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International Strategic and Security Studies Programme
NATIONAL INSTITUTE OF ADVANCED STUDIES
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BACKGROUND & FOCUS

The International Atomic Energy Agency (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;
c. open sources and third parties[1].

The IAEA's analyses consists 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), CSA and under the Additional Protocol Agreement (APA) or that obtained on a voluntary basis.

Under the Additional Protocol Agreement, signatory states are required to provide IAEA inspectors information on all parts of the nuclear fuel cycle that include uranium mines, processing facilities, fuel fabrication & enrichment plants, nuclear waste sites as well as any other location where nuclear materials may be present. The IAEA Verification measures include on-site inspections, visits, and as well as ongoing monitoring and evaluation[2].

This has vastly increased the amount and type of information that States will have to provide to the IAEA. At the same time, the burden of verification has also vastly multiplied as far as the IAEA inspectors are concerned. The IAEA is therefore likely to find itself in a situation where physical verification of the declared nuclear facilities will become increasingly difficult.

Monitoring and evaluating undeclared facilities especially those related to the early parts of the nuclear fuel cycle such as uranium mining and milling also become a very important component of the verification activities. Development of newer methods and technologies that can strengthen verification protocols would therefore be very useful[3].

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[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

Though several studies have addressed the usefulness of satellite images for monitoring various parts of the nuclear fuel cycle[4] not much work has been carried out to assess their utility for monitoring Uranium mining and milling operations.

While India is a declared nuclear weapon state the activities of her neighbours in the nuclear realm are shrouded in secrecy. This situation is often made more complicated by a lot of ambiguous information pouring in from a number of sources especially from the west. It is therefore difficult for a strategic analyst or policy researcher to make a meaningful assessment of the uranium production capacity of a country since there is very little reliable data.

Image processing specialists within the country have also not made any efforts to develop suitable algorithms that describe in detail how satellite images can be used to identify Uranium mines and mills.

From a practical viewpoint there are at least two aspects of a mill operation that require attention from image analysts.

The first aspect is of course to clearly identify a mill site as a uranium mill site

Several studies in the West have demonstrated that satellite images can be used to identify uranium mill sites at least to a limited extent[5][6][7]

Building on this work, a more recent study used features associated with the various processes used for the extraction of Uranium that are visible in a satellite image for the identification of a Uranium Mill and this has been dealt exhaustively in an earlier NIAS report[8]

Once a mill has been identified as a Uranium Mill, it is also important to see whether methods can be developed to estimate the production capacity of such a mill.

This report focuses on methods that can be used to estimate the production capacity of a Uranium mill after the mill has been identified as a Uranium producing mill.

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[4] Jasani B, Niemeyer I, Nussbaum S, Richter B, and Stein G. International Safeguards and Satellite Imagery (2009), Springer Verlag.

[5] 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

[6] 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

[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] S.Chandrashekar, Lalitha Sundaresan and Bhupendra Jasani, Identification of Uranium Mill sites from Open Source Satellite Images, NIAS Report R34- 2015, September 2015.

After briefly reviewing our earlier work on a unique method for identifying a Uranium mill and separating it from other mills such as copper mills we look at the basic design considerations that determine the capacity of a mill.

From these design principles that determine capacity we then look at the various mill processes and their related observables in a satellite image.

We then try to assess whether some measurements on some of these observables can be related to the basic parameters that determine the capacity of the mill.

We then link these measurements to a model of the production process.

Based on the relevance and importance of the measurement to the production process we develop an empirical equation that connects the production capacity, the measurements from the images as well as other variables that can be obtained from information available in the public domain.

We then go on to apply this empirical relationship to some other sites that are not part of our sample set to check the veracity and robustness of our findings.

Algorithm for Identifying a Uranium Mill from Satellite Images

A detailed study[9] that used spectral signatures of a uranium mine and milling facility to identify a uranium mill was done by a group from SANDIA Laboratories. The Ranger mine in Australia was used as an example to demonstrate this.

A major conclusion that emerged from this study was that hyper spectral images do not provide special signatures to differentiate the uranium mining and milling operations from other mining and milling operations such as copper, vanadium, rare earth elements etc. The study makes it clear that even tailings ponds, in which the residues from the mining and milling operations are dumped, do not provide useful signatures to a space based sensor.

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[10].

An even earlier study tried to evaluate the utility of satellite remote sensing for identifying Uranium

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

[10] 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

mines and mills[11]. 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.

The International Strategic and Security studies Programme (ISSSP) at NIAS tried to extend these studies to include a larger number of uranium mill sites across the world to get a comprehensive understanding of the milling processes involved in converting the ore into yellow cake.

The satellite images of 13 uranium milling operations across the world were analysed to arrive at an algorithm to identify a milling site as a uranium milling site and importantly to differentiate it from a copper milling site.

The methodology was based not on the spectral signatures but on the shapes of specific features correlated with the material flow within the mill. The results of this comprehensive work are available as a NIAS report[12]

Having identified a uranium mill, it is useful to determine whether a quantitative assessment of the production capacity can be made.

Uranium Mill Capacity – Design Considerations

The ore grade along with the sizes of the various equipment used in a mill obviously determine how much yellow cake will be produced in the mill.

Generally all mills are designed to process ores of average grade from mines located close by.

In some mills if the ores are from different mines, the ore grade has to be blended before it can be processed (Key Lake mill, for example).

The ore grades from the same mine also vary. Usually the grade comes down over time.

As a consequence the amount of ore that has to be processed for producing the same amount of yellow cake year after year would increase.

Figure 2 shows the ore grade and the amount of ore processed for several years for the Ranger Mill in Australia, a commercial Mill.[13]

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[11] B.Jasani, H.A.Smartt, D.Blair, C.L.Stork, J.Smith and M.Canty, Evaluation of remote sensor systems for monitoring uranium mines, SAND 2005-3528C.498620, (2005)

[12] S.Chandrashekar, Lalitha Sundaresan and Bhupendra Jasani, Identification of Uranium Mill sites from Open Source Satellite Images, NIAS Report R34- 2015, September 2015.

[13] Data from Mudd, G.M.,(2011) Compilation of Uranium Production History and Uranium Deposit Data Across Australia, Pp22

From this plot it is obvious that the two trend lines are mirror images of each other. Whenever the ore grade comes down, the amount of ore processed goes up.

