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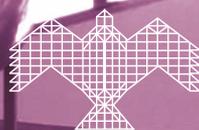
S.Chandrashekar
Lalitha Sundaresan
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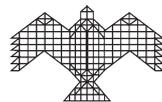
International Strategic and Security Studies Programme

NATIONAL INSTITUTE OF ADVANCED STUDIES

Bangalore, India

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EXECUTIVE SUMMARY

Openly available satellite imagery now provides a possible way to monitor nuclear fuel cycle activities. The early detection of new Uranium mining and milling operations and the routine monitoring of existing mines and mills using such imagery could make a valuable contribution to the oversight and monitoring function of organizations such as the International Atomic Energy Agency (IAEA).

A review of the existing literature suggests that Uranium mines do not offer special spectral or spatial signatures that uniquely identify them in a satellite image. However the various processes involved in the conversion of Uranium ore into yellowcake, offers interesting possibilities for the use of satellite imagery. A sample set of 13 mills across the world were selected for investigation. For each of the mill sites detailed process flow sheets were built up using information available in the public domain.

Satellite imagery especially Google Earth (GE) Images were then studied to generate a set of interpretation keys. These keys link the operations in the mill sites to the observables in the satellite image. The shapes and sizes of the features seen and their position in the process chain provided a set of signatures that could be used to identify a Uranium mill.

Analysis of 13 Uranium mills across the world revealed the following:

- The most commonly visible feature in the satellite image is the Counter Current Decantation (CCD) unit which is used to remove all suspended solids from the leached liquor.
- The leaching operation which precedes the CCD operation provides a number of features that can be seen in the satellite image. These include leaching tanks, autoclaves, pug leaching setups, presence of smoke or steam emanating from buildings, chimneys of acid plants, chimneys linked to hot leaching, sulphur heaps, sulphur storage tanks or acid storage tanks. One or more of these features were observable in all 13 mills.
- A solvent extraction or an ion exchange step or a Resin in Pulp step follows the CCD operation. While the ion exchange columns are easily identifiable in a satellite image, solvent extraction processes are not obvious. However, in some of the mills in our sample, repetitive patterns of buildings along with co-located solvent storage containers help to identify the solvent extraction process.
- It is difficult to identify features that are unique to the last step of the extraction process - precipitation and drying. Wherever Ammonia is used as a precipitating agent ammonia tanks which have a characteristic shape provide a readily identifiable feature.

While the CCDs, leaching and ion exchange processes have clear spatial signatures, the other processes do not always provide robust signatures. Many other minerals such as Copper, Zinc, Manganese, Rare Earths (RE), Vanadium and Phosphorus may share similar extraction processes and provide similar signatures.

Our methodology for identifying a Uranium mill therefore had to be modified. If we could find features linked to the process steps in the extraction of these minerals that are different from the process steps of Uranium we would then be able to separate out Uranium mills from other mills that share some of the process steps.

Copper mills are the most likely candidates for misclassification. The processing of copper tailings coming out of froth flotation or of low grade ores may exhibit the leaching – CCD – solvent extraction sequence that is seen in a Uranium mill. However the differentiating factor for the extraction of copper is that after solvent extraction it goes to an electro winning facility instead of a precipitation facility. The typical signature provided by an electro winning facility can therefore be used to separate out a Uranium mill from a copper mill.

Copper Tailings Plants are also often associated with large mainstream copper mills. Such copper mills are on an average four to five times larger in size. They also use froth flotation units and smelters that are easily identifiable in a satellite image. These can be further used as differentiators between copper and Uranium mills.

Analysis of the Nchanga Copper Mill and some other copper mills confirms the logic of these discrimination features.

The application of this classification logic to the Olympic Dam Mill that produces copper with Uranium as a byproduct once again confirms the robustness of these discriminating features.

Zinc and manganese may also use an acid leaching step - - CCD - solvent extraction sequence as a part of their extraction process especially while processing the tailings. However, since the final operation will involve electro winning instead of the precipitation step which is characteristic of Uranium, such mills can also be differentiated from a Uranium mill. Scale, smelters and froth flotation units can also be used as additional discriminators.

The extraction of Rare Earths (RE) from RE containing ores also involves acid leaching. In the current scenario where RE concentration levels are on the higher side and made even higher through steps like froth flotation the absence of a CCD unit and the presence of multiple solvent extraction facilities should enable one to separate out a RE facility from a Uranium mill.

Mills that process ores containing both Uranium and Vanadium can be confused with a dedicated Uranium mill. However the presence of more than one solvent extraction sequence will enable one to separate out a combined Uranium Vanadium mill from a stand-alone Uranium mill.

Through the systematic application of this logic an image analyst will be able to identify a Uranium Mill as a Uranium Mill. By eliminating Copper, Zinc, Manganese, Rare Earths, Vanadium and Phosphorus extraction operations the probability that the CCD – Acid Leaching sequence that is seen in the satellite image is indeed Uranium is significantly enhanced.

A decision tree created out of these empirical findings provides an easy-to-use algorithm for the identification of a Uranium mill from satellite imagery.

BACKGROUND

Uranium in its varied forms is a very important nuclear material. Its extraction from ore and its conversion into several different forms is the starting point for the entire nuclear fuel cycle. Since it can be used in nuclear reactors for the production of electricity as well as in a nuclear weapons programme there is a global need for monitoring various activities related to the entire nuclear fuel cycle. Concerns of proliferation of nuclear weapons have also created an international regime that exercises a fair degree of control over the entire nuclear fuel cycle.¹

The mining of Uranium and its conversion through a milling process into U_3O_8 commonly called yellowcake is the first step of a complex conversion cycle that determines how the mined material will be used.²

High resolution satellite imagery is now freely available making it possible for analysts to consider using such imagery for making assessments regarding the nuclear fuel cycle activities of various countries of interest.³

This report discusses the possible use of such satellite imagery for identifying and monitoring Uranium mining and milling activities.⁴

It seeks to answer the following questions:

Can we identify Uranium mines using available satellite imagery?

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

Are there other extraction processes that share similar features with Uranium Extraction processes? If the answer is yes, 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?

USE OF SATELLITE IMAGERY FOR IDENTIFYING URANIUM MINES & MILLS

The geological conditions under which Uranium bearing ores can be found across the world has been extensively researched and documented. The various steps involved in mining, beneficiation of the ore and its further processing into the commonly used yellowcake form has also been studied in great detail.⁵

Though satellite imagery has been extensively used as a first step in the exploration process for locating new sources of various materials including Uranium, it has not been used in a major way for looking

¹ Some time back IAEA introduced the Additional Protocol which means that various member states of the IAEA will face greater monitoring and oversight of their nuclear activities. These would include mining as well as milling activities.

² Mining and milling activities for most exploited ore bodies are generally closely located in order to minimize the costs of having to haul large quantities of material over long distances.

³ Jasani.B, Pesaresi.M, Schneiderbauer and Zeug.G (Eds), "Remote Sensing from Space - Supporting International Peace and Security", Springer (2009), pp. 167-188.

⁴ Most of the analyses carried out in this report are based on Google Earth imagery except for Key lake mill where we used Quickbird satellite image provided by Digital Globe Inc. However higher resolution multi-spectral data available from various commercial sources can also be used to refine and improve what we have tried to do here.

⁵ See International Atomic Energy Agency, "Uranium Extraction Technology", Technical Report Series No. 359, International Atomic Energy Agency Vienna 1993.

at existing or newly created mining or milling operations for assessing whether they are used for the production of Uranium.

Researchers at the Sandia National Laboratory⁶ have addressed in considerable detail the problem of using satellite remote sensing for identifying Uranium mines and mills. Using the Ranger mine in Australia as a case study, they looked at 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. They also tried to link the various operations including the use of various chemical reagents for processing the Uranium ore to spectral signatures that could be identified from space. A unique aspect of this study 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. Such a decision tree enables one to look at each step in any observed extraction process and connect it to possible candidate materials that share the same process. The study concluded that though hyperspectral data could help in categorizing different bodies of ores into very broad types it would not help in distinguishing between different elements of economic importance that occur in smaller quantities within that broad ore body. Thus the Ranger ore body could be identified as a magnesium chlorite from the spectral signature of the large area stockpiled ore. Though such an ore body could contain Uranium it could also contain other elements that were also commercially important. The occurrence of Uranium within such an ore body is so small that it provides no visible signature to the satellite sensor.

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 used at Ranger. Since acid leaching is a common step used in the extraction of several elements it does not help in clearly identifying a Uranium mill. Another study looked at the utility of satellite images for IAEA to verify the reports submitted by the concerned country on the operational schedules of a Uranium mine and mill.⁷

A later study also tried to evaluate the utility of satellite remote sensing for identifying Uranium mines and mills.⁸ In this report too, the various steps used in the Uranium mining and milling operations of known Uranium sites are used to develop a set of keys that could then be extended to look at other sites for possible Uranium mining and milling activities.

APPROACH & METHODOLOGY

Our approach towards identifying Uranium Mining and milling operations draws upon these earlier studies.

A critical review of the reports suggests that Uranium mines do not offer any special signatures that

⁶ Christopher L. Stork, Heidi A. Smart, Dianna S. Blair, and Jody L. Smith, "Systematic Evaluation of Satellite Remote Sensing for Identifying Uranium Mines and Mills", Sandia Report SAND2005-7791, Printed January 2006

⁷ R. Leslie, P. Riggs and V. Bragin, "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

⁸ Bhupendra Jasani, "Monitoring Uranium Mining and Milling", Department of War Studies, King's College, London, UK, March 2009.

differentiate them from mining operations for other elements.⁹ Since concentrations of Uranium within the larger ore bodies are so small they do not offer any special spectral signatures that can be observed by a space based sensor. The SANDIA report referred to earlier makes it clear that even tailings ponds, where the residues from the mining and milling operations are dumped, do not provide useful signatures to a space based sensor.

The study therefore focused on Uranium milling operations rather than the mining activities though these often go hand in hand as one continuous operation.

Rather than developing a set of functional keys and signatures based upon observations of a single or a few Uranium operations we extend the coverage to include a larger number of Uranium milling operations across the world.

Before engaging in this exercise we needed to build a comprehensive understanding of the various common steps and processes involved in the conversion of various kinds of Uranium ores into yellow cake. After building up this understanding we can use publicly available information of all kinds from different sources to build up a comprehensive understanding of the Uranium operations at a particular site. This information includes a complete description of the specific operations and the process flow sheets for each and every one of the known Uranium mills.

Once the relevant flow sheets for each of the known Uranium sites has been built up we then study the satellite imagery and build up an interpretation key that links the flow sheet operations to the observables in the image.¹⁰

Specific image signatures for each step or process are also generated as a part of the overall key for interpretation.

The observable features for each of the mills in the sample set are compiled into a key development Table. The most commonly occurring features across the sample set along with their signatures are then used as the basis for the development of a decision tree.

This study does not deal with heap leaching or with in situ leaching operations which may involve different observables in the satellite imagery. It only covers general hydrometallurgical milling operations involved in Uranium extraction.

URANIUM MINING AND MILLING PROCESSES – AN OVERVIEW

Uranium deposits occur in several different forms depending on their geological setting. Generally fifteen different types of deposits are listed.¹¹ However out of the 15 types conglomerates (19%),

⁹ Sometimes scale can be used as an additional dimension to reduce errors of classification. However in the case of Uranium commercial considerations are not the sole driver for the decision to set up a mining and milling operation. National Security considerations are equally if not more important drivers of such decisions. This may require the exploitation of deposits that may not be economically viable.

¹⁰ Our analyses use Google Imagery as is available in Google Earth. We do not use any spectral analyses for our interpretation.

¹¹ See International Atomic Energy Agency, “Uranium Extraction Technology”, Technical Report Series No. 359, International Atomic Energy Agency Vienna 1993. p 7

sandstones (44%) and veins (22%) account for the majority of exploited Uranium resources currently.¹²

Uranium Mining is carried out either through underground or open pit mines.¹³

The nature of the deposit dictates the choice of the process adopted at a particular site. Uranium occurs in two forms - the tetravalent form and the hexavalent form - in the various ore bodies with which it is associated. Uranium in the hexavalent is easier to extract from the ore body through the choice of a suitable leaching agent such as an acid or alkali. However if Uranium occurs in the tetravalent form it needs to be converted into the hexavalent form during the leaching operation. In acid leaching operations this is best done through the presence of ferric ions in the leaching solution. Oxidant addition such as Manganese dioxide (Pyrolusite) which helps in the rejuvenation of the ferric ion from its ferrous state or Sodium Chlorate greatly facilitates the leaching process.

If the nature of the ore body is such that it requires a large amount of acid for extracting the Uranium, alkaline leaching can be adopted. This typically involves the use of a mixture of sodium carbonate and sodium bicarbonate as the leaching medium. For the easy conversion of tetravalent Uranium Oxygen may also be used as a reagent.

An overview of the typical processes used for the extraction of Uranium is in Figure 1.

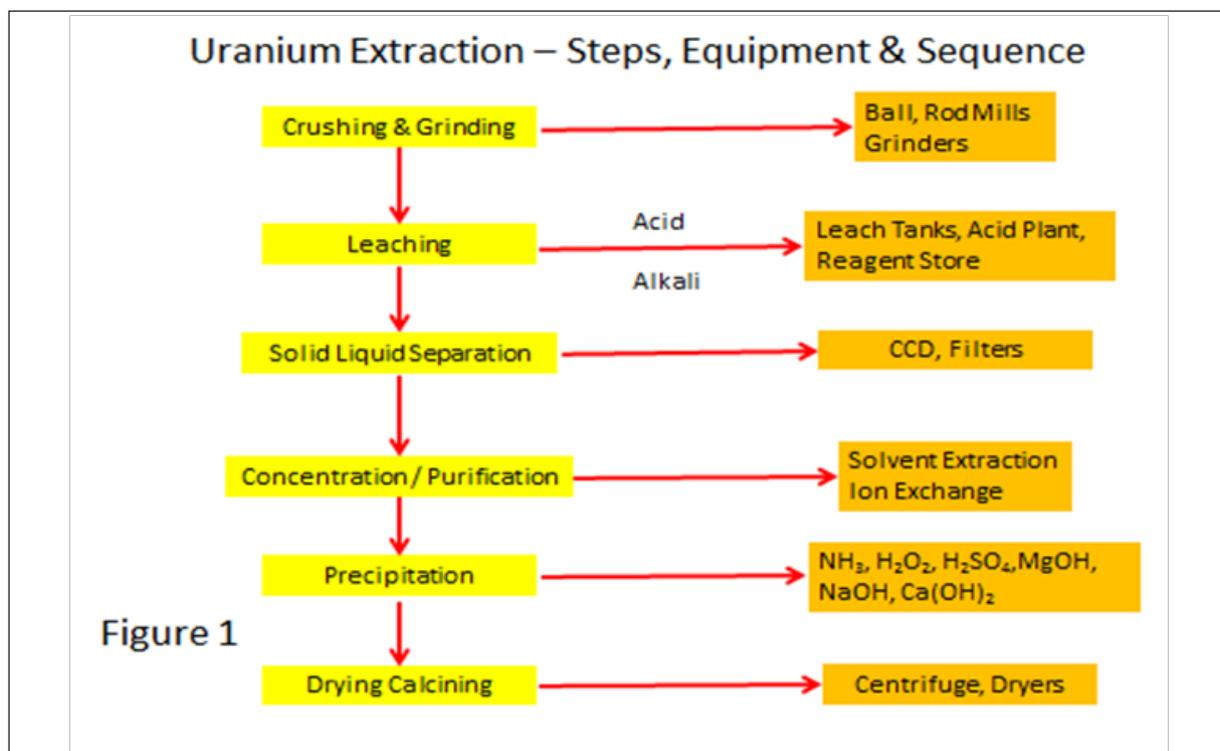


Figure 1 Uranium Extraction Process – Important Steps

¹² See International Atomic Energy Agency, “Uranium Extraction Technology”, Technical Report Series No. 359, International Atomic Energy Agency Vienna 1993. p 19

¹³ For a detailed look at the mining operations see Chapter 2 of International Atomic Energy Agency, “Uranium Extraction Technology”, Technical Report Series No. 359, International Atomic Energy Agency, Vienna 1993.

