Serial Gravity Concentration: a New Tool in Mineral Processing*

J. H. HARRIS, MEMBER,† B.Sc., A.R.S.M.

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SYNOPSIS

The arts of jigging, screening and hydraulic classification are reconsidered. It is shown that in any gravity concentration process the losses of liberated values are not only in the fines, but also in a middle range controlled by the relative sizes of the gangue and of the mineral sought, and that these losses are irrecoverable by any repetition of the process without change of nature of the feed. In systems previously employed, total losses were the sum of numerous separate losses arising from parallel treatment of narrow bands of sizes separated from a long-range feed. Use of a new system is reported, wherein the gravity concentration stages are in series with rejection of barren oversize by screening between stages. The result is a stage-reduction of losses in almost geometric progression until they are economically negligible. It is proposed that this system be called 'serial gravity concentration'.

THE DULANG IS A FORM OF PROSPECTING PAN used in the East. It is turned out of wood, in the shape of a segment of a hollow sphere. Its diameter is usually about 22 in. (558 mm), its depth about 4½ in. (114 mm), and it weighs 6½ lb (2·948 kg). It is used both for the winning of minerals from rich alluvials and for the estimation of values in alluvials. The motions employed are compounded of panning and vanning. Fig. 1 shows *dulang*-washers at work recovering cassiterite in Malaya.

Prospecting of tin-bearing alluvials in Malaya is carried out by the methods described by Harrison[1] using Banka drills operated either mechanically or by hand. The samples obtained are washed in a *dulang* and the resulting rough concentrates cleaned by careful hand-dressing to yield a final concentrate which is dried and weighed. It is clear that *dulang*-washing is scarcely capable of total recovery of values. The fact that some cassiterite would amost certainly be lost has always been recognized, but it has been assumed that these losses would consist of 'fine tin', probably irrecoverable by any known mineral-dressing process and therefore of no practical importance.

In an attempt, however, to determine the extent and nature of these losses in the prospecting unit under the author's charge, some tests were made. The results, described here, were so unexpected that they demanded

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†Chief Research Officer, Department of Mines, Research Division, Ipoh, Federation of Malaya.

[1] etc. See list of references at the end of the paper.

Fig. 1.—Dulang-*washers at work in Malaya.*

a critical review of the theory and practice of gravity concentration in general. In consequence the author evolved and successfully put into practice[2] a new approach to mineral processing, a method which, it is now proposed, should be named 'serial gravity concentration'.

RECOVERY OF CASSITERITE BY *DULANG*-WASHING

Synthetic samples were made up by taking barren tailings from which all cassiterite had been scrupulously removed by repeated gravity and high-tension separation, adding ilmenite, zircon and pyrite (minerals commonly associated with cassiterite in Malayan alluvials) in more-or-less average amounts and then alluvial cassiterite in known weights and of known sizing so as to reproduce alluvial ores bearing various values.

These samples were handed to the *dulang*-washers with the instruction that they should be washed as carefully as possible. The cassiterite so recovered was screened into the original size-ranges and weighed, with the results shown in Table I.

Several interesting features emerge from these results:

(*a*) Losses occur in the finer sizes, as would be expected.

(*b*) Nevertheless, substantial quantities of cassiterite finer than 200-mesh B.S. (76μ) can be recovered by the *dulang*. This is at variance with current experience since, in most practical evaluation in Malaya and owing, presumably, to poorly-controlled *dulang* operation, cassiterite finer than 200-mesh is seldom, if ever, reported although recent work has shown it to exist.

(*c*) Serious losses occur of cassiterite in a *middle range* of sizes, neither very coarse nor very fine (in this case between 30-mesh and 100-mesh B.S.) (500 and 152μ) which had not previously been suspected.

TABLE I.—*Recovery of Cassiterite by* Dulang-*Washing*

Size range (B.S. screens)		Recovery of cassiterite (expressed as percentage of that originally added)			
		A 0·3 kati/yd³*	B 0·5 kati/yd³	C 1·0 kati/yd³	D 2·0 kati/yd³
μ	+ 10	100	100	100	100
1670	− 10 + 16	100	100	98	97
1000	− 16 + 30	99	96	100	100
500	− 30 + 60	63	60	55	53
252	− 60 + 100	63	61	58	50
152	− 100 + 150	97	100	95	98
105	− 150 + 200	100	100	100	100
76	− 200 + 240	68	60	55	47
65	− 240 + 300	60	61	45	45
53	− 300	17	20	10	6

*kati/yd³ × 1·33 = lb/yd³; kati/yd³ × 0·7891 = kg/m³.

