CCDs of diameter 13m.

Using the empirical equation, we estimate the production capacity of the mill to be 244 tonnes which compares well with the nominal capacity of 190 tonnes.

Figure 8: Google Earth Image of Turamdih Mill

9. Conclusion

This paper demonstrates how publicly available images from Google Earth can be a very useful research tool to identify a uranium mill. It is also a very useful tool to study the development of the mill site, as one can obtain past images.

It is possible to identify a uranium mill in a satellite image using the spatial features of the equipment used in the extraction process.

It is also possible to distinguish a uranium mill from a copper mill since the spatial features associated with the copper mill are different from that of the uranium mill. The presence of the electro winning facility in a copper mill enables us to differentiate it from a uranium mill.

An empirical equation is provided to generate a rough estimate of the production capacity of a uranium mill identified on a satellite image. The number of CCDs, the diameter of the CCD and the ore grade are the key factors used to make this estimate.

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References

[1] https://www.iaea.org/safeguards/safeguards-in-practice/information-collection-and-evaluation

[2] INFCIRC/540, Article 2(v), Model protocol additional to the agreement(s) between state(s) and the international atomic energy agency for the application of safeguards, IAEA, Austria, Reprinted 1998.

[3] Cooley, J. N., 2006, International Atomic Energy Safeguards under the treaty on the Non-Proliferation of Nuclear Weapons: Challenges in implementation In: Avenhaus, R., Kyriakopoulos, N., Richard, M., and Stein G. (ed), *Verifying Treaty Compliance, Limiting Weapons of Mass Destruction and monitoring Kyoto Protocol Provisions*, Springer, Berlin, 61-76.

[4] "Use of commercial satellite imagery in strengthening IAEA safeguards", Chitumbo K, Robb S and Hilliard J in Bhupendra Jasani and Gotthard Stein (eds.), *Commercial Satellite Imagery – A tactic in nuclear weapon deterrence*, Springer and Praxis, 2002, pp. 23-48

[5] IAEA Information Series, *Tools for Inspection*, Division of Public Information, 04-46161/F S Series 3/03/E.

[6] Steinmaus, K., Norman, C., Ferguson, M., Rialhe, A. & J. Baute (2013): The Role of the Geospatial Exploitation System in Integrating All-Source Analysis. In: Proc. INMM 54th Annual Meeting, 14-18 July 2013.

[7] Photo Interpretation Student Handbook., 1996, National Imagery and Mapping Agency, Pp 434 -439 (http://sites.miis.edu/geospatialtools2013/files/2012/07/Photo-Interpretation-Student-Handbook.-Photo-Interpretation-Principles.pdf)

[8] Joint Photographic Intelligence Report, Uranium mining and milling complex, Pyatigorsk, USSR, Unclassified Report Published CIA, 1959, Pp16. (http://nsarchive.gwu.edu/NSAEBB/NSAEBB186/doc01.pdf)

[9] Ruffner,K.C.., 1995, CORONA America's First satellite Program, History Staff Centre for the Study of Intelligence, CIA, 1995, Washington D.C., Unclassified Report.Pp 159. https://www.cia.gov/library/center-for-the-study-of-intelligence/csi-publications/books-and-monographs/corona.pdf

[10] Jasani,B, I Niemayer, S Nusbaum, B Richter and G Stein, *International Safeguards and Satellite Imagery*, Springer Verlag, 2009

[11] Richard, J M., Paquette J P, Elbez J, New and Emerging Trends in Satellite Imagery, Presented at IAEA 2014 safeguards Symposium, (https://www.iaea.org/safeguards/symposium/2014/home/eproceedings/sg2014-papers/000042.pdf)

[12] d'Angelo, P., Rossi, C., Minet, C., Eineder, M., Flory, M. & I. Niemeyer (2014): High Resolution 3D Earth Observation Data Analysis for Safeguards Activities. In: Proc. IAEA Symposium on International Safeguards: Linking Strategy, Implementation and People, Vienna, October 20-24, 2014 (https://www.iaea.org/safeguards/symposium/2014/home/eproceedings/sg2014-papers/000163.pdf)

[13] Niemeyer I, Listner C, Canty M.(2014), Advances in the Processing of VHR Optical Imagery in Support of Safeguards Verification, Paper Presented at Symposium on International Safeguards: Linking Strategy, Implementation and People IAEA-CN220, Vienna, Oct 20-24, 2014 Session: New Trends in Commercial Satellite Imagery. (https://www.iaea.org/safeguards/symposium/2014/home/eproceedings/sg2014-slides/000273.pdf)

[14] Niemeyer, I., Nussbaum, S. Tueshaus, J. Listner, C. (2013), Advances in detecting changes at nuclear facilities using very high-resolution optical satellite imagery, Paper Presented at 54th INMM Annual Meeting, Palm Desert, USA, 14 Jul 2013 - 18 Jul 2013.

[15] Canty, M., Jasani, B., Lingenfelder, I., Nielsen, A.A., Niemeyer, I., Nussbaum, S., Schlittenhardt, J., Shamoni, M. & H. Skriver (2009): Treaty Monitoring. In: Jasani, B., Pesaresi, M., Schneiderbauer, S. & G. Zeug (Eds.) (2009): *Remote Sensing from Space. Supporting International Peace and Security. Springer*, Berlin: 167-188

[16] Jasani, B. (2004), Identification of Key Features of Nuclear Reactors for Interpretation of Images from Remote Sensing satellites, *Journal of Nuclear Materials Management*, Vol. XXXII, No. 3, Spring 2004, pp. 28-36.

[17] Nussbaum S and Menz G, *Object-based image analysis and treaty verification*, Springer, 2008.

[18] Lévesque J, Neville, R.A, Staenz K (2001), Preliminary Results On The Investigation Of Hyperspectral Remote Sensing For The Identification Of Uranium Mine Tailings, Proceedings ISSSR, Quebec City, 2001.

[19] Neville, R.A., Staenz, K., Levesque, J., Truong,Q.S.Bob, and Borstad, G.A. (2001) Hyperspectral Analysis of Imagery of a uranium mine site, Presentation at the ISSSR conference, Quebec City,, Canada.

[20] R. Leslie, Riggs, P and Bragin, V. (2002)Satellite Imagery for Safeguards Purposes: Utility of Panchromatic and Multispectral Imagery for Verification of Remote Uranium Mines, *Paper presented to Annual Meeting of the Institute of Nuclear Materials Management,* Orlando, Florida, 23-27 June 2002.

[21] Jasani, B., Smart, H. A., Blair, D., Stork, C. T., Snoth, J and Canty, M. (2005), Evaluation of remote sensor systems for monitoring uranium mines, Proceedings of the 27th Annual Meeting, Symposium on safeguards and nuclear materials management, ESARDA, 10-12 May 2005, London.

[22] Christopher L. Stork, Heidi A. Smartt, Dianna S. Blair, and Jody L. Smith (2006), Systematic Evaluation of Satellite Remote Sensing for Identifying Uranium Mines and Mills, Sandia Report SAND2005-7791, January 2006.

[23] Truong Q.S.Bob, Lim J, Borstad, G, Brown L.N, Parsons G, and Mulvie J. (2008), Capabilities and Potential Safeguards Applications of High Resolution Imagery, Paper Presented at ESARDA Conference, Tokyo, 2008.

[24] International Atomic Energy Agency, Uranium Extraction Technology, *Technical Report Series No. 359,* International Atomic Energy Agency Vienna 1993.