The correlation coefficient between these variables for our sample set of mills is -0.75, for the period 1983 – 2001. The Yellow cake production during the periods 1983 to 1991 hovered around 3000 Mtonnes; it was around 4300 Mtonnes during 1997 to 2001. Between 1991 and 1995 the production came down significantly to as low as 1300 Mtonnes.If we compute the correlation coefficient for the first two periods separately, the correlation coefficient is -0.85 which reflects the strong inverse relationship between the ore grade and the amount of ore processed

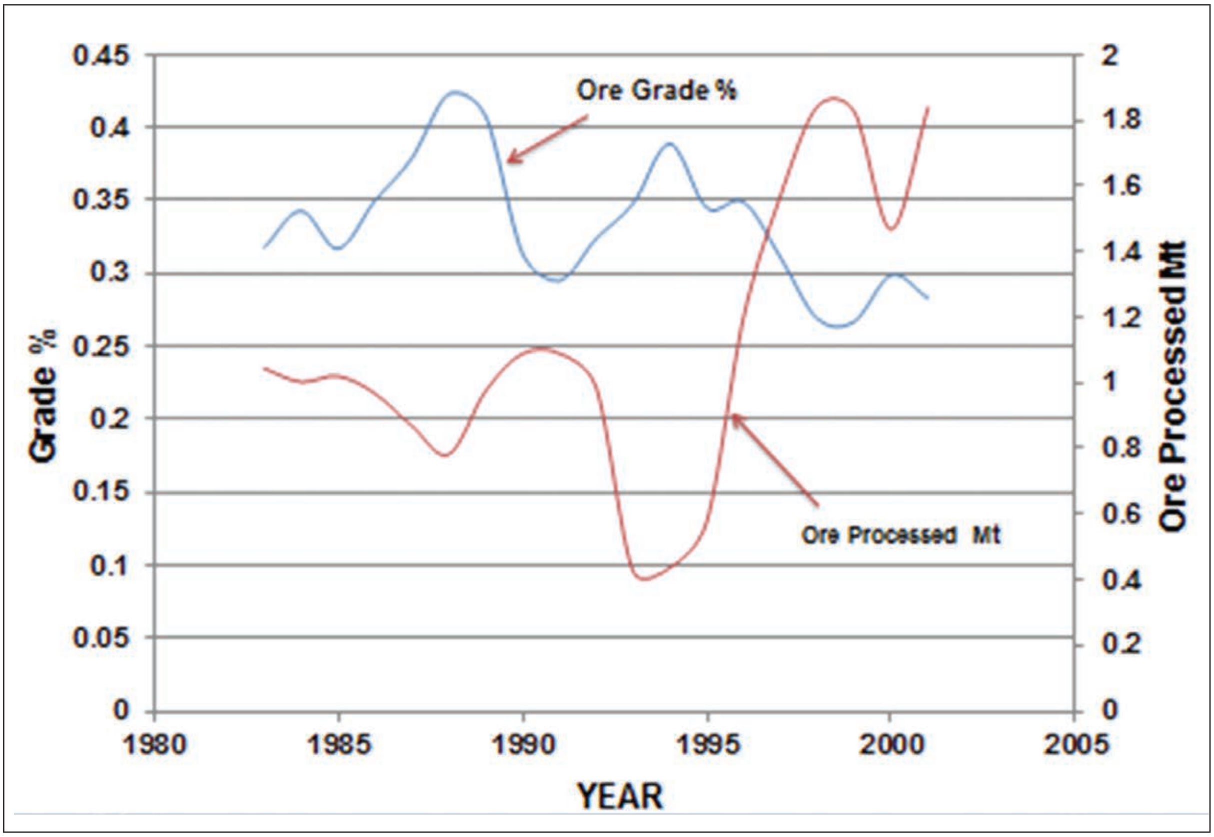

Figure 2 Year to Year Variations in ore grade and amount of ore processed in Ranger, Australia.

Now, if we consider the product of the ore grade and the amount of ore processed as one variable and look at the trend in this variable with time along with the yellow cake production, we see an interesting picture as shown in Figure 3. The correlation coefficient now is as much as 0.99.

This shows that in addition to an average ore grade, if we could use the amount of ore processed, we will be able to estimate the production.

However, data on the amount of ore processed is not readily available for most of the mills.

It is clear from the above considerations that if we can find a surrogate variable based upon measurements on the satellite image that correlates well with the quantity of ore that is processed by the mill we might be in a positon to fit a suitable relationship between Capacity, ore quality and the surrogate measure for the quantity of ore processed.

Uranium extraction involves crushing the ore, leaching it with a suitable leachant to dissolve the Uranium, separating the uranium containing solution from other impurities, concentrating the Uranium through a solvent extraction or ion exchange process and then precipitating the uranium from the concentrated Uranium containing solution.

All of these processes need to process a certain volume of Uranium containing solution in order to produce the required quantity of Uranium. For a given capacity of the mill the ore grade will largely determine how much volume will have to be processed at each one of the above steps.

