

# Article Recovery of Rare Earth Oxides from Flotation Concentrates of Bastnaesite Ore by Ultra-Fine Centrifugal Concentration

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Abstract: Historically, the ability to effectively separate carbonate gangue from bastnaesite via flotation has frequently proven to be challenging without sacrificing significant rare earth oxide (REO) grade or recovery. However, in light of the fact that the rare earth bearing minerals often exhibit higher specific gravities than the carbonate gangue, the possibility exists that the use of gravity separation could be used to achieve such a selective separation. This however is complicated by the fact that, in cases such as this study when the liberation size is finer than 50 microns, most traditional gravity separation methods become increasingly challenging. The aim of this study is to determine the applicability of centrifugal concentrators to beneficiate ultra-fine (UF) bastnaesite and calcite bearing flotation concentrates. By using a UF Falcon, it was possible to achieve initial gravity REO recoveries exceeding 90% while rejecting on the order of 25% to 35% of the total calcium from an assortment of rougher and cleaner flotation concentrates. Additionally, when additional stages of cleaner UF Falcon gravity separation were operated in an open circuit configuration, it was possible, from an original fine feed of 35 microns containing 50.5% REO and 5.5% Ca, to upgrade up to approximately 59% REO and 2.0% calcium. While not the goal of this study, these results also support previous limited data to suggest that UF Falcons are potentially capable of treating a wider range of materials than they were originally designed for, including feeds rich in heavy mineral content.

Keywords: rare earth elements; bastnaesite; gravity concentration; UF falcon concentrator

## 1. Introduction

## 1.1. Ultra-Fine Falcon Concentrators

Although gravity separation as a whole is one of the oldest mineral processing methods, its effective use has typically been constrained to coarser particle sizes. Although the traditional Falcon [1] and the Knelson separators [2] helped expand this into finer applications, there remains an appetite to go finer still. The development of the ultra-fine (UF) Falcon concentrator started in earnest in 2003 in order to better treat a tantalum flotation concentrate in light of a change to a finer mineralogy. To this end, the first industrial UF Falcon was commissioned on April 2005, making it a relatively young technology at the time of writing compared to Knelson and traditional Falcon centrifugal concentrators. In its debut, a single UF Falcon was able to outperform and replace the entire previous gravity circuit consisting of Mozely gravity separators and cyclones as is pictured on the following page in Figures 1 and 2 [3,4].

UF Falcons operate on a similar principal to other centrifugal concentrators, namely in the use of a spinning bowl to induce stratification of light and heavy minerals, however there are a number of differences in terms of the unit itself. Most significantly, as the name suggests, the UF Falcon is specifically intended to treat finer feeds of between 75 and 3 microns. Another consequence of the use of such comparatively fine feeds is that the UF



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Falcon, including at lab scale, utilizes no fluidization of water. Additionally, it is capable of higher G-Forces than traditional continuous Falcons, with a maximum value of up to 600 Gs. Lastly, the UF bowl is nearly vertical, with the gravity concentrate retention zone consisting of a single variable lip ring in the case of industrial scale units. A side by side comparison of bowl cross sections of the industrial continuous, and UF Falcons are shown below in Figure 3.



Figure 1. Original TANCO tantalum gravity circuit, recreated for legibility [3].



**Figure 2.** Replacement of TANCO gravity circuit with a single Falcon UF 600, recreated for legibility [4].

Due to the bowl configuration in the UF Falcon, it is only available as a semi-batch unit, however, this also enables it to achieve, a wide range of mass pulls reportedly up to 90%, although 40% is considered a more operationally typical upper bound [5].

The drawbacks, compared to other centrifugal concentrators, are that the UF Falcon exhibits a comparatively high unit power consumption per ton of solids. Additionally, at the time of writing, the largest commercially available model has a typical maximum throughput of only 2 tph solids with an installed motor of 60 HP. The ability to build a larger unit is reportedly limited by mechanical considerations necessary to induce 600 Gs,



thus for the foreseeable near future the use of UF Falcons is practically restricted to treating low throughput process streams.

Figure 3. Cross sections of bowl of continuous (left) and UF Falcon (right) [5].

#### 1.2. Whole Ore Gravity Testing via Methods Other Than UF Falcon

Although treatment of REE bearing minerals has historically occurred via a wide diversity of methods [6], this and an affiliated study appear to represent the first ever use of an UF Falcon in an REE application.

