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The liaison between mine planning, coal processing and marketing in a life of mine (LOM) plan

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Abstract. A flowsheet can be developed such that the Life Of Mine (LOM) plan can be examined for various flowsheets, particularly how the fine coal should be treated. Simulation software, such as Limn: The Flowsheet Processor can be used to determine possibly the most important criteria for a mine development, i.e. what quality should be produced from a resource?

1 Introduction

Usually, in the first stages of a project, a reserve is identified, drilled and a mine plan developed. The decision as to what quality is to be made is often subjective and based on some marketing knowledge. A mine plan will give the tonnages, qualities and washabilities to be fed to a coal washing plant from the mining sequence. The decision of what product to make and whether to treat or not treat the fine (minus 1 mm fraction) coal can be better made by simulating various plant configurations against the mine plan. The Life of Mine (LOM) plan can be run sequentially using a simulation program such as Limn: The Flowsheet Processor. From this, the best quality for the life of the project can be determined, as well as the plant configuration for the particular project.

In this study, it is assumed that the plant must produce a moisture adjusted product, expressed as Net Calorific Value as Received (NCVAR), which includes total moisture % and air-dry calorific value (ADCV), which is the most realistic scenario. Fines inherently have a larger surface area and therefore a higher total moisture than coarser coal, so if fines are added back, they will have a lower NCVAR than the equivalent coarse coal ADCV. It also assumes that the coal's coarse feed fraction, nominally 50mm x 1mm, will be treated in 1 stage of Dense Medium Cyclones (DMCs). The -1mm fraction is fed to a classifying cyclone where it is separated into nominal plus and minus 0.15mm size fractions, with the, -0.15mm ultrafines, being discarded. The 1mm x 0.15mm fines, can be discarded or it can be treated and added back to the coarse product.

The "best" overall product quality is a trade-off, as the higher the quality of the product, the lower the yield, but the higher the revenue per tonne. If fines are to be added back to the total product, the coarse coal may have to be washed to a higher quality to compensate. How the fines are treated is a critical decision, but one often taken with too little thought. The "default decision" is to install spirals and high frequency (HF) dewatering screens, because it is the cheapest option. This choice was mostly correct when better coal was being mined in South Africa, but increasingly coal is sourced from 4 Seam, which is finer and of inherently lower quality than 2 Seam. This has led to many traditional spiral plants being installed but being turned off when the required NCVAR quality cannot be made.

2 Mine plan

Most software packages that are used to develop mine plans can output data in Excel format (including csv). The data can then be fed into a Limn simulation. The mine plan used for this paper is loosely based on a real project which has been adjusted and arranged in nominally monthly periods. This case study is used only to illustrate a methodology of examining a LOM project and all the assumptions, e.g. coal pricing, are specific to this case.

2.1 Borehole data

The initial mine plan is derived from borehole data, usually cores crushed to -25mm. A significant issue is that normally a feed will have washabilities that differ for each size fraction. However, as the borehole is effectively mono size, i.e. 25mm x 1mm, this variations in washability per size cannot be simulated unless large core boreholes or bulk samples are also used.

The mine plan is based on tonnages related to mining equipment choices and conditions, and market requirements. The mine plan may often encompass multiple seams being mined, which may need to be first evaluated to determine whether mined coal should be beneficiated at all, or if washed batchwise or blended. This can be investigated using the same simulation approach but is not addressed in this paper. The mine plan shown in this paper is based on a 4 seam operation and **Error! Reference source not found.**shows the first 8 periods of the mine plan for the 1.35, 1.4 and 1.45 densities. The actual densities available are 1.35, 1.4, 1.45, 1.5, 1.6, 1.7, 1.8 and 2.3 (sinks).