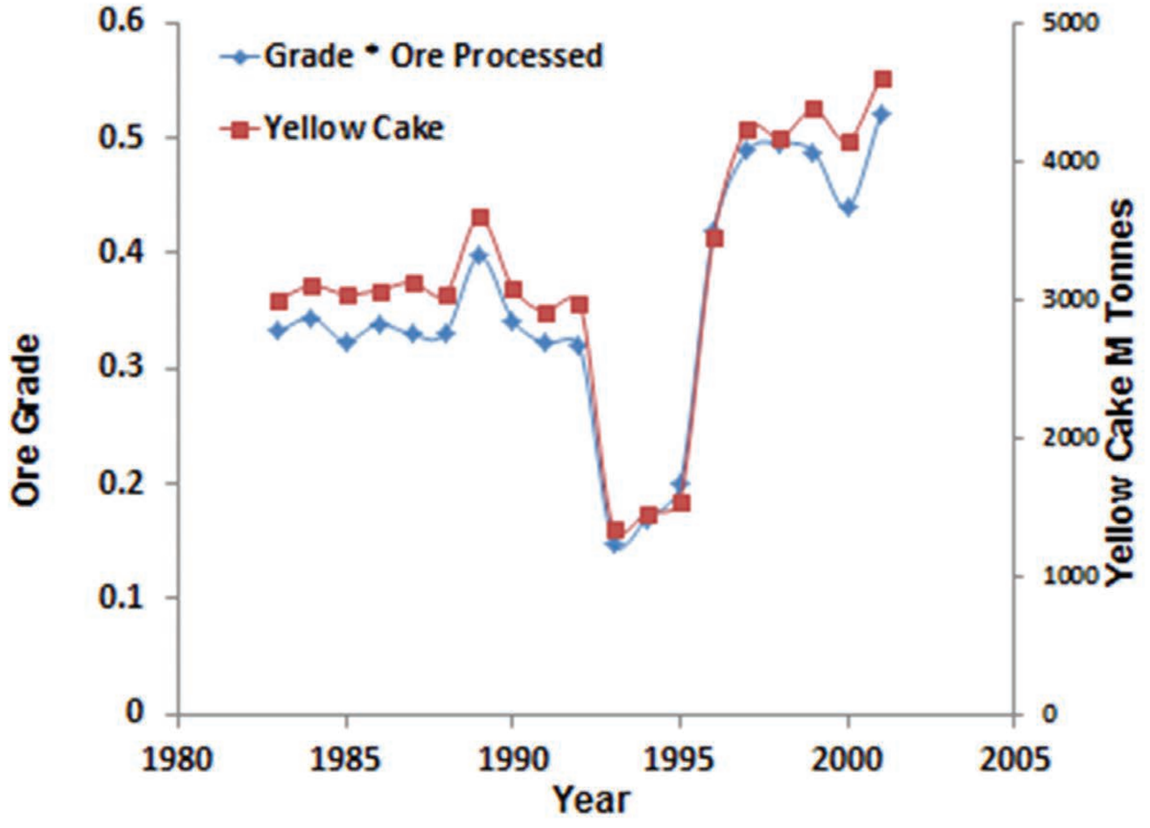

Figure 3 Annual yellow Cake Production compared with the Ore Grade(%) and Amount of Ore Processed

As the capacity of a mill is increased for a given ore grade this volume of ore processed will also increase proportionately.

However process equipment needed to process these volumes mostly come in combinations of cylindrical and spherical shapes. They also exhibit scale economies.

For such equipment to double the throughput the dimensions of the equipment such as diameters do not have to be doubled but increased by a factor that is more than one but less than two.

Any empirical model or production function used for the estimation of the capacity of a Uranium Mill will have to take into account these scale effects and the model must be able to estimate these scale related coefficients.

Keeping these basic considerations in mind we go on to examine the various process related observables in a satellite image in order to evaluate their utility for the estimation of Uranium mill capacity.

Measurements on Satellite Images of a Uranium Mill

Figure 4 provides an outline of the various processes used for the production of Uranium and the features that may be visible in a satellite image associated with these processes.

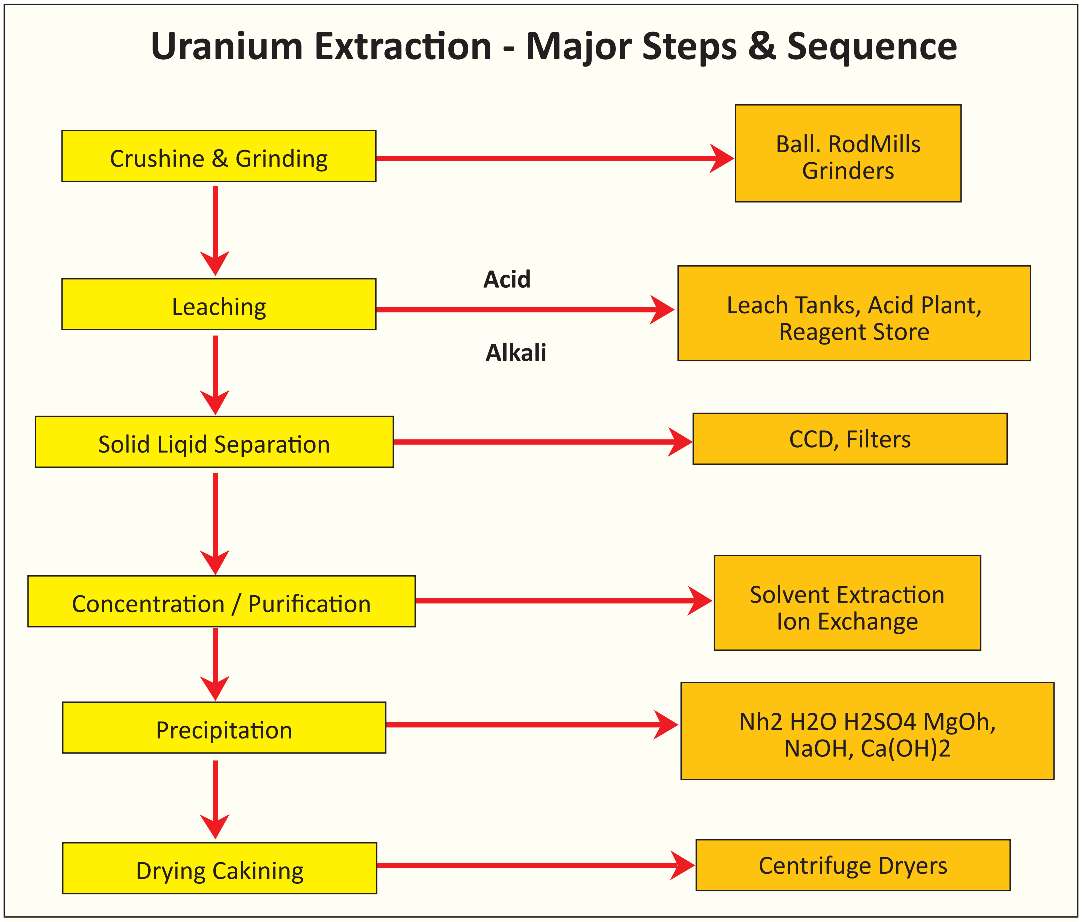

Figure 4 Uranium Extraction Process Steps

From the image analysis and the algorithm that has been developed it is clear that the identifiable spatial features of a typical uranium mill are:

- The leach tanks or other features associated with leaching such as acid plants, acid & sulphur storage tanks, sulphur heaps etc.
- The Counter Current Decantation (CCD) Units also called thickeners in common parlance
- Buildings that house the Solvent Extraction (SX) units or the assembly of Ion Exchange (IX) units; the solvent containers are sometimes visible;
- Buildings where the drying, precipitation and packing of the final product (Yellow cake) takes place;
- If Ammonia is used for precipitation these tanks are visible and can be identified.

Another feature that one cannot miss is the tailing pond located close to the mill site.

Though in principle measurements on leach tanks should enable us to estimate the volume and through this the amount of ore processed they are not always visible.

Other features associated with the leaching operation such as acid tanks, Sulphur tanks or even Sulphur heaps do not easily allow any useful measurements that can be directly linked to the volume of solution processed and to the mill capacity.

If the number and dimensions of the solvent extraction or ion exchange units can be measured their throughputs could be derived.

This could give an indication of the volume and could be used as a surrogate for the quantity of ore processed in an empirically determined production function.

While the identification of these units is possible from a variety of considerations quantitative measurements are not always possible on them because they are mostly located inside the building. Though measurements on them would no doubt be useful for estimating mill capacity these measurements cannot be made in the normal course.