For contextual purposes, it should be noted that prior to gravity testing of flotation concentrates, a number of UF Falcon tests, as well as other gravity methods such as traditional Falcons and shaking tables, had been performed on whole ore materials which are described in the material and methods section. These tests consisted of multiple pass scoping tests, as well as a design of experiment matrix for evaluation of parameters impacting a single pass performance, and represent the first time any party has attempted to treat this material via a UF Falcon. Furthermore, the scoping test work revealed that the specific configuration of the upstream feed tank and agitator system could have profound impact on UF Falcon performance, such that a poor configuration could artificially reduce total REO recovery by as much as 20% while simultaneously negatively impacting grade. Thus, a proper configuration was arrived at and used for all follow-up testing, including the DOE matrix.

In doing so, it was revealed that the most significant parameters for the UF Falcon were pulp density and grind size, followed by RPM to a lesser degree. Additionally, the multiple pass scoping testing revealed that it was possible to achieve REO recoveries approaching, but not exceeding, 90% while rejecting on the order of 30% Ca. Although this was indicatively highly promising, further gravity separation testing of whole ore materials was abandoned however to prioritize analysis on flotation products due to the even more promising results of parallel flotation studies by Everly and Williams [7–9].

#### 2. Materials and Methods

# 2.1. Materials

Molycorp Minerals (Greenwood Village, CO, USA), provided samples of both crushed ore and Mountain Pass cleaner flotation concentrate (MPC) used for this and other parallel studies. The crushed ore sample consisted of approximately 1 ton of minus 9.53 mm material, as packaged collectively in four 55-gallon drums. The whole ore sample was subsequently blended and split using a modified cone and quarter methodology combined with a Jones splitter to yield individual samples of approximately 30 kg. This material also served as the source of samples for rougher flotation work later performed by Nathaniel Williams [9].

The MPC sample as received in a 5 gallon bucket was not fully dry, thus it was treated in a drying oven alongside splitting representative samples of approximately 1.5 kg each. Additionally, these individual split samples were subjected to dry cobbing utilizing the Falcon L40's protection screen to remove coarse foreign contamination of road materials, including pebbles of up to approximately 12.7 mm diameter, that had accumulated due to storage of the MPC product outside at the mine site. This removal of contamination was also necessary to assure safe testing conditions relative to laboratory equipment limitations.

#### 2.2. UF Falcon Scoping Testing

Four different scoping tests were performed on whole ore material, each of which utilized different parameters and/or upstream ancillary equipment. The purpose of this testing was ultimately three-fold; first, to compare against historic test work performed with a traditional laboratory Falcon (Sepro Mineral Systems Corp., Langley, BC, Canada). Second, the tests were performed for multiple passes so as to maximize REO recovery, and lastly, to determine a proper feed tank and agitator configurations.

#### 2.3. UF Falcon Concentrator DOE Testing

Stat Ease Design-Expert 10 software (Stat-Ease Inc., Minneapolis, MN, USA) was used to generate a two factor Design of Experiments (DOE) matrix for test work performed on the laboratory UF Falcon Concentrator (Sepro Mineral Systems Corp., Langley, BC, Canada). The factors chosen were RPM (controlled by specifying frequency on the Variac controller attached to the L40 Falcon unit), and feed pulp density. Both parameter ranges were selected to mirror the values used in a prior DOE matrix performed on whole ore material save for the exclusion of the variable of grind time

The range of pulp densities of 10% solids (by weight) up to 20% solids was based on reported acceptable operating boundary ranges for industrial UF Falcon units. It should be noted that the UF Falcons are reportedly capable of processing as low as 5% solids. However, given that the envisioned flowsheet would entail UF Falcons operating in series with respect to the flow of gravity tailings, the use of 5% solids for the representation of a first stage feed was deemed inappropriately low in this context.

The range of RPM values was dictated by a number of considerations. For the lower bound (930 RPM), this is synonymous with a G-Force of 50 Gs, which is the lowest value an industrial unit would be designed. The selection of 1320 RPM (100 Gs) as an upper bound for the DOE matrix was due to anticipated mass pull considerations rather than industrial G-Force values. In general, it is recommended that industrial UF Falcons can yield up to 40–50% mass pull, although reportedly significantly higher values are possible. Prior scoping work performed on ground whole ore materials suggested the mass pull could approach values on the order of 30% to 40% even at comparatively low G Forces of approximately 69 Gs. As mass pull was expected to be proportionate to the square of the RPM value (based on an equation proposed by Kroll et al.) [10], it was deemed reasonable at the time to use a comparatively modest G-Force of only 100 Gs so as to restrict anticipated mass pulls to recommended ranges.