Period	1	2	3	4	5	6	7	8
WASH RD	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35
PLANT FEED TONNES	17,496	39,730	38,977	41,080	58,988	57,927	107,977	109,213
WASH YIELD	0.0223	0.0329	0.0184	0.0139	0.0023	0.0036	0.0131	0.0220
WASH CV	29.3453	29.7970	30.3740	30.3869	30.2108	30.0414	29.8460	30.1911
WASH ASH	9.5791	9.0724	8.4955	8.3999	7.8374	8.0112	8.4498	8.1137
WASH TS	0.6086	0.6839	0.7624	0.7708	0.6958	0.6411	0.5195	0.3771
WASH IM	2.6953	2.6256	2.5201	2.5367	2.7671	2.8887	2.9894	2.9258
WASH VM	27.5939	30.1626	33.5646	33.4272	30.3435	29.5818	27.9057	26.6625
WASH FC	60.1318	58.1399	55.4197	55.6362	59.0517	59.5182	60.6556	62.2977
WASH RD	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
PLANT FEED TONNES	17,496	39,730	38,977	41,080	58,988	57,927	107,977	109,213
WASH YIELD	0.1464	0.0924	0.0882	0.0684	0.0201	0.0359	0.0544	0.0820
WASH CV	28.8013	29.1766	29.5939	29.4924	28.8299	29.0268	29.2353	29.4906
WASH ASH	10.9020	10.2327	9.4040	9.5757	10.9805	10.6632	10.0656	9.6287
WASH TS	0.5925	0.5476	0.5497	0.5511	0.4912	0.4861	0.4883	0.4021
WASH IM	2.9962	3.1047	2.9568	2.9702	3.1314	3.1456	3.1048	2.9724
WASH VM	25.5618	26.2396	27.3640	27.2372	26.0862	26.2372	26.6420	26.2280
WASH FC	60.5449	60.4266	60.2772	60.2189	59.8055	59.9555	60.1904	61.1707
WASH RD	1.45	1.45	1.45	1.45	1.45	1.45	1.45	1.45
PLANT FEED TONNES	17,496	39,730	38,977	41,080	58,988	57,927	107,977	109,213
WASH YIELD	0.3048	0.2708	0.2469	0.2225	0.1991	0.1850	0.2010	0.2158
WASH CV	28.1357	28.4107	28.7453	28.4708	27.8962	28.2935	28.3110	28.4756
WASH ASH	12.5266	12.0735	11.2784	11.7137	12.5834	12.1956	12.0582	11.8621
WASH TS	0.5222	0.4819	0.4907	0.4729	0.3913	0.4772	0.4640	0.4106
WASH IM	3.0021	3.1211	3.0067	3.0340	2.9938	3.1952	3.0542	2.9312
WASH VM	24.5426	24.8920	25.4303	25.1238	24.8682	24.9364	25.6190	25.6783
WASH FC	59.9277	59.9127	60.2845	60.1284	59.5546	59.6726	59.2688	59.5284

Fig. 1. Example of mine plan

In Fig. *2*, the mine plan data is converted into a format suitable for use in Limn.

Period	16							
Cumulative	1.35	1.4	1.45	1.5	1.6	1.7	1.8	2.3
WASH YIELD	0.33	4.36	15.20	28.95	55.86	69.78	77.60	100.00
WASH CV	29.52	29.21	28.25	27.51	26.00	24.96	24.22	20.24
WASH ASH	9.42	9.65	12.29	14.07	17.32	19.92	21.81	31.81
WASH TS	0.58	0.62	0.57	0.50	0.49	0.47	0.47	0.89
WASH IM	3.01	2.94	2.98	3.03	3.21	3.14	3.08	2.70
WASH VM	27.61	27.91	26.20	24.75	22.54	21.84	21.47	19.43
WASH FC	59.96	59.51	58.53	58.15	56.93	55.10	53.64	45.02
Fractional	1.35	1.4	1.45	1.5	1.6	1.7	1.8	2.3
WASH YIELD	0.33	4.04	10.83	13.75	26.91	13.92	7.83	22.40
WASH CV	29.52	29.18	27.86	26.68	24.38	20.78	17.58	6.47
WASH ASH	9.42	9.66	13.36	16.03	20.82	30.36	38.66	66.44
WASH TS	0.58	0.62	0.55	0.43	0.48	0.37	0.48	2.33
WASH IM	3.01	2.94	3.00	3.09	3.40	2.86	2.56	1.40
WASH VM	27.61	27.93	25.51	23.14	20.17	19.00	18.20	12.35
WASH FC	59.96	59.47	58.13	57.74	55.61	47.79	40.58	15.15

Fig. 2. Period 16 converted into washability table

The washability for each time period of the mine plan **Error! Reference source not found.**is fed into a simulation of a wash plant for the entire LOM. This is repeated for different product target qualities and using different plant configurations, and the results can be compared.

