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Article

Ultra-Fine Centrifugal Concentration of Bastnaesite Ore

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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 µm, most traditional gravity separation methods become increasingly challenging. The purposes of this study is to determine the applicability of gravity concentrators to beneficiate bastnaesite from deleterious calcite bearing flotation feed material. Via the use of a UF Falcon, it was possible to achieve rougher gravity REO recoveries approaching the upper 80% range while rejecting on the order of 30% of the total calcium. In terms of purely REO recovery, this represents a significant improvement over results obtained via a traditional Falcon in previously reported studies.

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

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1. Introduction

1.1. Ultra-Fine Falcon Concentrators

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. 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 muti-gravity separators (Mozely MGSs) and cyclones as is pictured in Figures 1 and 2 [3,4].

UF Falcons operate on a similar principle 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 to 3 µm. Another consequence of the use of such comparatively fine feeds is that the UF Falcon, including at laboratory scale, utilizes no fluidization 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.

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.

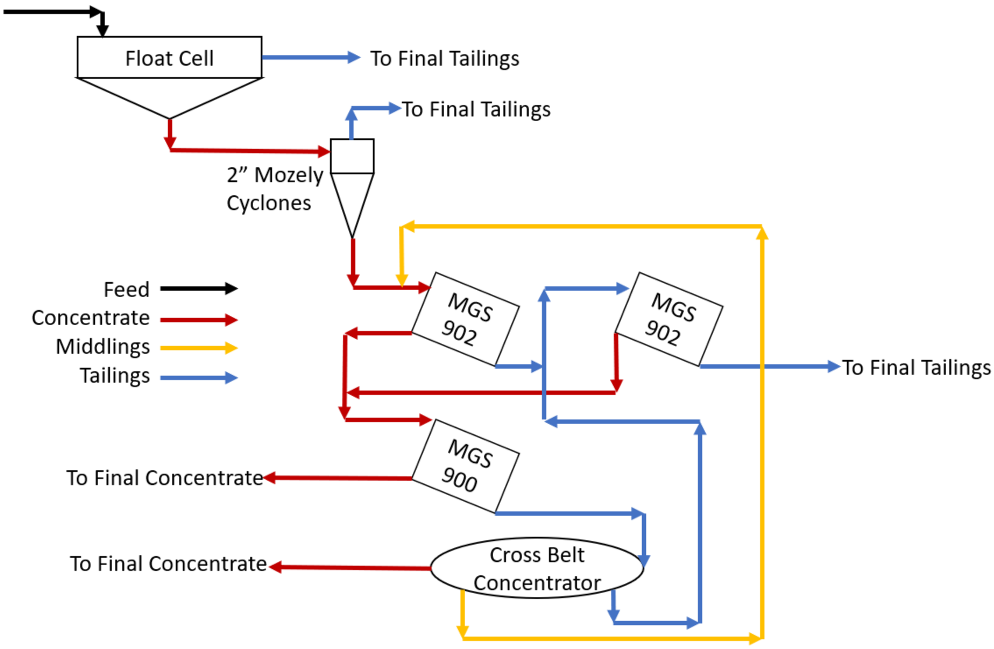

Figure 1. Original TANCO tantalum gravity circuit, recreated for legibility, adapted from [3,4].

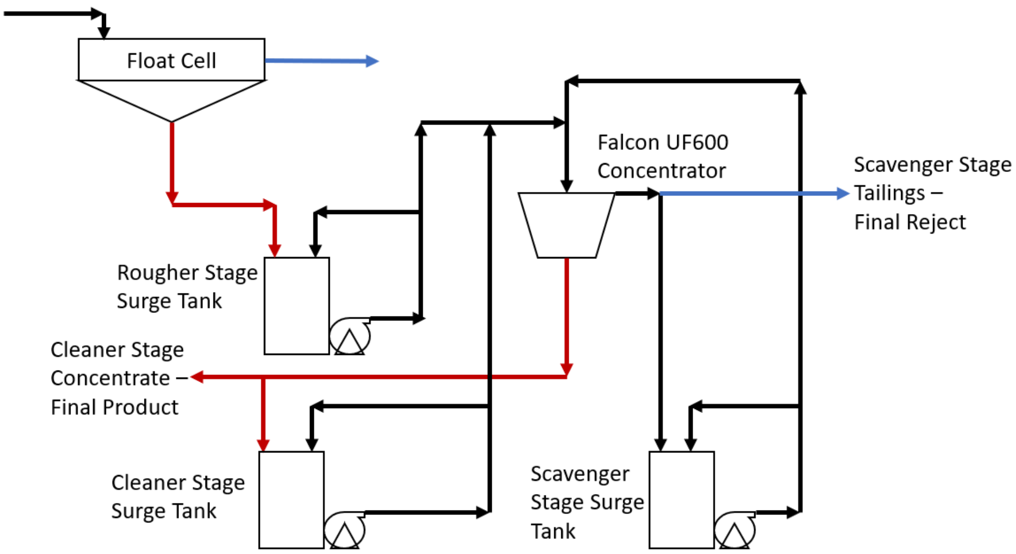

Figure 2. Replacement of TANCO gravity circuit with a single Falcon UF 600, recreated for legibility, adapted from [3,4].