Additionally, the feed volumetric flowrate, via the use of the tailings flowrate as a proxy indicator, was held to near constant values between 4 and 5 L/min via dynamic tuning of the discharge value on the feed tank. This was deemed to be a more favorable method for controlling flowrate than using a constant value position given the use of variable pulp densities. The tailings flowrate was monitored via the use of a stop watch, in which a second party would indicate the passing of 15 or 30 s intervals, coupled with the use of a 5 gallon bucket with 1 L intervals from 2 L to capacity. Due to the relatively crude

precision of the bucket's interval markings, the same tailings bucket was used for every test to assure consistency.

For the DOE matrix testing, each test consisted of only a single pass, after which the resulting UF Falcon bowl gravity concentrate was reclaimed into a container and subjected directly to drying in a drying oven for 24 to 36 h so as to avoid potential loss of fines to filtration. The resulting gravity tailings were subjected to pressure filtration, followed by drying in a drying oven. Both resulting dry products were subsequently subjected to massing and assaying via X-Ray Fluorescence (XRF).

### 2.4. UF Falcon REO Recovery and Grade Maximization Testing

A flowsheet is shown later in Figure 11 regarding the overall distribution of gravity streams used for both REO recovery and grade maximization testing programs.

With some known exceptions, the pulp density and RPM values used in both the recovery and grade maximization testing were based on the "optimal" values derived from the DOE matrix testing. In testing where multiple stages of UF Falcons in series were evaluated, with the exception of only one test (REO recovery maximization, Pass 4), the prior stages gravity tailings were filtered, dried, assayed, and re-pulped to the original feed pulp density used in the upstream units. Additionally, RPM was deliberately increased in the case of 1st Cl Test 2 to yield a G-Force of 200 Gs, and in the case of 2nd Cl Test 1, the pulp density was unintentionally elevated to 17% solids.

#### 3. Results and Discussion

## 3.1. Characterization and Mineralogy

The particle size distributions of the as-received MPC material, as well as a sample of recent tailings from Mountain Pass (MP tails) and a single unrepresentative pulverized whole ore specimen, are shown below in Figure 4. The MPC material exhibits a P80 of approximately 35 microns, while the MP tails are coarser at approximately 55 microns. These would be considered borderline to excessively fine particle sizes for treatment by more traditional methods of gravity separation, however it is necessary to grind to such a size in order to achieve liberation of bastnaesite.

Table 100. 200, 400, and 500 mesh, from which transverse particle mounts were prepared. The MLA data was obtained by the XBSE method. The MLA determined the modal mineral content of the MPC material sample by size fraction as shown below in Table 1, as well as the overall composition of respective whole ore and final tailings samples in Table 2, while an example of a false color image of an unspecified size fraction are shown further below in Figure 5. It should be noted that the sampling representivity of the specific whole ore specimen submitted for mineralogical analysis was later determined to be poor compared to that of other materials evaluated during this study, including compared to the other whole ore samples used for the actual gravity separation testing, which made use of an alternative splitting procedure in response to this original sampling error. However, it is deemed sufficiently indicative of the whole ore material to warrant inclusion in Table 2.

