GRAVITY SEPARATION OF ULTRA-FINE (- 0.1mm) MINERALS USING SPIRAL SEPARATORS

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ABSTRACT

Spiral separators have undergone continuous development over the past 40 years. The focus of some more recent developments has been towards the processing of progressively finer mineral particles.

New model spiral separators have now been developed that are specifically designed to treat material finer than 0.1 mm.

Design features are discussed and performance data on a variety of ore types are presented to illustrate the effectiveness of gravity separation on material below 0.1 mm in size using fine mineral spiral separators. Comparisons are made with data generated using spiral separators designed for treating feeds of a more conventional size range for this type of equipment.

Keywords
Gravity concentration, Spiral separators

INTRODUCTION

Gravity concentration of minerals has traditionally been recognised as a low cost and environmentally friendly process for the separation of minerals. In recent years a number of new process technologies have emerged allowing ever-finer materials to be successfully processed. Fine mineral spirals separators are just one of these new emerging technologies that have the potential to efficiently separate mineral species down to 30 micrometres in size. Spirals separators are simple, low energy consuming devices that separate minerals based on their respective densities and have proven to be metallurgically efficient and cost effective since their widespread commercial introduction more than 50 years ago.

A broad range of spiral separator designs is available for various applications including different density minerals, varying particle sizes and range of feed grades. Depending on the application, each spiral separator model has a unique profile, pitch and features to ensure it performs efficiently. Conventional spiral separators have had limitations with respect to particle size with a top limit of around 1 to 2 millimetres and a lower limit of around 75 micrometres. Very fine heavy particles below approximately 75 micrometres are typically swept up in the highly turbulent outer regions of existing trough designs and are lost to tailings due to their failure to migrate inwards to the central concentrate collection area. In addition very coarse particles are also swept along in the outer region of the spiral trough due to the large overturning moments causing them to roll along at high velocity owing to the low friction encountered attributable to the rolling action. For spiral separators to perform efficient separations outside the traditional operating window described above, unique conditions need to prevail in the flowing medium. Such conditions can only be provided by the trough geometry, trough features and/or feed characteristics e.g. flow rate or density.

Considerable effort has been expended on the development of new gravity separators in an effort to achieve separations at finer sizes and more discreet processing capabilities to accommodate such difficulties as smaller particle density differences. The greatest efforts appear to have been reserved for high gravity devices with new machines such as the Kelsey jig, Campbell jig, the continuous Falcon separator, and the Mozely MGS. These devices generally provide greatly enhanced "gravity" forces that are generated in a drum type mechanism rotating at high speed around a central axis. Size separations down to less than 10 micrometres are achievable and good metallurgical performance on minerals with small density differences is achievable in some circumstances. However, all of these enhanced gravity machines are mechanical in nature and generally have higher costs both from a capital and operating perspective.

A recent development is the FM1 spiral separator; designed to operate down to 30 micrometres whilst achieving acceptable recoveries. This new model spiral separator is aimed at rougher/recovery type applications with upgrade ratios typically in the range 2 to 4.

FM SPIRAL SEPARATOR DEVELOPMENT

Concentration in a spiral separator is effected through a system of interdependent processes that take place in the flowing medium. The slurry flowing down a spiral trough has a cross section which varies in depth; the inside flow (closest to the centre column) being very shallow - typically less than 1 to 3 millimetres. With increased radius, the depth of the flow increases. At the outside edge of the trough the flow can be 20 millimetres or more in depth. The velocity of the flow varies somewhat proportionately to the depth of the flow. Accordingly, despite the very high down trough slope at the inner edge of the trough, the flow velocity in this area remains low. At the same time, the flow at the outer edge of the trough attains its greatest velocity despite the greatly reduced down trough slope in this area.

The flow velocity and cross sectional profile depend on the trough geometry, pitch and flow rate of feed material entering the trough. With increasing flow, the depth and velocity at the inner portion of the trough remains relatively unchanged. However, the flow depth and velocity at the outer region increase. Accordingly, it is in this area of the flow regime that the Reynolds numbers and hence the turbulence can be most dramatically modified by appropriate selection of a trough profile and pitch and flow conditions.

The flow rate has a significant effect on the motion of particles both down and across the trough, providing transportation, stratification and separation. Once the flow regime and the water profile is fully developed it remains in a highly stable condition. The secondary water flows, which develop perpendicular to the primary flow and frictional drag effects, contribute to the mineral separation processes taking place on the spiral trough. (Holland-Batt 1989)

The key factor to be dealt with in the design of a fine mineral spiral separator is the overall control of turbulence (Reynolds numbers) across the entire trough to insure conditions throughout the flowing medium are conducive to controlled settling (Holland-Batt 1991). These conditions change significantly across the trough as pulp density and centrifugal force (a function of velocity and radius) change and must be suitable for the separation processes to take place. Due to the low settling velocities encountered by very fine mineral particles, the separation processes take longer to fully develop. Accordingly, a fine mineral spiral separator is typically longer than traditional troughs to allow these very delicate processes to produce an adequate separation. In addition, due to the lamina flows and the relatively small bed depths on a spiral trough of such a design, a longer residence time is required for useful separation to occur.

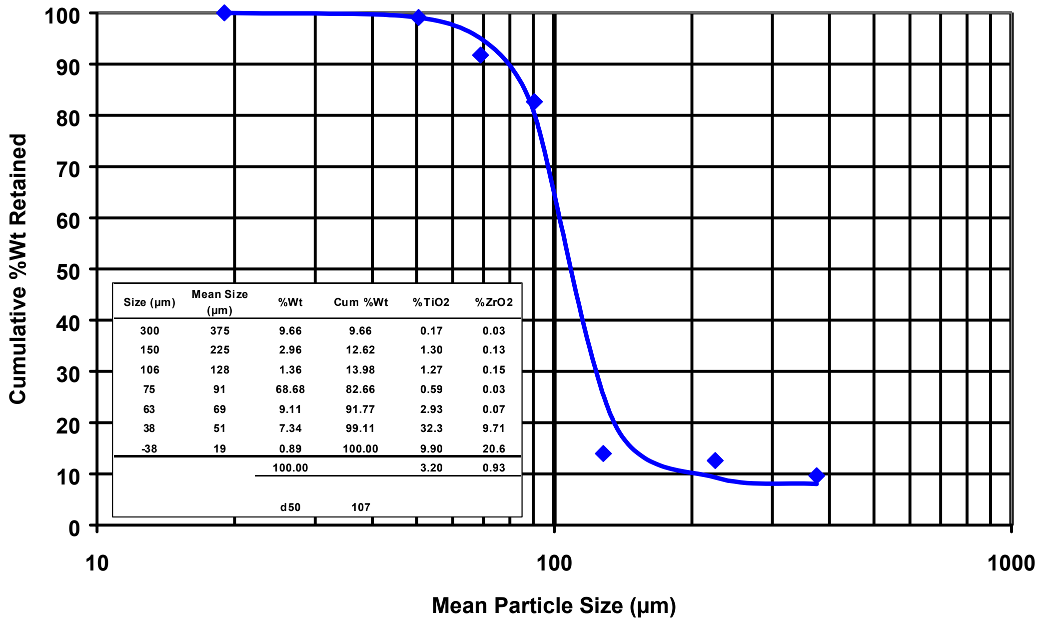
A feature of spiral troughs of this design requires that greater attention is needed in feed preparation to insure feed sizing is maintained within reasonable limits especially in regard to top size. Other features include variable profile geometry to create the conditions described above. In contrast to conventional mineral spiral separators (Holland-Batt 1995,1) no repulpers are used for FM applications, as they tend to introduce excessive turbulence that will result in reduced recoveries of the heavy mineral fraction.