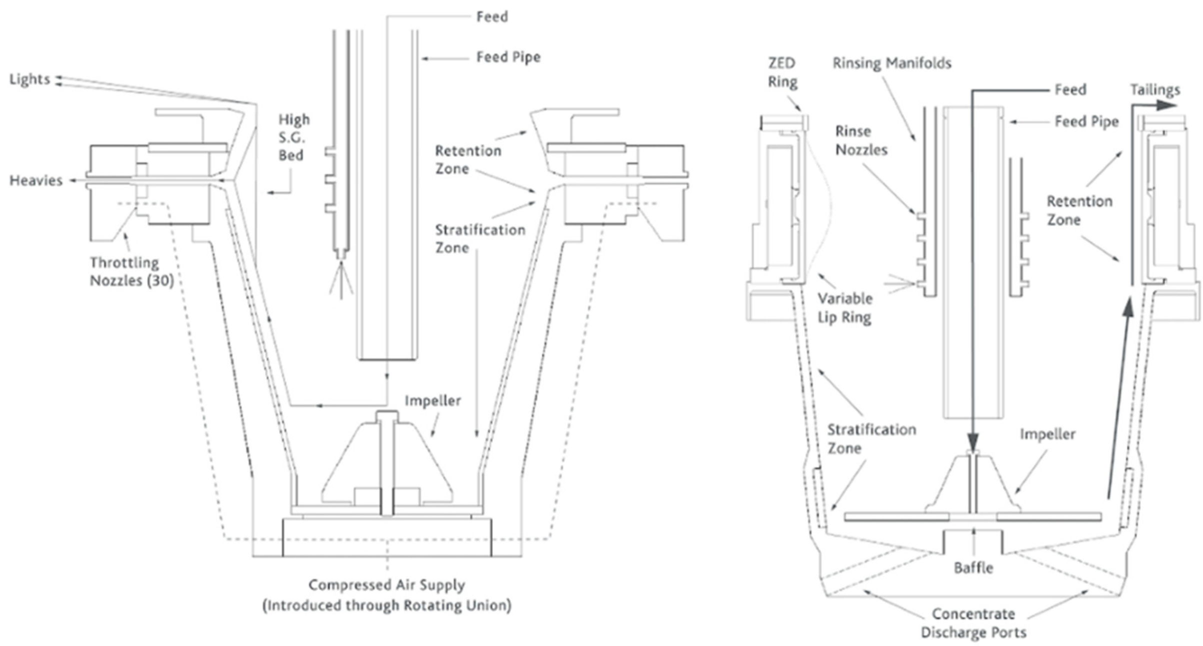

Figure 3. Cross sections of bowl of a continuous (**left**) and UF Falcon (**right**), adapted from [5].

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

For contextual purposes, it should be noted that other gravity methods such as traditional Falcons and shaking tables, were also tested on whole ore materials in this and prior studies such as that of Thompson et al. [6], and Schriner and Anderson [7,8]. Equally significantly, no previous studies identified to date have ever subjected whole ore materials to treatment via a UF Falcon.

Thompson et al. 2011 study included a battery of heavy liquid separation (HLS) characterizations as well as a variety of gravity separation testing via a traditional Falcon and shaking tables. The specific outcomes of these tests were not reported in detail. However, it is known that all of the tests failed to yield a concentrate grading 40% REO or greater. It was also observed that an unstated portion of acid consuming gangue was rejected to the float fraction in HLS testing at a specific gravity (SG) of 3.1. It should also be noted that neither the deportment nor abundance of barite, a high SG non rare earth element (REE)-bearing mineral, was reported in regards to any gravity testing. Additionally, even at a fine grind of 100% passing 38 microns, reportedly neither shaking tables nor the traditional Falcon yielded preferential upgrading of REE bearing minerals to their respective concentrates. Finally, a mineralogical analysis indicated that composite particles containing higher ratios of dolomite and quartz compared to REEs reported to the gravity tailings, which in turn yielded "high" REE losses [6].

In a previous study (Schriner' and Anderson, 2015), a design of experiment (DOE) matrix utilizing a traditional Falcon indicated that the optimal outcomes were achieved at the finest ground particle size, lowest feed rate, and lowest applied G-Force of 100 Gs (equivalent to 1320 revolutions per minute (RPM) for the device). In Schriner and Anderson's testing, feed pulp density was held constant at a value of 10% solids by weight as the feed tank configuration prevented the use of higher values without excessive settling or exceeding the limits of the agitator. Additionally, scoping testing by Schriner and Anderson on both Wilfley and Diester style shaking tables suggested either could potentially yield a significant rejection of calcium [7,8].

In this study, four passes through a traditional Falcon at the optimal grind time and RPM conditions proposed by Schriner and Anderson [7,8]. For the sake of clarity, each pass consisted of feeding repulped tailings solids from the previous pass, while each concentrate was collected separately, such as depicted in Figure 4.