Mineral	Formula	100	100  imes 200	200  imes 400	400 imes 500	-500	Modal
Bastnaesite	(Ce <sub>0.5</sub> La <sub>0.4</sub> Nd <sub>0.1</sub> )(CO <sub>3</sub> )F	51.4	36.5	53	60.6	57.9	56.9
Parisite	$Ca(Ce_{0.4}La_{0.3}Nd_{0.3})_2(CO_3)_3F_2$	11.8	13	17	15.4	15.5	15.7
Monazite	(La,Ce)PO <sub>4</sub>	2.84	1.43	3.31	4.5	6.65	5.54
Synchysite	Ca(Ce <sub>0.5</sub> La <sub>0.4</sub> Nd <sub>0.1</sub> )(CO <sub>3</sub> ) <sub>2</sub> F	2.68	3.77	4.48	4.03	3.26	3.62
Total REE Minerals	-	68.72	54.7	77.79	84.53	83.31	81.76
Calcite	CaCO <sub>3</sub>	9.19	19.9	7.67	4.57	7.3	7.23
Dolomite	CaMg(CO <sub>3</sub> ) <sub>2</sub>	4.29	7.89	2.62	1.05	0.54	1.2
Barite	BaSO <sub>4</sub>	6.65	3.55	2.66	1.88	1.60	1.92
Quartz	SiO <sub>2</sub>	4.33	6.1	2.44	1.21	0.67	1.23
Celestine	SrSO <sub>4</sub>	0.91	0.77	0.61	0.52	0.57	0.58
Strontianite	SrCO <sub>3</sub>	1.08	1.42	2.96	3.95	4.06	3.76
Other	-	4.83	5.67	3.25	2.29	1.95	2.32

**Table 1.** Mineral content by size fraction (mesh) for the MPC material MLA specimen.

 Table 2. Modal mineral content for the Mountain Pass whole ore and final tailings samples and selected subsequent materials generated via UF Falcon gravity separation.

Mineral	Formula	MP Whole Ore	MP Final Tailings	Williams' Gravity Conc.	MPC UF 3rd Cl Conc	MPC UF P4 Tails
Bastnaesite	(Ce <sub>0.5</sub> La <sub>0.4</sub> Nd <sub>0.1</sub> )(CO <sub>3</sub> )F	12.9	5.1	56.9	75.7	29.7
Parisite	$Ca(Ce_{0.4}La_{0.3}Nd_{0.3})_2(CO_3)_3F_2$	1.81	0.72	15.7	8.43	15.3
Monazite	(La,Ce)PO <sub>4</sub>	0.84	0.74	5.54	7.53	3.73
Synchysite	$Ca(Ce_{0.5}La_{0.4}Nd_{0.1})(CO_3)_2F$	0.67	0.18	3.62	2.49	8.74
Total REE minerals	-	16.23	7.02	81.76	94.2	58.4
Calcite	CaCO <sub>3</sub>	21.3	28.6	7.23	1.3	24.2
Dolomite	CaMg(CO <sub>3</sub> ) <sub>2</sub>	16.2	13.0	1.2	0.23	3.83
Barite	BaSO <sub>4</sub>	20.9	25.0	1.92	1.02	2.54
Quartz	SiO <sub>2</sub>	5.97	8.39	1.23	0.19	2.82
Celestine	$SrSO_4$	8.59	3.29	0.58	0.22	0.32
Strontianite	SrCO <sub>3</sub>	1.57	1.74	3.76	2.11	3.55
Other	-	9.24	12.96	2.32	0.70	4.4



**Figure 4.** Particle size distributions of MPC (Mountain Pass cleaner flotation concentrate) and other Mountain Pass MLA (Mineral Liberation Analysis) materials.



Figure 5. False-color image from MLA of the MPC material. Values represent surface area percentages.

Given that there is a high degree of inter-locking between various REE mineral species such as bastnaesite and parisite (an REE and Ca bearing mineral), the liberation profile for individual REE mineral species, as shown below in Figure 6, is significantly less than the total REE mineral group liberation in the MPC material as shown further below in Figure 7. When REE minerals are considered as a group, rather than on an individual species basis, this suggests that approximately 85% of the REE minerals as a group are fully liberated in the MPC material MLA sample. This high degree of liberation suggested that no further grinding would initially be needed when treating MPC material via gravity separation within the scope of this study. As gravity performance is often hindered by finer particle sizes, the inclusion of grinding was further deemed not only unnecessary but potentially even detrimental. However, future studies may potentially observe benefits from the inclusion of a regrind circuit at some portion of a multi-stage gravity flowsheet to increase the overall liberation without subjecting the entire mass of material to further size reduction.



Figure 6. Mineral liberation by individual REE mineral species in MPC material MLA sample.

## 3.2. UF Falcon DOE Matrix Results

Four responses of the UF Falcon tests performed on MPC material were evaluated: REO grade, REO recovery, Ca grade, and Ca recovery. Of these responses, only those related to Ca were considered statistically significant based on an analysis of variance (ANOVA) in Stat Ease 10. As the goal was to optimize the parameters by prioritizing rejection of Ca, it was still considered applicable to construct a desirability surface. From this analysis, it was indicated that the proposed optimal parameters were 1320 RPM and 15.1% solids. The results of this DOE testing are shown below in Table 3, including test DOE 7, which was intended to validate the proposed optimal parameters.



