Abstract: With depletion of high grade iron ore deposits and stringent mining, environment and forest conservation acts/rules, the importance of using medium and low grade iron ore is getting emphasis eventually. Till now the slimes were rejected in tailing dams after washing of iron ore but now it is thought of recovering of iron values from ultra fines also. There are large fine dumps which are still lying unutilised. Demand for iron ore is expected to rise by more than 200 million tonne per year to meet the internal demand & export. This additional requirement of iron ore will need beneficiation of low grade ore/fines to get the major portion of increased demand. This paper deals in brief to use of available methodologies for beneficiation of iron ore in Indian context. Special emphasis has been in the area of advance process control & automation for increased production, process stability improvements, better use of raw materials, reduced maintenance, improved safety and improved process knowledge.

The environmental and social impacts of mining are gaining increasing attention. At the same time, the wellbeing of people is largely based on raw materials available in the soil and ground and the competition for available water and energy is becoming more intense. Effective utilisation of our mineral resources both secures the supply of raw materials and creates the prerequisites for balanced and sustainable regional development far into the future. Responses to these challenges require innovative technological developments throughout the entire extraction and production chain. This calls for improved technologies for increasing production efficiency while further reducing water, raw materials and energy usage.

India is endowed with significant iron ore reserves, estimated at 25.25 Billion tonne apart from Banded Haematite-Quartzite (BHQ) and Banded Haematite-Jasper (BHJ). However, the proven economically mineable reserve is only 7.2 billion tonne, of which the high reserve grade is only 1.3 billion tonne. Considering more than 200 million tonne addition in existing iron ore production by 2020, there is an urgent need for conservation and sustainable use of our natural resources. More than that, there is also a need for effective utilization of low-grade iron ore and fines, through suitable beneficiation technologies. Although India is blessed with large reserves of iron ore, the performance of blast furnaces had been at lower levels. This has been mainly due to the presence of high levels of impurities in the feed material contrary to the blast furnace chemistry requirement. National Steel Policy aimed at a steel sector, which is not only productive but achieves global benchmark in terms of efficiency. The world is now concerned about energy efficiency and Carbon dioxide control measures. The steel-making involves various processes that result in extensive consumption of natural resources and energy. Unfortunately, our domestic benchmarks are far below the world standards. In order to increase the efficiency of blast furnace, combinations of the most suitable properties of the feed material must be ascertained. Our future sustenance and self-sufficiency would depend upon this issue of adaptation of technology for utilization of fines and low-grade ores, including magnetite.

*   ED, Projects, RMD, SAIL
**  AM, Projects, RMD, SAIL
*** SM, Projects, RMD, SAIL
In precise terms, the Fe content greater than 65% is desirable and the impurities such as Na, K, Pb, Zn, Cu, Cr, Zn, S, and P should be as low as possible. Alumina and silica content should be within permissible limit for better fluidity of slag. ROM iron ore should be beneficiated to lower the impurities in order to improve the feed quality & characteristics of sinter or pellet.

**Low grade Beneficiation Techniques**

The occurrence of Indian iron ore deposits are mainly of haematite, magnetite, goethite and siderite. However, world production for iron is mostly by extensive use of haematite and magnetite as principle oxide feed. Since in India the haematite ore is main source of raw material for iron making, this article covers mainly advancement made in haematite beneficiation. Till now most of haematite mines is high quality with respect to iron content and requires sizing and washing only. As high grade reserves of haematite are depleting the Indian mining scenario is changing. In order to maximise the ore reserve utilization and meet stringent product quality required by end users industry, rigorous beneficiation techniques are employed. For high grade ore, crushing and dry screening are sufficient to give desired quality material. Some times wet screening is done by introducing high pressure water, jets over screens, fines are classified and ultra fines are deslimed by hydrocyclone. If desired quality is not met then after classification any one or in combination of gravity concentration, magnetic separation, flotation, selective flocculation and pelletisation techniques are adopted to achieve desired quality. Now there is a trend of integrating geology, mineralogy, mineral processing and metallurgy to build a spatially-based model for production management that quantitatively predicts:

- quality of concentrates and tailings,
- metallurgical performance, like metallurgical recoveries and throughput,
- Environmental impact such as fresh water usage for tons produced.