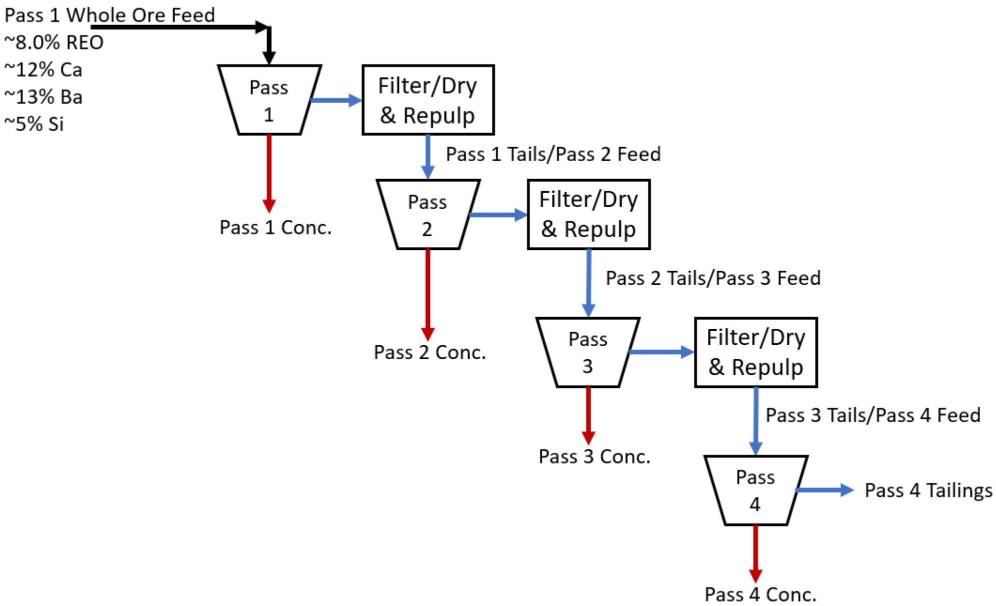

Figure 4. Generalized flowsheet of whole ore Falcon and UF Falcon testing. REO: rare earth oxide.

This process yielded a cumulative REO recovery of approximately 57% with a corresponding calcium rejection of 76% as shown in Figures 5 and 6. Direct comparisons of outcomes between this and Schriner and Anderson's study is challenging however due to differences in respective head grades, assaying methodology, and the inability to duplicate Schriner and Anderson's optimal feed rate.

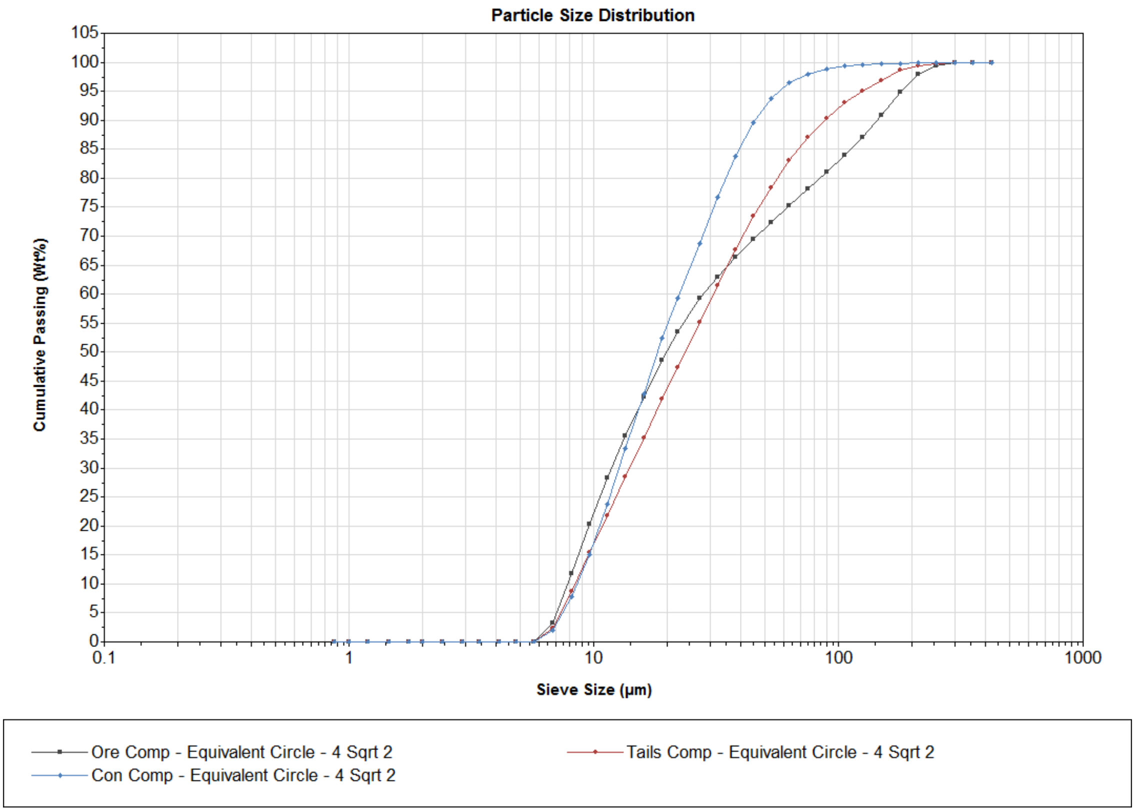

Figure 5. Particle size distributions of MPC and other Mountain Pass MLA materials.