Figure 7. Mineral liberation by grouped REE minerals in MPC material MLA sample.

Test	Con	ditions	Grav Co	onc Mass	Gra	de, %	Recovery, %	
(MPC)	RPM	Pulp, wt%	Grams	<b>Rec,</b> %	Ca	REO	Ca	REO
DOE 1	930	20	680.4	41.13	3.63	55.26	28.9	44.51
DOE 2	930	10	603.4	37.39	4.37	53.85	28.93	39.83
DOE 3	1320	20	633.4	38.61	3.83	53.79	24.65	41.61
DOE 4	1320	10	546.1	36.61	3.66	55.49	24.85	39.82
DOE 5	1141	15	612.7	39.28	3.74	54.78	26.74	42.12
DOE 6	1141	15	630.7	40.72	3.62	55.37	27.43	44.09
DOE 7	1320	15.1	608.6	42.00	3.79	54.98	28.63	45.46

Table 3. UF Falcon DOE Matrix conditions and results.

Similar to prior experiences with the use of a UF Falcon to treat whole ore material, it was apparent that pulp density was a strong factor. Moreover, in line with the testing on whole ore material, the use of specifically 10% solids (and likely any lower values) was detrimental to performance by virtually any metric.

#### 3.3. UF Falcon REO Recovery Maximization Results

Due to the relatively low recovery obtained during the DOE matrix testing, the Pass 1 gravity tailings from tests 5, 6, and 7 were each individually reprocessed at optimal, or near optimal in one instance, conditions to continue to yield more recovery via the inclusion of subsequent passes in a manner typical of most UF Falcon testing programs. This was aided by the fact that, in light of the strong impact of pulp density compared to RPM, DOE tests 5 and 6 first passes had been coincidentally performed at nearly optimal conditions. The flowsheet used for this recovery maximization testing is shown in the upper half of Figure 10 shown later in this report.

Given that feed solid masses of approximately 500 g or smaller becomes increasingly difficult to treat representatively in the lab, it was necessary to combine the Pass 2 tailings

from tests 5, 6, and 7 into a single combined feed of approximately 1 kg for pass 3. A fourth and final indicative pass was performed at an unmeasured atypically low pulp density, estimated to be on the order of 9% solids or less, given that the pass 3 tailings had not been filtered and were already borderline at the 500 g threshold. (It is possible incidentally to quickly estimate the tailings solids mass within +/-50 g without filtering or drying via knowing the feed mass, the empty mass of the UF bowl, and immediately weighing the bowl and wet concentrate given that it is usually a repeatedly consistent value of somewhere between 70% to 83% solids, the specific value depending on the gravity concentrate's composition). The resulting 261 g of pass 4 gravity tailings represented decidedly too little mass to justify even indicative scoping testing compared to the value of getting a more direct assay. Previous test work on whole ore material, as well as subsequent test work by Williams, suggest that this pass 4 gravity tailings was potentially amenable to further treatment had a sufficient mass been available to test this.

The results of this testing are shown below in Figures 8–10. As can be seen, REO recovery can exceed 90% while still achieving moderate amounts of Ca (and by proxy calcite) rejection, and approach 96% REO at a more modest rejection. This greatly exceeds REO recovery records previously observed on relatively coarser whole ore materials via any gravity method other than via the use of a UF Falcon, particularly that of the traditional Falcon even after multiple passes had been performed [11]. Although semi-quantitative in nature, mineralogy results suggest on the order of 20% of the calcium in the MPC material is associated with REE/Ca bearing minerals such as parisite and synchysite, which if factored out from the overall Ca grade/recovery results, would only amplify the apparent extent of calcite and dolomite rejection to levels more analogous to the Ca results observed when treating whole ore material via a UF Falcon.



Figure 8. Cumulative REO grade/recovery for MPC UF Falcon recovery maximization testing.



**Figure 9.** Cumulative gravity concentrate Ca grade vs REO recovery for MPC UF Falcon recovery maximization testing.



Figure 10. Cumulative Ca recovery vs REO recovery for MPC UF Falcon recovery maximization testing.