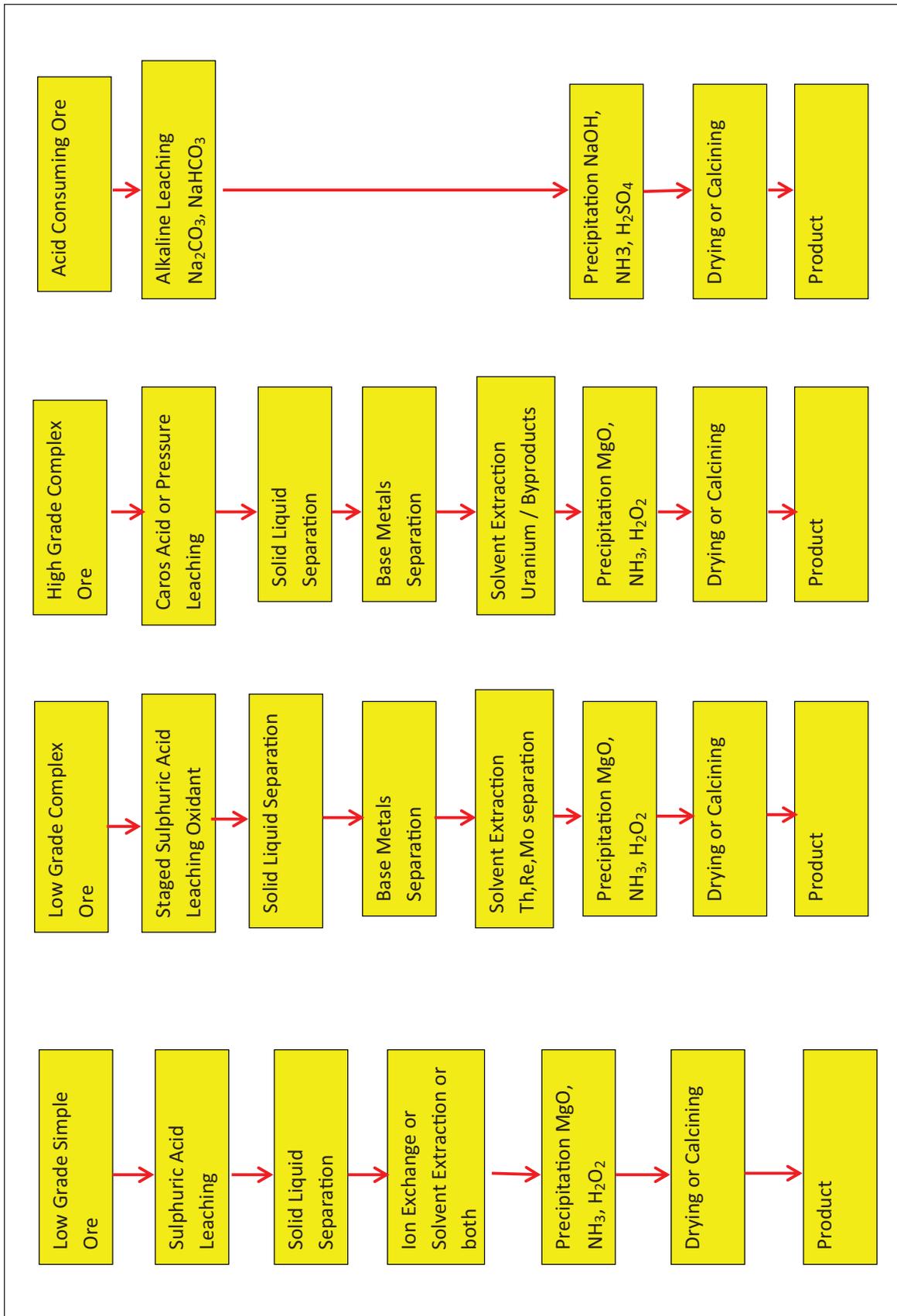


Figure 2 Nature of Uranium Deposit and Extraction Process

A simplified overview of how the nature of the Uranium deposit affects the overall process is in Figure 2.¹⁴ The focus of the approach adopted in this report is to look at Uranium extraction practices across a sample of mill and from them derive a set of observable keys and a sequence that is unique to a Uranium extraction operation. If there is indeed such a set and sequence of observables we also want to be able to apply this knowledge to look at a satellite image of any milling operation and based on its interpretation, decide whether it is a Uranium milling operation.

SAMPLE SELECTION AND ANALYSIS OF CURRENT URANIUM MILLING OPERATIONS

For our study we selected 13 Uranium Milling operations from around the world. Table 1 provides details of these mills. Annexures 1 to 13 provide a detailed interpretation for the Uranium extraction operations at each of the above sites. The various features that can be seen on the satellite image which are associated with each of the major operations at the site have been compiled and presented in Table 2.

Table 1 Sample Set of Uranium Mills

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
Australia	Olympic Dam	30 27 S 136 52 E	BHP Billiton	1988
Malawi	Kayelekera	9 59 S 33 42 E	Paladin	2009
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

OBSERVABLE FEATURES OF A URANIUM MILL IN A SATELLITE IMAGE

Based upon a review of Table 2 we can identify certain features in a typical Uranium Mill.

Though crushing, grinding and slurry preparation facilities are identifiable in most of the images¹⁵ they do not offer any special features associated with only a Uranium Milling operation.¹⁶ Radiometric sorters are used in many Uranium mills to improve the ore quality. However they cannot be uniquely identified in a satellite image.

¹⁴ Adapted from International Atomic Energy Agency, “Uranium Extraction Technology”, Technical Report Series No. 359, International Atomic Energy Agency Vienna 1993.

¹⁵ In some cases the ore is prepared elsewhere maybe at the mine site itself and moved to the mill.

¹⁶ Most of them are general purpose crushing and grinding equipment with no special features that can be seen in a satellite image.

Table 2 Uranium Mill Features Observable in a Satellite Image

Mill	Acid Plant	Sulphur Store	Acid/Alkali Storage	Hot Leaching	Leach tanks	CCD	Solvent Extraction	IX Column	Ammonia Tanks
Sweet Water Mill	Not Present	Not Present	Seen	Not seen	Not seen	Not Seen	Building – no feature seen	NA	Seen
Rabbit Lake Mill	Seen	Seen	Seen	Not seen	Some seen outside	Seen	Building – no feature seen	NA	Seen
Ranger	Seen	Seen	Seen	Not seen	Seen	Seen	Pattern seen – Solvent Recycle	NA	Seen
Mclean Lake	Seen	Seen	Not seen	Not seen	Not seen	Seen	Building – no Feature seen	NA	Seen
Key Lake	Seen	Seen	Seen	Smoke seen	Not seen	Seen	Building seen – Solvent recycle	NA	Seen
Arlit	Seen	Seen	Seen	Not seen	Pug Leaching	Seen	Pattern seen – Solvent Recycle	NA	Seen
Rossing	Seen	Seen	Seen	Not seen	Seen	Seen	Pattern seen – Solvent Recycle	Seen	Not Seen
Langer Heinrich	NA	NA	Seen	Heat Exchanger	Seen	Seen	NA	Seen	Not Used
Olympic Dam	Seen	Seen	Seen	Not seen	Seen	Seen	Pattern seen – Solvent Recycle	NA	Seen
Kayelekera	Seen	Seen	Seen	Not seen	Seen	Not Seen	NA	Resin in Pulp IX	Not seen
Krasnokamensk	Seen	Not seen	Seen	Chimneys seen	Autoclave leaching	Seen	NA	Seen	Not Seen
Rozna	NA	NA	Seen	Smoke seen	Not seen	Seen	NA	Not seen	Not seen
Feldiora	NA	NA	Seen	Chimney seen	Autoclave Leaching	Seen	NA	Seen	Not Seen

The most commonly visible feature on the satellite image is the Counter Current Decantation (CCD) unit which is used to remove all suspended solids from the leached liquor. The separation of the leached liquor from the solid material (termed solid liquid separation) is the most expensive part of the Uranium extraction process. **Figure 3** shows the CCDs of some of the mills in our sample set.

In all the cases except the Sweetwater Mill in USA and the Kayalekara Mill in Malawi the CCD is clearly and obviously visible in the satellite image.

The Sweetwater Mill also uses CCD units but this is housed inside a building and therefore cannot be seen in the satellite image.¹⁷

The only case where the CCD approach for separating the solid from the leached solution has not been used is the Kayalekera Mill in Malawi. This mill uses a Resin in Pulp (RIP) technology.¹⁸ According to information in the public domain the original extraction process at this site did propose the use of CCD.¹⁹

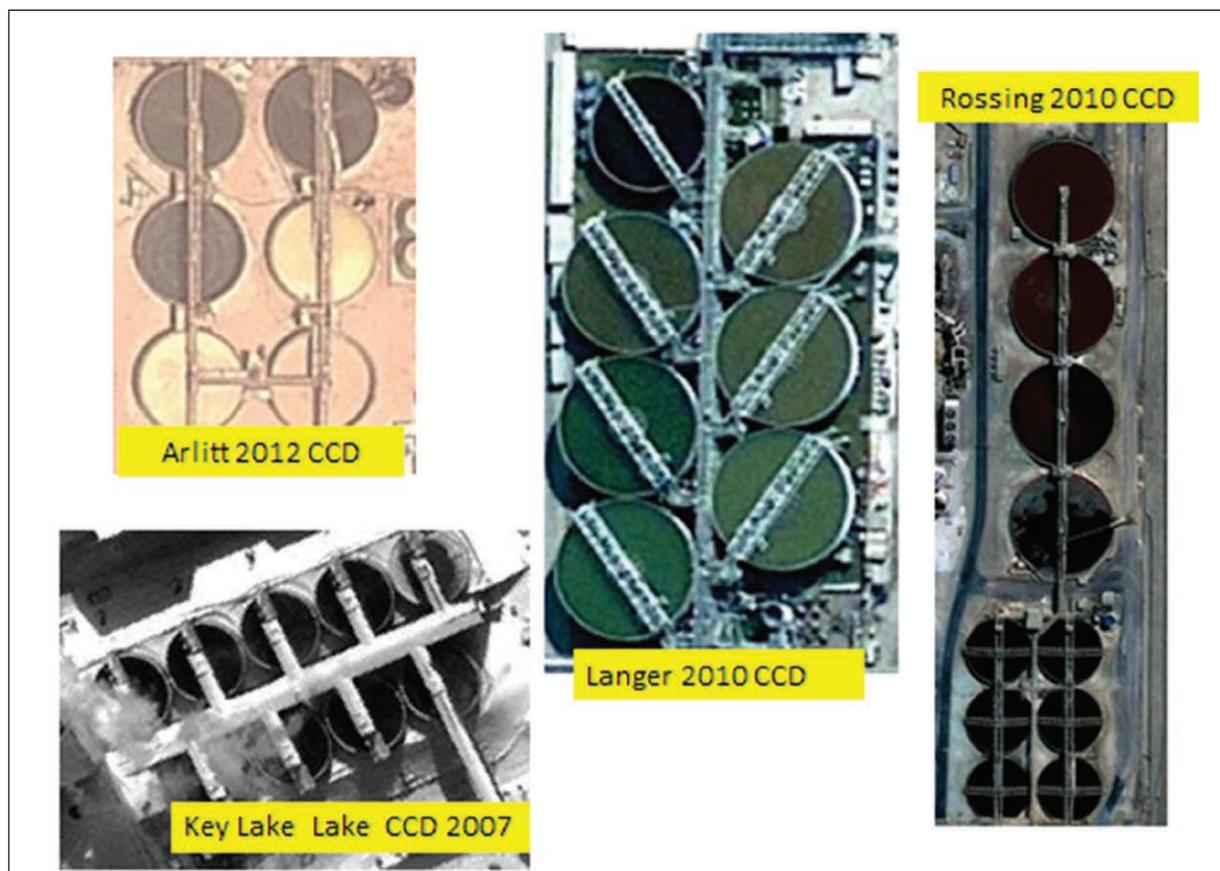


Figure 3 Counter Current Decantation Units as Seen in GE Image

¹⁷ This mill closed in 1984.

¹⁸ In RIP technology the dissolved Uranium is absorbed in a resin and then the resin with the absorbed Uranium is later separated from it. This is similar to the ion exchange route except for the fact that newer resins make this approach attractive especially since this can eliminate the more expensive CCD technology for the separation of the solids and liquids after the leaching step.

¹⁹ Brief on the Kayalekera Uranium Project put out by the Aveng Engineering & Projects Company available at <http://www.e-pc.co.za/projects/kayalekera-uranium-project>

They also suggest that the use of RIP has delayed the ramp up for achieving full production.²⁰ More recently the mill operations have been put on hold due to low Uranium prices.²¹

Thus the evidence suggests that the most obvious feature to look for in a Uranium milling operation would be the CCD.

Further scrutiny of the flow sheets of the mills in our sample set tells us that all the 13 mills also use leaching. 10 of the 13 use acid leaching while the Langer Heinrich, Rozna and Feldiora mills use alkaline leaching.

In four of the ten mills that use acid leaching the leaching tanks are clearly visible. These are Ranger, Rossing, Olympic Dam and Kayalekera. **Figure 4** shows typical leach tanks and leaching sections of some of the mills in our sample.

The Arlitt mill in Niger uses a special method of leaching called pug leaching to deal with a particularly difficult ore at that site. The Krasnokamensk site in Russia uses autoclaves – a combination of higher temperature and higher pressure - for acid leaching. In some cases hot leaching is also seen via the plumes emanating from the building where leaching takes place.

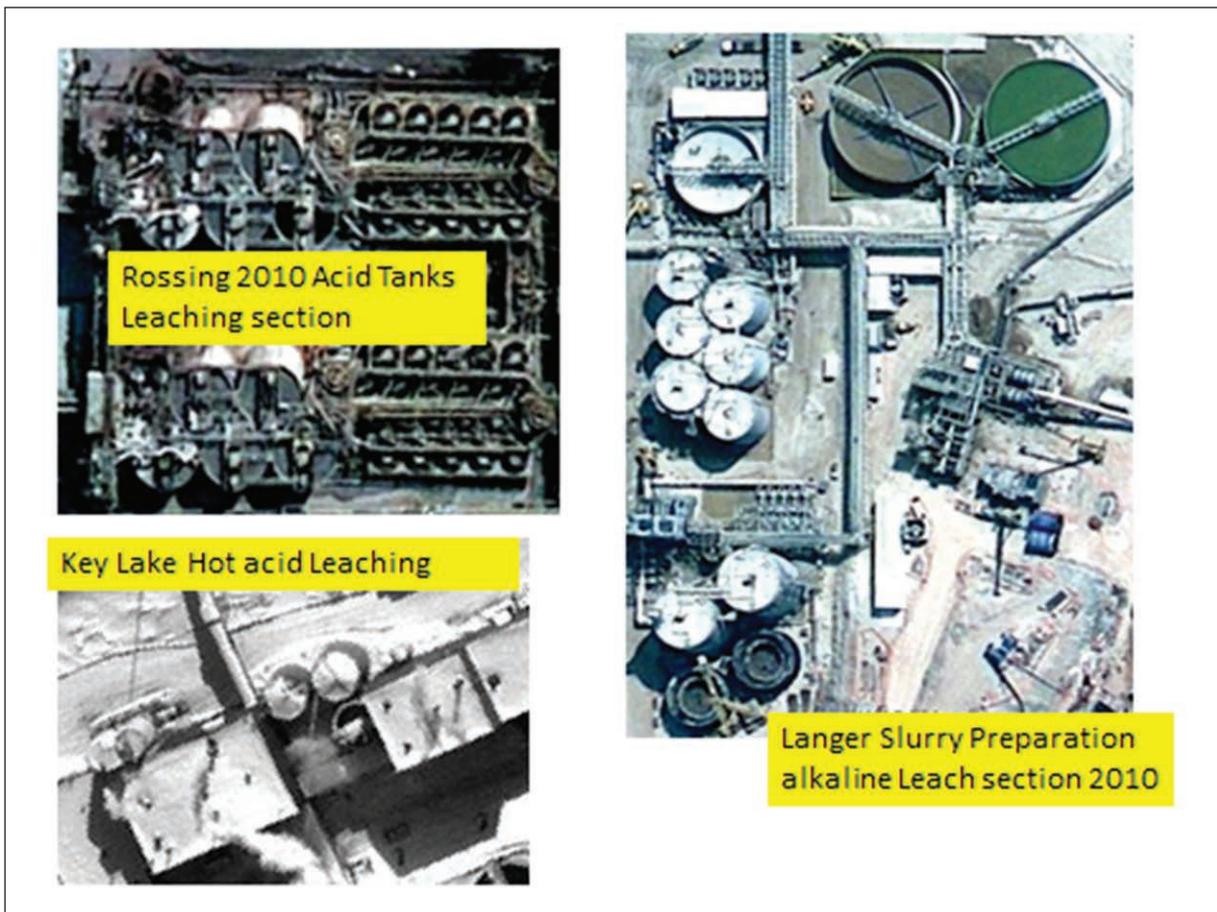


Figure 4 Leach tanks as seen in a GE image

²⁰ Paladin Energy Ltd., Annual Report 2011

²¹ <http://www.mining.com/paladin-suspends-malawi-mine-66181/>

In the case of acid leaching, sulphuric acid can be produced on site from burning sulphur or brought from outside and stored at the mill site. In a few cases such as the Olympic Dam copper Uranium mill sulphuric acid can be produced on site from the smelting of sulphide containing Copper Uranium ores. Acid plants, Sulphur heaps, Sulphur storage tanks, Acid storage tanks provide visual evidence that the process involves acid leaching. In all the ten cases of acid leaching in our sample set at least one of these signatures is available.

In many acid leaching operations certain oxidants are added to facilitate the leaching process. These include Sodium Chlorate, Manganese Dioxide (Pyrolusite), Air, Oxygen and Caro's Acid. Many of them must be stored in containers close to the leaching facility and may provide additional indication of the leaching operation. If oxygen is used there could be an oxygen facility co-located with the mill. The Sweetwater, Olympic Dam, Rabbit Lake and Mclean Lake mills use sodium chlorate as an oxidant. Rossing and Ranger use Manganese di oxide as the oxidant while the Key Lake Mill uses oxygen. The presence of ferric ions is necessary for the conversion of tetravalent Uranium into the more acid soluble hexavalent form. The addition of ferric ions in the form of Ferric Sulphate may be needed in some cases.

Some or all of these oxidant additions may be stored in containers near the acid leaching site. While they may not provide clear signatures of the type of oxidant used they provide some kind of indirect corroborative evidence of a leaching process especially if it takes place inside a closed building.

In Feldiora the leaching section can be identified using the chimney that characterizes most alkali leaching operations. Normally alkaline leaching involves the addition of both sodium carbonate and sodium bicarbonate for Uranium ores. Storage tanks close to the leaching site – they can be of different sizes – would be one indication of alkaline leaching. Such storage can be seen at the Langer Heinrich site in the slurry preparation area just preceding the leaching operation.

At the Rozna site alkaline leaching takes place inside a building and therefore there is no direct observable. However at the leaching site two storage tanks can be discerned.