Holland-Batt (1995,2) indicated that on conventional spiral separators, the greatest recovery and grade are obtained from the first 2 to 4 turns of the spiral separator, with further, but reduced performance gained from additional turns. For the FM spiral separator a contrary effect has been observed, with improved grades being obtained progressively down the spiral separator. It is for this reason that the FM1 spiral separator has multiple off-takes that need to be operated such that larger cuts are taken progressively down the spiral trough.

The FM1 spiral separator has been successfully demonstrated in the treatment of minerals in the size range 30 to 60 micrometres at capacities over 1 tonne/h per start. Higher feed rates can be used for coarser material; however optimum performance can be expected at lower unit loadings especially as feed material becomes finer.

DEVELOPMENT TESTWORK

During development of the FM1 prototype spiral separator, extensive testing was conducted on a fine-grained Australian mineral sand. The size/assay characteristics of the classified feed material used in the spiral development testwork are given in Fig.1. The size distribution was such than this feed would not normally be considered amenable to concentration using conventional spiral separators.



Size (μm)	Mean Size (μm)	%Wt	Cum %Wt	%TiO2	%ZrO2
300	375	9.66	9.66	0.17	0.03
150	225	2.96	12.62	1.30	0.13
106	128	1.36	13.98	1.27	0.15
75	91	68.68	82.66	0.59	0.03
63	69	9.11	91.77	2.93	0.07
38	51	7.34	99.11	32.3	9.71
-38	19	0.89	100.00	9.90	20.6
		100.00		3.20	0.93
		d50	107		

Fig.1 Fine grained Australian mineral sand size analysis

A series of approximately 90 tests was conducted under a range of operating conditions and varying configurations with respect to concentrate off-take splitters. It was determined that recovery performance was marginally enhanced by taking smaller concentrate splits more often. A configuration including a total of five auxiliary off-take splitters, plus the conventional knife gate splitters at the bottom of the trough, was considered to be practically viable, whilst maintaining optimal performance.

Early in the test program it became apparent that satisfactory performance (for this particular feed type) could only be achieved at lower than conventional feed rates. Many of the tests were carried out at feed rates between 0.5 to 1.5 tonnes per hour per start. Feed parameters that were varied included the solids feed rate and pulp density in order to determine a set of operating conditions that would gives optimum performance.

From each test, a recovery curve was generated based upon TiO_2 assay results. Performance was measured by TiO_2 recovery at 50 per cent mass distribution to concentrate ("r50") interpolated from the recovery curves. A sub-series of tests was conducted and categorised into three feed rate ranges and three pulp density ranges.

Fig.2 indicates a linear relationship between feed rate and recovery for each of three pulp density ranges. Highest recoveries are achieved at the intermediate pulp density range (36 to 40% solids). The data show clearly that recovery performance diminishes with increasing feed rate. At a feed rate of 0.8 tonnes per hour, 87 to 88% TiO_2 recovery was achieved in the lower pulp density ranges. Extrapolation of the upper-most fitted line indicates that 90% TiO_2 recovery could be achieved by reducing the feed rate to 0.6 tonnes per hour. Fig.3 shows that the relationship between recovery and pulp density is less well defined. The data indicate that higher TiO_2 recoveries were achieved at intermediate pulp density levels. As the feed pulp density approaches 50 per cent solids, recovery begins to fall appreciably.

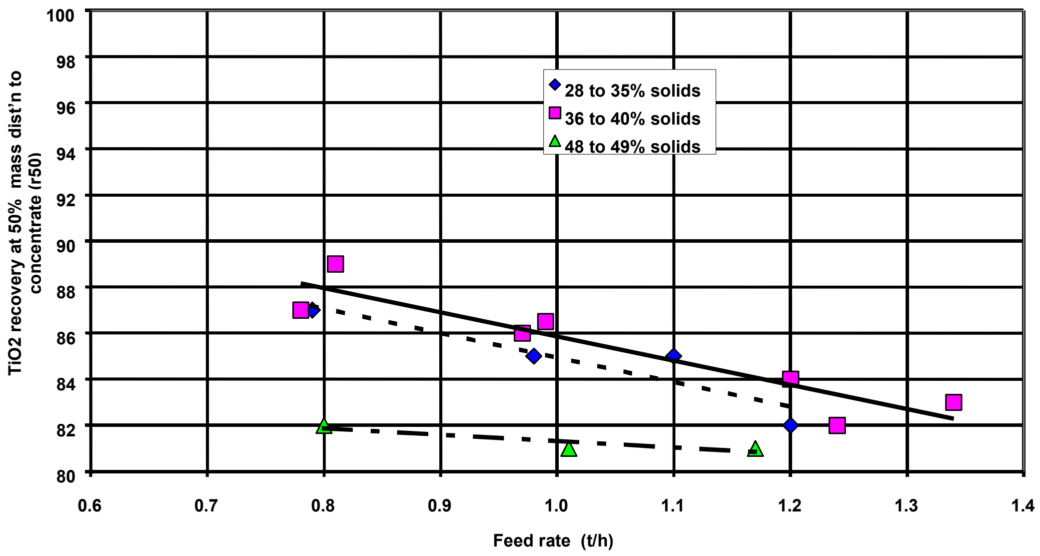


Fig.2 FM1 spiral performance on fine-grained Australian mineral sand – Effect of feed rate on TiO_2 recovery