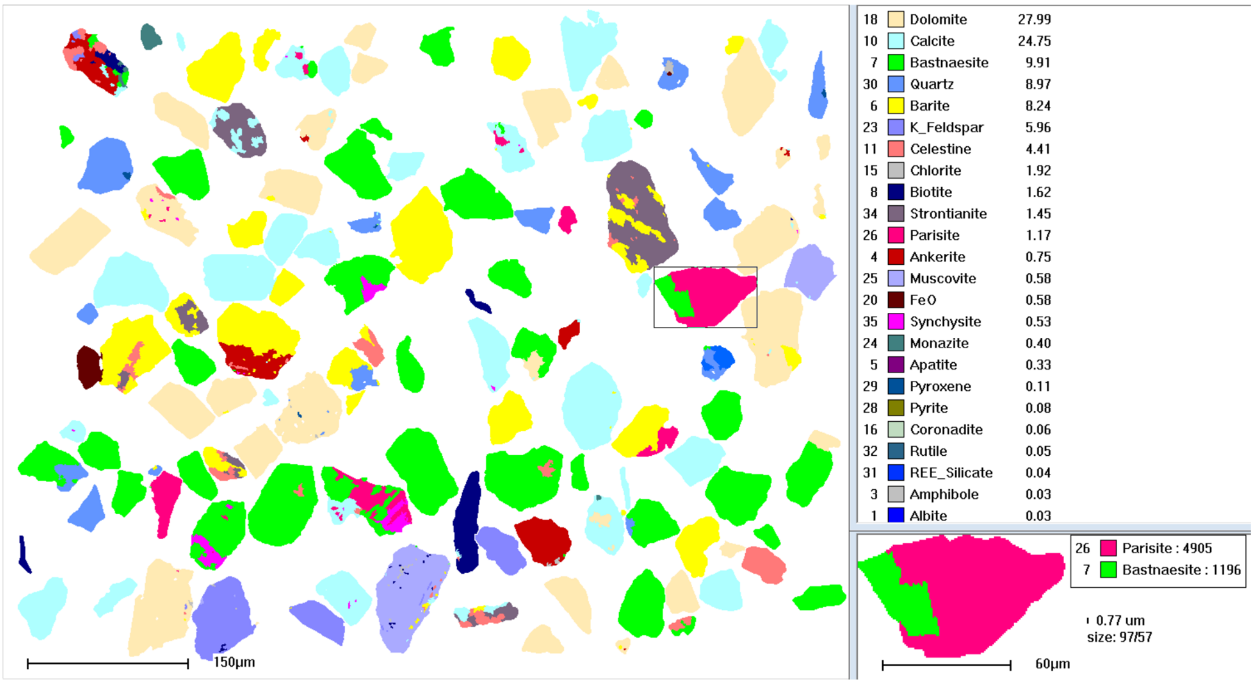

Figure 6. False-color image from MLA of the whole ore specimen. Values represent surface area percentages.

Additionally, scoping tests performed via a Wilfley shaking table yielded gravity concentrates exhibiting a markedly low calcium content on the order of 2 to 3% Ca. However, partially attributed to issues regarding the installation of the device itself, recovery of REO was often low, with values on the order of 15% to 20%.

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), (MP Materials, Las Vegas, NV, USA) used for this and other parallel studies.

The crushed ore sample consisted of approximately 1 ton of minus 3/8″ 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. Selected buckets were then subjected to further two stage crushing via a roll crusher at 4.8 mm and 2.4 mm gap spacing. Upon completion of roll crushing, smaller samples on the order of 1 kg were split via a Jones riffle from the original 30 kg of ore. These individual 1 kg split samples were then subjected to batch grinding in a jar rod mill for either 75, 90, or 120 min to yield specific particle size distributions for the respective gravity testing. This material also served as the source of larger 10 kg samples for rougher flotation work later performed by Nathaniel Williams [9].

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 Falcon. Secondly, 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 three factor Design of Experiments (DOE) matrix for test work performed on the 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), feed pulp density, and 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.

Grinding time was varied as a proxy for varying the feed particle size distribution, with target P80s (i.e., 80% of the mass being finer than the given value) of 50, 40, and 30 microns corresponding to 75, 90, and 120 min, respectively.

Additionally, the feed volumetric flowrate, via the use of the tailing's flowrate as a proxy indicator, was held to near constant values between 4 and 5 L/min via dynamic tuning of the discharge valve on the feed tank. This was deemed to be a more favorable method for controlling flowrate than using a constant valve position given the use of variable pulp densities. The tailings flowrate was monitored via the use of a stopwatch, 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 at a temperature of approximately 125 °C 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 the same drying oven. Both resulting dry products were subsequently subjected to massing and assaying via X-ray Fluorescence XRF.

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 5. It should be noted that the sampling representativeness 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. Project constraints impeded the ability to later perform a second round of mineral liberation analysis (MLA) characterization on properly split whole ore samples. However, the results are deemed sufficiently indicative of the whole ore material to warrant inclusion in Figure 5 and Table 1. The MPC material exhibits a P80 of approximately 35 µm, while the MP tails are coarser at approximately 55 µm. 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 1. Modal mineral content for the whole ore MLA (mineral liberation analysis) specimen.