Alkaline leaching also involves some higher temperatures. Evidence of smoke, chimneys heat exchangers etc. could be additional things to look for.²²

A CCD operation preceded by a leaching operation that could be either acidic leaching using sulphuric acid or alkaline leaching seems to be common set of sequence features shared by all the mills.²³

Though in principle if the leached liquor contains a sufficient concentration of Uranium it can be directly precipitated it is normal practice to subject the leached solution to a further solvent extraction or ion exchange process.

Eight of the mills in our sample use Solvent extraction. Rossing uses both solvent extraction and ion exchange. Krasnokamensk, Feldiora and Langer Heinrich use ion exchange and Kayalekara uses a resin-in-pulp process which is also a variant of the ion exchange process.

²² Langer Heinrich has some spiral heat exchangers after the leaching operation. The Rozna Leaching building shows a chimney and smoke in one of the Google images of the Rozna Mill. The Feldiora site shows chimneys indicating a hot leaching operation.

²³ Though Reference 5 suggests that in the case of alkaline leaching the precipitation step can follow the leaching operation without the intermediate step of CCD this does not seem to be the case for the mills in our sample set.

Four of the mills that use solvent extraction – Ranger, Arlit, Rossing and Olympic Dam provide good signatures – a sequence of identical buildings linked to a storage tank containing the solvent which is recycled. **Figure 5** shows the Solvent extraction buildings for some of the mills in our sample set.

In the case of the Mclean Lake and Key Lake mills the repetitive sequence of similar buildings linked to specific or common solvent storage and recycle facilities is absent. However both of them have storage tanks that could contain the solvent in close proximity to the building. This provides indirect evidence that does suggest a solvent extraction operation after the CCD step.

The Sweetwater mill and Rabbit Lake do not show the typical repetitive sequence of buildings linked to a solvent storage tank. They do not seem to have any solvent storage facilities nearby either. With a better quality image maybe these can be seen.

In only four out of eight cases where solvent extraction operations are performed is it possible to link observable features in the image to a solvent extraction facility downstream of the CCD step.

In three of the four cases where Ion exchange follows the CCD step, the Ion Exchange columns provide a visible signature. In the case of the Rozna mill they are located inside a building and are not visible. **Figure 6** shows the ion exchange columns in some of the mills of our sample.

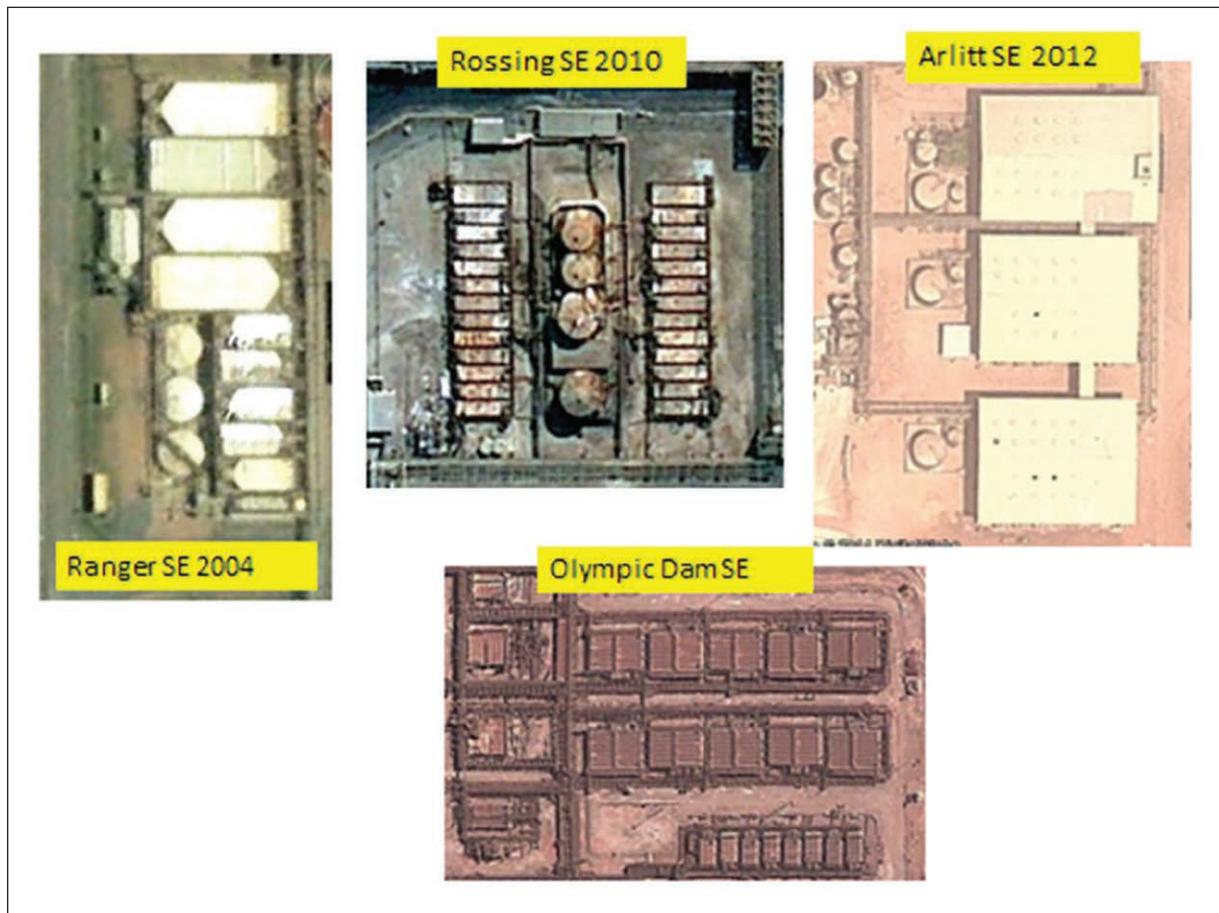


Figure 5 Solvent Extraction Buildings as seen in a GE image

In the case of the Kayalekera mill the Resin in Pulp Facility that also uses an Ion Exchange approach is visible. After the RIP the absorbed Uranium contained in the resin goes through an elution step which also uses an ion exchange approach.²⁴

In four out of five cases where ion exchange or Resin in Pulp is used we do have visible evidence of the ion exchange process.

Therefore in seven out of the 13 mills in our sample we can identify a solvent exchange or an Ion exchange facility.

After the solvent extraction or ion exchange operation the pregnant solution that contains most of the Uranium in solution goes through a precipitation step.

Precipitation from the stripped solution involves the use of several possible reagents. For acid leached and solvent stripped solutions Hydrogen Peroxide, Magnesia, Ammonia or Ammonium Hydroxide are normally used.²⁵ Since many countries are imposing additional controls on Ammonia related pollutants some countries such as Canada are moving towards the use of Hydrogen Peroxide.²⁶ Hydrogen Peroxide

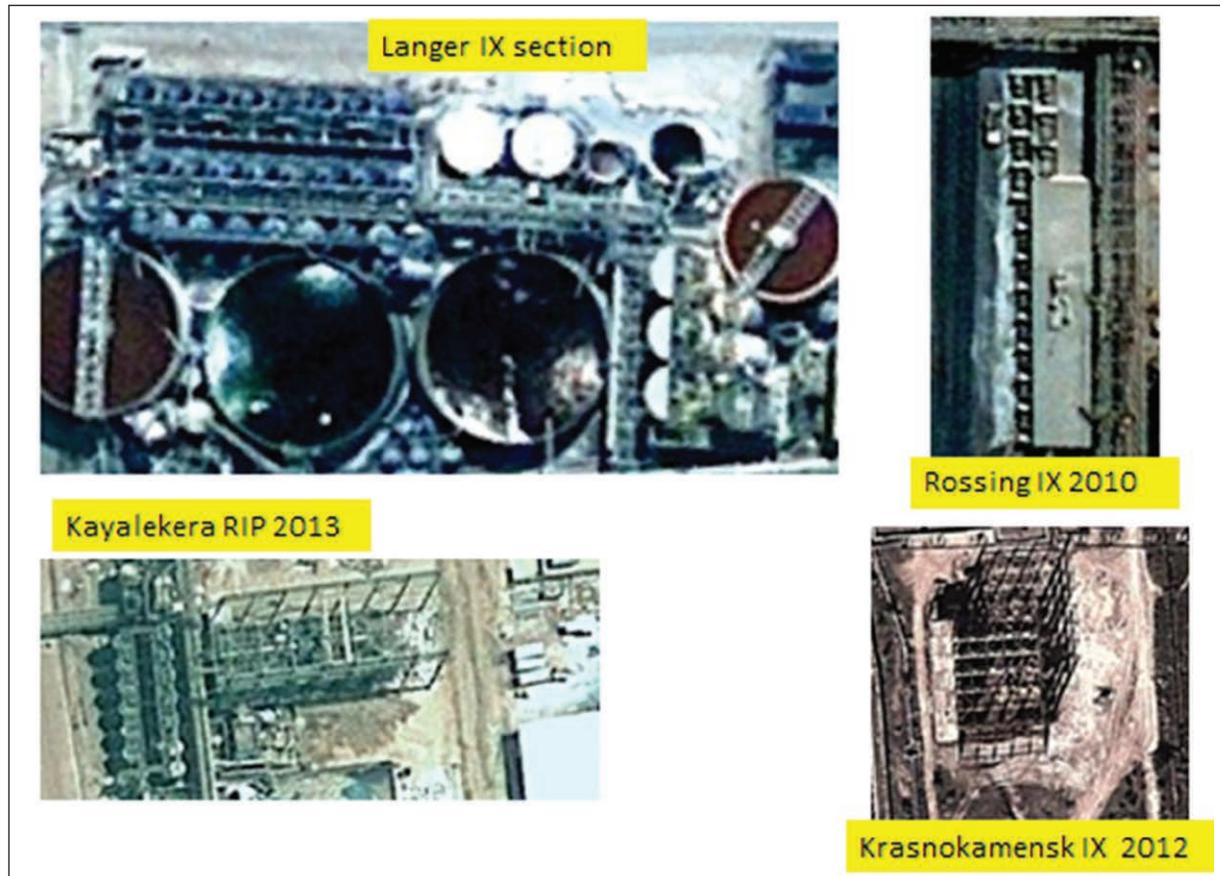


Figure 6 Ion Exchange columns as seen in a GE image

²⁴ Elution removes the absorbed uranium from the resin using ion exchange.

²⁵ Reference 5 pp 239-242. Rabbit Lake has replaced Ammonia with Hydrogen Peroxide since 1986. Key Lake and Mclean Lake mills produce Ammonium Sulphate as by product to take care of the environmental aspects.

²⁶ The Rabbit Lake Mill has replaced Ammonia with Hydrogen Peroxide. The Key Lake and Mclean Lake operations produce ammonium sulphate as a byproduct to minimize the impact of Ammonia on the environment.

precipitation also eliminates the co-precipitation of other contaminating metals like Vanadium and may be preferred if the ore contains Vanadium in significant quantities.

For precipitating the Uranium from alkaline stripped solutions Sodium Hydroxide is the normal reagent. In case Sodium Hydroxide is not suitable Magnesium Hydroxide can also be used.²⁷ If there is a possibility that the precipitate may be contaminated with other co-precipitating metals such as Vanadium, Hydrogen Peroxide can also be used. In case Hydrogen Peroxide is used the stripped alkaline liquor must first be neutralized by the addition of acid.

In most of the images, storage containers in the vicinity of the precipitation step are seen. However only Ammonia storage containers seem to have a clear signature as can be seen in **Figure 7**.

Ammonia can be used for precipitation both from acidic leaching as well as alkaline leaching operations. These containers can be located and identified in seven of the mills in our sample set. In all the cases where Ammonia is used to precipitate the Uranium these containers can be identified. In some cases they are close to the precipitation facility. In other cases they are located farther away but could be moved to site if needed.

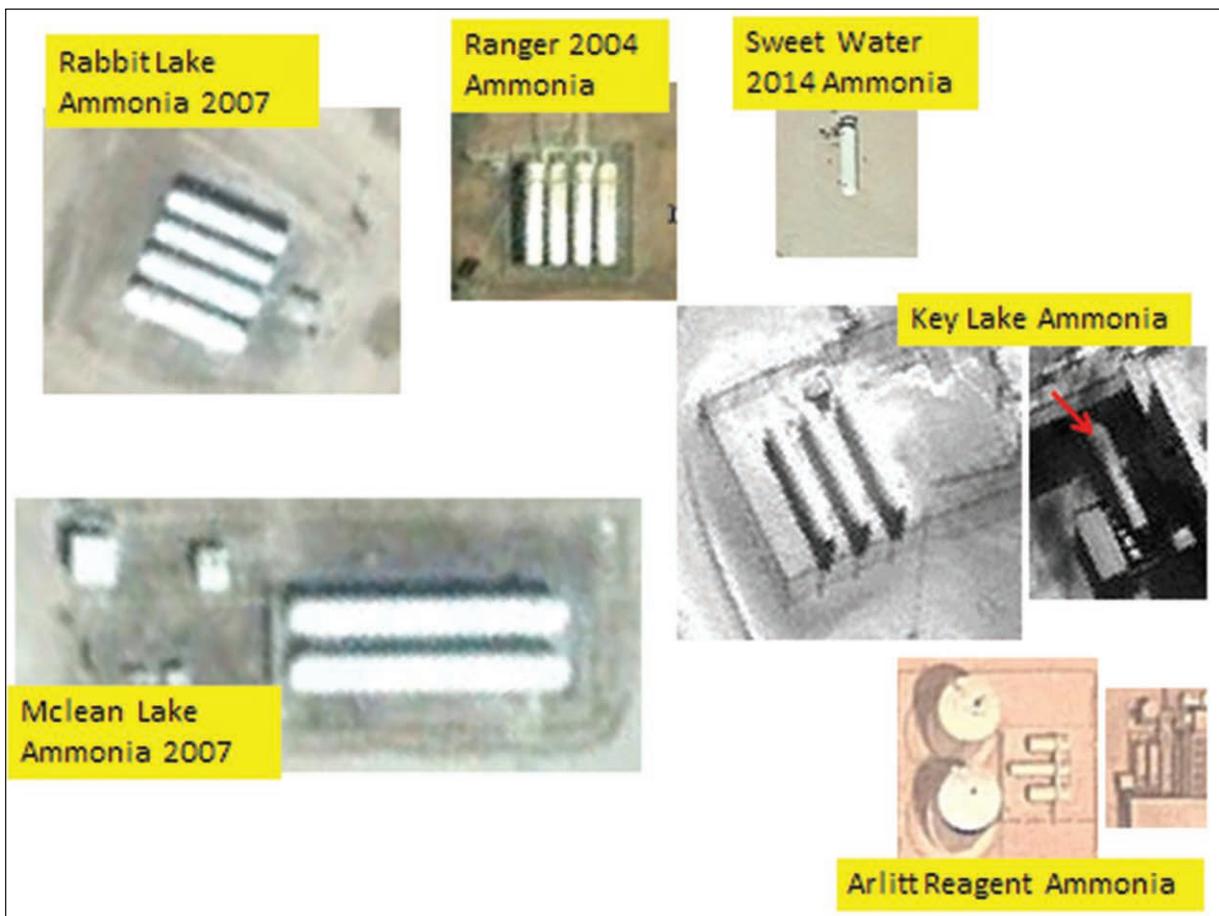


Figure 7 Ammonia Storage Containers as seen in a GE image

²⁷ Calcium hydroxide could also be used as in the Kayalakera Mill in Malawi.

The presence of Ammonia containers when linked with the other steps in the sequence – Leaching, CCD, solvent extraction and or Ion Exchange - would clinch the case for a Uranium extraction operation.

In all the mills some storage facilities are visible close to the precipitation facility. While they could provide some corroborative evidence for a precipitation operation they do not provide clinching evidence for a Uranium Mill.

The last step in the Uranium mill is the drying, grinding and packing step. While these could be logically located based on the flow none of these steps provide a clear visible signature that can be used to identify a Uranium operation.

IDENTIFYING A URANIUM MILL USING SATELLITE IMAGES

In terms of the observables in a satellite image the following sequence can be adopted based upon the keys derived from our sample set of Uranium mills. This is depicted in **Figure 8** through a decision tree.

The presence of CCD equipment within the layout of the facility;

The presence of an acid or alkaline leaching operation that is linked to the CCD step;²⁸ this could be confirmed on seeing the leaching tanks directly or by inferring acid leaching operations from the presence of autoclaves, pug leaching setups, presence of smoke or steam emanating from buildings, chimneys of acid plants, chimneys linked to hot leaching, sulphur heaps, sulphur storage tanks or acid storage tanks; A solvent extraction or an ion exchange step or a Resin in Pulp step after the CCD operation;

The presence of Ammonia tanks within the proximity of the other identified features;

Other corroborative features could be storage tanks for oxidants and non-ammonia precipitation reagents near the leaching and precipitation steps respectively.

The sequence that we have identified for the Uranium extraction operation from our sample set may be indicators of a Uranium Mill. However it is possible that other flow sheets for other materials could follow the same or a similar sequence of operations.

In view of these factors we have to find ways and means to separate out Uranium milling operations from other extraction operations that use a similar sequence of operations.

SEPARATION OF URANIUM MILLS FROM OTHER MILLS USING SIMILAR EXTRACTION PROCESSES

Apart from Uranium, Acid leaching is also used for the extraction of Copper, Zinc, Manganese, Rare Earths (RE), Vanadium and Phosphorus.²⁹

²⁸ Even if the leaching operations are inside a closed building, acid production, acid storage containers and sulphur heaps provide indirect evidence that establishes an acid leaching operation. Alkaline leaching may also involve some heating and may be seen as smoke coming out of the leaching operation or show up in the form of Heat exchangers close to the leaching site.