The most visible and obvious feature that stands out across the sample of mills are the CCD thickeners. They are almost always present in Uranium mills and are also easily identifiable.

Measurements on their diameter which can be easily linked to their volume in a production function are also simple.

If measurements on the CCD diameter can be connected to the production process and if this could in turn be linked to other variables that influence capacity we might then be in a position to formulate an empirical relationship between measurements, mill capacity and other variables of interest.

In order to do this we might want to understand in some more detail the role that the CCD operation plays in the production of yellow cake.

The Role of the CCD in the Production of Yellow Cake

From basic ore processing considerations it is fairly clear that the number of CCDs needed and their diameter is directly dependent on the volume of leached material that has to be handled at any given mill. This volume in turn is dependent on the total annual output of any mill as well as the average concentration of the ore that has to be processed.

The solid – liquid separation achieved using CCD thickeners represent 40% of the capital costs of setting up a mill. Hence mill designers are careful while deciding the number of CCDs and their dimensions.

The efficiency of solid-liquid separation and washing and the type and size of equipment needed are largely dependent on the kind of ore being processed.

The efficiency of a CCD thickener circuit is a function of the number of stages and the amount of water used as well as the percent solids in the thickener underflow.[14] Washing efficiency of 98% or more is aimed at in most mills.

The number of CCDs as well as their diameter may also be depend on whether the further downstream operation after the CCD step at a particular mill site uses solvent extraction or ion exchange.

Since as a general rule ion exchange is used to handle lower concentrations one would expect that mills that use ion exchange may have to handle larger volumes of leached ore and may therefore require larger diameter CCDs than those required for solvent extraction.

Thickener sizes (area of the CCD) is usually worked out using Coe and Clevenger equation which expresses the area A of the CCD in terms of the free settling rate R, Specific gravity S of the liquid which in this case is water, initial liquid to solid weight ratio F and final liquid to solid weight ratio D[15].

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[14] See pages 60-61 in Significance of Mineralogy in the development of flowsheets for processing uranium ores, IAEA Technical Report Series No. 196.

[15] See pages 48-49 in Manual on laboratory testing for uranium ore processing, technical reports Series No.313, IAEA 1990 for a detailed procedure.

The number of CCD stages may be anything from 3 to 8.

Some mills have 4 stage circuits with roughly 3 litres of water per kilogram of ore passing through the circuit.

Some others have 7 or 8 stages with only about 1 litre of water per kilogram of ore washed.

Milling operations in locations where water is scarce generally have more number of stages. Operational problems are more likely in this case but greater efficiency is also achieved.

Based upon the above design and technology logic it would appear that diameter measurements made on CCD circuits could form the basis of an empirical relationship that links these measurements with other relevant variables for estimating the capacity of a Uranium mill.

Information on mill capacity as well as average ore concentration is available in the public domain for the mills in our sample set. The satellite images available make possible the measurements of the CCD diameter wherever they are seen. For the Sweetwater Mill this information is available in the public domain.

The availability of this data set therefore makes possible the establishment of an empirical relationship between CCD measurements and mill capacity.

Methodology for Estimation of an Appropriate Production Function

We have used data from 11 mills located in different parts of the world. The choice of these mills for our analysis purpose is determined purely by the availability of data on the parameters of interest. This means availability of a good satellite image from Google Earth which will allow us to make measurements on the CCD diameter.

A direct approach to relate the production capacity with the observables would be to use the ore grade and the volume of the CCD (which essentially determines the volume of the ore processed) as independent variables.

Ideally the volume of the CCDs will be a useful parameter. However, since the depth of the CCD cannot be easily measured from the satellite image, it is not possible to obtain the volume.[16]

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[16] Generally two types of CCDs are used. High rate thickeners and normal thickeners. Their shapes are different. What we see from a satellite image is only the top circular portion of the CCD. For more details of the design of the CCD see “Hydrometallurgy in Extraction Processes, Vol 1, by C.K.Gupta and T.K.Mukherjee, CRC Press, August 1990.

One way out of this situation is to look at the CCD dimensions, which indirectly provides data on the volume of ore processed. So, for our purpose we could take the number of CCDs and the area of the CCDs as measurable parameters from the satellite image.

The area of the CCD could be obtained from the diameter, since it has a visible circular cross section. The area in turn can be linked to volume through the use of a suitable exponent in the production function that captures economies of scale across our sample set of mills.

Thus a measurement of the area would enable us to link it to the volume and the quantity of ore processed by a suitable choice of an exponent that will be estimated by the production function used.

We had also noted during our investigations into the CCD process that in addition to the ore grade, cost considerations determine the number of CCDs and the diameter of the CCDs.

Since, there may be other considerations in deciding on these two variables, the number of CCDs, and the diameter could also be treated as independent variables.

Using this data set we tried to fit an empirical relationship between the capacity of the mill with key inputs into the mill operations such as the average ore concentration, the total volume of material handled by the CCDs, the number of CCDs and the diameter of the CCDs. Since the relationship is based on volumes to be processed the use of various non-linear production functions is necessary.

The identifiable features from a satellite image for our purpose are the number of CCD circuits, the area of the CCD or the diameter of the CCD. The ore grade is also an important input that determines the production capacity of a mill. All of these are available for the mills that we have studied. Essentially our approach has been to empirically relate the capacity of the mill with these three variables.

After experimenting with different forms of the production function that used some or all of the above variables we came up with an empirical equation relating the production capacity with the ore grade, number of CCDs and the area of the CCD.

Table 1 provides the data used in the analysis.

Production capacity of a mill as given in the Red Book refers to the nominal level of output expressed as tonnes of Uranium per year based on the design of the existing plant and facilities under normal commercial operating practices.

Yellow cake production may vary from year to year in the mills. While the actual production may change due to a number of external factors the production capacity as linked through ore quality and the quantity of ore processed will not change unless there has been some modification in the milling process.

To take care of some of these problems it may therefore be necessary to look at the historical details of a mill site.

Table 1
Data from the Sampled Mills

Country	Name of mill	Capacity (tonnes U) P	Ore Grade (% U_3O8) G	CCD Nos. N	CCD Diameter (meters) D
USA	Sweet Water	350	0.048	6	9.75
Canada	Rabbit Lake	4615	0.79	4	30.00
Canada	Key Lake	7200	3.4	8	20.00
Canada	McClean Lake	3077	1.22	8	12.85
Niger	Arlit	2330	0.30	6	23.00
Namibia	Rossing	4000	0.03	10	56.32
Namibia	Langer Heinrich	1425	0.05	7	23.15
Romania	Feldiora	1120*	0.12	4	28.00
Czech Republic	Rozna	3200*	0.378	5	25.00
Russian Federation[17]	Krasnokamensk	3000	0.18	6	52.00
Australia	Ranger	4660	0.13	8	34.65
Most capacity data taken from Uranium 2009: Resources, Production and Demand, A joint Report by OECD Nuclear Energy Agency and IAEA, 2010, called the Red Book. For the Feldoria, Rozna and Krasnokamensk sites estimating capacities is more complex. Details of how these were estimated are provided in Annexure 1					

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[17] Data for Russia is taken from http://www.skeptictank.org/treasure/GP2/DIMARAPP.TXT. Data Reported by Priargunsky Mining & Chemical works.