Mineral	Formula	100	100 × 200	200 × 400	400 × 500	−500	Modal
Bastnaesite	$(Ce_{0.5}La_{0.4}Nd_{0.1})(CO_3)F$	11	14.2	15.3	13.3	12.5	12.9
Parisite	$Ca(Ce_{0.4}La_{0.3}Nd_{0.3})_2(CO_3)_3F_2$	2.28	2.04	1.57	1.59	1.74	1.81
Monazite	$(La,Ce)PO_4$	0.78	0.67	0.63	0.7	0.94	0.84
Synchysite	$Ca(Ce_{0.5}La_{0.4}Nd_{0.1})(CO_3)_2F$	0.69	0.66	0.64	0.53	0.7	0.67
Total REE minerals	-	14.75	17.57	18.14	16.12	15.88	16.22
Calcite	$CaCO_3$	20.4	21.1	20.7	22.4	21.6	21.3
Dolomite	$CaMg(CO_3)_2$	18.6	22.6	24.6	23.2	12.1	16.2
Barite	$BaSO_4$	6.01	7.26	11.2	14.7	29.4	20.9
Quartz	SiO_2	14	10.3	7.33	5.66	3.11	5.97
Celestine	$SrSO_4$	3.77	4.24	5.44	6.95	11.3	8.59
Strontianite	$SrCO_3$	1.45	1.49	1.68	1.72	1.58	1.57
Other	-	21.02	15.44	10.91	9.25	5.03	9.25

The mineralogical composition of the whole ore specimen and other materials were determined by mineral liberation analysis (MLA). This was achieved by subjecting the samples to wet sieving at screen sizes of 100, 200, 400, and 500 mesh, from which transverse particle mounts were prepared. The MLA data was obtained by the X-ray backscattered electron (BSE) method. The MLA determined the modal mineral content of the whole ore specimen are shown in Table 1, while an example of a false color image of an unspecified size fraction are shown in Figure 6.

3.2. UF Falcon Scoping Results

The first of the scoping tests demonstrated that a single pass with the laboratory UF Falcon was effectively matching the results of 4 cumulative passes of a traditional Falcon despite the use of lower RPM settings. With the inclusion of a second pass, this first scoping test had already broken the previously reported maximum achieved REO recovery via 3 passes on a traditional Falcon, and by the third pass was approaching, but not exceeding, 90% REO recovery as is shown below in Figure 7. Additionally, the fact this novel method of processing exhibited any degree of selectivity against calcium, as shown in Figure 8, was also considered favorable, given the goal was to maximize REO recovery while simultaneously minimizing that of calcium to the concentrate. These initial results were sufficiently promising enough to justify a complete immediate shift of focus away from a traditional Falcon or shaking tables in favor of further UF Falcon testing.

The second scoping test was originally intended to evaluate the impacts arising from the use of a finer grind size. However, this test unintentionally revealed that the nearly flat bottomed, unbaffled feed tank was mechanically inappropriate for use in further testing. These issues were myriad, and effectively resulted in a non-uniform flowrate and solids content in the discharge slurry throughout any given pass. A third scoping test was performed with a new baffled conical feed tank to diagnose if any further changes were needed upstream of the Falcon itself. While procedurally an improvement over the second test thanks to the changes in the feed tank, it ultimately highlighted that a higher-powered agitator would be required. Thus, a fourth and final scoping test was performed with an upgraded agitator, the results of which, as shown below in Figures 7 and 8, appeared to greatly resolve all issues encountered thus far. This configuration, as photographed in Figure 9, was preserved for the later DOE matrix testing. It is strongly recommended that any reader considering performing such testing utilize a similar setup. When compared against the results of the later DOE testing, it is clear that trials in which feed slurry issues occurred exhibited noticeably lower concentrate REO grades despite the use of otherwise comparable test parameters.

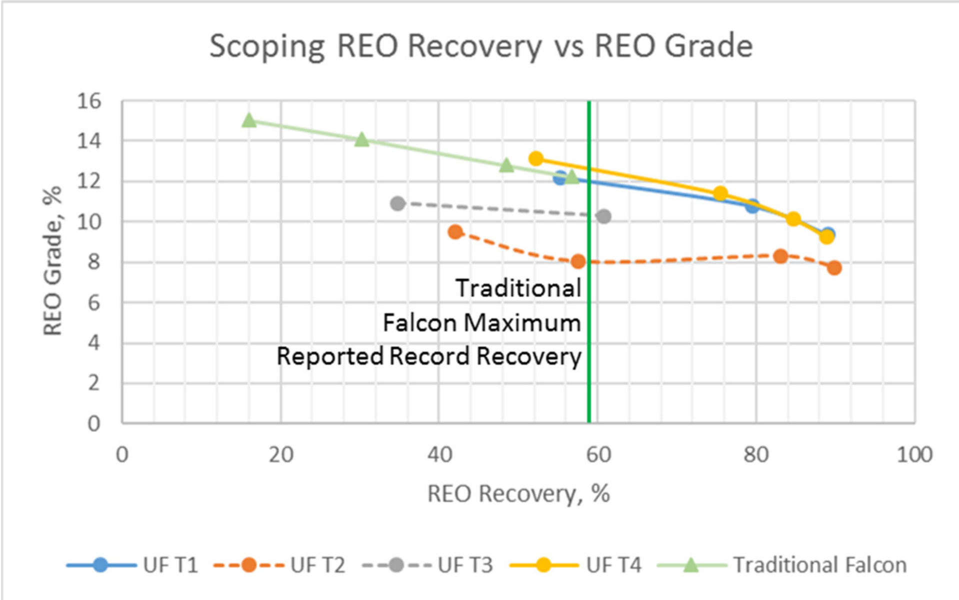

Figure 7. Scoping traditional and UF Falcon REO Grade/Recovery results. Tests shown with dashed lines indicate artificially poor performance due to suboptimal ancillary equipment. Overlaid is the previous traditional Falcon REO recovery record, after 3 passes, of 59.2%, as set by Schriner [5,6].