The most unexpected outcome of the above work was the discovery of this loss of heavy mineral in the *middle range*. It was confirmed by numerous tests of the performance of jigs in actual full-scale operating plants and by tests of other gravity-concentration processes, which will be reported elsewhere. An explanation of this curious phenomenon was sought by reviewing current theories of gravity concentration, particularly of jigging.

REVISED THEORY OF JIGGING

The theory of jigging was well summarized, with an exception which will be submitted, by Taggart.[3] Previous work by Richards[4] included experiments (Table 49, p. 201) which indicated the inevitability of a loss of heavy mineral in the *middle range*, but the significance of the results was not recognized at the time. A recent study is reported by Kirchberg and Hentzschel[5] who conclude that equal settling phenomena are of less importance in jigging than mechanical effects due to dilation and contraction of the bed and that settling according to specific gravity is obtained, irrespective of grain size, and Williams[11] gave some valuable results obtained by jigging, the significance of some of which appeared to have been overlooked, as pointed out by the present author and I. R. M. Chaston in a written contribution to the discussion.[12]

Considering the situation in the bed of a jig to which is being delivered a de-slimed long-range feed, say between 1 in. (25·4 mm) and 300-mesh B.S. (53μ) in size, in which the mineral sought is liberated: ignoring the ragging, the disposition of the grains of gangue at any instant when the bed is at rest will be much as indicated in Fig. 2 (blank circles).

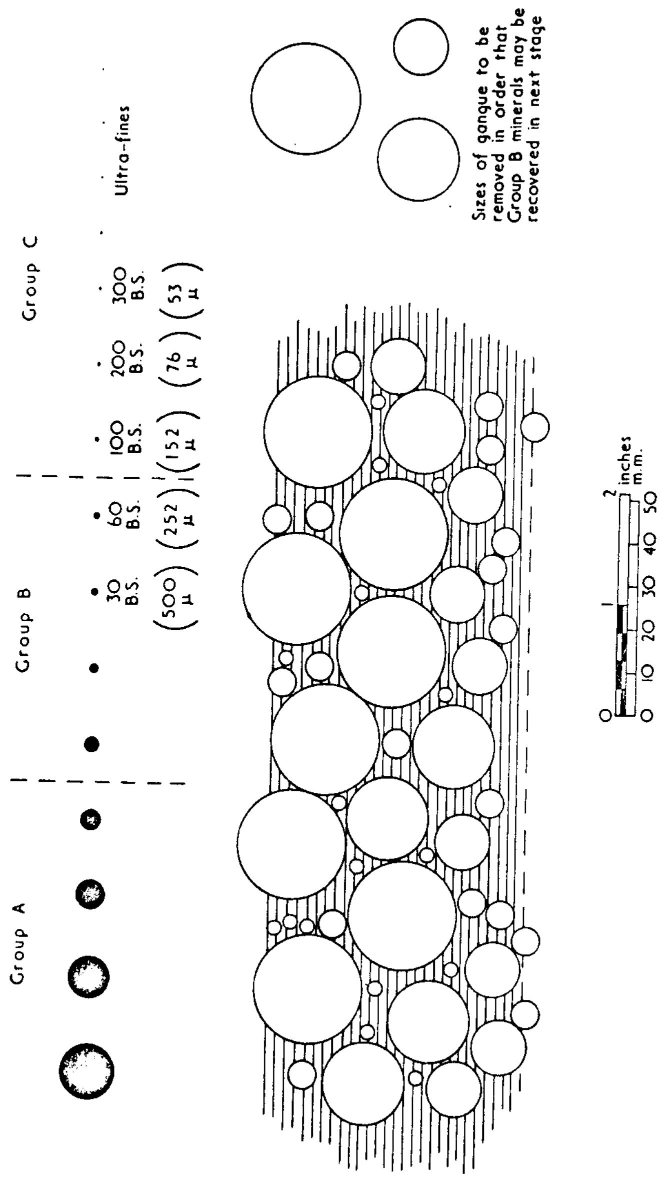

Fig. 2.—Diagram to illustrate phenomena in jigging with a long-range feed.