There are several issues that need to be kept in mind while using the data available in the public domain.

- Generally uranium mills process ores from one or two mines located close by. The ore grade will not be a unique value and has a range. We have assumed an average ore grade value for our data analysis.

- For example we have taken the average ore grade of 0.12 % in the case of Feldiora mill in Romania since in this mill ores are treated from three different mines with varying ore grades.

- We need to also remember that before feeding into the mill, the ores will be crushed, ground and will be brought down or up to a reasonably uniform grade.

- In some cases, the planned production capacity is available from the company annual reports in which case we have used the value specified. In that case we find that ore grade is also known and can be directly used in our analysis.

From these observations, and noting that the relationships between each of these factors and the production capacity is non-linear we have tried to fit an empirical exponential fit of the form

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

Where P = Production capacity in Metric tonnes of Uranium
k, a, b and c are constants
G = Ore grade U_3O_8 concentration in %
N = Number of CCDs
A = Area of the CCD in meter square.

We have chosen to use the area of the CCD rather than the diameter since the basic estimation is based on a volume relationship and area would therefore provide a better way to capture the scale exponent of the production function than the diameter.

Expressed in logarithmic form, the empirical equation obtained using the 11 sample mill data is

Ln P = 3.112976 + 0.457613*LnG + 0.956309*Ln N + 0.561587*Ln A

The Predictions using the empirically derived best fit relationship and the error in percentage terms are shown in Table 2.

Table 2
Estimated & Nominal Production Comparison

Country	Name	Predicted P	Nominal P	Error %
Romania	Feldiora	1354.75	1120	-20.9598
Canada	Rabbit Lake	3467.43	4615	24.8661
Czech Republic	Rozna	2493.75	3200	22.0703
U S A	Sweet Water	401.41	350	-14.6886
Niger	Arlit	2434.56	2330	-4.4876
Russian Federation	Krasnokamensk	4817.18	3000	-60.5727
Namibia	Langer Heinrich	1251.39	1425	12.1832
Canada	McClean Lake	3166.65	3077	-2.9136
Canada	Key Lake	8320.77	7200	-15.5663
Australia	Ranger	3463.12	4660	25.6841
Namibia	Rossing	3781.54	4000	5.4615

Review of the Results

In six out of 11 sample mills the estimated production values are higher.

These are the mills in Romania, USA, Niger, McClean Lake and Key Lake in Canada and the Krasnokamensk mill in the Russian Federation.

The Sweetwater mill in USA is currently closed and in the Google Earth image, the CCDs were not seen. The diameters and the number of CCD stages were taken from the available company reports.

As already indicated there are several problems in the data pertaining to the Feldiora mill in Romania.

The error is significantly larger in the case of Russian mill.

This mill uses ion exchange columns rather than Solvent extraction although the ore grades are not very poor.

The higher estimated values suggest that given the ore grade and the number and diameter of CCDs this mill should have a higher production.

This also suggests that perhaps the process efficiency is low. Another reason could be that the mill is actually designed for a larger production.

In five out of 11 cases the empirical equation underestimates the nominal capacity.

This underestimation varies from 5 % to 25%.

With the kind of error associated with the ore grade values used in the estimation process, it is possible to have only this level of accuracy. Also, the Production Capacity numbers taken from the Red book does not have the same level of accuracy for all the countries. What is important is that with access to better data, agencies like the IAEA can improve upon the model used.

In the following section we demonstrate the use of this empirical equation in estimating the production capacities of the mills not included in our sample data.

The case of Olympic Dam Mill

The Olympic Dam mill (30 27 S 136 52 E) in Australia produces both Copper and Uranium. It is primarily a copper mill and produces uranium as a by-product.

However, Olympic Dam has been the largest producer of Yellow cake in Australia in the last decade.

The production began in 1988 when the 2.2 Mt of ore was treated to produce 1400 t U3O8 (1190 t U) as well as 65 000 t refined copper, and associated refined gold and silver. Since then expansions of the capacity of the mill has been taking place.

A major expansion of was completed in 1999 resulting in the production of 4600 t of yellow cake. As against 2.2 Mt of ore treated initially, the mill now treats around 9.0 Mt of ore each year.

The processing facilities consist of a copper concentrator, hydrometallurgical plant, copper smelter, sulphuric acid plant, copper and gold/silver refineries[18][19]

Expansions included a Svedala autogenous mill, additions to the flotation sections, two counter-current decantation thickeners, an electric slag-cleaning furnace, a new anode furnace gas-cleaning plant and additional electro-refining cells.

The detailed process flow diagram for the Olympic dam site is available in the IAEA report The extraction process is described in our earlier report[20].

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[18] http://www.mining-technology.com/projects/olympic-dam/

[19] McKay, A.D. & Miezitis, Y., 2001. Australia's uranium resources, geology and development of deposits. AGSO – Geoscience Australia, Mineral Resource Report 1.

[20] International Atomic Energy Agency, "Uranium Extraction Technology", Technical Report Series No. 359, International Atomic Energy Agency Vienna 1993 pp 289-297.

The detailed interpretation of the satellite image of this mill site is reproduced from the earlier report[21] in Annexure 2.

In the case of Olympic Dam the original uranium ore grade is 0.06%.

The production of Uranium starts with the generation of tailings from the initial froth flotation process which still contains some copper.

This is subjected to further leaching and 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 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.

In this process therefore the uranium ore grade when it enters the CCD circuit has to be used in our empirical model. After froth flotation, the uranium ore grade is higher and is estimated to be close to 2.4 %[22]

There are 5 CCDs in this uranium circuit with a diameter of 15m each.

Using these values in our empirical equation we estimate the production capacity of uranium to be 3081 M tonnes. The Red Book gives the yellow cake production capacity of Olympic dam as close to 4000 M tonnes. This is in line with our other estimates.