Additionally, the Pass 4 tailings, while distinctly enriched in Ca, were still relatively rich in REO with a grade of 31% REO. It must be emphasized that the inability to continue to recover these REO values was not due to an inherent metallurgical performance, but rather due to material availability in context of equipment and experiment limitations.

## 3.4. UF Falcon REO Grade Maximization Results

In an effort to demonstrate the upper limits of possible gravity concentrate grades, additional stages of cleaner gravity UF Falcon separation were performed on the combined pass 1 through 3 concentrates of DOE tests 5, 6, and 7, collectively representing on the order of 91.9% REO recovery. The flowsheet used in this testing program, along with highlights of results, is shown below in Figure 11.



**Figure 11.** Overall flowsheet for MPC UF Falcon REO recovery and grade maximization testing programs. The overlaid values represent the estimated selected cumulative performance.

Given that this testing was performed in open circuit with the goal of maximizing REO grade, rather than in recirculating locked cycle conditions, the cumulative recovery values drop considerably with each subsequent stage of cleaner gravity treatment. In industrial conditions, it would be more typical to operating in a locked cycle configuration to improve recovery via retreatment of intermediate stages gravity tailings. Given that the mineralogy suggests up to 85% of the REE minerals were liberated in the original MPC feed, the possibility exists that these intermediate cleaner stages' gravity concentrate grades could potentially be maintained even at higher overall recovery values.

Although locked cycle testing would be needed to confirm the extent of any such recovery improvements, it was deemed to be impractical as such a test would require as much as double the entire supply of MPC material that was available for use in the study to assure a minimum of six cycles could be performed. Although few examples exist, the work of Grewal and Neale included such a laboratory locked cycle UF Falcon flowsheet to treat a fine Sn flotation concentrate material with a feed grade of 7.7% Sn, as well as a coarser Sn tailings with a feed grade of 0.15% Sn. In both cases, the locked cycle results exhibited profoundly higher recoveries at similar final concentrate grades (approximately 50% Sn) as had been achieved in open circuit conditions [12]. Thus, the low penultimate REO recovery to the 3<sup>rd</sup> Cleaner Concentrate is not in itself a cause for concern given the use of open circuit testing conditions. Personal correspondence indicated that such a locked cycle test would have also been prohibitively time intensive relative to the project schedule even if sufficient material had been available [13].

In a related parallel study by Nathaniel Williams, utilizing the optimal parameters derived in this study's DOE matrix testing, Williams performed a 3 pass gravity separation test with a UF Falcon on approximately 1.4 kg of an enhanced rougher flotation concentrate sample derived from a 10 kg float test on whole ore material. The moniker of "enhanced" refers to the use of an alternative flotation collector than the traditional fatty acid. The details regarding the composition and rougher flotation recoveries of this enhanced collector are known, however they are intentionally withheld from this paper.

## 3.5. Williams' UF Falcon Results

An author of this study was present alongside Williams during the aforementioned gravity test work [9], which made use of the same L40 laboratory Falcon concentrator, UF

bowl, feed tank, agitator, and the dedicated 5 gallon tailings bucket (as well as comparable flowrates) as was used in this study following generally the same procedures. It is noteworthy however that this material exhibited a greater propensity for sanding than the MPC material, and was generally speaking more troublesome with respect to slurry handling. Identifying what, if any, and how much of an impact this ultimately had on the results is challenging at best given the existing data sets.

The flowsheet and results of this test work on both a per pass and cumulative gravity basis are summarized below in Figure 12.



**Figure 12.** Flowsheet of Williams' UF Falcon test work on enhanced rougher flotation concentrate. Ca, Ba, and Si grades have been converted from the original reported values of CaO, BaO, and SiO<sub>2</sub> from the source documentation [9].

The use of only 3 passes was due to the constraints of the original available rougher flotation concentrate sample mass, as an insufficient gravity tailings mass existed to properly perform a 4th pass. Due to the experimental configuration and the relatively high heavy minerals content, a feed solids mass of approximately 500 g per pass is considered the minimum cutoff point to allow for further gravity treatment, although greater masses are preferable if otherwise practical. Williams' results echo those of the REO recovery maximization testing, demonstrating that recoveries of greater than 90% REO can be achieved via the use of UF Falcon while still achieving some degree of calcite rejection. There are a few key differences that hinder direct comparisons beyond the respective upstream flotation recovery values. One of these differences is the presence of a higher amount of barite in Williams' rougher flotation concentrate as opposed to the near absence of barite in the MPC material. As barite is a heavy mineral exhibiting often similar gravity recoveries to REO's, it can dilute the resulting gravity concentrate's REO grade. Even when bearing in mind this and other differences in respective feed grades, on a per pass basis Williams' material indicatively exhibited a greater degree of selectivity against calcite than the MPC material.

