CHAPTER-7

GRAVITY CONCENTRATION OF IRON ORE

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INTRODUCTION

Gravity concentration process is the oldest beneficiation method known to mankind. This is a physical process and exploits the differences in densities of minerals to bring about a separation. Although with the advent of froth flotation, the relative importance of gravity concentration has declined in twentieth century but still on an average higher tonnage of material is treated by gravity concentration than flotation. The gravity separation processes are comparatively cheap and environmentally friendly. It finds immense application in the processing of iron ores besides coal, beach sands, gold, diamonds, platinum, baryte, fluorspar, tin, tungsten ores etc.

The major limitation with the gravity concentration is the treatment of fines and ultrafines. In the fine size ranges the fluid and viscous forces become dominant relative to the gravity and this in turn affects the separation efficiency. However, significant development has been made in this field by introducing enhanced gravity separators like Knelson, Falcon, Kelsey Jig, Multigravity separator and water–only cyclone etc. These equipments generate higher gravity by application of centrifugal force and are capable of concentrating fines and ultrafine particles.

PRINCIPLE

Gravity separation of two minerals, with different specific gravity, is carried out by their relative movement is response to force of gravity and one or more other forces. Normally one of the forces is the resistance to motion by a viscous fluid e.g. water. So, besides the specific gravity the factors like size, shape and weight of the particles affect the relative movement and hence the separation. The ease or difficulty of separation depends upon the relative differences in these factors.

The 'Concentration Criteria' (CC) which gives an idea of the amenability of separation of two minerals, can be expressed by

$$CC=\frac{(d_H - d_F)}{(d_L - d_F)} \quad \ldots (1)$$

Where d_H = specific gravity of the heavy mineral
d_F = specific gravity of the fluid
d_L = specific gravity of the light mineral

Generally, when the quotient is greater than 2.5 (whether positive or negative), then gravity separation is relatively easy. With a decrease in the value of the quotient the efficiency of the separation decreases and below 1.25, gravity concentration is not feasible.

As mentioned above besides the specific gravity, the motion of a particle in a fluid also depends on its size. The efficiency of gravity concentration increases with an increase in particle size. The particle movement should be governed by the Newton's Law, Eq.2

$$v = \left[3gd\frac{(D_s - D_f)}{D_f}\right]^{1/2} \qquad \ldots(2)$$

where, v = terminal velocity of the particle, D_s=density of the solid, D_f = density of the fluid, and d = diameter of the particle.

For small particle the movement is dominated mainly by surface friction and these respond poorly to commercial high capacity gravity separators. To reduce the size effect and for making the relative motion of the particles specific gravity dependent, a closely sized feed is desirable.

RANGE OF EQUIPMENT

A wide range of gravity separators based on stratification, shaking surface, flowing film, density, centrifugal dense media, enhanced gravity are available for concentration of various types of ores with feed of varying particle size distribution. The operating particle size range of common separators is shown in Fig. 7.1. However, all may not find application in the case of iron ores. The equipment that has potential use by the iron ore industry for the particles typically above 50 microns is mainly heavy media separation (HMS), jigging and spiral. Some of the gravity concentrators are compiled in Table 7.1

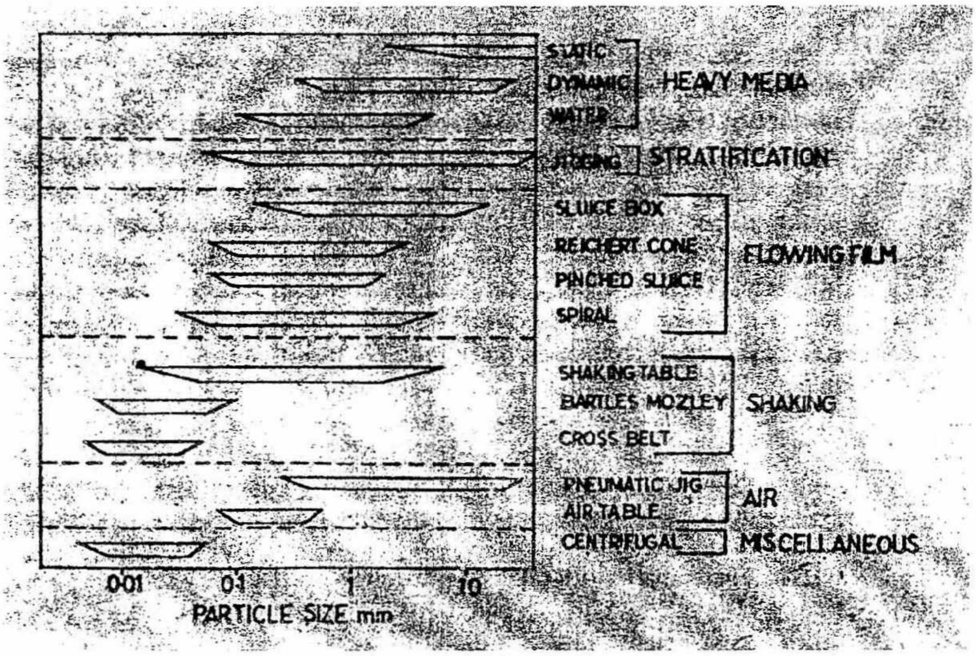

Fig. 7.1: Operating particle size range of common gravity separators.