The case of Turamdih Mill, India

Turamdih mill is located in Jharkhand, India and operated by the Uranium Corporation of India Ltd. This plant is operational since 2007. The mill processes ore from Turamdih, and Banduhurang mines. The plant uses acid leaching and ion exchange processes. The process flow chart is at Annexure 3. The interpreted mill facility is shown in Figure 5 below. The installed capacity of this facility is 3000 t of ore

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[21] S.Chandrashekar, Lalitha Sundaresan and Bhupendra Jasani, Identification of Uranium Mill sites from Open Source Satellite Images, NIAS Report R34- 2015, September 2015.

[22] Donald I Bleiwas, “Estimated Water Requirements for the Conventional Flotation of Copper Ores”, USGS Open File Report 2012-1089, 2012. According to this report a typical flotation design will increase copper concentration from a value of 0.5% in the ore to 27% in the concentrate or a factor of 54 times. Olympic Dam processes a copper uranium ore. Based on this we have assumed an enhancement of 40 times the initial concentration for the Uranium Tailings coming out of the forth flotation. A higher value of 50 times might provide a better fit and a lower error.

per day[23] The nominal production capacity of this mill is 190 tU per year.

There are three CCD thickeners with a diameter of 13.0 meters. The ore grade according to the Red Book is 0.034%. Using this data in our empirical equation gives an estimated production of 244.0 M tonnes which compares reasonably with the quoted production capacity.

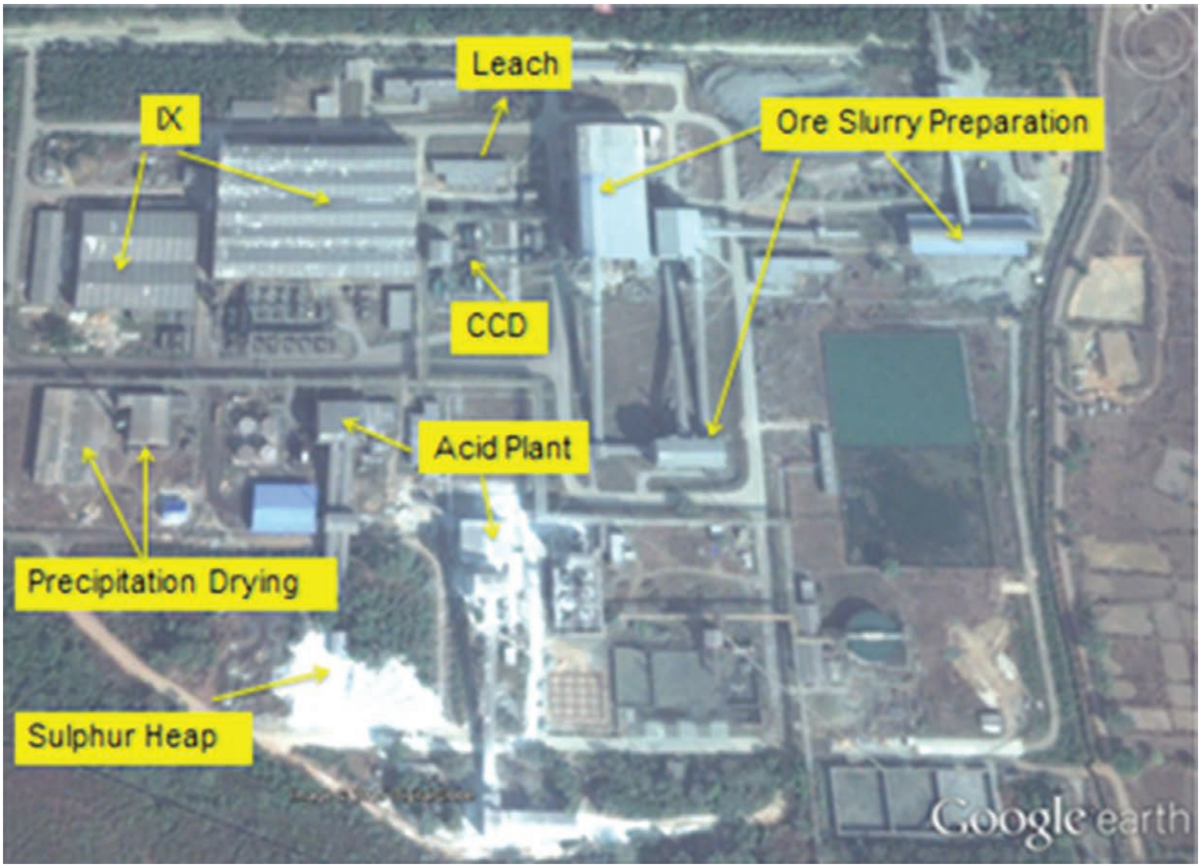

Figure 5 Turamdih Mill in India

The Case of Dera Ghazi Khan Uranium Mill, Pakistan

It is very difficult to make estimates of uranium reserves in Pakistan and more so of the amount of uranium mined each year. The size of the milling facility could give an idea of the extent of mining activities. An overview of the Pakistan uranium extraction plant in Dera Ghazi Khan (29 59 N 70 35 E) is shown in Figure 6. The image is dated October 16, 2014.

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[23] Uranium 2009: Resources, Production and Demand, A Joint Report by the OECD Nuclear Energy Agency and the International Atomic Energy Agency 2010.

Uranium deposits in Pakistan are known to occur in Dera Ghazi Khan District in Sulaiman Range, the Bannu Basin and Issa Khel in Mianwali district and Kirthar Range in South Pakistan.

The first uranium mine in Pakistan was opened at Baghalchur, and a Uranium mill was established at Dera Ghazi Khan in 1977-78. Baghalchur is supposed to have provided low grade uranium at grades of 0.05%U.

A milling facility capable of processing 300 tonnes of Uranium ore was set up at Dera Ghazhi Khan. This was at first a pilot plant and what is actually seen in Figure 7 is a facility which came up later.

Figure 6 Pakistan Dera Gazi Khan – Uranium mill overview

(The area within the rectangular portion is the mill site.)

The Pakistan mill has six CCD thickeners with a diameter of 15 m (Figure 7).

Assuming the average ore grade to be 0.03% the production capacity of the mill is estimated as 525 M tonnes using our empirical equation.

This is of course much higher than 30 tonnes of yellow cake which is claimed to be produced at this site annually. Clearly the mill has been designed to produce much more than what it is currently producing.

Generally commercial mills will operate continuously and if there is a down time, it will be because of specific reasons. The method we have proposed does not take into account the number of days the mill operates as a parameter in the estimating equation, since this is not available. Although this may not be important for commercial mills, incorporating it in the estimation of production capacity of strategic[24] mills is necessary.

Strategic Mills are built by the State and it is usually designed for a higher capacity. Thus estimates of production capacity by our method will be higher than what is quoted in the Red Book.