Most of the ROM iron ore contain lot of impurities that needs beneficiation before use. Extent to which beneficiation techniques are employed, depends on the level and nature of diluents and the form of distribution of the gangue and impurities in the ore structure. Liberation of ore is essential to make it amenable for any concentration techniques. For selection of any technique, it is essential to do first mineralogical evaluation which gives insight into ore and gangue association, grain size etc. Therefore, research on utilization of low grade iron ore to produce quality raw material will play a key role in future—a fact acknowledged by the iron and steel industry. Iron ore from the same mine may look the same, but its response to beneficiation technique can vary enormously. For that matter, each source of iron ore has its own peculiar mineralogical characteristics and requires specific beneficiation and metallurgical treatment to get the best product at lesser cost. The choice of beneficiation treatment depends on the nature of the gangue present and its association with the ore structure.

Following principal process technologies/equipments are available for iron ore beneficiation:

- Scrubbers (Attrition & Drum) and Log Washers
- Heavy Media Separation & Jig
- Teeter Bed Separators (like Flotex density separator, Allflux Separator etc.)
- Centrifugal concentrator, Spirals & Reichert cone
- Magnetic separation (LIMS, MIMS, WHIMS, HGMS & VPHGMS)
In the past abundance of good quality haematite ore deposits met our steel industry’s demand and export. Low price of iron ore till 20th century overlooked ultra fines recovery. With depletion of high grade ore and in pursuance of stringent environmental and forest clearance laws/regulations, to meet the demand of high quality ore on sustainable basis, the iron ore beneficiation will become a reality in India. To provide input raw material it will be desired to increase the production from mines thus necessitating lowering of cut off grade and exploitation of low grade resources.

Since no single technique of beneficiation will suffice for any one type of deposits for its full life cycle necessitating combination of techniques to fulfill desired objective, So careful selection of process route and its in-built flexibility will be key to develop any iron ore deposit. Since some places, combination of magnetite with haematite is available, so it will add more complexity in circuit. As liberation size will become finer, it will be a challenge to recover ultrafine this will result in more iron ore concentrate which can be used in iron making as pellets.

**Iron Ore Beneficiation - Current practices in India**

First iron ore jig was installed in Barsua iron ore mine of SAIL. With the technology of bottom air pulsation added with modern process control features and improved product discharge mechanism, Batac jig of Humboltz Wedag have been successfully installed and operated at Noamundi iron ore mines of TISCO. ESSAR has successfully installed iron ore beneficiation plant at Bailadila region in Dantewada district of Chattisgarh. It is based on raw material from NMDC in form of slimes and fines. JSW has commissioned 10 Mt/yr low grade beneficiation plant in its integrated steel plant and has further expanded it to 20 Mt/yr capacity recently.

The Kudremukh plant in Karnataka was the first big iron ore beneficiation plant in India. It mainly processes complex haematite and magnetite ore. It got pelletisation facility for pellet making from the concentrate of beneficiation plant. Pellets are not for domestic consumption rather exported for revenue generation. Throughout its life, plant flow sheet got improved from original design as per need due to change in ore characteristics or due to economic considerations. Though Kudremukh mine and beneficiation plant were closed due to environmental consideration, its pellet plant kept running based on ore procured from local non-captive mines. It used Gyratory crusher, autogeneous mill, ball mill, screens, flotex density separators, magnetic separator, derrick screens, floatation and thickeners as main beneficiation equipments. A lesson has been learnt from the Kudremukh plant operation that for even exploitation of same deposit, the flow sheet keeps on changing and it is necessary to have continuous R & D effort throughout project life cycle to be competitive in market. In Goa region of mines there are plants which use magnetic separation and hydrocyclone as major technique for low grade ore beneficiation. The circuits in such cases are simple depending on ore characteristic.

The large scale iron ore beneficiation plant specially designed for slimes and low grade fines is located in Bailadila region by ESSAR group. It uses ball mill, spirals, high gradient magnetic separation and thickener as main processing units. Beneficiation plants in iron ore processing were installed in Barbil region by BRPL based on allflux separator, wet high intensity magnetic separator, rod mill and ball mill. Bhushan group
has also installed beneficiation plant. The JSPL, SAIL and EMIL are in process of installing the low grade iron ore beneficiation plant in this region. All these plant will be based on haematite ore as raw material.