²⁹ Christopher L. Stork, Heidi A. Smart, Dianna S. Blair, and Jody L. Smith, “Systematic Evaluation of Satellite Remote Sensing for Identifying Uranium Mines and Mills”, Sandia Report SAND2005-7791, Printed January 2006 p 36 and p 41

It is possible that for some of these a CCD step linked to a solvent extraction or ion exchange may follow the acid leaching operation especially if the concentration of the element of interest is on the low side. In such a situation some of these extraction operations could share many of the same steps that are used for Uranium. If we could eliminate some or all of them based upon some signatures that their extraction process may have we can increase the confidence level that the sequence of operations that we are seeing is a Uranium Mill.

Of the various elements that could share some or all of these features the most probable confusion with Uranium is likely to come from some Copper extraction operations. Possible ways for separating a Copper mill from a Uranium mill is addressed in the next section.

URANIUM COPPER MILLS SEPARATION

An overview of a typical copper extraction operation is available in the SANDIA report.³⁰

From the mining point of view there are no major differences that can be used to separate out a copper mine and a Uranium mine.

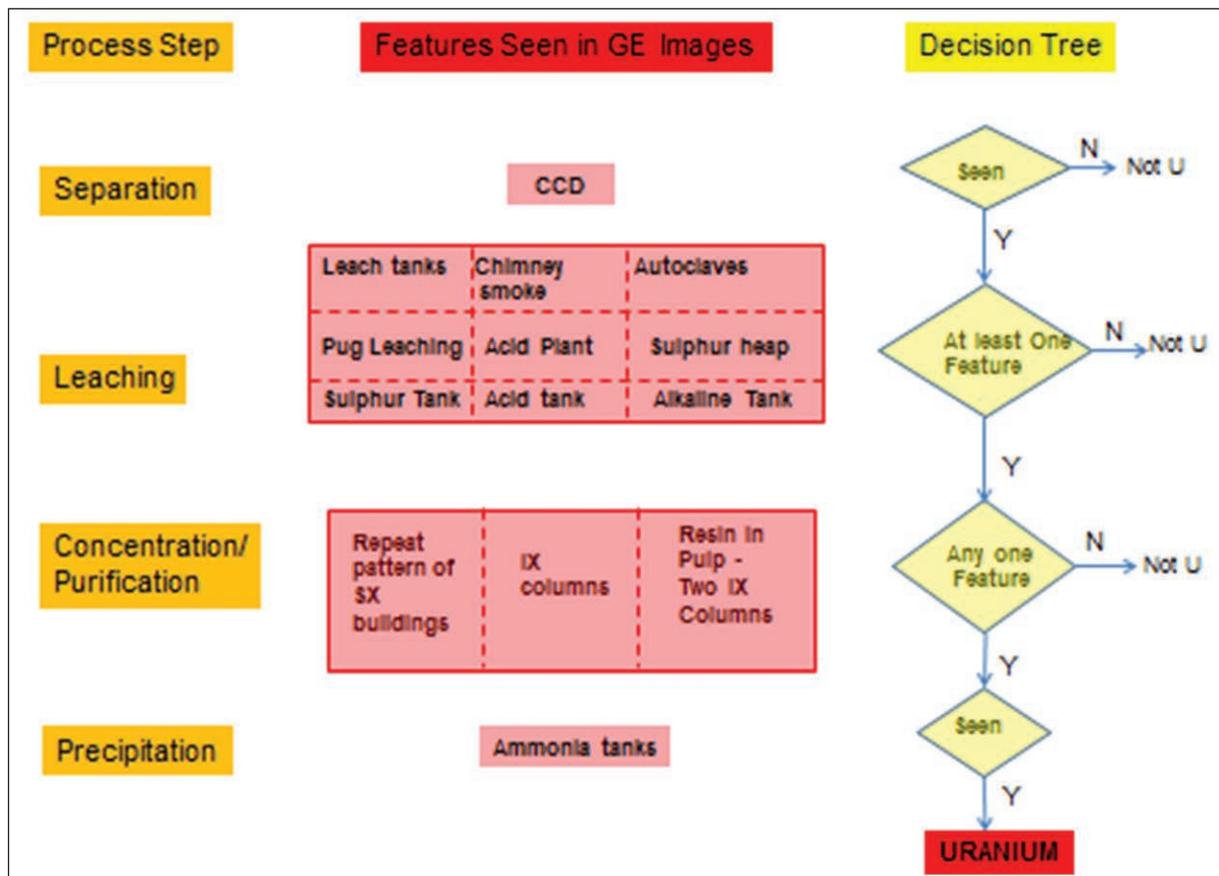


Figure 8 Identifying Uranium Mill Using Satellite Images Basic Decision Tree

³⁰ Christopher L. Stork, Heidi A. Smart, Dianna S. Blair, and Jody L. Smith, “Systematic Evaluation of Satellite Remote Sensing for Identifying Uranium Mines and Mills”, Sandia Report SAND2005-7791, Printed January 2006, pp 36-37.

However Copper and Uranium differ in some of the process details. These can be used to separate out a copper mill from a Uranium mill.

One major difference between a dedicated Uranium Mill and a dedicated copper mill has to do with scale of operation.

Annual consumption of copper is around 17 to 18 Million tonnes whereas the annual demand for Uranium is only around 70000 tonnes. For economic viability Copper mills have to produce a much larger outputs than Uranium mills.

Copper occurs mostly in the Sulphide or Oxide forms. If copper occurs as a Sulphide after crushing and grinding it goes through a froth flotation process to concentrate the copper part. The froth from the flotation process contains the bulk of the copper though the tailings could also contain copper. The froth is dried and a copper concentrate is produced. This can then be sent directly to a smelter located elsewhere or to a smelter on site. 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.³¹

The tailings from the froth flotation may still 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 Electro Winning Facility for the extraction of copper.

In a typical mill processing a sulphide copper ore the acid leaching - CCD - Solvent Extraction sequence is very similar to what we see in a Uranium mill. It is normally associated with the processing of tailings coming out of a froth flotation process. **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.**

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

VALIDATION OF FINDINGS FOR THE SEPARATION OF COPPER MILLS FROM URANIUM MILLS

To validate these findings we looked at the flow sheet of the Nchanga Copper Mine and mill in Zambia.³²

³¹ Current trends towards integrating various processes in one facility may result in a single facility that performs all these operations. The Copper smelter at Nchanga is supposed to be one such integrated facility that produces high purity copper from the concentrated copper froth arising from the flotation step.

³² SANDIA Report also uses the Nchanga Mine to illustrate the differences between Uranium and Copper Milling processes. Nchanga also produces a small amount of cobalt. Since this is extracted out of the slag produced in the smelter it does not come in the way of classifying this as a pure copper operation.

The interpretation of the Google Earth image of this mill is in Annexure 14.

The Nchanga mill is located very close to the Nchanga underground and Nchanga open pit mines. The Underground mine contains a mixture of oxide and sulphide ores whilst the open pit mines largely provide an oxide ore.

The crushed and ground ore from the underground and open pit mines are first subject to a froth flotation process to produce a higher concentration of Copper. After drying the floated froth concentrate goes through an integrated smelter / refinery / electro winning facility that produces high purity copper. This main production line does not have an acid leach – CCD – Solvent Extraction – Precipitation sequence. None of the features of a typical Uranium operation are seen and therefore it is obviously not a Uranium production mill.

However the Nchanga mine and mill site also houses a Tailings Processing Facility. In this facility the tailings from the flotation process – that is stored in a tailings pond – are subjected to an Acid Leaching – CCD – Solvent Extraction sequence very similar to what is used in a Uranium Mill. However the satellite image shows that the final step here is an electro winning process that is easily identified in a satellite image. (See Annexure 15, D)

This feature obviously separates out a copper operation from a Uranium milling operation. Annexure 15 provides an interpretation for the Tailings Processing Facility at Nchanga. **Figure 9** provides a comparison between the process steps for a pure copper and a pure Uranium Mill operation.

Though the acid leaching CCD solvent extraction sequence does not occur in the main Nchannga Copper production line it could occur in other locations depending on the concentration of copper in the froth or on whether the copper froth also contains some other metal that can be extracted.

The presence of froth flotation units and smelters, both of which can be easily identified in a satellite image and which do not occur in a Uranium Mill provide additional corroborative evidence of a copper operation.

SEPARATION OF URANIUM MILLS FROM COPPER MILLS THAT PRODUCE URANIUM AS A BYPRODUCT

Our preliminary survey of the open domain information also revealed that some copper mills also produced Uranium. This raises the question of how we can separate out the Uranium part of the operation from the copper part.

The Olympic dam mill is one mill that produces both Copper and Uranium. Operations at this site can therefore be used as a basis for improving our identification of key differentiators between Copper and Uranium extraction processes and how these would be revealed when both of them are being produced together.

The IAEA Report provides a detailed flow sheet of the various operations at this site.³³ This along with the available Google Earth images for Olympic Dam Copper – Uranium Mill was used to interpret the various operations at this site and how these operations would show up in the satellite image. The detailed interpretation is in Annexure 9

³³ International Atomic Energy Agency, “Uranium Extraction Technology”, Technical Report Series No. 359, International Atomic Energy Agency Vienna 1993 pp 289-297.

Olympic Dam produces about 194000 tonnes of copper from an average ore grade of about 1.6% and about 4000 tonnes of Yellowcake from the same ore which has an average U_3O_8 content of 0.06%. It is therefore primarily a copper mill with Uranium coming out as a byproduct.

The ore is a sulphide ore and is produced in an underground mine. The crushed and ground ore is made into slurry and subjected to froth flotation. The froth contains most of the copper while the Uranium is in the tailings. The froth is concentrated but still contains some Uranium. This concentrated froth is subjected to an acid leach step to dissolve the residual Uranium. The process is controlled in such a way that most of the copper is still retained in solid form.

This copper containing residue is further concentrated by removing the liquids in a CCD type concentrator circuit. The solid residue that contains most of the copper is then sent to a smelter. The smelter is also linked to a Sulphuric acid plant that produces some of the acid needed by the mill.

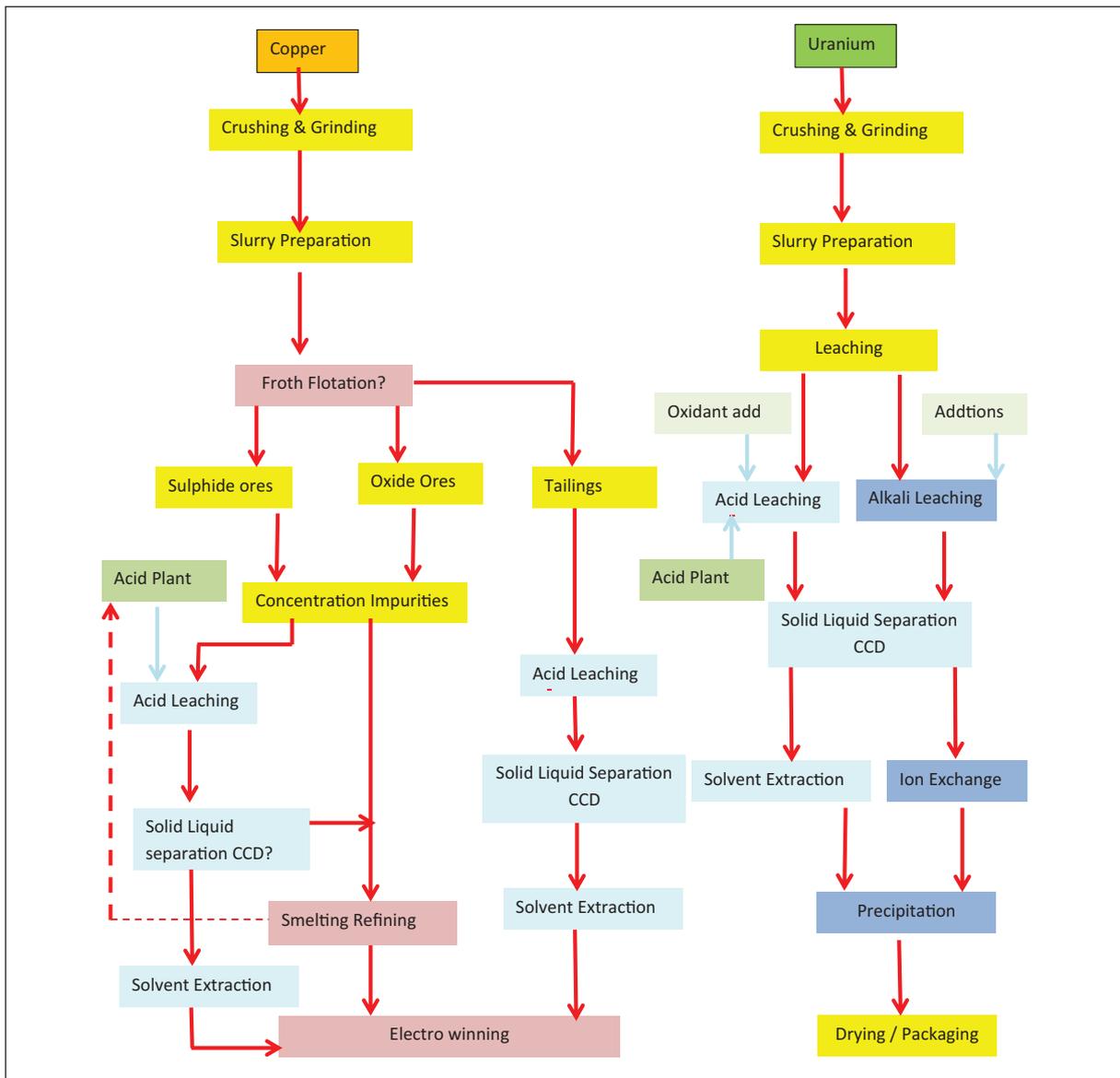


Figure 9: Separation of Copper & Uranium Mills

From smelting it goes into a copper refinery that produces a purer grade copper product. The final step is for the copper product to be converted to a high grade copper product through an electro winning facility. The production of Uranium starts with the generation of tailings from the initial froth flotation process. This still contains some copper. This stream along with the solution stream from the copper acid leach operation is subjected to further leaching. The liquor from this operation is concentrated by sending it through a CCD circuit. The pregnant liquor that contains most of the Uranium and some copper then goes through a first solvent extraction step that removes the copper. The copper containing solution from this first solvent extraction process is sent to the refinery or directly to the electro winning facility. The copper separated liquor which contains most of the Uranium then goes through a second solvent extraction process to concentrate the Uranium. The stripped concentrated Uranium containing solution is treated with Ammonia to precipitate the Uranium. This is then dried and packaged.

Though this sequence of operations is in consonance with the pure copper extraction process of **Figure 9** there are still some differences.

An analyst looking at the satellite image of this mill will see two sequences that correspond to the acid leach – CCD part of a typical Uranium mill. The first sequence occurs after the concentration of copper through the froth flotation process where the residual Uranium in the froth concentrate is removed selectively through an Acid Leach operation. This is also followed by a CCD type concentrator circuit from where the copper concentrate goes directly to the smelter and then on to the Electro-winning Facility.

The second sequence occurs when the tailings of the froth flotation process along with the solution from the copper leach operation are combined as an input into a second acid leaching solution dissolving the Uranium and residual copper. This is also followed by a Uranium CCD circuit.

The Uranium CCD circuit is then linked to two solvent extraction steps – the first for copper and the second for Uranium. The Uranium solvent extraction step is followed by a precipitation step that uses Ammonia (Ammonia tanks are seen in the image) and a drying and packaging step. The stripped solution from the copper solvent extraction facility is directly sent to the copper refinery / electro winning facility for conversion to pure copper.

In the Olympic Dam site both the smelter and the electro winning facility have clear identification features visible in a satellite image.³⁴ The froth flotation facility can also be identified. In addition, acid plants, acid storage, sulphur storage signatures can also be seen.

Apart from an Electro-winning Facility, a smelter and a froth flotation unit, a combined Copper Uranium mill will also have two solvent extraction units in sequence after the CCD circuit for dealing with the froth flotation tailings.

The presence or absence of these features may enable us also to separate a combined Copper Uranium Mill from a pure Uranium or a pure Copper Mill.

Based on the findings of the processes at the Olympic Dam site, **Figure 10** provides details of how a Copper Uranium combined mill can be distinguished from a pure Uranium Mill.

³⁴ This is a very long building. In many cases individual cells where the cathodes are plated can also be seen.

SEPARATING URANIUM MILLS FROM ZINC AND MANGANESE MILLS

Two other commercially important metals also use an acid leaching step as a part of their extraction step. These are Zinc and Manganese.

About 11 million tonnes of Zinc and about 15 million tonnes of Manganese are produced every year. Just as in the case of copper the scale of these operations would be significantly different. The flow sheet for the mainstream Zinc and Manganese producers would also be significantly different and there would therefore be no basis for confusing it with a Uranium operation. An ore beneficiation step such as flotation may be necessary to ensure that the metal concentration is sufficient to cater to these scales.³⁵ Additional operations such as smelting, refining and electro winning may also be necessary. At such large scales the Acid Leach CCD solid liquid separation sequence may not be viable.

However just as in the case of copper many of the major Zinc and Manganese operations may generate a large quantity of tailings. Some of these tailings may contain significant quantities of Zinc or Manganese that could also pose environmental issues. It is possible just as in the case of the Nchanga copper mine and mill that the recovery of the metals from tailings as a byproduct could become attractive and useful. In such a situation one could see an Acid Leach – CCD – Solvent Extraction flow sheet attached to a main Zinc or Manganese production mill.