When a country sets up a uranium processing mill for strategic purposes, the design considerations may be quite different from that of a commercial mill. Applying our method directly to these mills is bound to provide gross over estimates of the production capacity. The ore grade quoted may also be highly overstated and there is no mechanism to verify this.

Historical GE images or better still commercial satellite images could however be used to monitor such mills frequently to get an idea about the activities of the mills.

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[24] We are using the term Strategic mills to indicate that the uranium production in these mills may not be for civilian purposes and also that the mill may not be under IAEA safeguards.

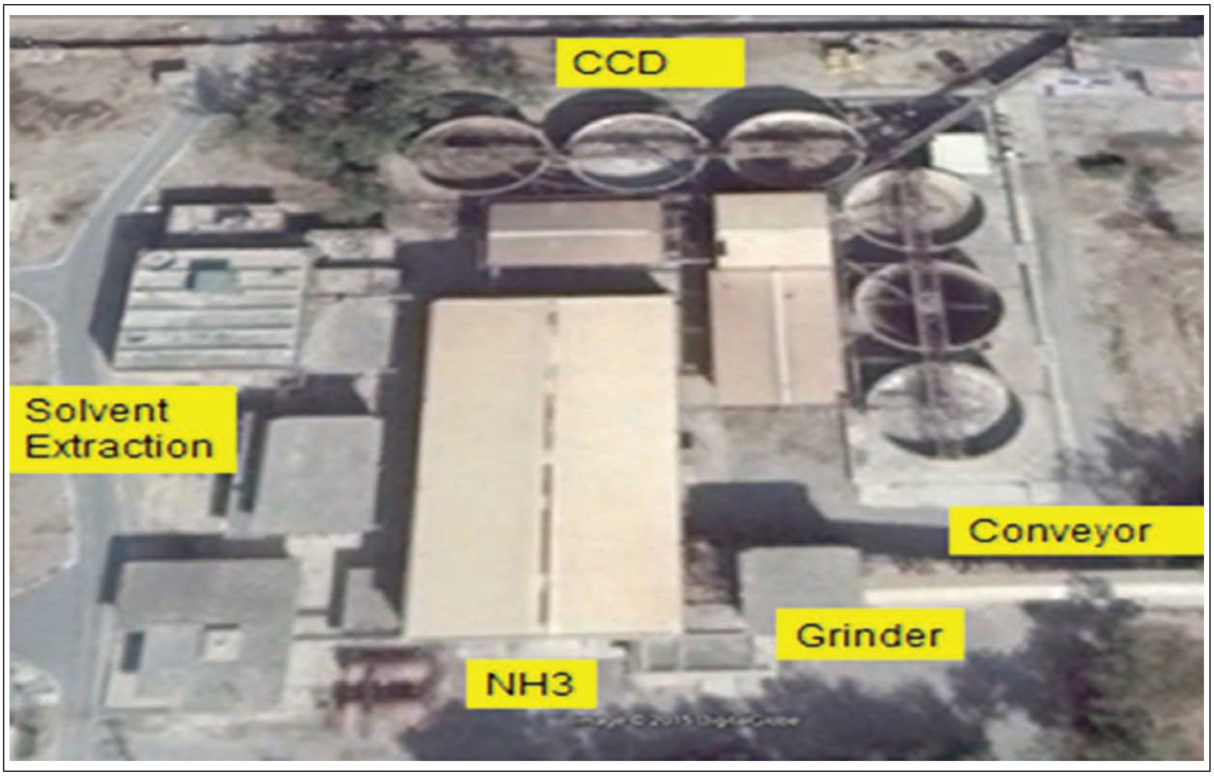

Figure 7 GE image showing the Pakistan mill area in 2014

CONCLUSION

In this study we have demonstrated the use of satellite images of uranium mill sites available in the public domain (Google Earth images) to estimate the yellow cake production.

The most visible feature of an Uranium mill are the CCD thickeners used for solid liquid separation. The area and number of the CCD thickeners together with the ore grade are used in an empirical equation to estimate the production capacity of an Uranium mill.

This approach is useful for the purpose of monitoring changes and developments in the existing facilities. It could also be used to get an estimate of the production activity in undeclared uranium mills.

In applying this approach to estimate production capacities of Strategic Mills, the following points have to be kept in mind.

Strategic Mills may not operate continuously on all days of the year.

If the uranium ores are not easily available in the country, and ores from other sources are being processed, the ore grade data available in the Red Book may not reflect the grade of the ore processed and hence there could be gross error in the production capacity estimation by our equation.

Generally Strategic Mills are designed for higher capacities. The actual production may be less and again the data available from the Red Book may not be correct.

The approach provided here can however be improved upon by agencies having access to actual data on ore grade and the number of days of mill operation

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ANNEXURE 1

There is an issue of the capacity of the Rozna and the Feldiora mills.

The measurements on the Rozna CCD devices suggest a larger capacity than the production given in the published data.

The Red Book (2010) provides capacity as 400 tonnes of Uranium per year with ore concentration of 0.378.

The industrial production of uranium in Czechoslovakia began in 1946.

The peak production of about 3 000 tU was reached around 1960 and production remained between 2 500 and 3 000 tU/year from 1960 through 1990, when it began to decline.

During the period 1946-2003 a cumulative total of 108649 tU were produced in the Czech Republic.

The Red Book retrospective brought out in 2006, gives the production capacity values in Tonnes for Czechoslovakia / Czech Republic for selected years between 1970 and 2003.

Year	1970	1975	1980	1985	1990	1995	2000	2003
Capacity	3000	2750	3750	3550	3550	1000	680	450

For our purpose we have taken the average of the production for the period 1970 to 1990 and thus the nominal production capacity is taken as 3200 tonnes.

In the case of Feldiora mill, the Red Book gives the production figures as 300 Mt.

However, given the ore grade which is as much as 0.12% it appears that this value is far lower than what could be expected. We have looked at the history of this mill[25] and have taken the production capacity as 1120 M tonnes.