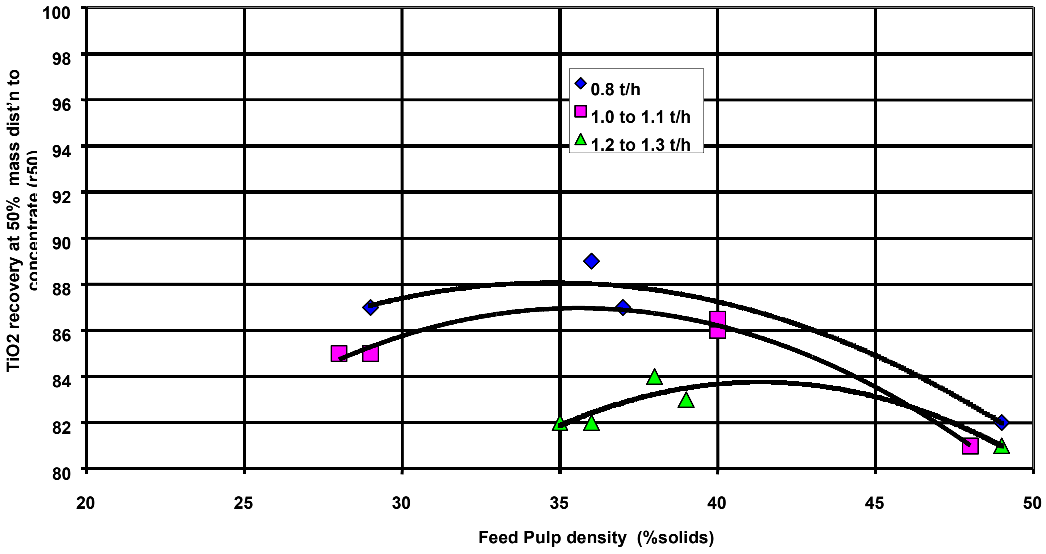


Fig.3 FM1 spiral performance on fine-grained Australian mineral sand – Effect of feed density on TiO_2 recovery

Multi-stage processing in a rougher/scavenger configuration resulted in improved overall performance, with TiO_2 recoveries of 90 and 93% being achieved at yields of 45 and 50% respectively.

Size-by-size recovery data (Fig.4) indicate that maximum TiO_2 recovery occurs in the 100 to 105 micrometer range.

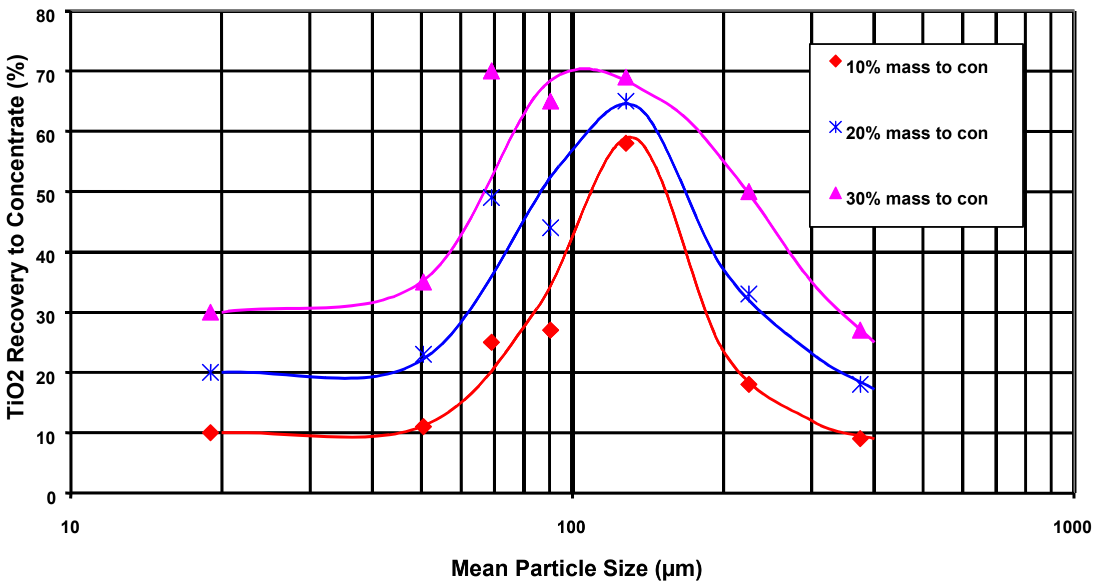


Fig.4 FM1 spiral performance on fine-grained Australian mineral sand - TiO$_2$ recovery by size

OTHER APPLICATIONS

Following the development testwork further testing was carried out on a variety of feed types using the FM1 model fine mineral spiral separator. Much of this work has included assessment of the performance of the FM1 spiral separator in parallel with a conventional mineral spiral separator (model MG4C), considered to previously represent the best performing unit on finer sized feed materials. The results of this work are reported below in the form of yield /recovery curves. Size-by-size recovery data have also been established for a number of applications.

Silica Sand

In work conducted on a fine Australian silica sand it was found that the FM1 spiral separator was able to perform three separation duties simultaneously. From feed material characterised Fig.5, a heavy mineral fraction was able to be rejected from the inner region of the trough, and an organic fraction was also able to be rejected from the outer edge of the trough by splitting off a stream into which most of the water reported. The reject stream, containing most of the water and organics, also contained ultra fine silica sand particles. The removal of these ultra fine silica sand particles effectively upgraded the sand product by classification. Data from a typical test are given in Table 1 and Fig.6.

Table 1 – FM1 spiral performance on Australian silica sand - Typical test results

		Organics		HM		-75µm	
Fraction	Mass %	Grade (%)	Dist'n (%)	Grade (%)	Dist'n (%)	Grade (%)	Dist'n (%)
Heavies	11.9	0.04	6.8	0.50	56.7	12.87	24.4
WaterTail	8.4	0.58	70.3	0.14	11.3	19.50	26.3
Sand Product	79.7	0.02	22.9	0.04	32.0	3.88	49.4
Feed	100.0	0.07	100.0	0.10	100.0	6.26	100.0