For ease of illustration the grains are indicated as spherical and for clarity it is assumed that, at this instant, there are no grains of heavy mineral trapped in the bed. The interstices between the grains as drawn will be filled with finer grains of sand and silt as indicated by shading. Associated with this gangue will be grains of heavy minerals shown as filled circles, suspended at this instant above the bed and existing in a range of sizes from coarse to the very finest, divided into three groups A, B and C.

The combined actions in a jig are complex and include (*a*) periodic dilation and compaction of the bed; (*b*) an upward pulsion and a downward suction; (*c*) owing to differential acceleration, a net tendency of specifically heavy particles to fall and a relative net tendency of specifically light particles to rise.

If the feed contains excessive slime, a viscous medium is formed which tends to buoy up the finer particles of specifically heavy mineral and carry them into the tailing. If the flow across the jig be too violent there will likewise be losses of values carried mechanically into the tailing. Assuming, therefore, that we have a de-slimed feed at a reasonable flow rate, the mineral particles shown in Fig. 2 will have a chance of reaching the bed.

Those in Group A are too large to penetrate the bed when it is at rest. When, however, the bed dilates they fall and become nipped between grains of gangue (cf. Taggart,[3] p. 188). With successive dilations and contractions they become submerged and eventually penetrate the bed, emerge at the bottom, and are collected as either bed- or hutch-product.

Those in Group C are fine enough to penetrate the bed by filtration. They will do so, especially during the suction phase, provided that they succeed in reaching the bed at all. Many of them, however, will not be able to overcome the upward pulsion and the force of the cross-flow and will thus be lost into the tailing.

Now consider those in Group B. They are neither big enough to penetrate the bed by reason of specific weight nor are they small enough to penetrate by filtration. It is therefore almost impossible for them to be concentrated by any conceivable action of the jig. Some will penetrate by chance and the rest will be swept away into the tailing.

This, then, is the explanation for the loss of cassiterite from the *dulang* in the *middle range*. During *dulang*-washing the bed of material dilates and contracts much as in jigging. Minerals in Group A can be nipped and will penetrate by reason of their specific weight and part of those in Group C can penetrate by filtration. These will be collected; but a great part of Group B will not be collectable either by nipping or by filtration and they will be lost.

The significance of Richards's results can now be assessed. Table II, overleaf, is adapted from Richards[4] (Table 49, p. 201) and shows the results of jigging tests to note the behaviour of six different sizes of galena when paired with a standard size of quartz.

These results show that the critical size-range for galena in this system was from just above 0·665 mm to just above 0·495 mm. Above this range the galena was concentrated by nipping and below it by filtration. The ease of the latter is evinced by the result for the 0·107-mm galena. But

TABLE II.—*Jigging Quartz and Galena* (after Richards[4])

Diam. of quartz mm	Diam. of galena mm	Pulsions needed for separation	Per cent of galena brought down
1·735	1·735	257	100
1·735	1·090	302	100
1·735	0·665	748	98
1·735	0·495	337	99
1·735	0·241	190	100
1·735	0·107	86	100

at 0·665 mm difficulty of penetration can be detected and it can only be presumed that if all the sizes had been mixed and given about 300 pulsions the greater part of the 0·665-mm galena, the *middle range*, would have been lost into the tailing.

The rest of the figures in Richards's original table may be similarly analysed. They show that the critical range of sizes moved up or down depending on the suction employed, as can be well understood.

SERIAL GRAVITY CONCENTRATION

It is now proposed to offer a solution to the problem of recovering that mineral in Group B, *the middle range*, which has been shown to be irrecoverable by the jigging stage described. Clearly any further jigging *under the same conditions* will be useless. What needs to be done is to take the whole of the gangue shown in Fig. 2 into the tailing, together with the unrecovered mineral in Groups B and C, and to pass it over a screen which will remove the oversize lumps indicated at the right of Fig. 2. These may now be discarded since they are barren of values. The balance can then be thickened (e.g. with a hydrocyclone) and re-jigged under different conditions. The mineral grains in Group B now bear the same relation in size to the new gangue as those in Group A did to the old. The Group B grains can therefore now be collected by nipping and there is a further chance of collecting some more of Group C by filtration.