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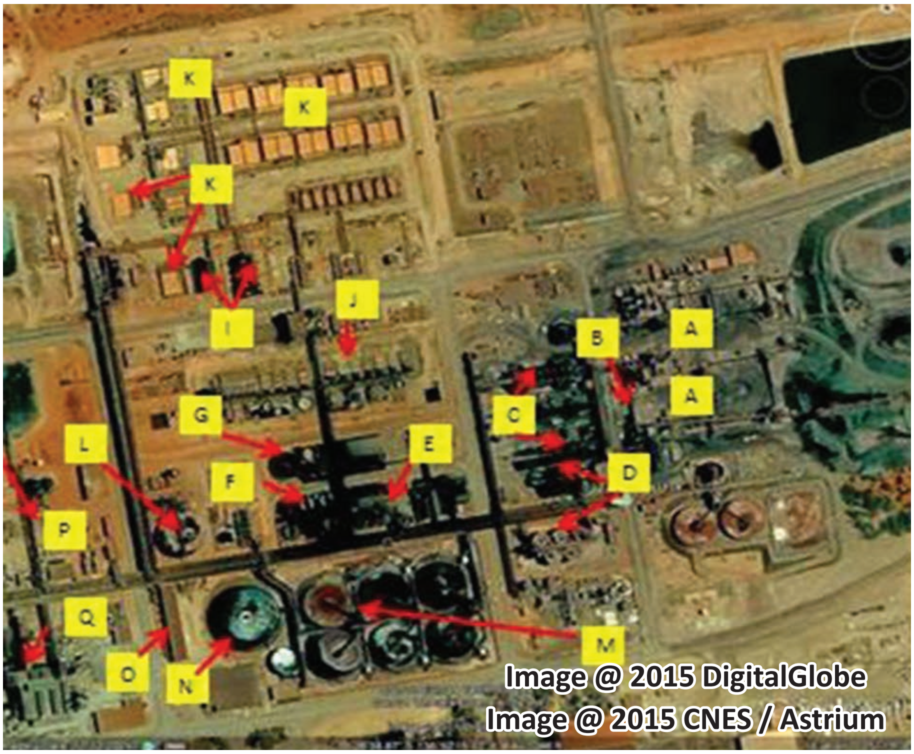
[25] 'Uranium production in Eastern Europe and its Environmental Impact - A literature survey' , Norman.R.E, ORNL, TM 12240, 1993. The report surveys production in Eastern Europe including GDR, Czech Republic, Romania, Hungary, Poland and the Soviet Union. According to this report page 10 uranium production in Romania (tonnes of uranium metal) could have been between 770 to 965 Metric Tonnes.

Annexure 2

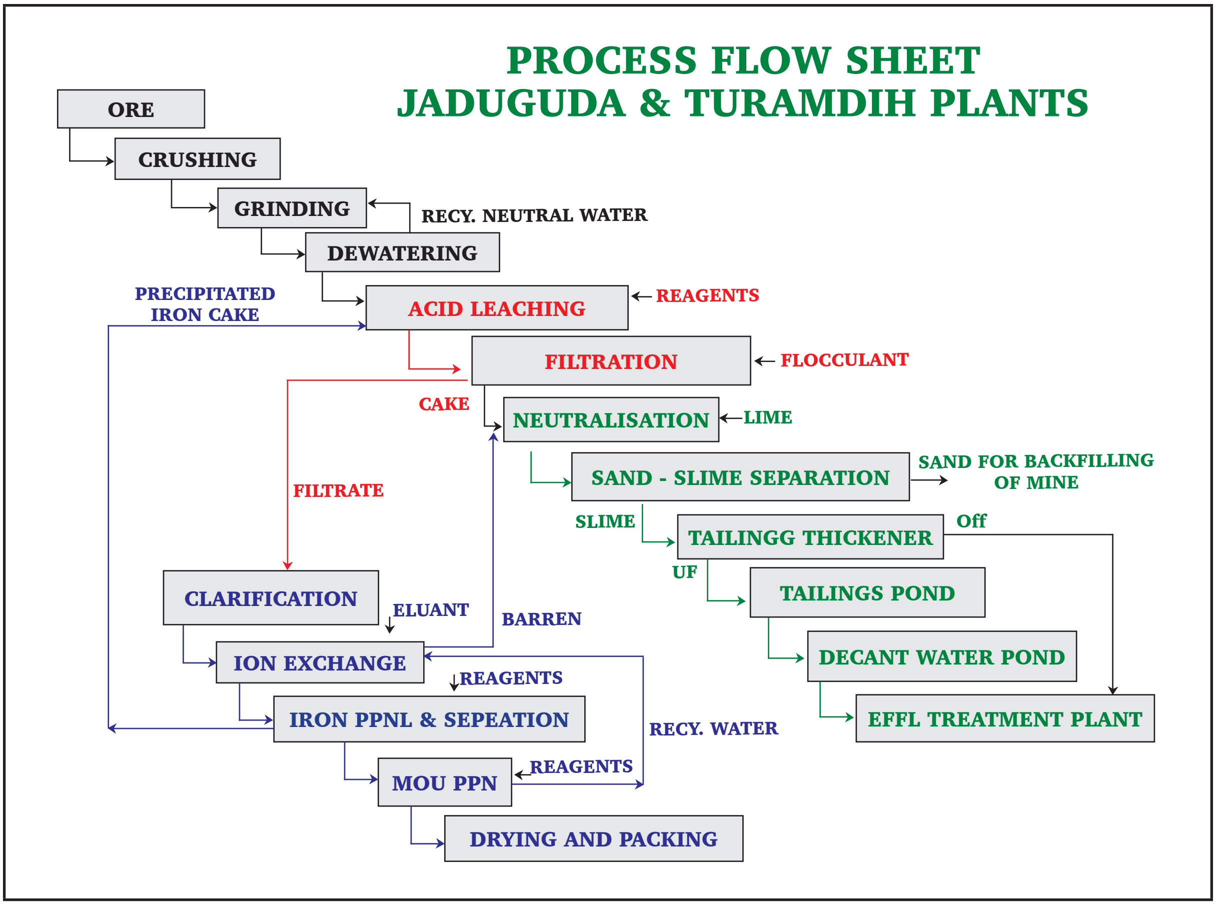
GE Image of Olympic Dam Mill showing the Copper & Uranium Mills
(30 26 43 S 136 52 11 E, October 30, 2012)



A- Crushing grinding
B - Slurry preparation
C - Froth Flotation
D Cu Leach
E - U tailing Leach
F - U CCD
G - U Clarifier-removed alater
I - Pulsed Column Sol Ex. - 1999 addition
J - Cu Sol Ex
K - U Sol Ex
L - U Slime Thikener
M- Cu CCD Thikener
N - Cu residue Clarifier
O - Pressure Filter
P - Cu residue prep
Q - Cu smelter

ANNEXURE 3[26]

Process Flow Sheet Turamdih Uranium Mill



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[26] Sourced From "Technical Developments in Uranium mining and milling in India", R.Gupta, International Symposium on Uranium Raw Material for the Nuclear Fuel Cycle: Exploration, Mining, Production, Supply and Demand, Economics and Environmental Issues (URAM-2009) http://www.pub.iaea.org/MTCD/meetings/PDFplus/2009/cn175/URAM2009/Session%201/9_63_Gupta_India.pdf