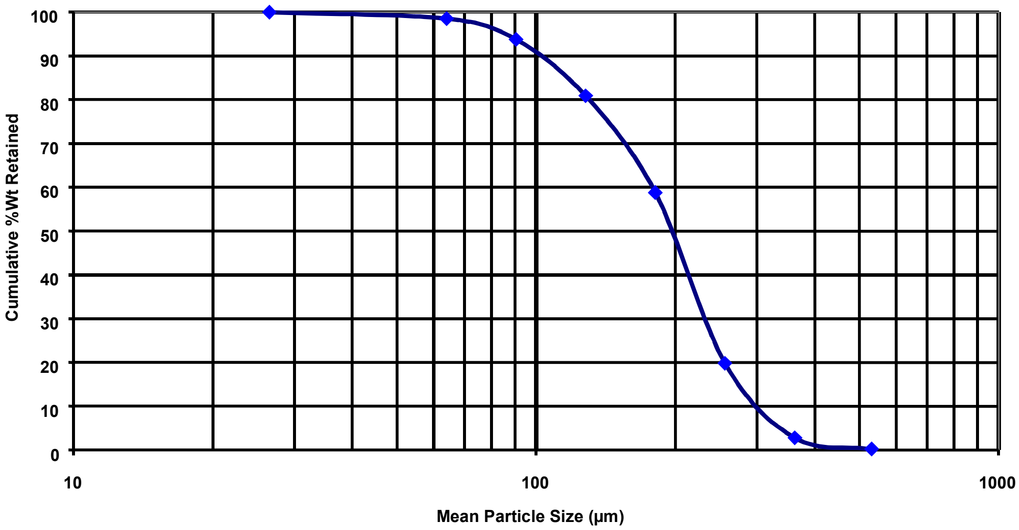


Fig.5 Fine Australian silica sand size analysis

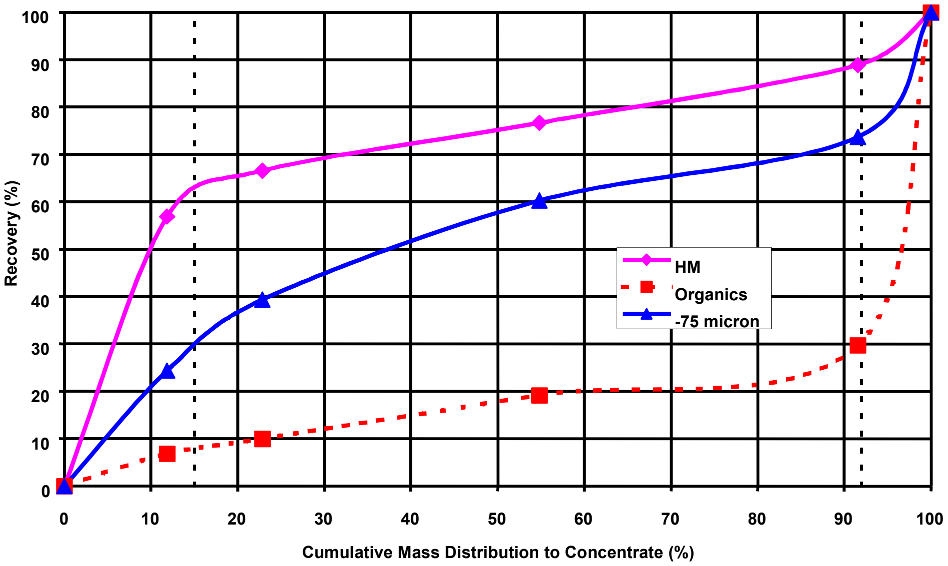


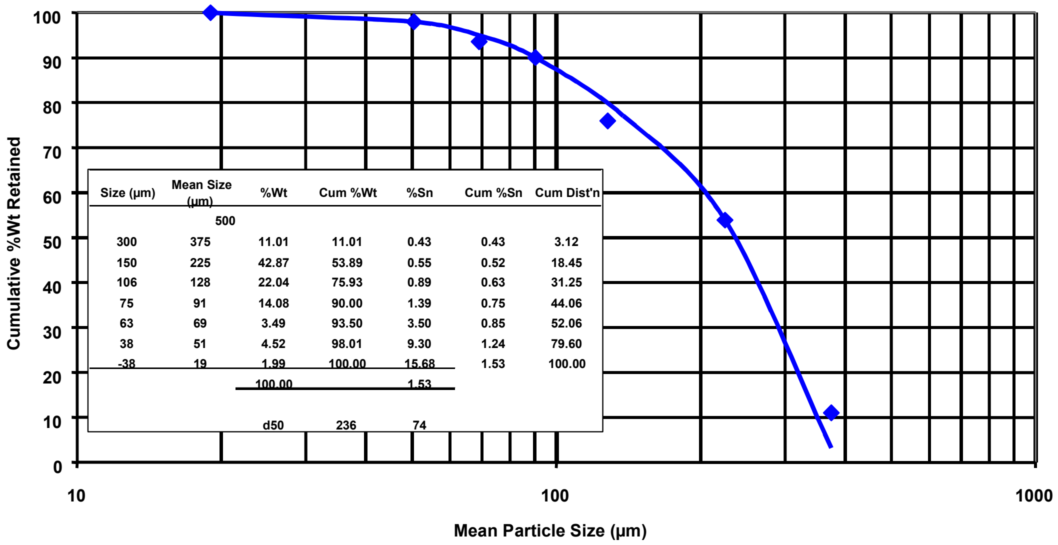
Fig.6 FM1 spiral performance on Australian silica sand – Recovery versus cumulative mass distribution to concentrate

At a yield of 80% to product, the heavy mineral (+2.85s.g.) content was reduced from 0.10% to 0.04%; corresponding to a 68% rejection of the heavy mineral. The organic content was reduced from 0.07% to 0.02%; corresponding to a rejection of 77% of the organics. No comparative data are available for a conventional spiral separator, as when the material was run on a conventional spiral separator it was observed that the flow was too turbulent to effect organic separation.

Tin tailings

A series of tests was conducted on reground and classified tin tailings. This material is characterised by size/assay data (Fig.7) in which the spiral feed has a d_{50} of 236 micrometres, and the contained cassiterite has a d_{50} of 74 micrometres. The testing involved the evaluation of the comparative performance of the

MG4B model spiral separator with that of the FM1 spiral separator. The objective was to achieve tin recovery of 40% with an upgrading factor of approximately four.



Size (μm)	Mean Size (μm)	%Wt	Cum %Wt	%Sn	Cum %Sn	Cum Dist'n
	500					
300	375	11.01	11.01	0.43	0.43	3.12
150	225	42.87	53.89	0.55	0.52	18.45
106	128	22.04	75.93	0.89	0.63	31.25
75	91	14.08	90.00	1.39	0.75	44.06
63	69	3.49	93.50	3.50	0.85	52.06
38	51	4.52	98.01	9.30	1.24	79.60
-38	19	1.99	100.00	15.68	1.53	100.00
		100.00		1.53		
		d50	236	74		

Fig.7 Tin ore tailings particle size distribution

The results, shown in Fig.8 indicate a clear relationship between performance and feed rate for each spiral separator. At low feed rates both spiral separators demonstrate comparable performance. However, the FM1 demonstrates a quantifiable advantage as the loading approaches 1.5 tonnes per hour. Extrapolation of the trend line indicates an expected Sn recovery of 72% for the FM1 at a feed rate of 1.5 tonnes per hour per start.