Once again since the final operation will involve electro winning instead of the precipitation step characteristic of Uranium. The presence of a visible electro winning facility will separate Uranium operations from a Copper, Zinc or Manganese operation.³⁶

We can on this basis conclude that the sequence of Acid Leach – CCD solid liquid separation – Solvent Extraction can occur as by product in a mainstream Zinc or Manganese Plant.³⁷

An electro winning step for Zinc and Manganese which can be identified on a satellite image as compared to a precipitation step for Uranium may help separate a Uranium operation from a Zinc and Manganese Tailings operation.³⁸

SEPARATING URANIUM MILLS FROM RE MILLS

The extraction of Rare Earths (RE) from RE containing ores also involves acid leaching. RE global demand is currently estimated to about 150000 tonnes as compared to an annual Uranium yellowcake demand of about 70000 tonnes. The scales of operation are therefore not too different.

Most of the world supply of Rare Earth Oxides (REO) came from The Mountain Pass Mine and Mill in the US till the late 1980's. In its original avatar the naturally occurring RE ore that contained both the

³⁵ http://www.mincopl.com/fileadmin/user_upload/projects/woodstock/Manganese_Market_Outlook_2012_ExecutiveSummary.pdf provides the executive summary of the CPM Group's Manganese Market Outlook in February 2012. For Manganese 44% grade is considered good. Grades containing up to 30 % are also exploited. Grades of 10% are considered low quality. For Zinc too these grades would be similar. If these ore concentrations do not occur naturally beneficiation of the ore may be necessary.

³⁶ Electrolytic Manganese Metal accounts for about 10% of the world demand of 15 Million tonnes of Manganese. See Reference 33.

³⁷ Though it is possible that such a sequence can be put together, only an empirical investigation will reveal whether this is current practice.

³⁸ Kemetco Research Inc , "The Recovery of Manganese from Low Grade Resources Bench Scale Metallurgical Test Programme Completed" provides a description of a typical flow sheet for handling low grade Manganese tailings.

bastanasite and monazite was separated into the bastanasite form concentrated through a special steam based flotation process to produce an RE concentrate with about 60% RE. This was then leached with Hydrochloric acid, separated into Heavy and Light RE fractions through a solvent extraction step. The Light RE fraction then went through a further solvent extraction step that separated the Cerium fraction of Light RE from the Lanthanum fraction. Each of these fractions was then subjected to further solvent extraction processes for separation of the other individual lighter RE fractions.³⁹

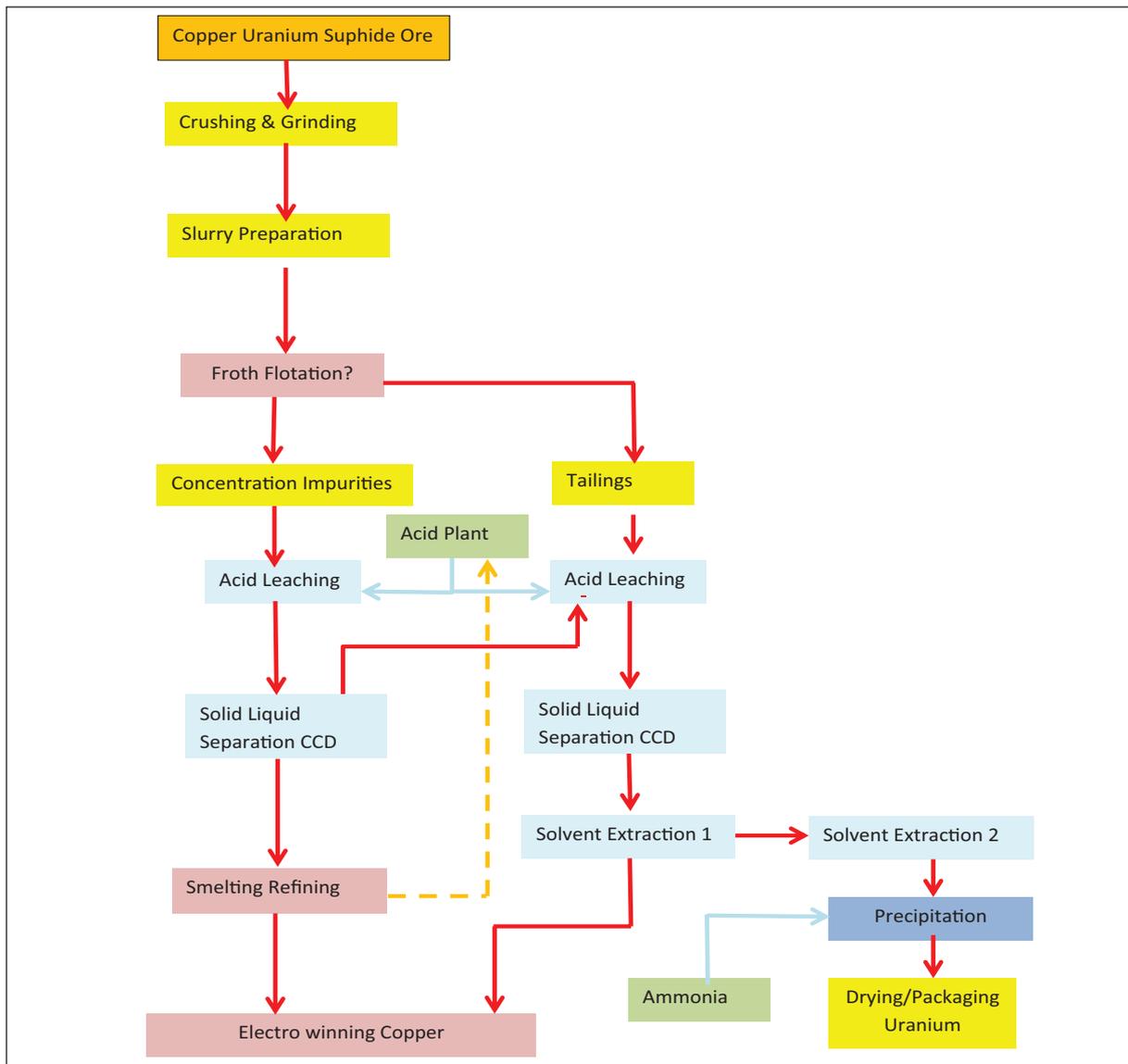


Figure 10: Process Sequence in Copper Uranium Mills

³⁹ For a detailed flow sheet of the Mountain Pass mill as of about 1995 please see Keith R Long et al “Principal Rare Earth Elements Deposits of the US – A Summary of Domestic Deposits and a Global Perspective” Scientific Investigations Report 2010 – 5220, US Department of the Interior, US Geological Survey, 2010. A simpler version of the flow sheet is available in US Environmental Protection Agency Report “Rare Earth Elements: A Review of Production, Processing, Recycling and Associated Environmental Issues”, Engineering Technical Support Center, Land Remediation and Pollution Control Division, National Risk Management Research Laboratory, Office of Research and Development, Cincinnati Ohio, EPA / 600/ R – 12/ 572 [December 2012], Appendix C p C-1.

After the Mine and mill were acquired by Molycorp a major expansion and cost reduction effort is underway.

The effort not only promises to improve the efficiency but also promises to reduce the environmental impact of RE extraction by recycling most of the water and reagents used for the extraction process. The new process improves the yield by not only processing the bastnasite but also proposes to take the RE elements from the monazite fraction as well.

Though the hot flotation and Hydrochloric acid leaching part and the solvent extraction steps largely remain the same the addition of a natural gas based power plant, a Hydrochloric acid Plant and a chlor alkali plant for the production of Sodium Hydroxide (for leaching the monazite) and Chlorine (for the acid plant) promises to reduce cost. The tailings from the acid leach and wastes from the other processes used are not stored in a tailings pond as done earlier but filtered by taking out the water which is recycled and producing a paste out of the residue. This is mixed with other materials and used as a material for landscaping in the area around the mill.⁴⁰

Annexure 16 shows a Google Earth Image of the leaching section of the Mountain Pass RE Mill in California along with the interpretation based upon the current processes used. Annexure 17 shows the Solvent Extraction and Precipitation section of the Mill.⁴¹

No CCD units are seen in the Mountain Pass Mill. The ore body here is relatively rich in RE (over 8%). The hot flotation step further concentrates the RE fraction prior to acid leaching. Therefore the RE rich liquor does not need a further elaborate Liquid solid separation effort.

Just as in the case of Zinc, Manganese and Copper it is possible that if RE demand increases pushing up prices processing lower quality ores may become viable. In such a situation we would see a similar sequence as we have seen for Uranium that involves acid leaching, CCD based solid liquid separation, solvent extraction and precipitation. However instead of one solvent extraction step we would see a series of solvent extraction steps as the different RE fractions are separated. Multiple and different solvent extraction facilities would indicate that this is an RE facility and not a Uranium facility. Additional steps in the flow sheet such as a flotation step for concentration of the ore may or may not be there. But in the case of an RE facility multiple RE solvent extraction facilities should provide a definite indication of an RE operation.

It is possible that not all the RE is fully separated and that only one output which is a mixture of all REO is produced. In such a situation it may be difficult to separate out an RE facility handling low grade ore from a Uranium mill and we need to look at other ways of separating them. In the current scenario where RE concentration levels are on the higher side and made even higher through steps like froth flotation the absence of a CCD unit and the presence of multiple solvent extraction facilities should enable one to separate out a RE facility from a Uranium mill.

⁴⁰ Molycorp Annual Report 2013, pp 6-7.

⁴¹ The Mountain Pass Mine has been bought and sold several times in the last ten years. Molycorp its latest owner has embarked on a major modernization effort that promises to make the Mountain Pass mine and mill one of the most efficient operations in the world.

SEPARATING URANIUM MILLS FROM VANADIUM MILLS

The other element whose extraction may sometimes use an acid leaching step is Vanadium.

About 72000 tonnes of Vanadium were produced globally in 2012.⁴²

This is very similar to the annual production of about 70000 tonnes of yellow cake.

Most of the Vanadium produced comes out of the Vanadium contained in steel or pig iron slag. The Vanadium produced in this way would employ very different extractive processes from the processes used to produce U_3O_8 .⁴³

Even if the extraction and processing step is dedicated only to Vanadium a typical process would still be very different.⁴⁴

Only ores containing both Uranium and Vanadium may provide a sequence of operations very similar to the operations required for the extraction of Uranium from a pure Uranium Mill.

Carnotite an ore containing Uranium and Vanadium is leached using sulphuric acid. After the removal of Uranium via solvent extraction the residual solution that contains the Vanadium is treated with iron powder and subjected to another solvent extraction step. After stripping with sulphuric acid a vanadyl sulphate solution is produced. This is then oxidized at high temperature with sodium chlorate and precipitated from solution as red cake (a mixture of sodium and Ammonium vandate) by the addition of Ammonia or Ammonium salts. This is then roasted to produce an alkali containing V_2O_5 product.

We can see that a Uranium – Vanadium combination ore may have some steps that are very similar to a pure Uranium extraction mill but will also have more than one solvent extraction and precipitation step. After the first solvent extraction step for Uranium it will have another solvent extraction step before the precipitation step. The presence of Ammonia⁴⁵ along with a second solvent extraction step could be a typical sequence for Vanadium precipitation after a primary Uranium extraction process.⁴⁶

SEPARATING URANIUM MILLS FROM PHOSPHORIC ACID PLANTS

Phosphoric acid is a key intermediate chemical for producing phosphatic fertilizers and a number of other phosphorus based compounds. It is often produced by the acid leaching of phosphatic rock. Apart from

⁴² TTP Squared Metals Industry Consultants & Atlantic Ltd., “Vanadium Market Outlook”, April 2013 at <http://atlantictld.com.au/upload/documents/VanadiumInformation/VanadiumMarketOutlook.pdf>

⁴³ http://www.gfe.com/userfiles/file/pdfs/Veroeffentlichungen/Chemicals_VanadiumandVanadiumCox492DC.pdf provides an extract of various processes used for the production of Vanadium and Vanadium compounds from Ullman’s Encyclopedia of Industrial Chemistry Vol A27 “Vanadium and Vanadium Compounds”.

⁴⁴ http://atlantictld.com.au/upload/documents/InvestorRelations/presentations/20100225_100228InvestorPresentation.pdf provides a process flow sheet for Vanadium production by Atlantic City the owners of the Windmurra Vanadium mine and mill. We have also looked at the satellite image of this Vanadium mill. The image observables as well as the flow sheet are quite different from those used in Uranium extraction process. Thus there is very little in common between a Pure Uranium mill and a pure Vanadium mill apart from the acid leaching step.

⁴⁵ Ammonia will precipitate both the Uranium and Vanadium part in the solution. Therefore if it is used, further processing to separate out the Vanadium from the Uranium may be needed. The use of Hydrogen Peroxide selectively precipitates only the Uranium leaving everything else in the solution. Its use especially in the Canadian Uranium mills is being adopted for this reason as well as to take care of the environmental regulation problems arising from the use of Ammonia

⁴⁶ Reference 41 p 374 provides details about the treatment of carnotite ores.

an acid leaching step the various processes employed in a mainstream phosphoric acid plant are very different. It is likely that phosphoric acid contains some residual Uranium that can be extracted. Reference 5 provides details of many such processes that have been developed for this purpose.⁴⁷ Current prices of Uranium do not make any of these processes commercially viable. However, it is possible that a country that does not have a very high quality Uranium deposit, could consider such an approach especially if it has good phosphate deposits. We have not included this possible route to Uranium production in this report.

CONCLUSIONS - KEY DIFFERENTIATORS FOR A URANIUM MILL

The sequence of Acid or Alkaline leaching – CCD – solvent extraction – precipitation is typical of 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 because of the Resin-in-Pulp alternative, 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.

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

In many cases solvent extraction facilities have features that can be identified through satellite imagery. Recycling of the solvent is also often an indicator of such a facility. However in some cases they may be housed inside buildings and cannot be seen.

Ion exchange facilities can also normally be seen in a satellite image. However here also in certain cases they may be hidden 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, Zinc and Manganese extraction mills that may in some cases share a similar Leaching – CCD – Solvent extraction sequence can be eliminated by using the presence of Electro-winning, Smelting and froth flotation facilities. All these facilities have clear satellite signatures and can be identified easily.

The presence of an Electro-winning facility along with two solvent extraction plants in sequence can also be used to identify a copper mill that produces Uranium as a byproduct. Even if the Solvent extraction facilities cannot be uniquely identified in the satellite image the presence of the Electro-winning facility

⁴⁷ Reference 5 pp 216 – 233.

will indicate that it is largely a copper mill.

In the same way the absence of a froth flotation facility and the absence of multiple solvent extraction facilities can eliminate Rare Earths.

Through such elimination of various alternatives that share the leaching step and in some cases the CCD as well as solvent extraction steps we can increase the probability that the mill we are seeing is indeed a Uranium Mill.

Figure 11 provides a decision tree that uses the above logic to decide whether a particular mill that has been imaged by a satellite can be categorized as a Uranium Mill.