Table 7.1: Some of the gravity concentrators

Separation Mechanism	Equipment
Stratification	Diaphragm or Plunger mineral jig, Baum jig, Batac jig, Circular jig, Pneumatic jig
Shaking surface	Shaking table, Slime table, Bartles-Mozley separator, Bartles cross-belt concentrator
Flowing film	Humpreys spiral, Pinched sluice, Reichert cone
Density	Dense media separation, Drum separator, Cone separator, Trough dense media separator
Centrifugal dense media	Cyclone, Vorsyl separator/Dyna separator, Autogenous dense media separator, Tri-Flo separator
Recent centrifugal and hindered settling classifier	Knelson separator, Falcon concentrator, Kelsey centrifugal jig, Multi gravity separator, Water-only-cyclone, Floatex density separator

CENTRIFUGAL SEPARATORS

In some of the gravity separation techniques centrifugal field is applied to enhance the gravity. Separators, where centrifugal field is employed, are called enhanced gravity separator (EGS) such as Kelsey Jig, Knelson, Falcon, MGS, Water only Cyclone.

The forces acting on a particle, which is settling under the influence of centrifugal field are gravity, drag, centrifugal buoyancy and frictional forces. However, gravity and centrifugal forces are predominant compared to other forces. The gravitational force acting on a spherical particle having diameter d, density σ and moving in a medium having density ρ is given by equation (3),

$$F_g = \pi/6\ d^3\ g\ (\sigma - \rho) \qquad \dots (3)$$

The centrifugal force is given by,

$$F_c = \pi/6\ d^3\ v^2 g\ (\sigma - \rho)/r \qquad \dots (4)$$

Where g is the acceleration due to gravity, v is the velocity and r is the distance of the particle from the axis of rotation.

The two forces can be written as,

$$F_g = m\ g \qquad \dots (5)$$
$$F_c = mv^2/r \qquad \dots (6)$$

Where m is the mass of the particle.

Equation (6) can be written in terms of N (revolution) rather than velocity v,

Substituting $v = r\,\omega = 2\,\pi\,r\,N$ in Equation (6)

$$F_c = 4\pi^2 N^2\, r^2\, m/r$$

The magnitude of force due to centrifugal action can be written as,

$$F_c/F_g = 5.595 \times 10^{-4}\ D\,N^2 \qquad \dots (7)$$

Where D is the diameter of the drum or vessel in meters and N is RPM.

If a centrifugal separator having drum diameter 0.5 meter is rotating at 200 RPM, the acceleration on the particle is 11 times of g. If it is assumed that the limit of a particle size that can be treated in conventional gravity separator is 10 microns, then using Stokes Law, it can be shown that the centrifugal separator can recover particle up to 3 microns.

Multi Gravity Separator (MGS)

Simultaneous rotation and shaking of the cylindrical drum are the main features of MGS. Combined effect of centrifugal acceleration and forces in conventional tables is responsible for desired separation. The unit consists of open ended horizontal drum (slightly tapered) fitted with a gentle slope (Fig. 7.2). The drum is rotated in clockwise direction with a rotational speed between 100 to 250 RPM. Sinusoidal shaking action is applied on the drum axially. Frequency of shaking may be varied between 4.0 to 5.8 cps whereas the amplitude may be varied from 10 to 20 mm.

The separation mechanism is represented schematically in Fig. 7.3. Feed slurry is introduced continuously at the mid point on the internal surface of the drum through a mesh ring so as to reduce the turbulence due to entry effect. Wash water is added near the open end through a similar type of mesh ring. Flowing film forms on the internal surface of the drum. Heavier particles settle on the inner surface and move in the upward direction by shaking action and accumulate in concentrate stream. Lighter particles do not settle and are carried to the tailings end by wash water.