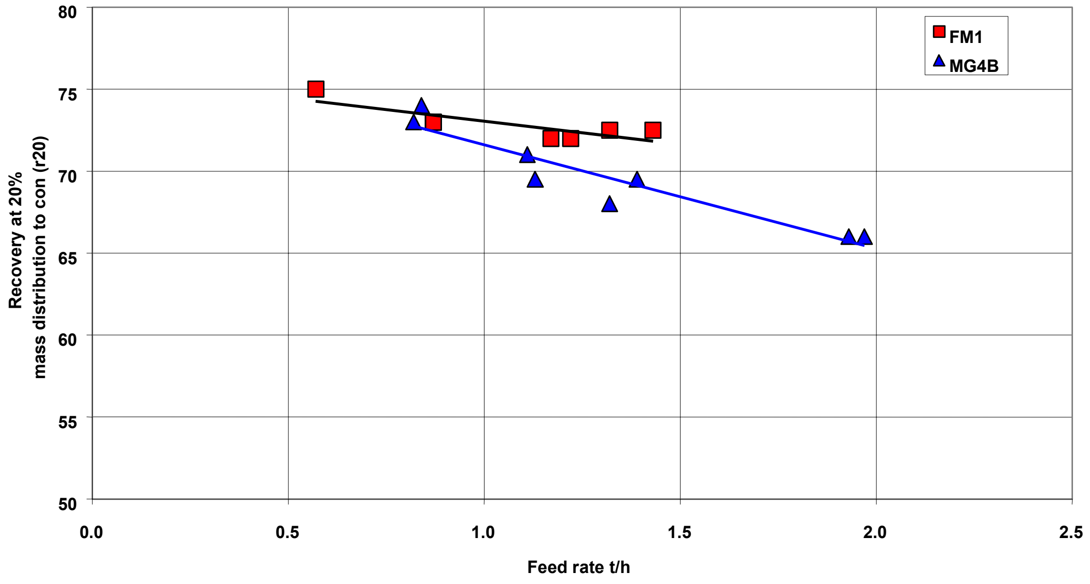
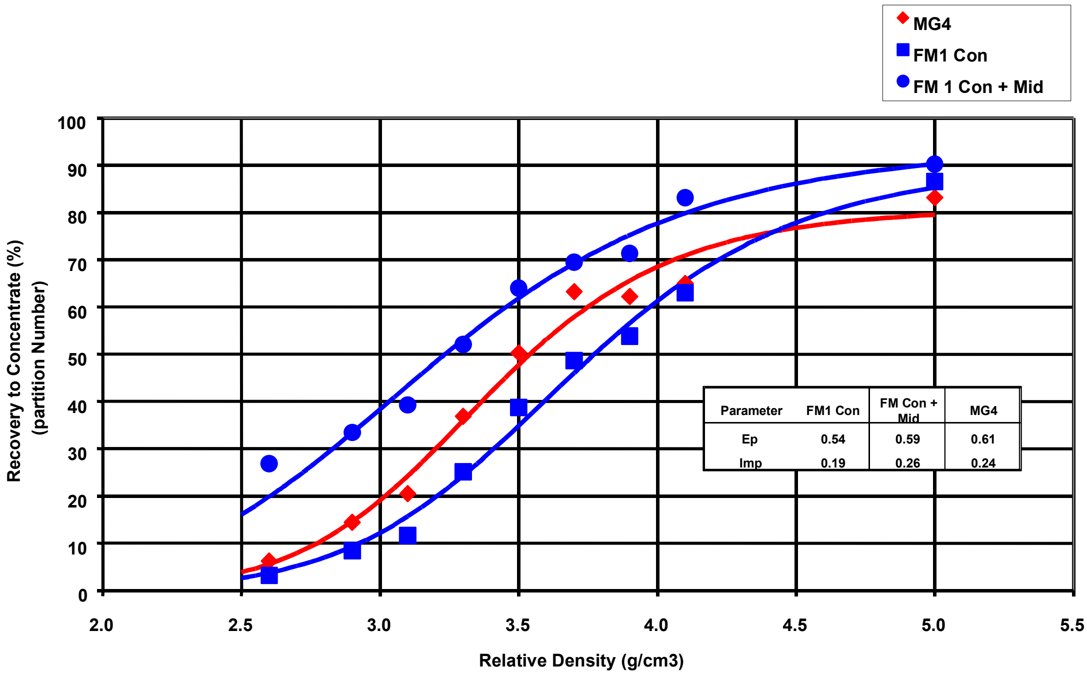


Fig.8 Comparative performance (FM1 and MG4B spiral separators) on classified tin tailings – Effect of feed rate on Sn recovery

Over the range of feed rates between 0.5 and 1.5 tonnes per hour, the FM1 spiral separator achieved Sn recoveries between 70 and 75 per cent at a yield of 20%. Upgrade ratios were typically greater that 5.

Samples from selected test series were subjected to sizing and densimetric fractionation in order to derive a partition profile. The results of this assessment are presented in Fig.9.