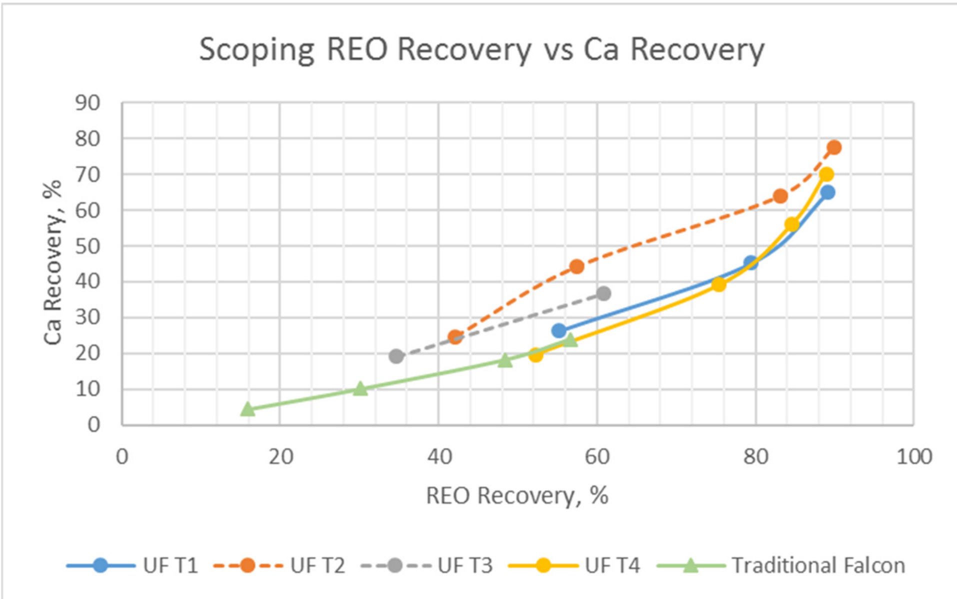

Figure 8. Scoping traditional and UF Falcon testing Ca recovery vs. REO recovery.

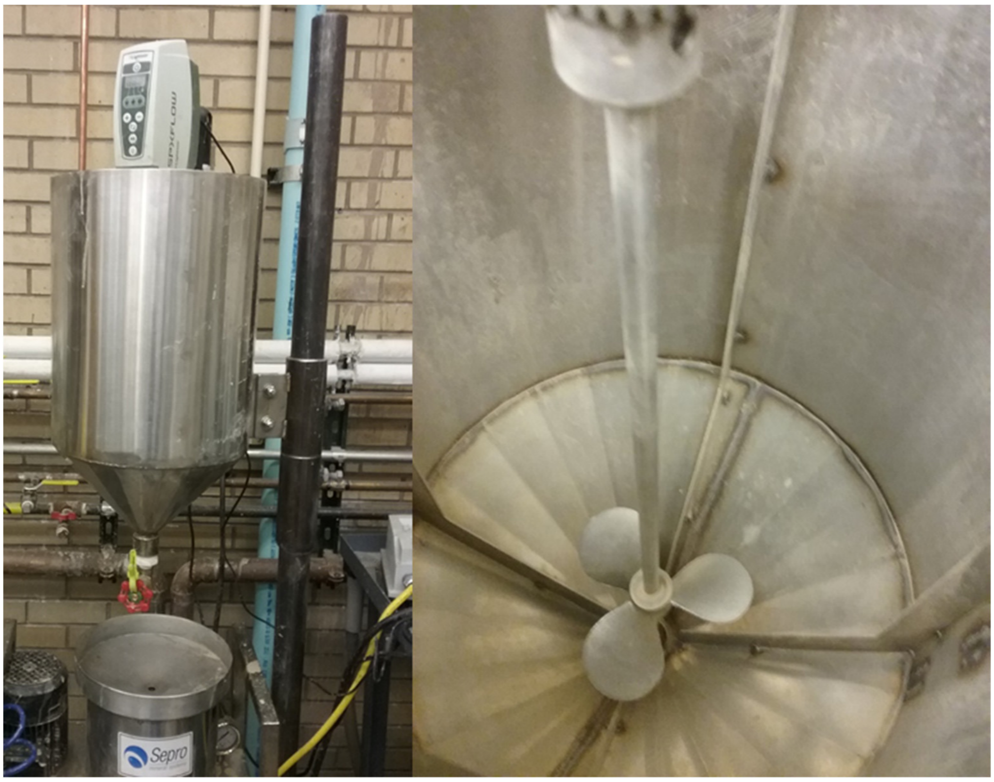

Figure 9. Feed tank, agitator, and laboratory Falcon optimal configuration as seen from the exterior (**left**) and interior (**right**).