Based on this analysis, it is clear in India that the installation of beneficiation facilities exclusively for low grade hematitic iron ore beneficiation is a reality (Excluding plant having only screening and classification facilities). Generally all plants will treat iron ore sourced from different mines as they do not have fixed mines for its raw material supply. It will be a major challenge to operate these plants at optimum efficiency level as process is generally very sensitive to the raw material characterization.

The striking feature of all these plants is that all have different flow sheets. Even in the same region, plants are planned with different flow sheets. Earlier except scrubbing and washing, no other technique was successful for lump iron ore upgradation. However, now Jigging is also getting prominence for lump and sinter fines beneficiation because of non-liberation of gangue material at required size level. For beneficiation of size range below 1/0.5 mm, complex circuit has to be designed based on ore characterization. But at industrial scale, proper data collection has to be done to make scientific study regarding grindability of ore, desliming size, enrichment ratio and recovery to establish bench mark in industry to understand the process sensitivity, process comparison and optimization. It will help in standardization of type and capacity of equipments on the basis of which modules can be developed for the particular region in future. Proper bench marks have to be developed for capital cost, operating cost, availability & utilization, energy consumption, media consumption and water consumption in Indian/regional context.

**Process Control and Automation**

Automation of processes in iron ore beneficiation is widespread but the control used is simple, open-loop, or closed-loop using rule-based and classical PID control. The process lines are large-scale and mechanically vigorous, so the control emphasis is on achieving continuous operation (with as little downtime as possible) and efficient extraction performance. However, now it is realized that it is possible to do better, and when the end product is a commodity like iron ore or another valuable mineral, it is easy to see that enhanced extraction performance quickly brings an economic return but there are some important communication and training barriers to overcome. Automation systems can be beneficial in many different ways. An assessment of their impact on a iron ore beneficiation plant should consider the following:

- Increased production
- Process stability improvements
- Better use of raw materials
- Reduced maintenance and improved safety
- Improved process knowledge

Many of these benefits are interrelated. The economic assessment of these benefits can be carried out by standard methodologies. It is important to stress that the benefits, arising from a potential implementation of an advanced automation solution, must be the core of its functional specification. The main objective for advanced process control is to establish a dynamic mathematical model, monitor the deviation from the model and
finally restore the original conditions of operation. The process of controlling a dynamic system is complicated especially in iron ore processing systems where a number of variables are involved simultaneously. In general, developments towards automatic control of plant operations have been commensurate with the development of computer science and instrument technology. Its implementation has resulted in consistent plant performance with improved yield and grade of the finished product with less manpower. The cost of manpower is an important component in operating cost. Any reduction in manpower will surely result in better rate of return for beneficiation facility.

The term "process control" therefore refers to an engineering practice that is directed to the collection of devices and equipment to control processes and systems. Computers find application in simple systems, such as single loop controllers and also in large systems as the Direct Digital Controller (DDC), Supervisory control systems, Hybrid Control Systems and Supervisory Control and Data Acquisition (SCADA) systems. Further developments in process control are supported by many secondary concepts such as computer aided Engineering (CAE).

A more thorough knowledge of process behavior, which has led to more reliable mathematical models of various important unit processes are being developed. Many of the mathematical models which have been developed theoretically, or "off-line", have had limited value in automatic control, the most successful models having been developed "online" by empirical means. Often the improved knowledge of the process gained during the development of the model has led to improved techniques for the control of the system.

The commonly used present system is the Distributed Control System (DCS). It is made up of three main components, the data highway, the operator station and the microprocessor based controllers. The data highway handles information flow between components ensuring effective communication. The microprocessor controllers are responsible for effective control of the processes and are configured to handle as single or multi-loop controllers. The operator station allows the control command to be given, maintain the system data base and display the process information. The displays normally used are the group and detail displays, trend displays and alarm annunciated displays.

Instrumentation and control of mineral processing operations is usually visualized as involving connected building blocks. Process control and instrumentation consider these blocks divided into three or four levels:

- Basic block
- Supervision block
- High level block
- "Watch dog"

A general description and function of these levels follow:

- **Level 1**
  This is the regulatory level where basic controls loops like, P+I control loops include control of feed tonnages from bins, conveyors, manipulating of bins, water addition loop
(in milling circuit) pump speed and sump level controls, thickener overflow density control etc are involved (depending on the process circuit).