Parameter	FM1 Con	FM Con + Mid	MG4
Ep	0.54	0.59	0.61
Imp	0.19	0.26	0.24

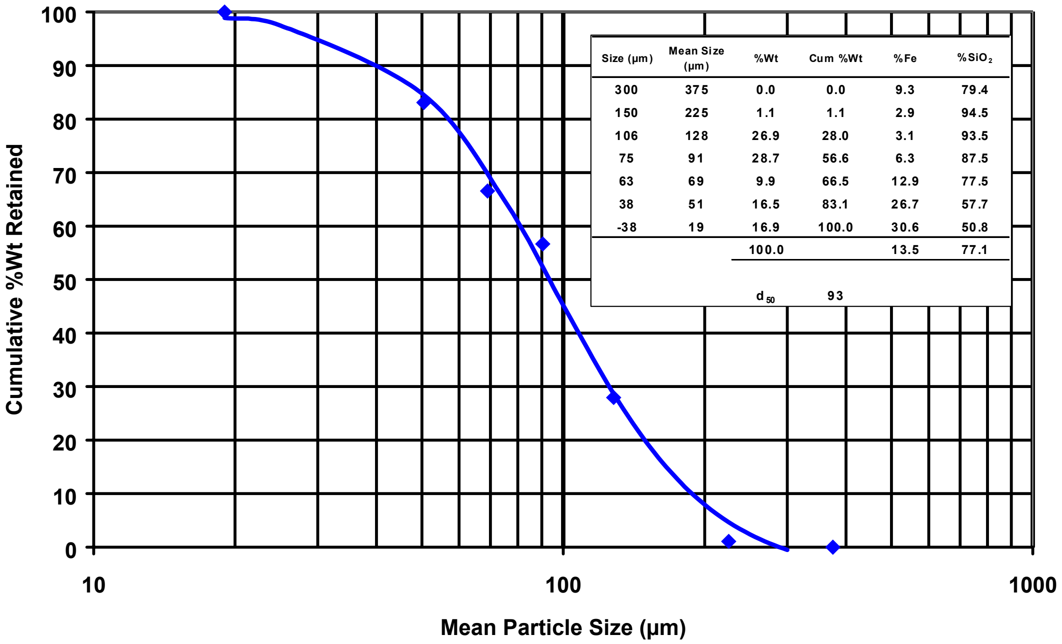
Fig.9 Comparative performance (FM1 and MG4B spiral separators) on classified tin tailings – Partition diagram

Iron Ore

The performance of the FM1 spiral separator on iron ore has been established using two feed types:

Feed Type 1

Feed type 1 is a classified fine fraction derived from a Canadian operation. The feed characteristics are shown in Fig.10.



Size (µm)	Mean Size (µm)	%Wt	Cum %Wt	%Fe	%SiO_2
300	375	0.0	0.0	9.3	79.4
150	225	1.1	1.1	2.9	94.5
106	128	26.9	28.0	3.1	93.5
75	91	28.7	56.6	6.3	87.5
63	69	9.9	66.5	12.9	77.5
38	51	16.5	83.1	26.7	57.7
-38	19	16.9	100.0	30.6	50.8
		100.0		13.5	77.1
		d_{50}	93		

Fig.10 - Type 1 iron ore feed sizing

The performances of the FM1 model spiral are given in Fig.11. The results indicate that, at the feed rates tested (1 to 1.5 t/h/start), the FM1 achieved concentrate grades of 62.1% Fe and 34.5% Fe at mass distributions to concentrate of 9.5% and 24.4% respectively. These data points correspond to Fe unit recoveries of 43.0% and 61.4% respectively. Comparative results on the MG4C spiral separator indicate lower Fe recoveries at equivalent mass distributions to concentrate. Furthermore, the concentrate grades achieved on the FM1 spiral separator are higher than those achieved on the MG4C spiral separator at equivalent concentrate mass distributions. The results indicating an incremental concentrate grade improvement at 12%Fe for the FM1 spiral separator over the MG4C spiral separator at a mass distribution to concentrate of 9.5%.

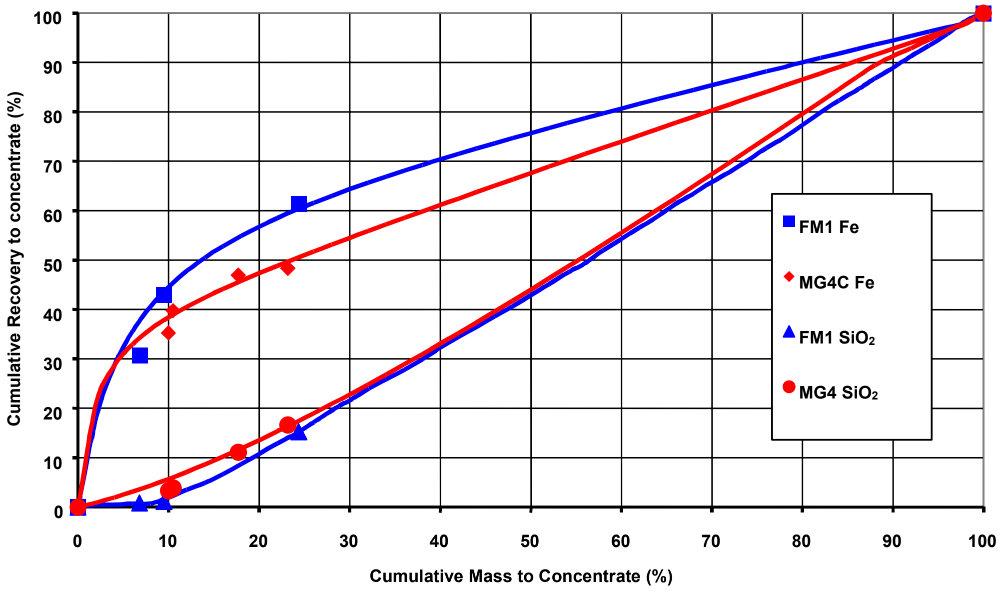


Fig.11 Spiral performance comparison (FM1 and MG4C) on fine iron ore (type 1) – Recovery versus cumulative mass distribution to concentrate

The size-by-size data (Fig.12) indicate that the Fe recoveries achieved by the FM1 spiral separator over the size range of 20 to 180 micrometres are consistently greater than those for the MG4C spiral separator. These data confirm the effectiveness of the new model FM1 spiral separator operating within a size range lower than that considered appropriate for more conventional spiral models.

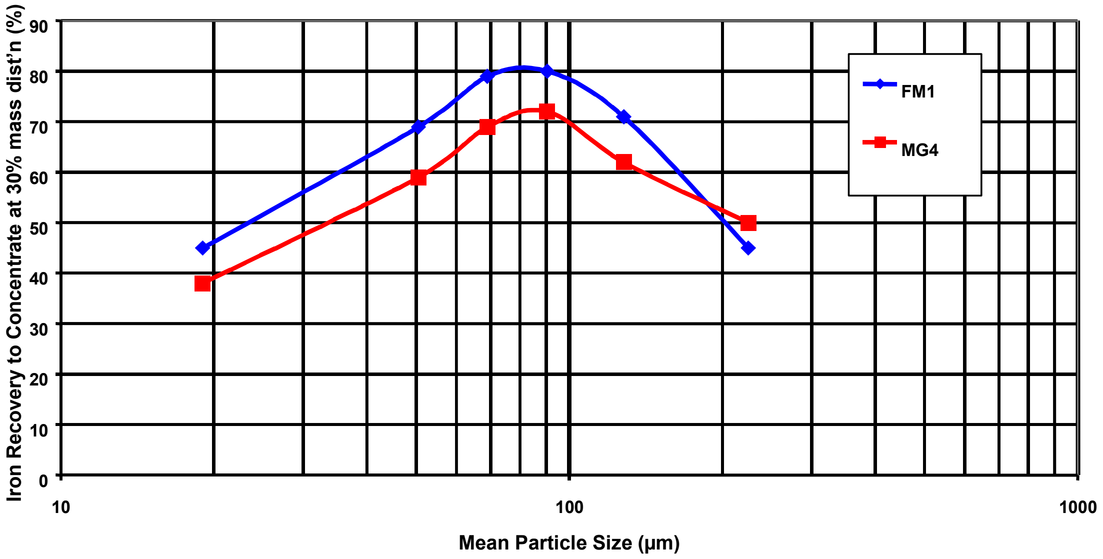


Fig.12 Size by size spiral performance comparison (FM1 and MG4 spiral separators) on fine iron ore (type 1)