Williams' study did not include any further stages of cleaner gravity separation, thus a comparison to the MPC REO grade maximization testing is not possible in the absence of

such data. This lack of testing was not due to a lack of diligence on the part of Williams, but rather due to the limited mass of resulting gravity concentrate sample relative to the requirements of such cleaner gravity test work [9].

#### 4. Conclusions

The use of an UF Falcon to beneficiate rougher or cleaner flotation bastnaesite concentrates represents a technically viable option for achieving partial to significant rejection of carbonate and other low SG gangue, such that it can be used in a complementary manner with an existing or modified flotation circuit.

From an economics perspective, however, the relative merits of using a UF Falcon circuit for REO beneficiation as opposed to utilizing any and/or additional cleaner flotation stages are strongly site specific, even if metallurgical performance of the respective treatment methods were otherwise comparable between project sites. Thus, it is best expressed in terms of controlling factors rather than absolute numbers. To be clear, there are certainly conditions in which the use of cleaner flotation would conceivably prove economically, and possibly also metallurgically, preferable to treatment via a UF Falcon circuit. In general, UF Falcons will be significantly more competitive as a brownfields expansion/replacement of an existing underperforming float circuit when nothing else has worked than as a green fields installation provided the competing flotation alternative is capable of exhibiting the desired level of performance. For project sites with lower unit electricity costs, that suffer from higher HCl unit costs (or similarly if they had problematic HCl availability constraints), have lower intended feed solids throughputs, lower tolerance to bleeding of process water, and /or which have a greater tolerance for larger initial capital costs, UF Falcons may prove an attractive option long term compared to the use of flotation. Further complicating efforts to meaningfully perform this analysis is the relative infancy and at present low market penetration of the UF Falcon, such that future development of the technology itself could reduce the impact of these UF Falcon specific considerations [14].

As of the time of the original study, the largest commercially available UF Falcon was the UF1500, which has a proposed suggested upper bound feed rate of 2 mtph of solids and can operate between 50 and 600 Gs, with a corresponding installed motor power of 45 kW [5]. Thus, they are relatively electricity intensive per unit of feed solids processed, such that competing flowsheets could reasonably include regrind stages and/or finer original grinding while still exhibiting lower overall electrical consumptions. Based on informal inquiry, a key limitation for creating any larger UF Falcons is the mechanical considerations associated with operating at such a high upper G force limit. However, if significantly lower G-forces could be tolerated while achieving satisfactory outcomes, let alone if they proved preferable as was this case in this test work, at a minimum this would considerably reduce the specific electricity consumption. At best, this trade-off for lower maximum G forces could enable construction of larger UF Falcon units than are currently available, which in turn could expand the applicable boundary conditions pertaining to throughput constraints and capital costs. Although the authors have chosen not to disclose to specific capital cost of a UF1500 unit in this paper, budgetary equipment quotes were obtained during the original study, which suggested that absolute payback could be obtained in a reasonable amount of time for such a brown fields replacement despite requiring a significant number of such units.

Furthermore, while UF Falcons were originally developed to treat feeds with relatively low heavy mineral contents [3,4], this study suggests that such a unit is also capable of treating feeds with relatively high heavy mineral content. Thus, if the comparison is no longer REO specific, but rather between the use of a UF Falcon circuit and another gravity circuit option to treat a relatively fine heavy mineral rich feed, the UF Falcon circuit could conceivably prove competitive based on performance alone. Although not evaluated as part of this study, works by Grewal and Neale also suggest the prospect that despite the name of the device, UF Falcons could potentially also treat feeds of up to 100% passing 212  $\mu$ m, thus the potential window for operation is possibly wider than initially expected [12]. Additionally, these results suggest that UF Falcons have the potential to operate with a wide range of synergy with any number of upstream unit operations, regardless, if that were gravity, flotation, magnetic, or even some other form of separation, including those performed at significantly coarser feed sizes.

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