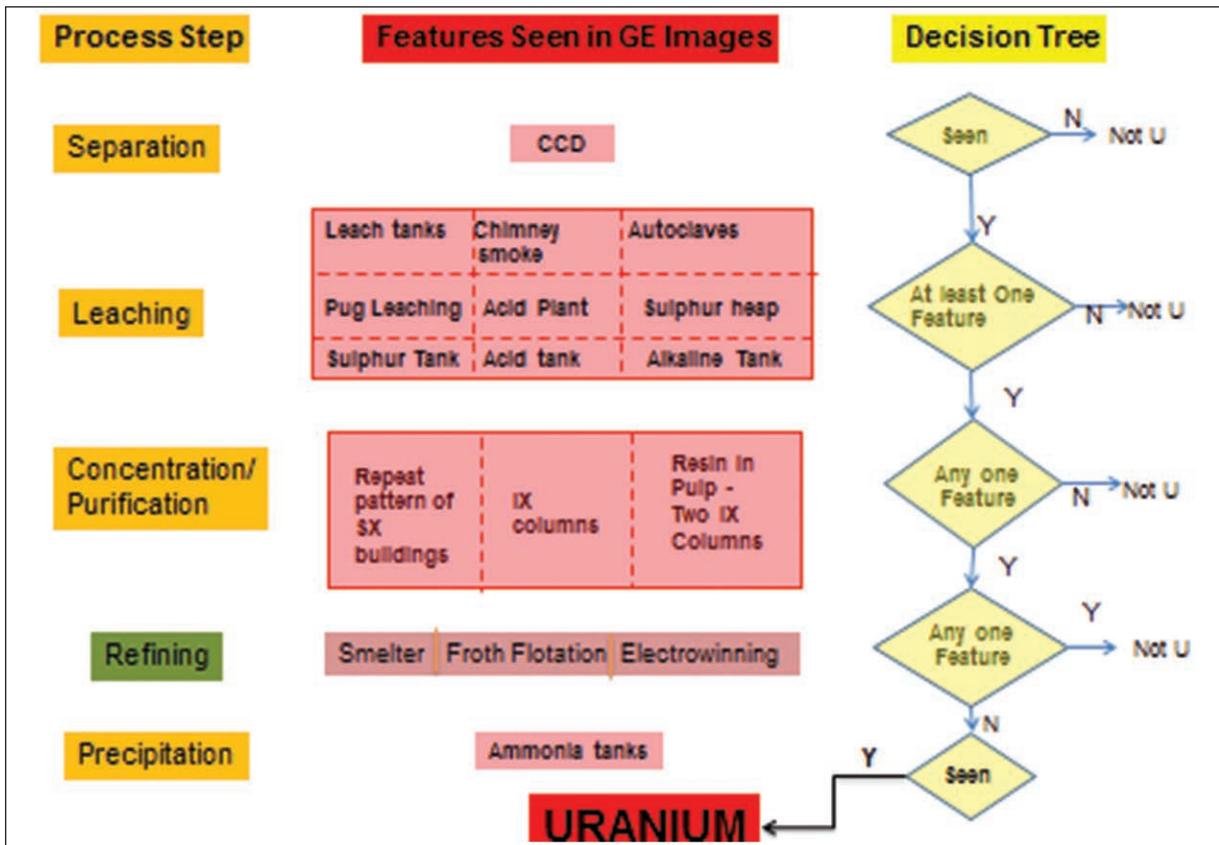
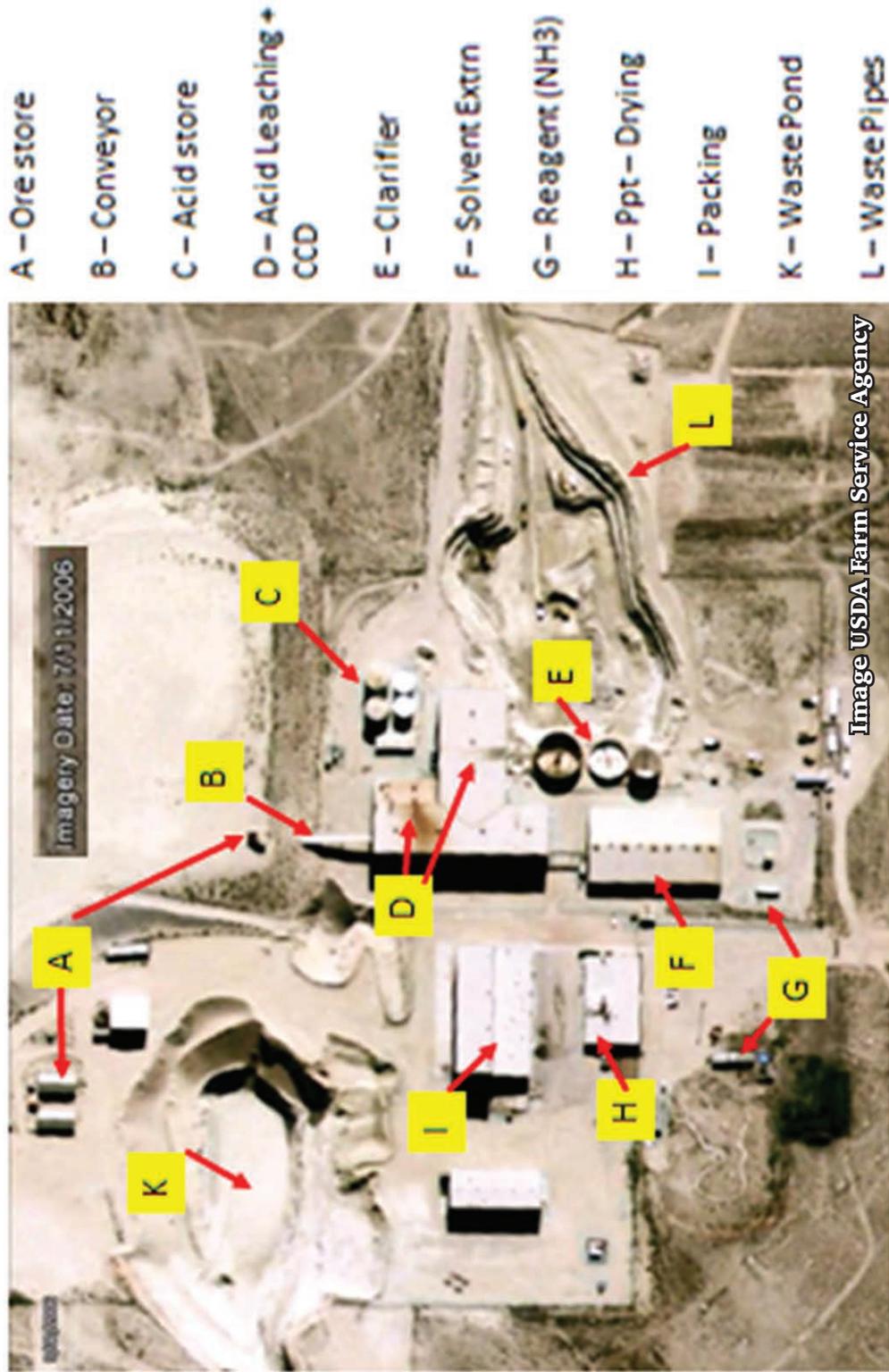


Figure 11: Decision Tree to Differentiate an Uranium Mill from other Mills

Annexure 1

Sweetwater Uranium Mill Wyoming USA - Mill Layout

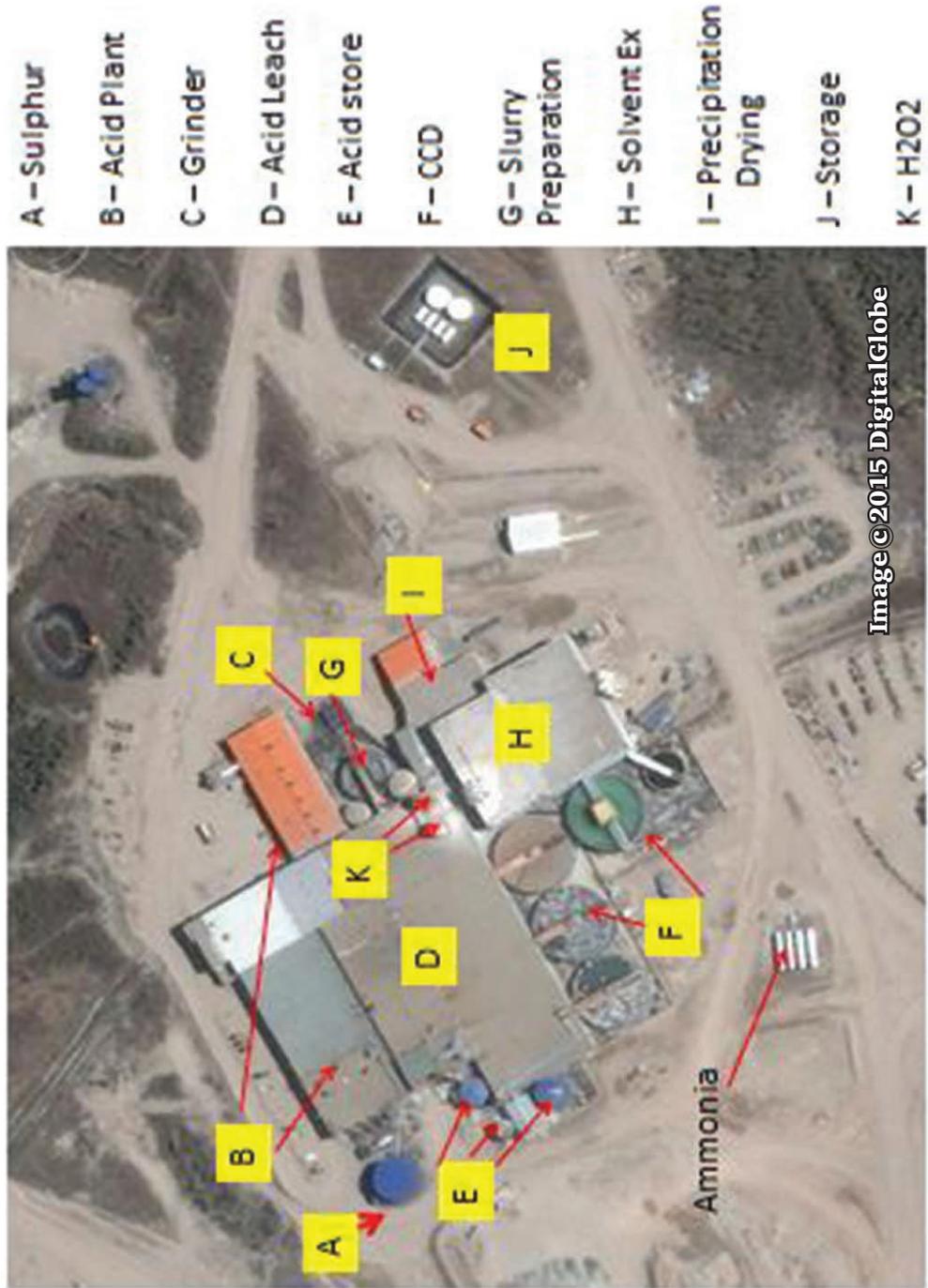
42 03 N 107 54 W November 7, 2006



Annexure 2

Rabbit Lake Uranium Mill - 29 May 2007

58 11 25N 103 42 36W May 29, 2007



Annexure 3

Ranger Uranium Mill

12 41 S 132 55 22E January 4, 2004

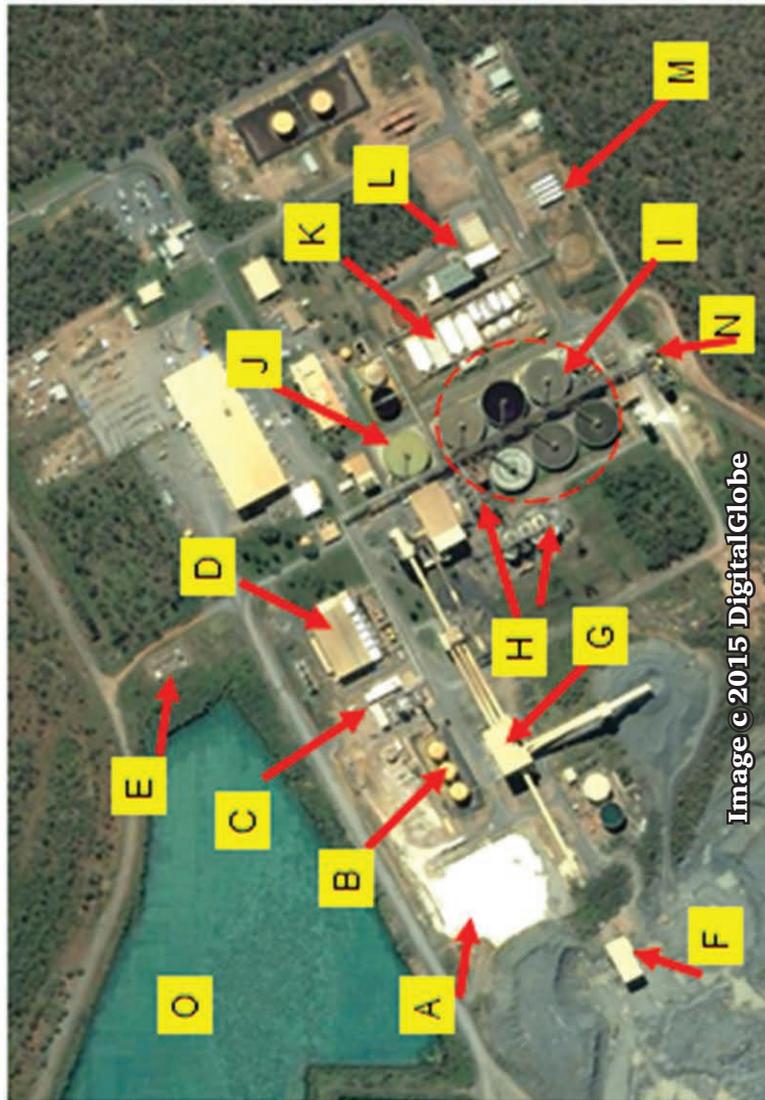


Image c 2015 DigitalGlobe

- A – Sulphur heap
- B – Sulphur store
- C – Acid Plant
- D – Power Plant
- E – Sub – Station
- F – Ore sorter
- G – Crusher conveyor
- H – Leach Tanks
- I – CCD
- J – Flocculant tank
- K – Solvent Extraction

- L – (AUD) Precipitation – drying
- M – Ammonia Storage
- N – Waste Water Treatment
- O – Tailings Pond

Annexure 4

McLean Lake Uranium Mill

58 20 23.38 N 103 50 05.78W May 29, 2007

- A – Ore
- B – Leach
- CCD – CCD
- C – Clarifier
- SE Solvent
- Extraction?
- D-Dryer
- D-Packing
- EPPT
- F Ammonia
- WT Water
- Treatment
- AP Acid Plant
- AmS Amm.
- Sulphate
- WH Warehouse

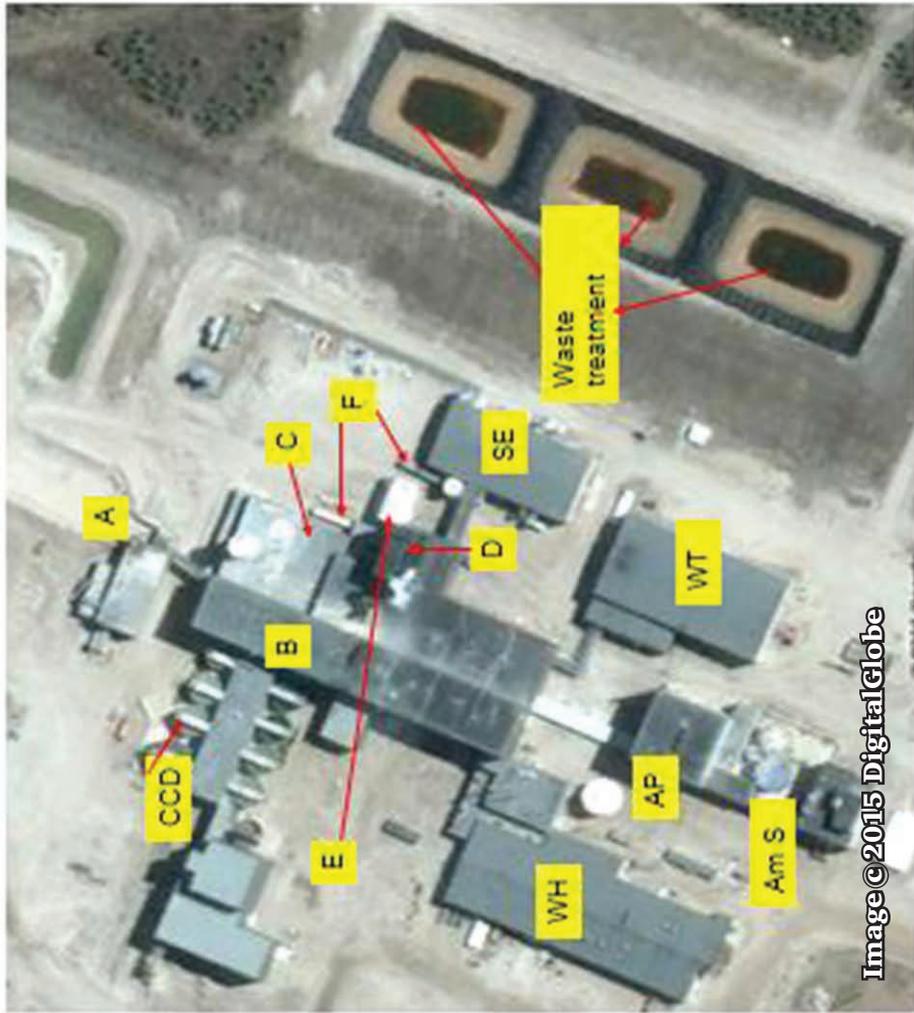


Image © 2015 DigitalGlobe

Annexure 5

Key Lake Uranium Mill

(This image is a Quickbird satellite image provided by Digital Globe Inc.)