3.3. 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 REO/Ca recovery ratio. These responses were considered statistically significant based on an analysis of variance (ANOVA) in Stat Ease 10 (Stat-Ease Inc., Minneapolis, MN, USA). As the goal was to optimize the parameters by prioritizing recovery of REO, it was applicable to construct a desirability surface, based on predictive responses such as is pictured in Figure 10.

Much like in the study by Schriner and Anderson, the use of the finest grind size respectively tested was considered optimal [7,8]. While from a liberation perspective it seems reasonable to expect that a finer grind is better, this would typically also hinder the prospects for gravity recovery. However, this does not appear to have functionally been the case as on an absolute REO recovery basis, there was relatively little difference between coarse and fine grind sizes at otherwise equal conditions. At the least, it certainly deviated from the expectation that recovery would be proportional to the square of the particle radius.

Similar to later experiences with the use of a UF Falcon to treat various flotation concentrates, it was apparent that pulp density was an unexpectedly strong factor. In line with later testing on flotation concentrates, the use of 10% solids (and likely any lower values) was detrimental to UF Falcon performance. This was counter to the initial expectations as conventional wisdom suggests that more dilute feeds are generally preferable for UF Falcons. It is interesting to note that this often had a more pronounced absolute impact on REO recovery than differences in grind size, especially at higher RPM values.

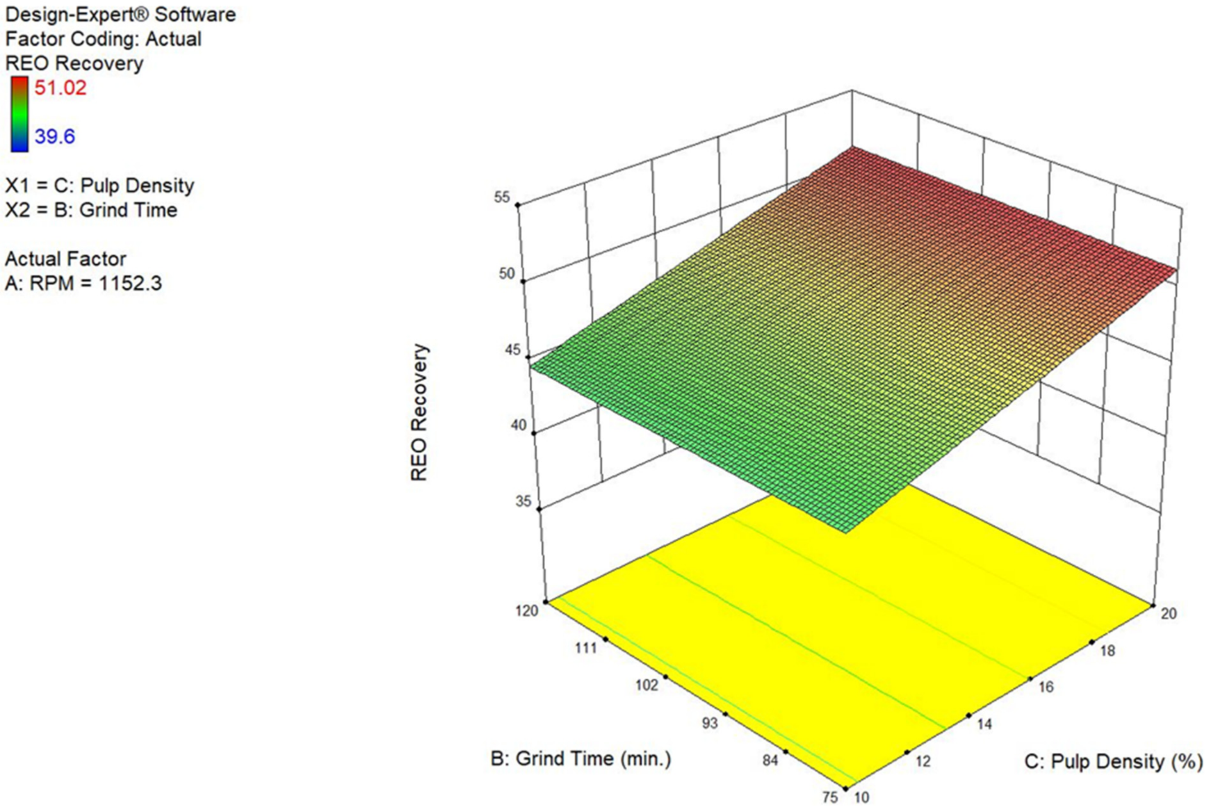

Figure 10. Predicted REO Recovery for Pass 1 UF Falcon tests at 1152.3 RPMs.

From this analysis, it was indicated that the proposed optimal parameters were 930 RPM, 17% solids, and a 120 min grinding time. The results of this DOE testing are shown below in Table 2.

Table 2. UF Falcon whole ore DOE matrix conditions and results.