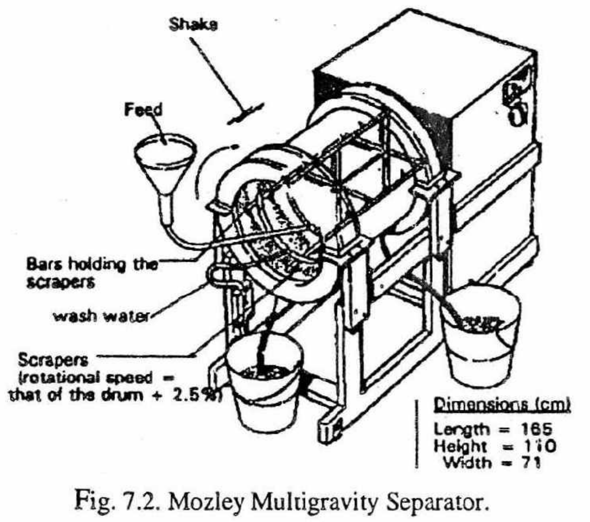

Fig. 7.2. Mozley Multigravity Separator.

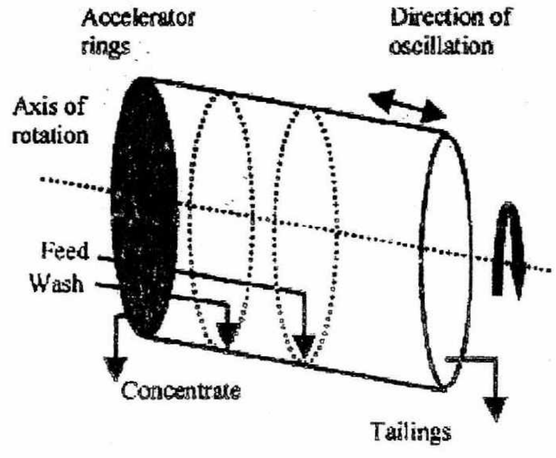

Fig.7. 3. Separation mechanism of MGS.

MGS has been applied successfully for gold, zinc, tantalum, tin, copper and lead. While the performance of the MGS was found to be superior compared to other fines gravity separators for reduction of alumina in iron ores, the low capacity is the major limitation in the application of MGS for the treatment of the iron ore slimes. However, with the development of higher capacity machines (30-50 tph), there is renewed interest in the possible use of MGS for iron ore applications.

Kelsey Centrifugal Jig (KCJ)

The KCJ is an enhanced gravity separator which utilises all the parameters of a conventional jig as well as the additional feature of being able to vary the apparent gravitational field acting on very fine particles and across the ragging bed. Whereas the dynamics in a conventional jig involve only specific induced movements, the KCJ takes a conventional jig and spins it in a centrifuge. The ability to change the apparent gravitational field by changing the rotational speed results in a major improvement in separation efficiency. This is particularly apparent for very fine minerals, as the enhanced field significantly reduces the effect of forces that hinder fine particle separation.

The KCJ offers high separation efficiency and has been evaluated for continuous operation and concentration of tin, beach sand, iron ore tailings and gold. More recently, a purpose built machine for iron ore industry, was first tested at IOC Canada in 1998 and IOC is considering the installation of a Kelsey jig beneficiation plant.

Knelson Concentrator

Knelson concentrator is a gravity-based centrifugal fluidized bed separator in which fine particles are separated by application of centrifugal force based on their specific gravity. A centrifugal field of about 60g could be achieved in this type of separator. This unit is widely used for recovering gold particles in a grinding circuit. The unit has the capability of beneficiating ultrafine coal.

Falcon concentrator

In Falcon concentrator also a centrifugal force of 300 'g' is produced unlike Knelson concentrator there is no back flow of water. The radial hindered settling velocity of each particle depends on its density and size. Thus heavier coarser particles have the highest radial velocity and lighter smaller particles have the lowest radial velocity. The heavier particle form a bed of particle just adjacent to the wall of the bowl and lighter particle layer remain at the furthest site from the wall. Weak parallel force component helps in migration of layers in upward direction. In the retention zone the upward movement of the heavier layer is restricted so as to report to overflow. Thus, the heavier particle layer remains at rest. Centrifugal force helps in control discharge of heavy materials through a pinch valve fitted on the wall of bowl in the retention zone. It is used widely in gold ore concentration, to some extent coal and tantalum.

Water only Cyclone (WOC)

Water only cyclone (WOC) is considered an enhanced gravity separator where particulate suspension forms a heavy medium and particles are separated on the basis of their specific gravity. It mainly consists of a vertical cylindrical body followed by a conical bottom like hydrocyclone. But the design of WOC is different from hydrocyclone. The unit has wider cone angle (80-140^0) where as the cone angle of hydrocyclone is smaller (10-70^0). The length of vortex finder is higher for WOC than hydrocyclone. The feed slurry is introduced tangentially from the top of the unit. The particle movement slows down at the conical bottom as its cone angle is wider and accumulated. Thus a bed of particle is formed which acts as heavy medium. This separator has various advantages such as (1) creation of autogenous dense medium (2) lack of any moving parts inside the unit; hence the maintenance and operating costs are very low (3) independent of particle surface properties; so oxidised ores/coals can be treated effectively (5) sharpness of separation is higher when compared to that of Spirals, Tables and fine ore Jigs and (5) cost of washing is very low.