Feed Type 2

A second sample of classified material from a different Canadian operation was subjected to testwork utilising the FM1 and conventional MG4 spiral separators. Feed characterisation data of this material is shown in Fig.13.

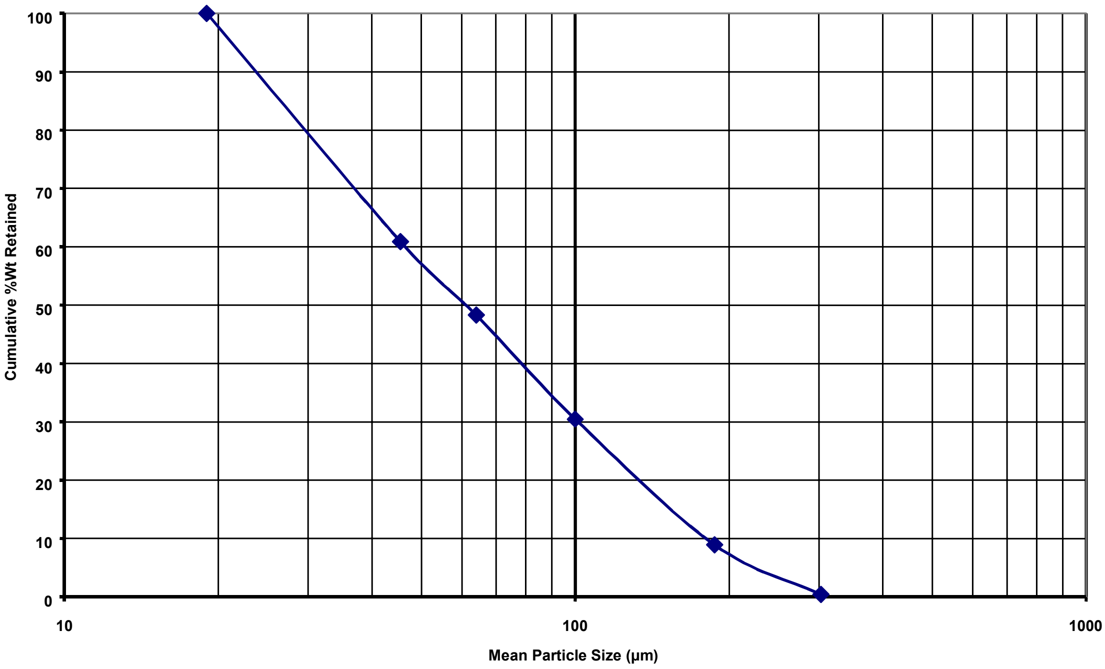


Fig.13 - Type 2 iron ore feed sizing

From the performance plotted in Fig.14, it is apparent from examination of the recovery curves that the FM1 spiral separator gave superior performance to that of the MG4 spiral separator.

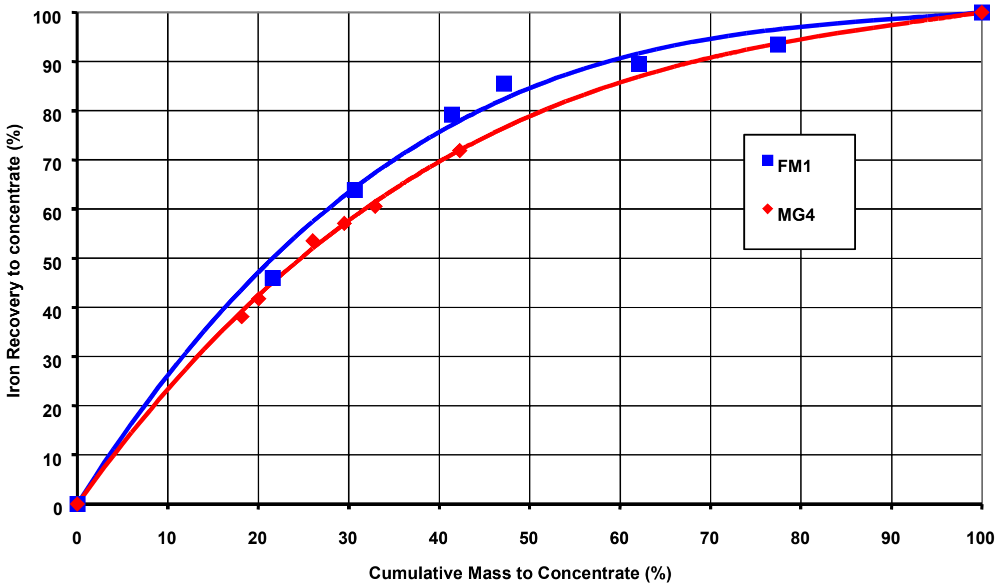


Fig.14 - Spiral performance comparison for type 2 iron ore fines

Copper

Flotation tailings material derived from a existing operation in Queensland, Australia was tested using an FM1 spiral separator in parallel with a MG4C model spiral separator. The feed characteristics are plotted in Fig.15.