57 12 48N 105 40 22W



A – Heat Exchangers

B – Acid Plant

C – Leaching Section

D – Diesel Sets – Power plant

E – CCD

F – Solvent Extraction – precipitation

G – Calcining Facility

H – Ammonium Sulphate Plant

Annexure 6

Arlit Mine & Mill Niger
18 47 N 7 21 E February 11, 2008

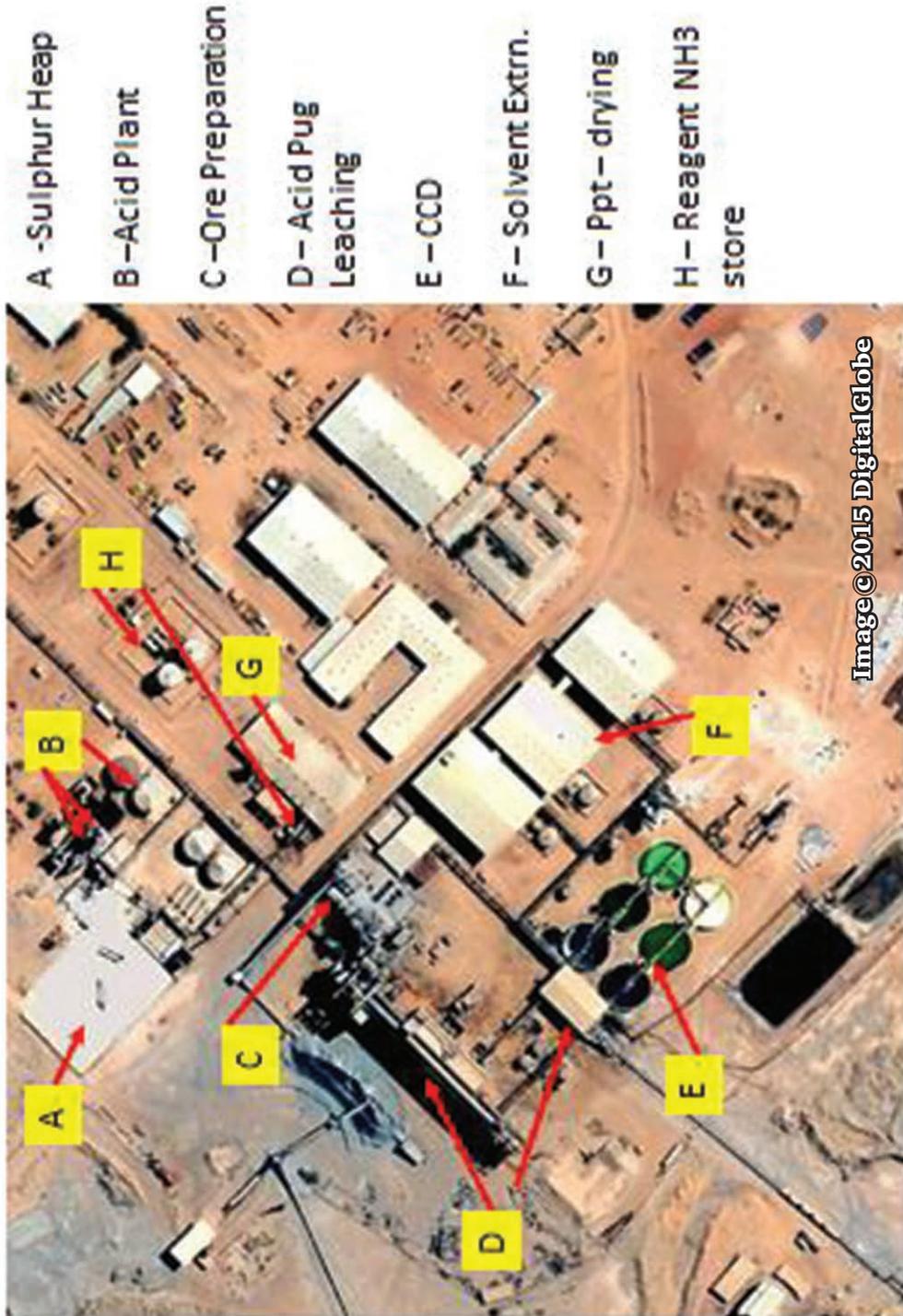
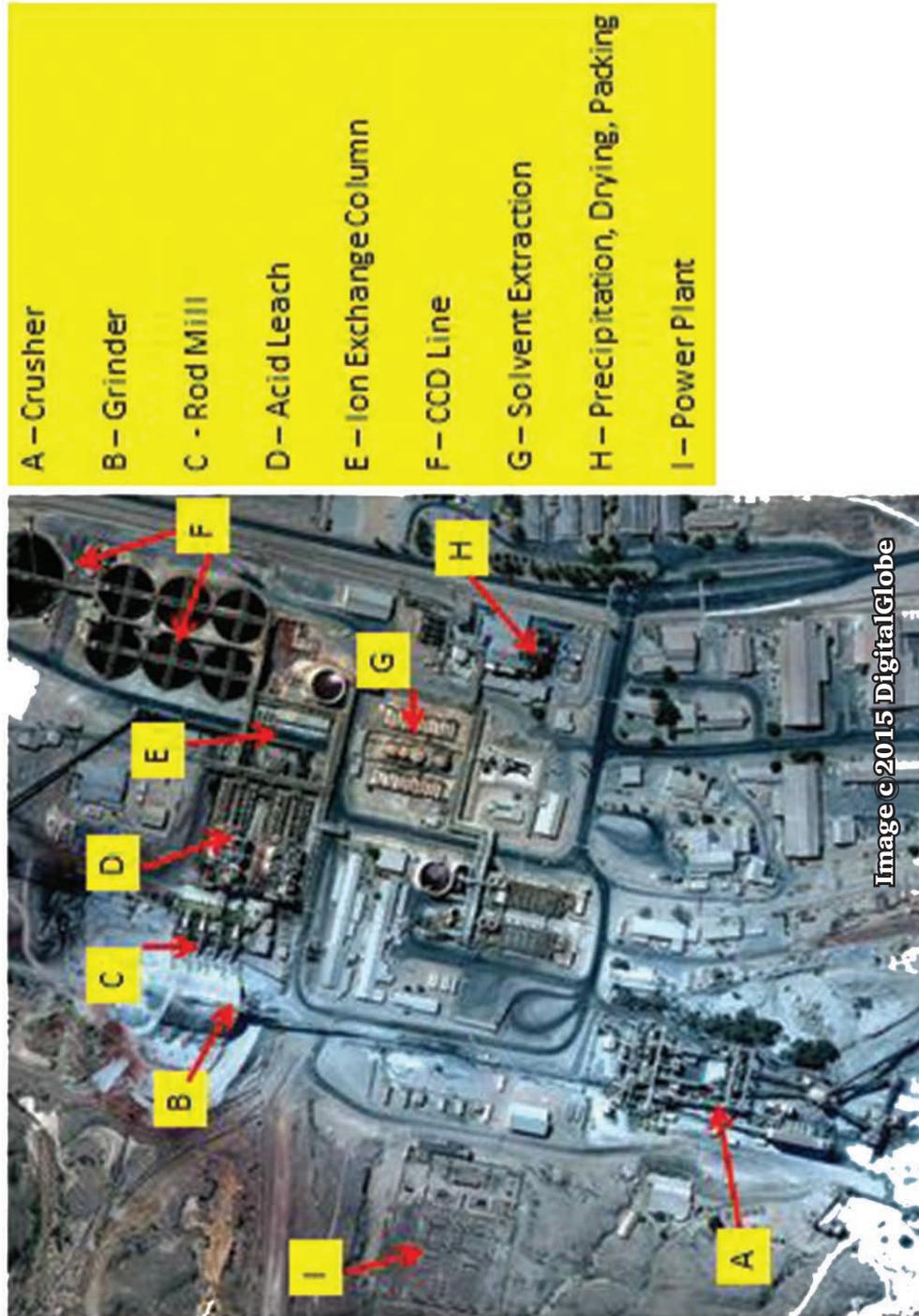


Image © 2015 DigitalGlobe

Annexure 7

Rossing Uranium Mill

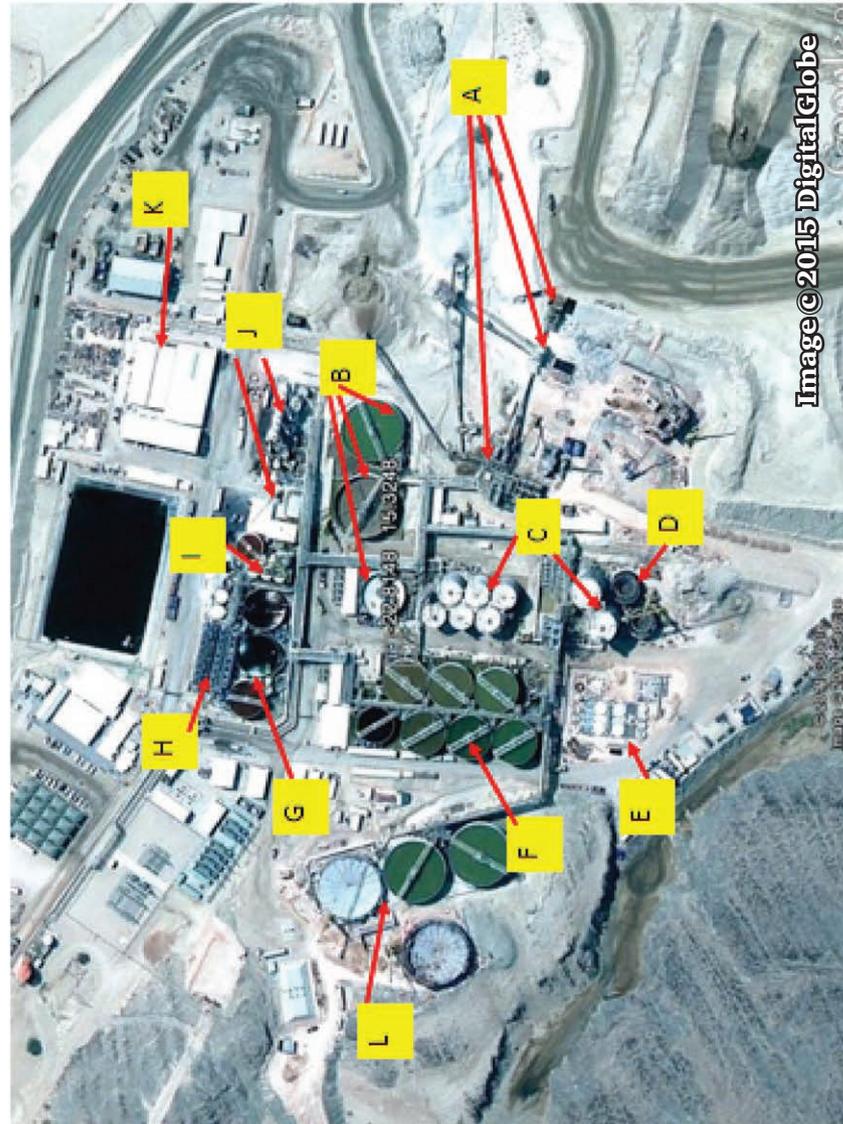
22 27 47S 15 02 37 E August 29, 2010



Annexure 8

Langer Heinrich Uranium Mill

22 48 52 S 15 19 31 E September 17, 2010



A – Ore Preparation

B – Leach preparation

C – Concrete alkaline leach tanks

D – Spiral Heat Exchanger

E – Leachant Conditioning Tanks

F – Hi Rate CCD

G – Hi Density CCD

H – Ion Exchange Columns

I – Reagent Storage

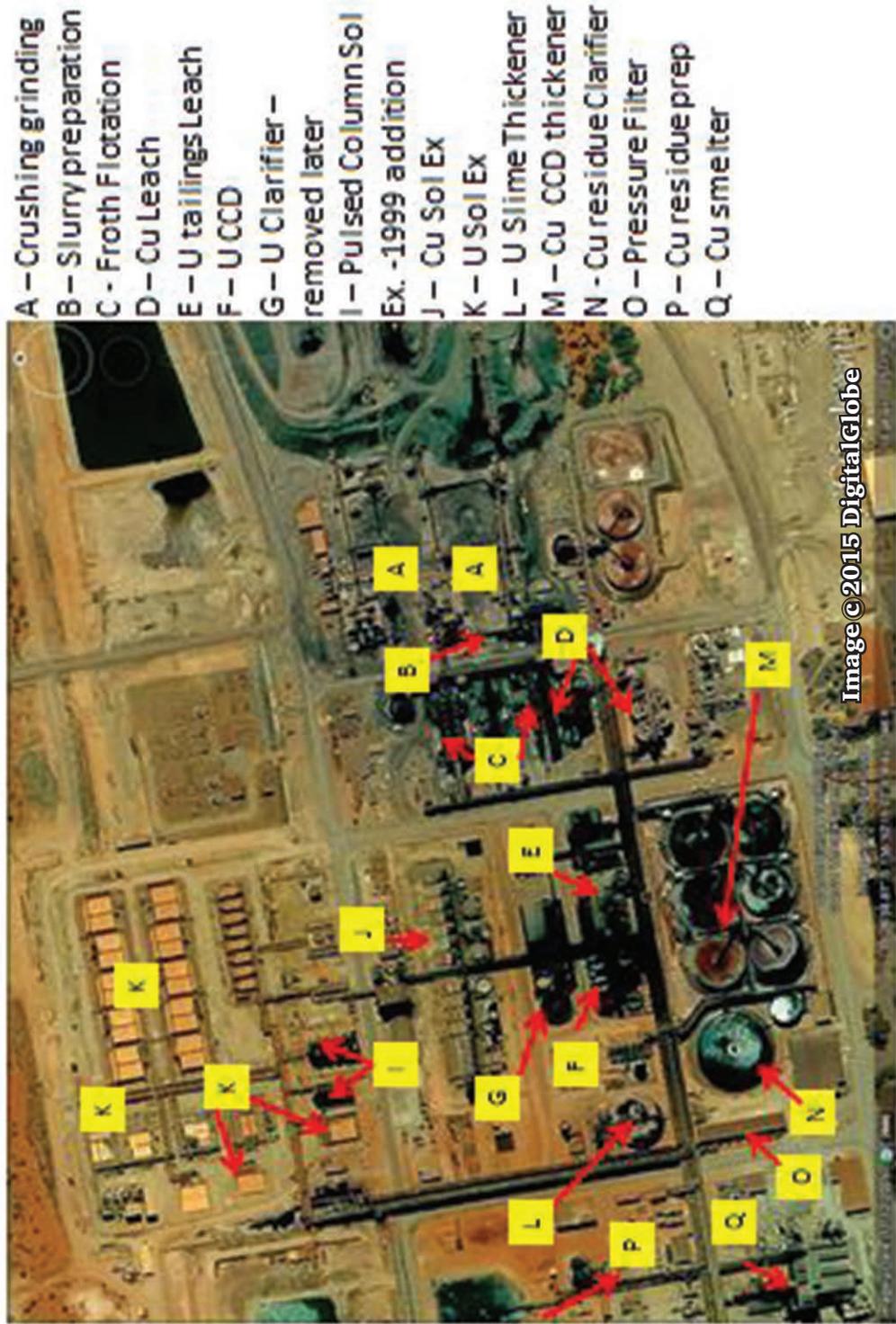
J – Precipitation drying -Packing

K- Storage – dispatch

L –Expansion project

Annexure 9

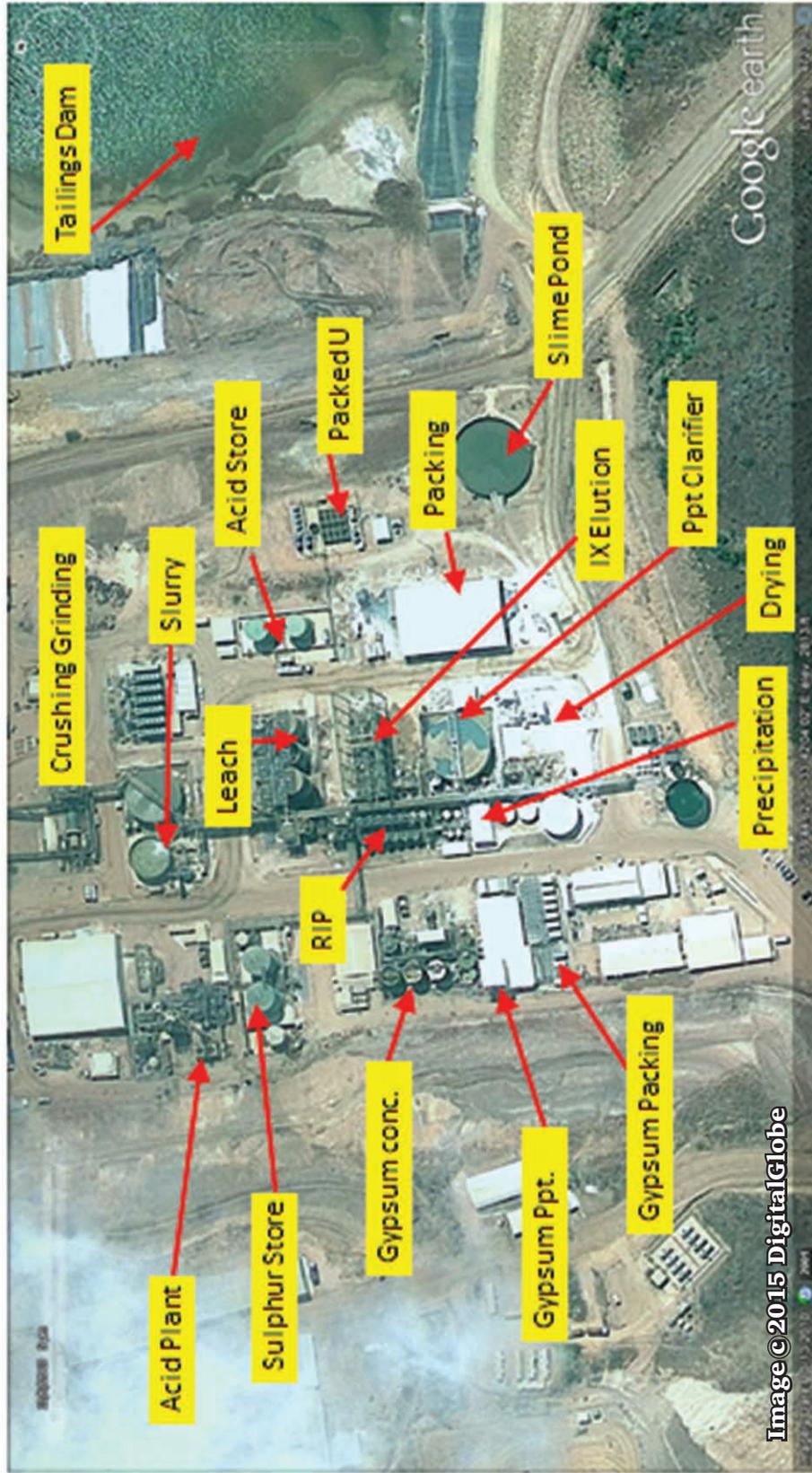
Olympic Dam Copper Uranium Mill
30 26 39S 136 52 15E November 12, 2005