PROCESSING OF IRON ORES

Processing of iron ores generally depend on the size and the nature of impurities present in the ore body. Crude ores in which iron particles are comparatively coarse and gangue component is comparatively fine are sometimes upgraded sufficiently by the feed preparation flowsheet only consisting of crushing followed by scrubbing and classification. The important gravity concentration techniques meant for processing lump as well as fine ores are discussed below.

Heavy Medium Separation (HMS)

Heavy medium separation involves using a mixture of fine media material, such as magnetite (SG 5.1) or ferrosilicon (SG 6.8), suspended in slurry of water, to produce a media slurry with a specific gravity that will allow low density material(s) to float, and other high density material(s) to sink. T he SG of separation is the SG of the media slurry, and can range from 1.45 (for coal), to around 2.8 (for diamonds). The separation principal is very simple, if the "liquid" media has a SG of 2.5, every mineral with a SG greater than 2.5 will sink and those lighter than 2.5 will rise to the top and float. One of the essential components of the HMS process is the media itself. The correct choice of the medium, and its effective control. both in terms of consistency and physical parameters, are essential for the efficient operation of the system. The efficiency of the separation can be determined by plotting the Tromp curve that is the partition coefficient against density. The partition coefficient is defined as the percentage of material in that density range reporting to the heavies or sink product.

Considering the wide application for HMS, many different designs of vessels have come to the market by the equipment manufacturer. Vessels fall into broad classification; static and dynamic.

The treatment of iron ore is major application and at one time accounted for half of the non-coal application in the USA. In South Africa, separations are carried out at densities as high as 3.8 kgL^{-1}. Typical performances of the HMS as applied to iron ores are given in Table 7.2.

Table 7.2: Typical Heavy Medium Separations of Iron Ores

Separator	Ore		Sep'n Sp. Gr.	Feed % Fe	Conc. % wt.	% Fe	Rec.	E.R.
	Type	Size,mm						
Drum	Siderite	100-10	2.95	28	87	31.8	97.7	1.12
DSM Cyclone	Oolite	8-3	2.64	26	72	32.7	84.0	1.24
Stripa	Hematite	60-6	3.08	35	64	49.0	94.0	1.4
DWP	Goethite	3-0.5	2.71	47	73	57.0	91.0	1.21

The world's largest HMS plant is the Sishin Export Concentrator of ISCOR, South Africa, with a design capacity of 5000 tph.

The crushed ore (90mm) is sized into four fractions and treated in four parallel HMS circuits as follow:

-90+30 mm: 5 Wemco Drums each with a capacity of 520 tph
-30+9 mm: 3 Wemco Drums each with a capacity of 346 tph
-9+5 mm: 4 DSM cyclones each with a capacity of 132 tph
-5+0.5 mm: 4 DSM cyclones each with a capacity of 520 tph

Jigging

Jigging is the process of sorting different minerals in a fluid by stratification, based upon the movement of a bed of particles, which are intermittently fluidized by the pulsation of the fluid in a vertical plane. The stratification causes particles to be arranged in layers with increasing density from the top to the bottom. This particle arrangement is developed by several continuously varying forces acting on the particles, and is more related to particle density than most other gravity concentrating device. The basic construction of a jig is shown in Fig.7.4.

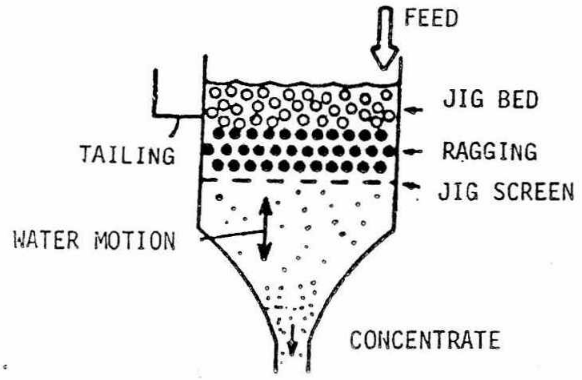

Fig. 7.4: Schematic representation of basic construction of a jig.