The losses at this stage will be in a new middle range, down towards the fine end of the original assemblage. If they are still worth recovering, a further stage may be added to the 'serial' process. This time a finer screen will be used, oversize again rejected and undersize thickened and concentrated. Since it is now fine, the method used will be tabling, spiralling, buddling or other such process rather than jigging. Although the above argument has been based on jigging as a first stage it is thought that, since all operations of gravity concentration are basically so similar, the 'serial' method can be used in all cases.

It will be noted that the amount of material to be treated grows less at each stage and that the overall tailings loss will tend to be reduced stage by stage in something like geometric progression (e.g. 30 per cent

loss in the first stage, 30 per cent of what is left in the second stage, 30 per cent of what is then left in the third stage and so on).

Formerly it was usual (Truscott,[6] Fig. 160, p. 247) to rely on sizing a long-range feed into a great number of short ranges by means of a multiplicity of screens, hydrosizers and so on and then treating each product in a separate gravity-concentration section *in parallel*. Reference to the Proceedings of the International Mineral Dressing Congress, Stockholm, 1957,[7] indicates that such procedures are still in use. It is, however, now submitted that, in each section, some of the *middle range* of mineral size would have been lost and that nothing could be done thereafter to recover it.

LOCKED PARTICLES

The foregoing discussion has been based on the assumption of a feed containing all free mineral. Where, however, this is not the case and some of the desired mineral is locked to grains of gangue, it will be found that locked grains tend to accumulate in the oversize from the screen after each stage of the 'serial' process. If this material is still ore it can be ground and returned to the circuit at an appropriate point.

APPLICATIONS

The method of 'serial gravity concentration' has proved to be remarkably successful in treating the alluvial and eluvial tin-ores of Malaya.[2] Virgin ground has yielded up to 50 per cent more tin than had previously been obtained by sluicing or jigging. Cassiterite previously thought irrecoverable has been extracted with ease from old tailings.

De-sliming has been shown to be an essential stage and this has been accomplished with hydrocyclones, designs for which have been evolved, based on the work of Chaston,[8] which ensure very large throughputs at a low pressure with a coarse feed, while still splitting effectively at 53μ. One instance may be cited where a cyclone 30 in. in diameter receiving a feed containing particles up to 1 in. in size and working with a natural head of 14 ft is handling nearly 3000 gal/min. The underflow from these cyclones carries about 40 per cent solids and this makes a good feed for the jigs. A long stroke (1½ in) is used with a frequency of 120–160 strokes per minute and it is then found that the jig has a high capacity and can catch cassiterite over a wide range of sizes down even to 300-mesh B.S. (53μ).

For the screening stages, the sieve-bend grizzly[2] and the fine sieve-bend[2,9,10] are of great value. They are cheap, non-blinding, stationary wet screens which require only a low head.

It is thought that 'serial gravity concentration' could be applied for the improved recovery of numerous heavy and semi-heavy minerals other than cassiterite, such as gold, diamonds, phosphates, etc. Many alluvial deposits, beach deposits, and the like have already been subjected to gravity concentration by natural forces and any attempt to treat them by gravity concentration again without changing the nature of the feed as described here must necessarily end in failure.

OPERATION OF JIGS

It has been common practice to use jigs with four cells, which can be shown to be not the best practice. There are numerous examples in Malaya of installations of 4-cell jigs in which heavy mineral will be caught in the first two cells only, scarcely any being recovered in the last two, although free mineral can readily be detected in the tailings. Even when properly fed and operated the performance of such a jig must be hampered by the fact that the addition of hutch water dilutes the pulp progressively from cell to cell. By the time the third cell is reached the pumping effort required to move the extra load results in an increased rising current. Since the coarsest particle of gangue still requires to be moved from cell to cell it follows that the effort put in to move it is bound to cause the finer particles of mineral and probably some of the coarser to rise as well and to overflow into the fourth cell. Here conditions are worse, no concentration can take place and the mineral, though free, is swept into the tailing.