Annexure 10

Kayalekera Resin In Pulp (RIP) Uranium Mill

9 59 44S 33 42 03 E October 13, 2010



Annexure 11

Krasnokamensk Uranium Mill Key Features

50 05 51 N 118 11 E September 11, 2011

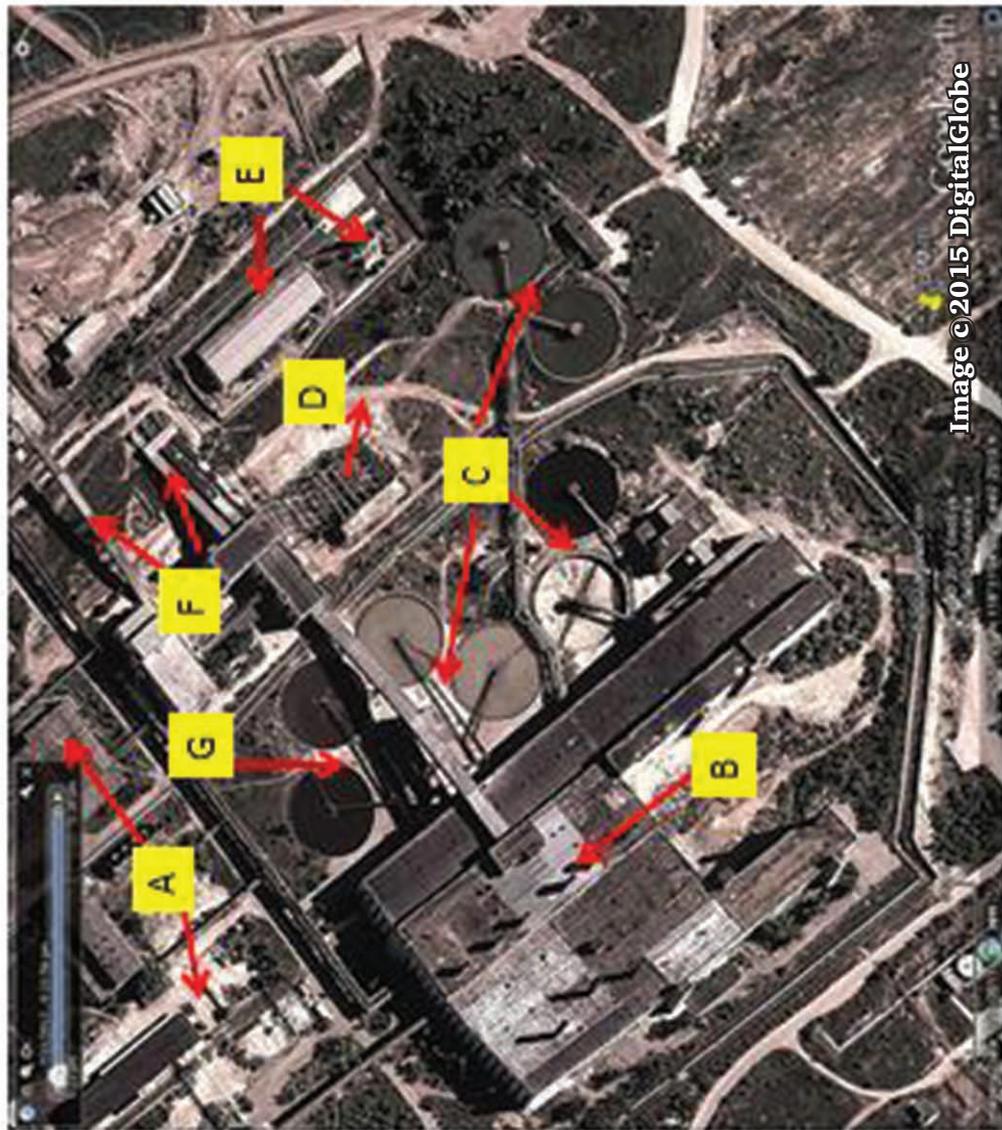
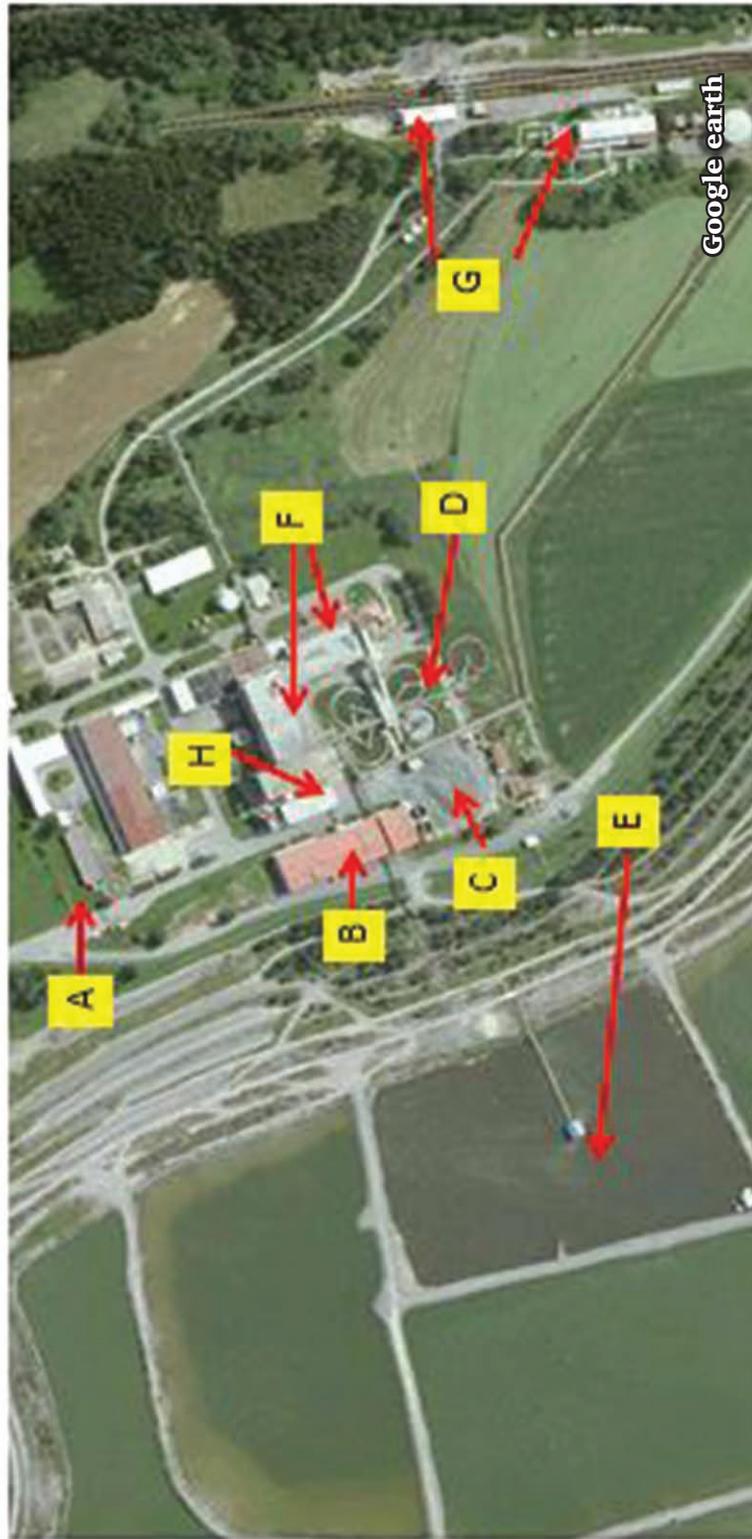


Image ©2015 DigitalGlobe

Annexure 12

Layout of Razna Uranium Mill
 49 29 38 N 16 13 42E May 1, 2009

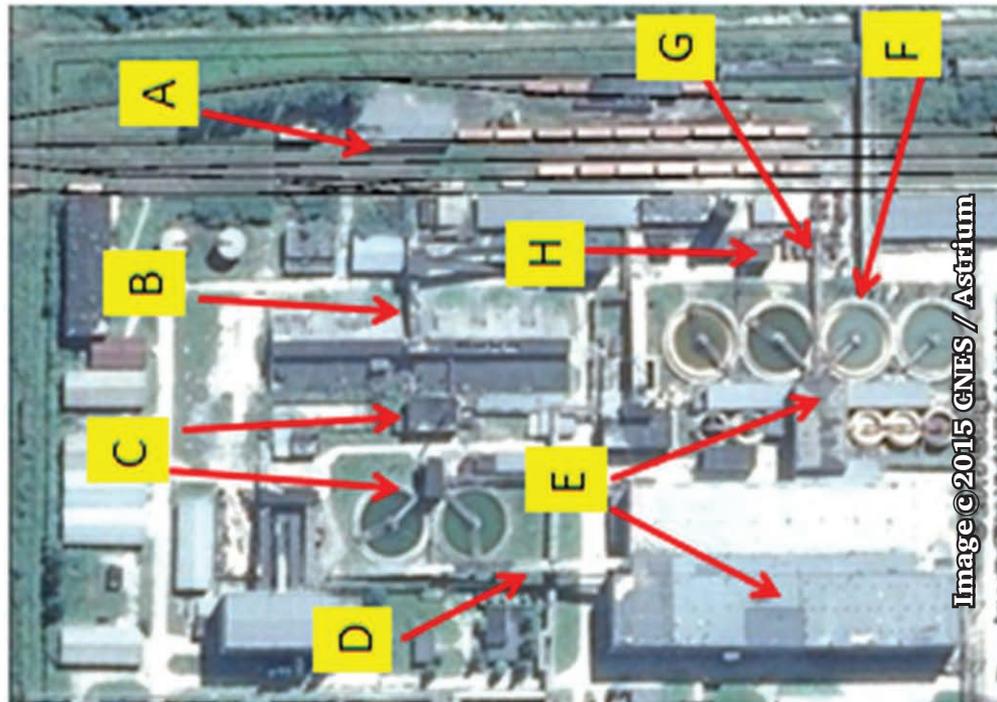


- A – Security Gate B – Crushing Grinding Slurry C – Ore Waste Pile D – CCD
- E – Waste Treatment Ponds F – Ion Exchange G – Precipitation & Packaging
- H – Alkaline Leaching

Annexure 13

Feldiora Uranium Mill Romania

45 50 31 N 25 30 9E August 1, 2014



A – Ore Receipt Station

B – Ore preparation

C – Slurry Preparation

D – Conveyor

E – Hot Leaching / Autoclave

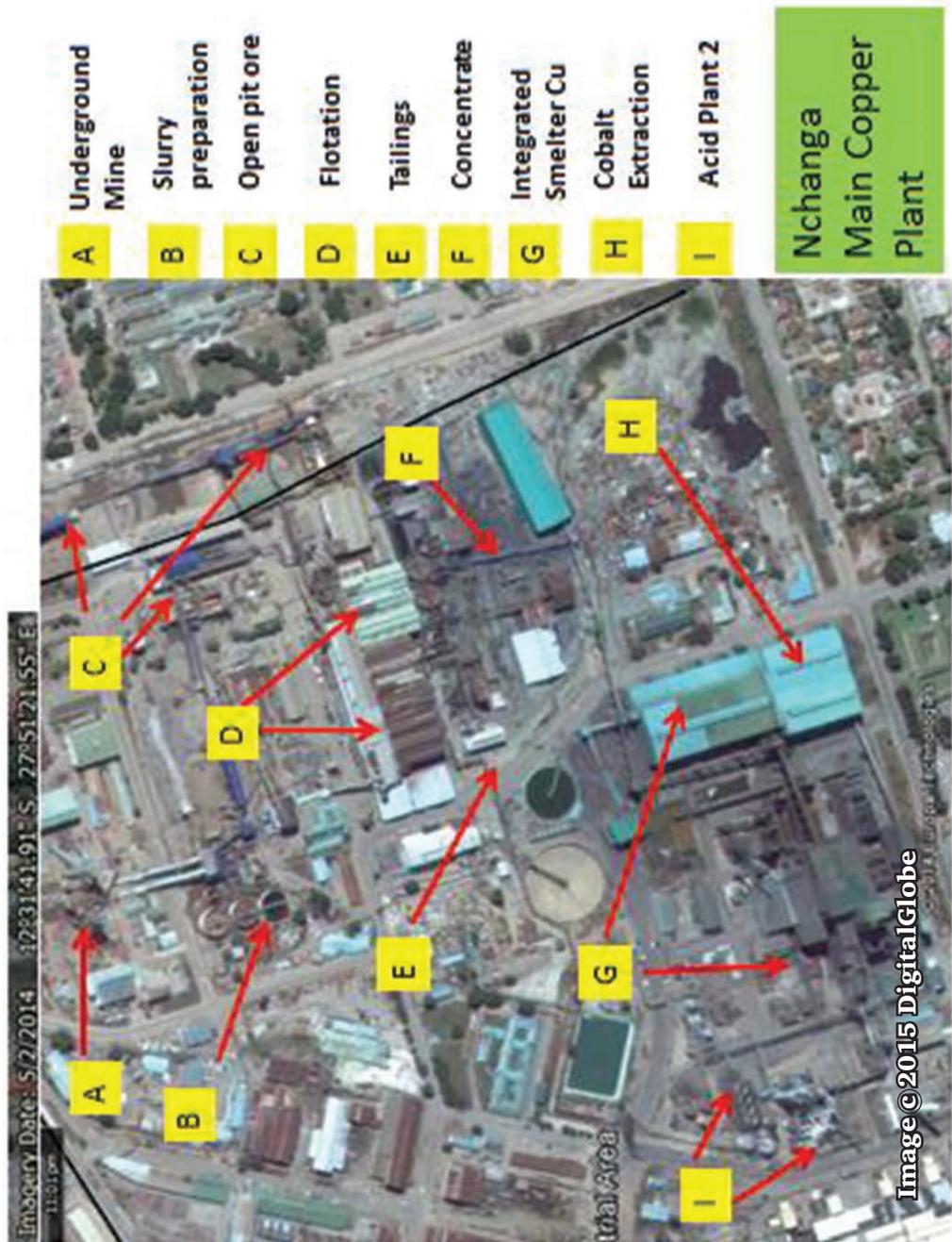
F – CCD

G – Ion Exchange / Resin in Pulp

H – Precipitation

Annexure 14

Nchanga Main Copper Mill
12 31 41S 27 51 22 E May 2, 2014



Annexure 15

Nchanga Tailings Copper Extraction Plant

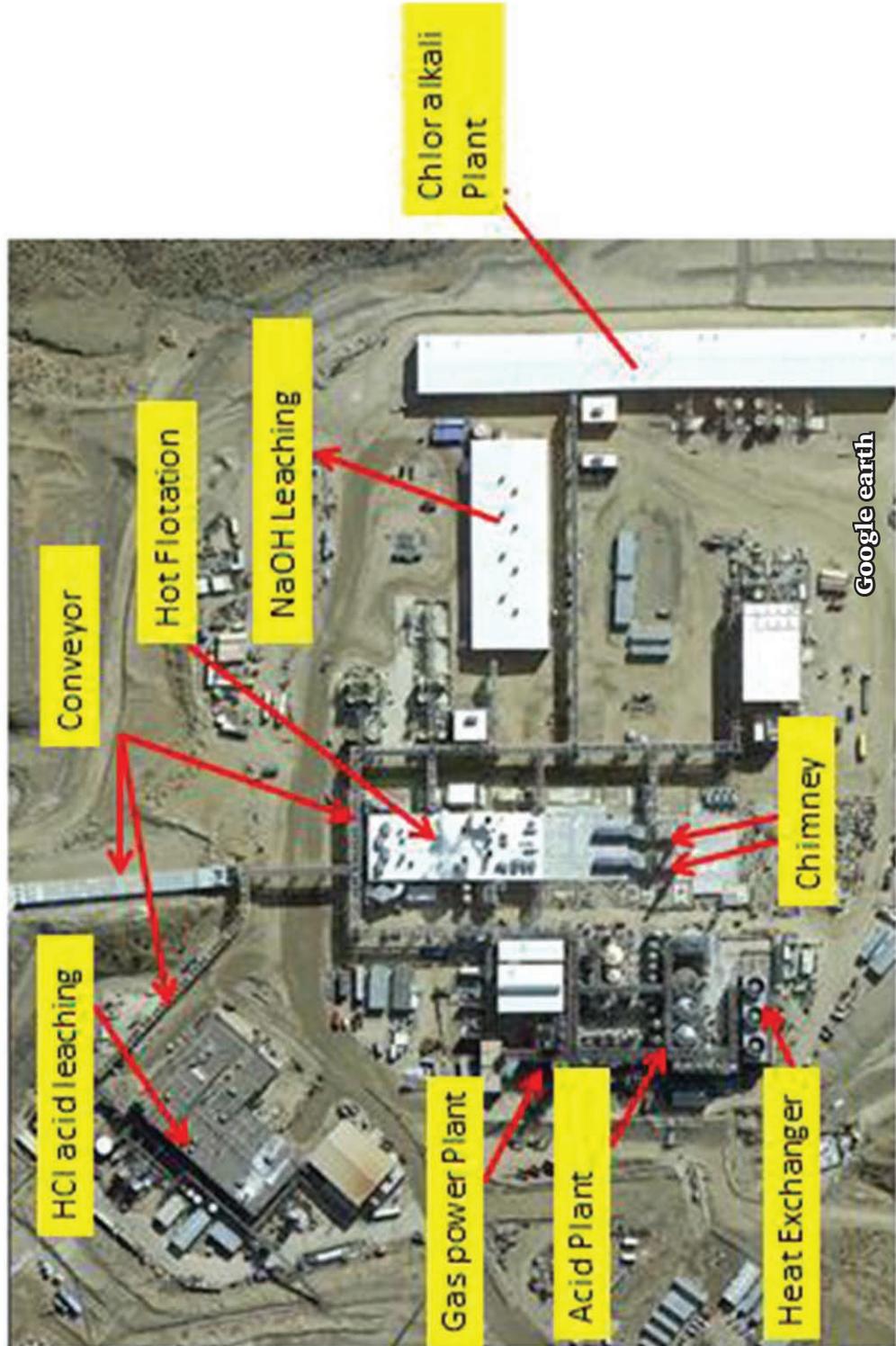
12 31 58S 27 50 47E May 2, 2014



Annexure 16

Mountain Pass RE Mill Leaching Section

35 28 45 N 115 31 28 W March 23, 2013



Annexure 17

Mountain Pass RE Mill Solvent Extraction Precipitation Section

35 28 52 N 115 31 36 W March 23, 2015