Jig has the widest operating range (200-0.1mm) of any gravity concentration device, however for iron ore the maximum lumpy ore size is limited to 30mm. Jigs can be classified on the basis of the method of effecting dilation of the bed, there being those in which the material being treated is moved through water (moveable screen) and those where the water is moved through the material (fixed screen). Fixed screen jigs can be subdivided according to the movement of water for example by plunger, diaphragm, pulsating valve etc Both the major classification can be again sub divided depending upon the method of removal of the heavy product from the screen.

Jigs along with spirals with a capacity of 3 Mtpa of feed was designed and constructed by Goldsworthy Mining Limited, Australia in the year 1988. Humboldt-Wedag SA recently installed a complete Batac jig system in an iron ore application at the Assmang Beeshoek Mine in Northern Cape, South Africa. The Eagle Mountain Mine, Kaiser Steel, USA and Lind Greenway Mine USA used to employ jigs to beneficiate iron ore. Tata Steel Ltd., India has installed a Batac jig of 250 tph capacity at Noamundi Iron Ore Minesfor processing of classifier fines (-10+0.15 mm).

Spiral

Spiral concentrator is one of the more common device used for gravity concentration of iron ore. This device is relatively higher in capacity, inexpensive and simple to operate. Generally, the feed enters the spiral channel as homogeneous slurry from the top. As the pulp flows around the helix of the spiral concentrator, stratification occurs in a vertical plane. This stratification is usually considered to be the result of a combination of hindered settling and interstitial trickling. It is likely that the Bagnold force also plays a significant role due to the relatively high rates of shear in the helical trough. The result is that, in the vertical plane, the heavies proceed to the lower velocity zones near the trough surface, while the lights tend to stratify above them in the higher velocity zones.

The helical twist of the spiral concentrator causes not only a flowing film velocity gradient to be set up in a vertical plane, but also a radial, or centrifugal, velocity gradient related to the other, in a horizontal plane. The net result is that the heavier and lighter mineral components of the streams are thus shifted laterally in opposite directions so that one is separated from the other.

One of the largest spiral plants is the Mount Wright Concentrator of Quebec Cartier Mine , treating upto 20 Mtpa of 30% iron ore in the form of specular hematite and producing a concentrate of 66% iron at a yield of 41%. A simplified flowsheet of Mount Wright Concentrator is given in Fig. 7.5. Other iron ore mines of Canada such as Wabush Mines, Carol lake and Grove Land had spiral installations to produce iron ore concentrates of varying capacities of 2-10 Mtpa.

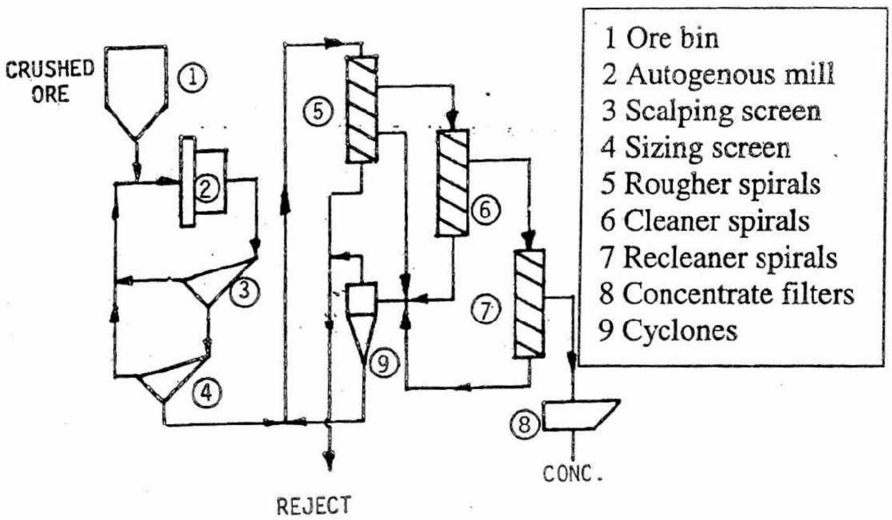

Fig.7. 5: Simplified flowsheet of Mount Wright Concentrator.

Floatex Density Separator (FDS)

FDS is a teetered bed gravity separation with a counter current operation. Liquid fluidisation coupled with hindered settling is the mechanism of separation in this unit. It consists of a vertical body, which may be rectangular or cylindrical. A feed distributor is fitted from the top of the unit, which is inserted to about one third of the height from the top. The feed slurry is introduced through the feed distributor. Teeter water enters uniformly from the bottom through a bank of perforated pipe and flows upward. The finer and lighter particles are carried to the overflow by the fluidized water and the coarser and heavier particles settle against the upward flowing water. Settled particles extend into a teetered bed forming an autogenous heavy medium.