- **Level 2**
  This is a supervisory control stage that includes process stabilization and optimizing, usually using cascade loop and ratio loops. For example, in a ball mill circuit the ratio loop controls the ball mill water while the cascade loop controls the particle size of product by manipulating the tonnage set point.

- **Level 3**
  Controls at this level include maximizing circuit throughput, limiting circulating load (where applicable).

- **Level 4**
  This is a higher degree of supervisory controls of various operations including plant shut downs for maintenance or emergency. It has been referred to level 4 controls as "watchdog" control.

**Advanced Control Tools and Applications**

The possibilities for developing control strategies in an industrial process are highly dependent on what sensors are available. In the case of mineral processing, sensors exist for measuring a variety of process variables such as those listed below:

- Feeder frequency, conveyor load and crusher chute level (crushing);
- Tonnage, water flow rate, mill speed, pulp level, pump speed, pulp volumetric flow rate, pulp density, cyclone and mill pressure, and the power draw of mills, Screens, pumps and cyclones (grinding);
- Pulp flow rate, cell and column pulp levels, air flow rate, reagent flow rate, wash Water flow rate and pH flotation.
- Pulp particle size distribution sensors in grinding and grade analyzers in flotation.

The last few years have seen a significant increase in the availability of industrial sensors for mineral processing, some of which incorporate highly sophisticated technologies. These include units that take granulometric size measurements on crushing or grinding belt conveyors. That determine mill operating states and characterize the surface froth in flotation cells. Model predictive control (MPC) embraces a complete family of controllers whose basic concepts are:

- Use of an explicit dynamic model to predict process outputs at discrete future time instants over a prediction horizon;
- Computation of a sequence of future control actions through the optimization of an objective function with given operating constraints and desired reference trajectories for process outputs; and
- Repetition of the optimization process at each sampling instant and application of the first value of the calculated control sequence (receding horizon strategy). These three characteristics allow MPC to handle multivariable, non-minimum phase, open-loop unstable and non-linear processes with a long time delay and the inclusion, if necessary, of constraints for manipulated and/or controlled variables.
The control sequence is obtained by optimizing an objective function that describes the goals the control strategy is intended to achieve. In classical MPC, an objective function minimizes the error between predicted outputs and the set-points during the prediction horizon as well as the control effort during the control horizon. The function may be expressed as

The optimization process may involve hard or soft constraints. For linear unconstrained systems this optimization problem is tractable and can be solved analytically, but in general applications it is common to take into account constraints or non-linearities in the process, and in such cases the optimization problem must be solved using iterative numerical methods.

A fundamental element in MPC is the model used to characterize the dynamic behavior of the process. The origins and formulations of such models are diverse, but may be classified as follows:

- Phenomenological or first principle models, in the vast majority of cases nonlinear and continuous time;
- Models obtained through numerical adjustments based on operating data using discrete time series, either linear or non-linear.

Models can be used to improve efficiency and sustainability of mineral processing in many ways. Notable among the non-linear models are neural networks, which are used to numerically approximate a highly complex non-linear function by interconnecting simpler processing elements such as adders, multipliers and sigmoid functions. As with linear time series models, the neural model must be calibrated by adjusting its parameters to the operating data, a task generally performed by a back propagation gradient algorithm.

Numerous alternative versions of MPC algorithms have been developed. They differ from one another as regards the model used to represent the process and disturbances, the cost function to be minimized, the constraints applied to each variable and the optimization algorithm employed. MPC has achieved widespread recognition in process industries, where it is currently utilized in more applications than any other advanced control technique. Even though the great majority of processes display non-linear behavior, very few MPC developments rely on non-linear models. If such a model is used, or if the objective function is not quadratic or subject to constraints, the optimization problem will not be convex, difficulties will arise regarding the existence of local optima and computational complexity will be much greater.

In recent years, the application of MPC to hybrid dynamic systems has emerged as a significant area of research. In these systems, continuous dynamic sub processes interact with discrete event detection elements and start/stop commands. Characterizing this type of system involves combining continuous with discrete variables and differential or difference equations with finite state automata or switching theory. Although this approach increases the complexity of the model, its potential for accurately capturing the dynamic of an industrial process is much greater.