Test	Conditions			Grade, %		Recovery, %	
	Rotational Speed, RPM	Grinding Time, min	Pulp, wt%	Ca	REO	Ca	REO
1	930	75	20	8.15	12.50	21.44	50.72
2	930	120	20	7.63	12.36	20.17	50.80
3	930	120	10	7.42	13.74	17.52	49.09
4	930	75	10	8.75	11.04	21.65	44.00
5	1320	75	10	8.44	11.63	17.93	39.60
6	1320	120	20	7.57	13.80	18.75	49.86
7	1320	75	20	7.99	12.77	21.54	48.88
8	1320	120	10	7.70	13.49	15.87	41.30
9	1141	90	15	7.67	12.97	18.32	47.20
10	1141	90	15	7.19	13.72	17.58	52.01

3.4. Scoping UF Falcon Scavenger Testing

Subsequent to the study by Williams, two samples of a bulk rougher flotation tailings processed in up to two stages of processing via the use of a novel collector were subjected to scoping UF Falcon testing. The purpose of this testing was two-fold. One, to see if additional REO recovery could be obtained beyond that of the rougher flotation circuit; and two, to further evaluate the prospects for byproduct barite recovery. Due to assay limitations when evaluating materials that are lean in REO content, it is unclear with any reasonable degree of confidence what portion of the remaining REO content managed to report to the resulting scavenger gravity concentrates. However, results for barite echoed those of earlier UF Falcon testing on whole ore materials, indicating that on the order of 70% of the barite could be obtained in two passes. Given that this barite recovery was analogous to prior testing, it is likely that the use of four passes would have potentially yielded on the order of 90% barite recovery.

It should be noted that the P80 of these bulk floatation tailings was approximately 40 microns, and that, via a subsequent MLA analysis, approximately 70% of the barite content in this sample was fully liberated. This implies the possibility of utilizing gravity separation as a means of producing byproduct non-REE bearing heavy mineral streams from tailings materials, which could potentially provide further economic buffer for an operation against notoriously unstable REO prices.

4. Conclusions

The use of an UF Falcon to beneficiate bastnaesite ore represents a technically viable option for achieving partial rejection of carbonate gangue whilst maintaining a comparatively high REO recovery. However, profound recent parallel advancements in flotation chemistry, such as that of Everly [11,12] and Williams [9], have identified no fewer than two novel collectors that can yield greatly superior selectivity against calcium at comparable, or better, REO recoveries than can be achieved via a UF Falcon absent the inclusion of cleaner gravity pre-concentration stages. In this particular case, the UF Falcon is perhaps more economically suited to treating flotation concentrates, provided its inclusion even proves technically necessary in light of proposed future cleaner flotation testing.

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References

1. Falconer, A. Gravity separation: Old technique/new methods. *Phys. Sep. Sci. Eng.* **2003**, *12*, 31–48. [CrossRef]
2. Knelson, B. The Knelson Concentrator. Metamorphosis from Crude Beginning to Sophisticated World Wide Acceptance. *Miner. Eng.* **1992**, *5*, 1091–1097. [CrossRef]
3. Deveau, C.; Young, S. Pushing the Limits of Gravity Separation. In *SME Annual Meeting*; SME: Southfield, MI, USA, 2004; Volume 5, pp. 5–84.
4. Deveau, C. Improving Fine Particle Gravity Recovery through Equipment Behavior Modification. In Proceedings of the 38th Annual Canadian Mineral Processors Conference, Ottawa, ON, Canada, 17–19 January 2006; pp. 501–517.
5. Sepro UF Falcon Website. Available online: https://seprosystems.com/products/gravity-concentrators/_falcon-uf-gravity-concentrators/ (accessed on 22 July 2018).
6. Thompson, W.; Lombard, A.; Santiago, E.; Sing, A. Mineralogical Studies in Assisting Beneficiation of Rare Earth Element Minerals from Carbonatite Deposits. In Proceedings of the 10th International Congress for Applied Mineralogy (ICAM), Trondheim, Norway, 1–5 August 2011; Springer: Berlin/Heidelberg, Germany, 2012; pp. 665–672.

7. Schriner, D.; Anderson, C. Centrifugal Concentration of Rare Earth Minerals from Calcite Gangue. *J. Metall. Eng.* **2015**, *4*, 69. [CrossRef]
8. Schriner, D. Advanced Beneficiation of Bastnaesite Ore Through Centrifugal Concentration and Froth Flotation. Master's Thesis, Colorado School of Mines, Golden, CO, USA, 2015.
9. Williams, N. Bastnaesite Beneficiation by Froth Flotation and Gravity Separation. Master's Thesis, Colorado School of Mines, Golden, CO, USA, 2018.
10. Kroll-Rabotin, J.S.; Bourgeois, F.; Climent, E. Physical Analysis and Modeling of the Falcon Concentrator for Beneficiation of Ultrafine Particles. *Int. J. Miner. Process.* **2013**, *121*, 39–50. [CrossRef]
11. Everly, D. Surface Chemistry of Novel Collectors and Their Application to Froth Flotation of Rare Earth Minerals. Master's Thesis, Colorado School of Mines, Golden, CO, USA, 2018.
12. Chapleski, R.C., Jr.; Chowdhury, A.U.; Wanhala, A.K.; Bocharova, V.; Roy, S.; Keller, P.C.; Bryantsev, V.S. A Molecular-Scale Approach to Rare-Earth Beneficiation: Thinking Small to Avoid Large Losses. *iScience* **2020**, *23*, 101435. [CrossRef] [PubMed]