FDS were installed at several major locations in Canada, Sweden and even in India. Iron ore company of Canada has modernized its spirals flow sheet to a combination of FDS and spirals to treat 6300 tph of ore at Carol lake Concentrator. LKAB of Sweden has also installed a number of FDS to reduce silica from 15% to 1% and reach high product grade.

SOME RESULTS ON GRAVITY SEPARATION OF INDIAN ORES

The present industrial beneficiation scheme used for hematite ores was basically developed for high grade ores with comparatively liberal product' s specifications and targeted for utilization of lumps and fines only. But for the exploitation of low grade ores and dumped fines and slimes, suitable beneficiation techniques are to be developed. Studies were carried out at NML towards developing processes involving gravity based techniques. Results of some of the gravity separation of iron ore fines are presented below.

Processing of Lump ores by Heavy Medium Separation

HMS can be successfully employed to decrease the laterite material of the ores due to the difference in specific gravity between the iron ore minerals and the laterite. There is a preferential rejection of the alumina over silica when lateritic materials are rejected. Table-7.3 presents results on HMS of selected iron ore samples from different sources. The study indicates a clear improvement in the grade for the sink product particularly in respect of alumina. The floats can be treated for further recovery of iron values after size reduction. Presently in India, no plant is working with HMS in view of the availability of relatively better grade ores and for economic reasons. HMS will assume significance in utilising the lean resources.

Table 7.3: Selected results on HMS of iron ore

Source	Feed Size, mm	Feed Assay, %			Product			
		Fe	SiO2	Al_2O_3	Wt.%	Assay, %		
						Fe	SiO_2	Al_2O_3
Joda	-50+10	64.4	1.60	3.01	64.4	66.5	1.0	1.87
Joda East Soft Laminated	-50+3.4	63.4	3.6	3.6	73.9	64.9	2.5	2.6
Joda East Mixed Hard -Spongy	-50+3.4	57.7	2.1	5.4	59.9	61.2	1.04	3.8
Naomundi	-50+10	65.77	1.25	2.65	59.3	68.1	0.6	1.3
Noamundi Soft Laminated	-50+3.4	60.11	1.26	5.98	71.9	61.50	1.10	4.56
Noamundi Hard-Lateritised	-50+3.4	63.80	1.90	3.30	82.5	65.70	1.06	1.74
Gorumahisani	-50+10	58.50	2.91	3.96	61.2	59.91	2.30	3.19
Badampahar	-50+10	60.49	1.82	2.93	59.9	61.80	1.60	2.60
Sesa Goa	-30+18	61.60	1.11	7.64	57.2	63.30	0.86	6.10

Processing of Iron Ore Fines

Studies were carried out on processing of fines using gravity concentration methods. Typical results on gravity separation of different samples are shown in Table 7.4.

Table 7.4 : Typical results on concentration of iron ore fines

Source and Feed	Feed Assay, %Fe	Process techniques	Product	
			Wt.%	Assay, %Fe
Noamundi washed fines	60.11	Splitting of feed followed by jigging of -9 +0.841 mm and tabling of -0.841 mm fraction	70.2	61.48
-3.36 mm classifier sand from Noamundi	59.40	Jigging	80.0	61.01
		Jigging of -3.36+0.6 mm and spiralling of -0.6 mm	63.2	62.25
Bonai,-3 mm	59.60	Jigging and tabling	51.6	61.31
Gua	59.00	Jigging	63.9	63.80
Dalli	58.52	Jigging and spiralling	65.8	65.40
Barsua	64.51	Spiralling	77.5	65.51

A typical gravity-cum-magnetic separation process for the processing of iron ore fines fro Gandhamardan is depicted in Fig.7.6. It was possible to get a product assaying 66.75 Fe with a iron recovery of 61.9%. Similarly, based on the detailed characterisation, laboratory and pilot scal beneficiation studies, process was developed for processing of a low grade and fine grained ore to product assaying over 65% Fe, suitable as feed to DRI pellet plant. The process flow-sheet schematically shown in Fig.7.7.