Currently many companies (like ABB, Andritz, Honeywell, Invensys, Metso Minerals, Mintek Emerson Process Management, Rockwell automation and SGS) working in the areas of instrumentation, automation and control are developing and offering commercial
products for mineral processing plants. Prominent MPC suppliers and technologies (Company –Technology) are as given below:

- ABB -Expert Optimizer
- Andritz- BrainWave™
- Emerson Process Management- Delta V
- Honeywell -Profit™ Suite
- Invensys -Connoisseur
- Metso Minerals -Optimizing Control System
- Mintek -StarCS
- Rockwell -Pavilion Technologies
- SGS -MinnovEX Expert Technology

The majority of existing mineral processing plants incorporate an excellent automation, communication and real-time information infrastructure, and with the basic stages thus in place, the time seems ripe for a widespread application of automation technologies in iron pre-processing and a broadening of their field of action.

New developments and products can be expected in the following areas:

- Visual sensors with greater accuracy and robustness.
- On-line hardness and mineralogy analyzers.
- New sensors for the measurement of grinding, classification and flotation variables.
- Additional new tools for advanced control that combine expert system (ES) with model-based control and continuous with discrete control (hybrid systems).
- Dynamic optimization applications for integrated processes and plant interconnection

If users are to fully reap the expected benefits of all this greater technological sophistication, certain shortcomings in the training of professionals and technicians charged with supervising and operating iron ore processing automation equipment will have to be resolved first. Technology can also contribute to strategies for overcoming these problems through the application of solutions already proven in other industries. These include certifications, continuing education, e-learning, project-based learning and operator training simulators. Most of the above advance features have been envisaged in upcoming iron ore beneficiation plants in SAIL.

Problem areas in iron ore beneficiation

The problem of alumina with reference to Indian iron ore is well researched and discussed at different forums. The benefit of alumina reduction in improved blast furnace performance and reduction in coke consumption is also well discussed. Although Indian iron ores are considered to be rich in iron content but due to preferential association of iron oxide mineral with finely disseminated alumina bearing minerals than with siliceous minerals, it has higher alumina content. Alumina is mainly contributed by clay, lateritic material and gibbsite and some alumina occurs as solid solution in iron oxide minerals viz., goethite and limonite. Silica is mainly contributed by quartz and the associated clay.

It is now time to have a holistic approach in overall utilization of country’s iron ore resources. So further studies had to be done on optimization in total value chain upto iron and steel production keeping integrated view on technological and economic
consideration. The testing of minerals in India is done mainly by SAIL RDCIS, NML, IMMT, IBM and R&D centre NMDC. The economic consideration is very important in utilization of low grade reserve. Therefore, during development and testing of material it is very important to assess the impact of each technology on overall economics of the project.

It is desirous to develop strong database of key performance indicators in iron processing industry. It will help in taking techno-economic decisions in time as well as reduce testing of raw material each time. Since each plant is having its own set of technological units, so comparative studies will play a very vital role in getting the idea of problems faced by industry. This is also true for furthering research impetus in right direction. Now lot of emphasis is planned for environmental conservation and climatic change. Since most of the iron processing plant will be of high throughput capacity, the bench marking have to be developed in energy consumption, water requirement and tailing disposal facilities.

**Conclusion**

Mineral beneficiation prevails since the human birth in various primitive forms and continuously changing with the growth in industry and demand of technology. Use of beneficiation techniques in iron ore industry in India has immense scope to cater the burgeoning demand of steel industry. Region specific integrated approach is to be developed to prepare the ore characterization database and standardization of beneficiation technology. Performance of adopted technology is a function of techno-economics; therefore it is suggested to choose the technique according to viability. The advance process control and optimization based on models is state of art feature of advance beneficiation technology. Regional database and standardized mineral beneficiation techniques would be key consideration for decision making to choose the right path for beneficiation of iron ore. Training of professionals and technicians in design, supervising and operating mineral processing plants and automation equipment is essential for ensuring robust design and optimised operation of iron ore beneficiation plant.
Reference:

2. Web site – www.steel.gov.in
5. J. Lynch (January 1977), Mineral Crushing and Grinding Circuits: Their Simulation, Optimization, Design and Control, Elsevier Scientific