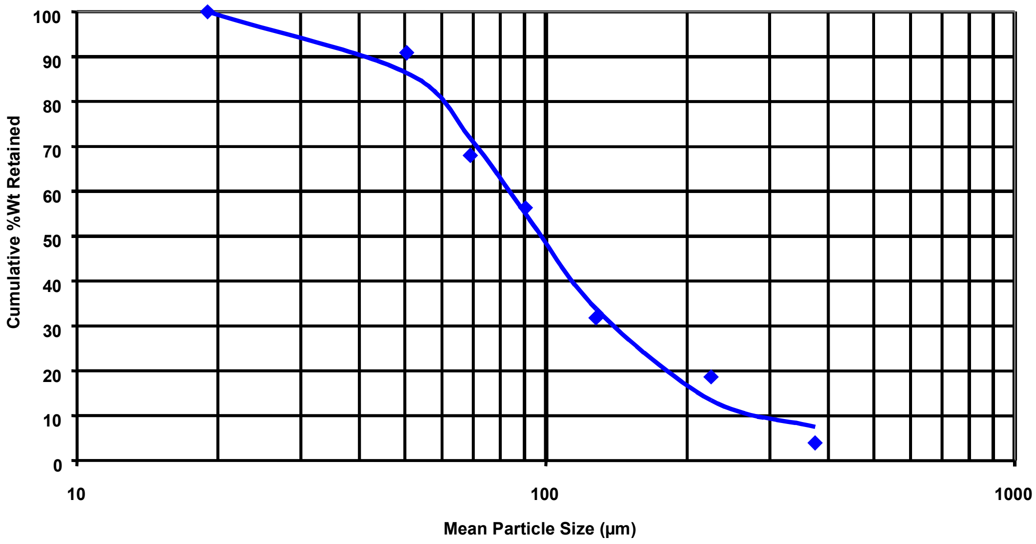


Fig.15 - Copper tailings feed sizing

The performances of the FM1 model spiral are given in Fig.16. The results indicate that although the performance curve is considered relatively flat, significant copper units can be recovered to the concentrate by utilising the FM1 spiral separator in this application.

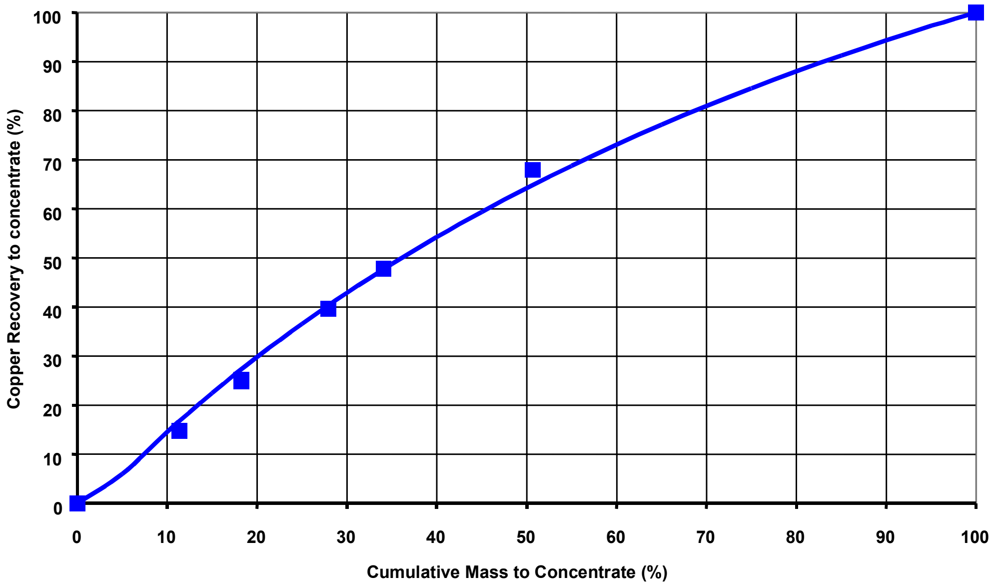


Fig.16 - FM1 spiral separator performance on copper

PROCESS IMPLICATIONS

The classical approach to fine gravity separation of ores involved classification of the feed into a number of relatively narrow size ranges followed by separate parallel treatment of the classified streams. This approach proved to be very successful particularly in the tin industry, and although since these times there has been movement towards reducing the number of classified parallel streams, the concept remains valid. The availability of spiral separator models that can effectively process material down to below 30 micrometres in size provides a means to design flowsheets that conform to the traditional concepts of gravity separation of parallel classified streams.

The utilisation of FM spiral separators to treat material in the size range below 0.1 millimetres and conventional spiral separators to process material above say 0.1 millimetres, provides a low cost option for a number of likely processing systems; including those applications in tin, chromite, and iron ore.

In some applications, such as fine iron ore upgrading or tailings re-treatment, the required separation can be satisfied with a single stage circuit. Upgrading of mineral sands ores for example, where very low grades are typical and concentrate grades of over 90%HM are required, multi-stage FM spiral circuits or FM spiral separators used in conjunction with other separation processes may be required.

Whether single or multi-stage spiral circuits are utilised, the availability of the FM model spiral will enable the benefits of spiral separators to be extended to encompass a wider size range of the total ore treated. Subsequent cost reductions will result from:

- Simplified operational requirements
- Lower capital costs
- Reduced operating costs
- Improved overall recoveries
- Greater versatility to handle variability of ore type and associated changes to size consist of ground (or naturally occurring) ores
- Reduced water demand
- Improved plant control.

Competing equipment is generally mechanically and operationally more complex, and invariably involves higher capital and operating costs compared to spiral separators. Any metallurgical performance gains must therefore be weighed against these cost and operational benefits.

SUMMARY & CONCLUSIONS

The availability of fine mineral (FM) spiral separators extends the cost effective size range for gravity separation using this technology down to well below that previously considered technically feasible using spiral separators.

Fine mineral spiral separators have proven to be effective in the beneficiation of a wide variety of ores, including iron ore, mineral sands, tin and tantalum ores and base metal ores.

The development of this equipment now provides alternative, relatively low cost processing options associated with the parallel processing of classified streams. Such flowsheet options will compete very effectively with other mechanically and operationally complex mineral processing unit processes, including flotation, magnetic separation as well as other gravity separation systems, such as jigs and centrifugal separators.

Overall metallurgical performance is expected to improve significantly over single stream spiral circuitry.

Future developments are expected to result in increased unit capacities and improved metallurgical performance for the FM range of spiral separators.

REFERENCES

Holland-Batt, A.B., Spiral Separation: Theory and Simulation, *Trans. Instn. Min. Metall. (Sect. C: Mineral Process. Extr. Metall.),* **98**, 1989, C46-60

Holland-Batt, A.B., Some design considerations for spiral separators, *Minerals Engineering,* Lake Tahoe, 1995.

Holland-Batt, A.B., The dynamics of sluice and spiral separators, *Minerals Engineering,* **8,1/2**, 1995, 3-222.

Holland-Batt, A.B. and Holtham, P.N., Particle and fluid motion on spiral separators, *Minerals Engineering,* **4(3/4)**, 457-482, 1991.