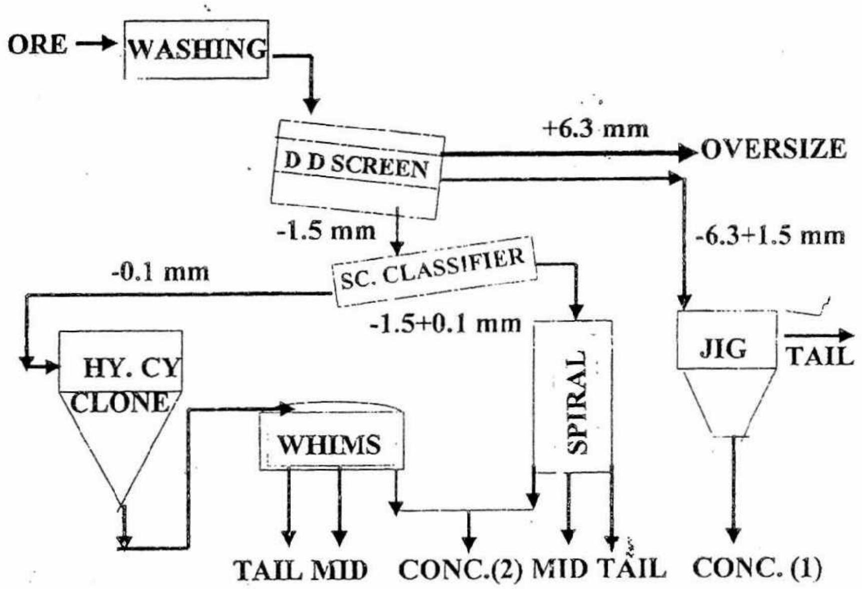

Fig. 7.6: Process flow-sheet developed by NML for beneficiation of iron ore fines from Gandhamardan.

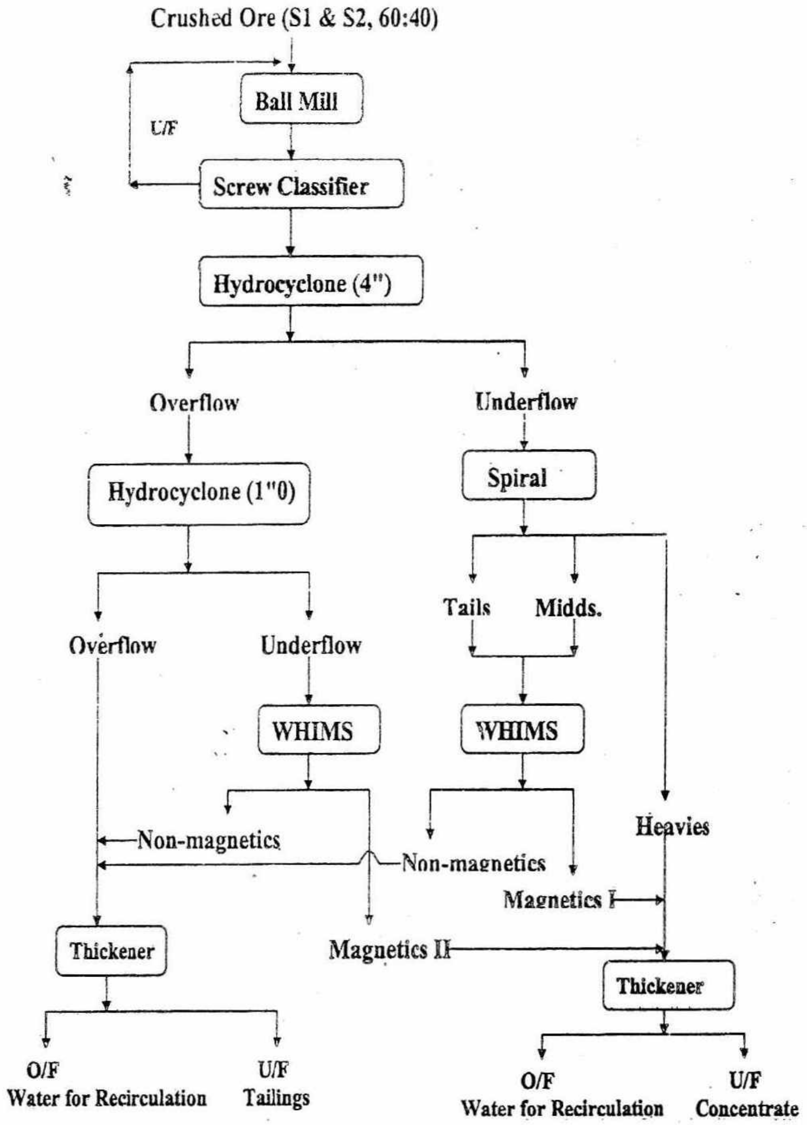

Fig.7.7 : Schematic representation of process involving spiraling developed by NML for beneficiation of low grade and fine grained iron ore sample to DRI pellet grade feed.