It is considered preferable to use two cells at the most for the initial concentration and then to proceed by the 'serial' system. The effect of stroke length also requires reconsideration. Formerly it was thought that the jigging of coarse material required a long stroke and that of fine material a short one. This may be true when parallel concentration is used and when each stage carries a short range of sizes. It has, however, been found by the present writer when using 'serial gravity concentration' that, when a long-range feed is jigged, provided that the feed is de-slimed and dense (say 40 per cent solids) a long stroke (say 1½- to 2-in) (35- to 50-mm) is found advantageous in the first stage of separation. The bed acts, in the manner already described, in such a way as to trap both coarser and finer mineral alike, within limits set more by the relative sizes of gangue and mineral than by the mechanical forces at work in the jig. At the end of a long upward stroke, when the bed is fully dilated and momentarily at rest, conditions are good for trapping coarser heavy grains (Group A, Fig. 2) while the succeeding long suction stroke does a great deal to draw fines and ultra-fines down through the bed. It should be noted that the suction stroke, though long, does not necessarily need to be powerful since its force can be counteracted at will by control of influx of hutch-water. There is thus little danger that the long stroke will suck excessive amounts of fine gangue into the hutch. In practice the grade of hutch concentrate is controlled to a great extent by the grade of the feed. Where the feed contains sufficient heavy mineral to create heavy-medium conditions just above the jig-screen the grade of concentrate will be good. If the grade of the feed falls off more fine gangue will be pulled. When treating patchy tin-bearing alluvials this variation is quite noticeable.

When the concentrating power of a jig is viewed in this way the mineral-dresser may with confidence use a long stroke in his 'serial' first stage or rougher jig, with the added satisfaction that the long stroke gives his jig a much greater capacity than he had at first thought possible. Any lingering fears that, due to the powerful pulsion, recoverable mineral will be lost quickly disappear when it is realized that such losses will tend to be recovered in the 'serial' second stage or first scavenger. This, if a jig, will need to be run at a shorter stroke and higher frequency than the rougher jig, in practice frequently ½ to ¾-in (12 to 19-mm) at frequencies of 200 strokes per minute and over. Here control becomes relatively more precise and it must be recognized now that the majority of any loss will be either in the ultra-fines or in the uncontrollable middle-range corresponding to the sizing at this point. If the losses are appreciable a 'serial' third stage, or second scavenger, will be installed, after which there is scarcely any likelihood of losses of any economic magnitude.

CLASSIFICATION AND SIZING

It has been postulated above that the most effective method of gravity concentration employs a roughing stage, followed by screening to remove barren gangue, followed by one or more scavenging stages in series. It will be noted that in this scheme of things hydraulic classification plays no part. There is a simple reason for this. At any stage of hydraulic classification of a pulp containing mixed, unsized, heavy and light minerals, the underflow will contain coarse heavy mineral, locked particles and some equivalent coarse lights, while the overflow will contain lights and some fine heavy mineral, a potential loss. If the overflow is not treated, the potential loss becomes an actual one and even if a succeeding gravity concentration process is employed there will still be a loss of an irrecoverable portion of the middle range of sizes as has already been shown.

When the 'serial' process is used, however, the classification between stages is done by screening. The reject is now barren oversize and/or locked particles. If the latter are insignificant in value the material becomes a true reject. If not, the material may be treated as a middling, ground and returned to the circuit. In neither event is there any economic loss of mineral.

It may thus be concluded that, since adequate methods are now available for economical wet-screening at all sizes, the need for hydraulic classification in any gravity concentration circuit is not apparent when 'serial gravity concentration' is employed.

SUMMARY

Gravity concentration is an art which plays an important role in the separation of minerals of different specific gravity, particularly where the desired mineral is liberated, or substantially so, as in the case of alluvial or eluvial ores. The present study has shown that losses of values, inherent in the methods employed, are due to causes different from those thought generally to be operative.

It is noted here that, when a long range of sizes occurs, the practice has previously been to endeavour to separate more-or-less narrow bands of this range by means of screen-sizing or hydraulic classification and then to treat each band by gravity concentration *in parallel*, selecting as far as possible a means of gravity concentration suited to the range of sizes in each band. In what has gone before it has been shown by experiment that overall improvement can be effected by utilizing suitable gravity concentration steps *in series*, a process which it is proposed be called 'serial gravity concentration'. The first stage is a rougher, the tailing