Processing of Iron Ore Slimes

The present practice of beneficiation of iron ores in India produces slimes (below 150 micron) which are not utilised and stored in tailings pond. Besides the loss of iron values, it poses environmental hazard. It is estimated that the generation of slimes is 10-20% of the iron ore mined and it amounts to 18 million tonnes per year. Iron ore slimes accumulated in different mines in the country along with their chemical characteristics are shown in Table 7.5. Any attempt to recover values from these slimes will eventually lead to additional supply of material for sinter feed and reduction of tonnage of slime to be discharged to tailing dams. However, proper characteristics need to be evaluated to find the amenability to beneficiation to produce a suitable additional raw material. R&D studies have been carried out on characterisation and beneficiation of slimes to recover iron values. Results of the studies on processing of iron ore slimes using hydrocyclone are summarised in Table 7.6.

Table 7.5: Production of slimes by different iron ore washing plants

Mines	Quantity, MT	Assay, %		
		Fe	Al_2O_3	SiO_2
Barsua	0.6	52.5	9.88	7.62
Bailadilla 5	0.5	61.2	2.81	6.84
Bailadilla 14	1.2	62.8	3.68	4.26
Bolani	0.4	59.8	4.8	4.10
Daitari	0.3	60.0	4.52	2.30
Donimalai	1.0	57.9	6.28	6.42
Kiriburu	1.6	60.4	4.96	2.96
Kudremukh	15.0	26.6	1.82	51.02
Noamundi	0.45	55.0	7.8	5.02

Table 7.6: Results on concentration of iron ore slimes by hydrocycloning

Source	Assay of Feed, % Fe SiO_2 Al_2O_3	Product	
		Wt.%	Assay, % Fe
Noamundi	58.50 4 22 5.90	66.4	62.10
Bolani	49.80 6.60 8.10	49.7	58.00
Meghataburu	57.65 4.38 5.95	54.9	63.52
Joda (Flaky)	48.72 11.23 12.27	45.1	61.76
Joda (Hard)	43.80 11.65 14.25	40.7	49.98
Gandhamardan	54.80 7.90 6.10	64.5	60.50
Bellary Hospet	57.60 8.00 5.90	60.0	66.90

It is often found that slimes rich in laterites/limonites do not respond well to hydrocyclones or the conventional gravity separators in lowering the alumina to 2% or below. Under such cases hydrocloning, in tandem with a suitable gravity separation device capable of treating fine particles, proves helpful in reducing alumina in the slimes. Typical results obtained using MGS are shown in Fig. 7.8.

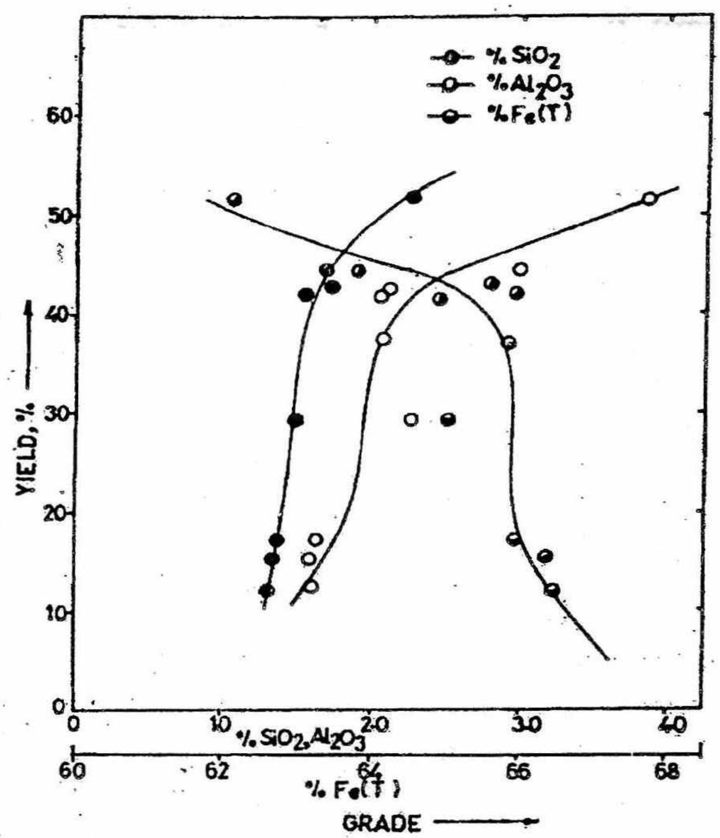

Fig. 7.8: Results on reduction of alumina and silica using MGS.

CONCLUDING REMARKS

Gravity concentration processes are the oldest beneficiation techniques known to mankind but its relative importance declined in 20th century. In recent times there has been an upsurge in interest, particularly in the development of newer fine gravity separators. Gravity separation is one of the major techniques used for beneficiation of low grade iron ores. With the increasing demand of quality iron ores these techniques can play a major role in exploiting low grade iron ores. Scale-up of some of the centrifugal separators will assume great significance in processing and utilization of dumped low grade fines and slimes.

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