2.2 Plant feed

Fig. *3***Error! Reference source not found.** is the most important output from the LOM. It shows a ramp up on start-up and a ramp down as the reserve is depleted.

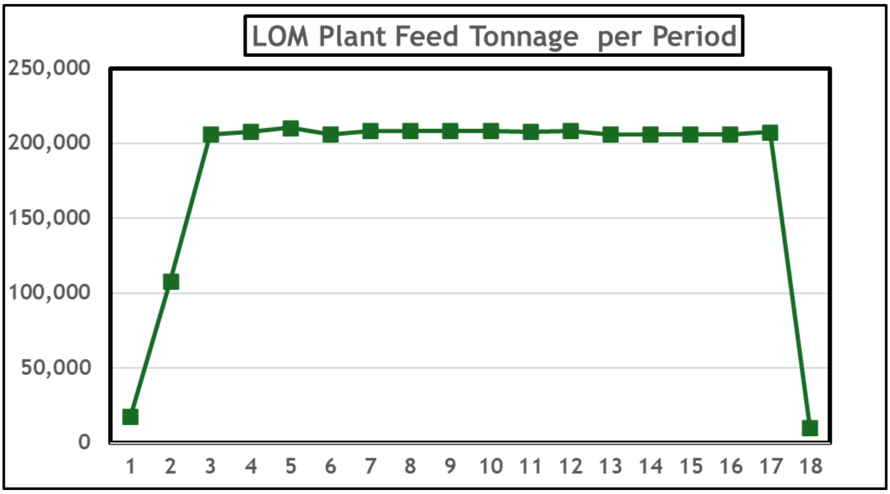

Fig. 3. LOM plant feed tonnage

It may well be that once run the plant simulation may show problems, such as major variations in tonnage, yields and/or quality, Fig. **4**, per period of time, which need to be smoothed in an iterative process by the mine planner. Significant changes in product tonnages or quality could be an issue for marketing or equipment utilisation when the mine is in operation.

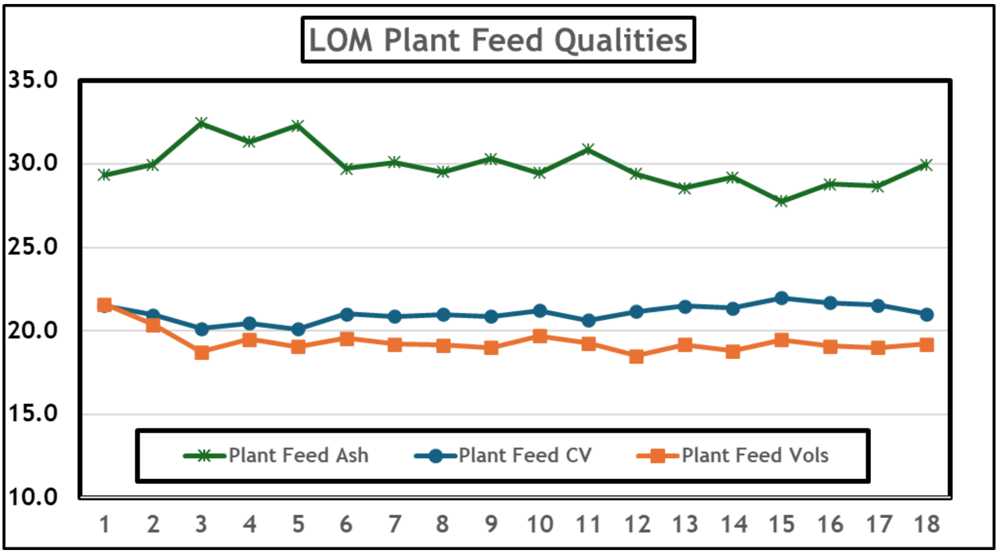

Fig. 4. LOM raw quality feed to plant

2.3 Particle size distribution (PSD)

The effect of PSD is very important in plant design and particularly, in the context of this study, the amount of fines and slimes in the feed. PSDs are often not simple to determine as plant feed often comes from multiple sources. In Fig. **5**, the various sources are shown and an average line derived. Laboratory data usually needs to be adjusted because of known systematic lab errors related to wet/dry and/or square/round aperture screening. Ultrafines, -0.15mm, are often under reported so that a known value from an area/seam such as 6% is used and the PSD curve fitted back.

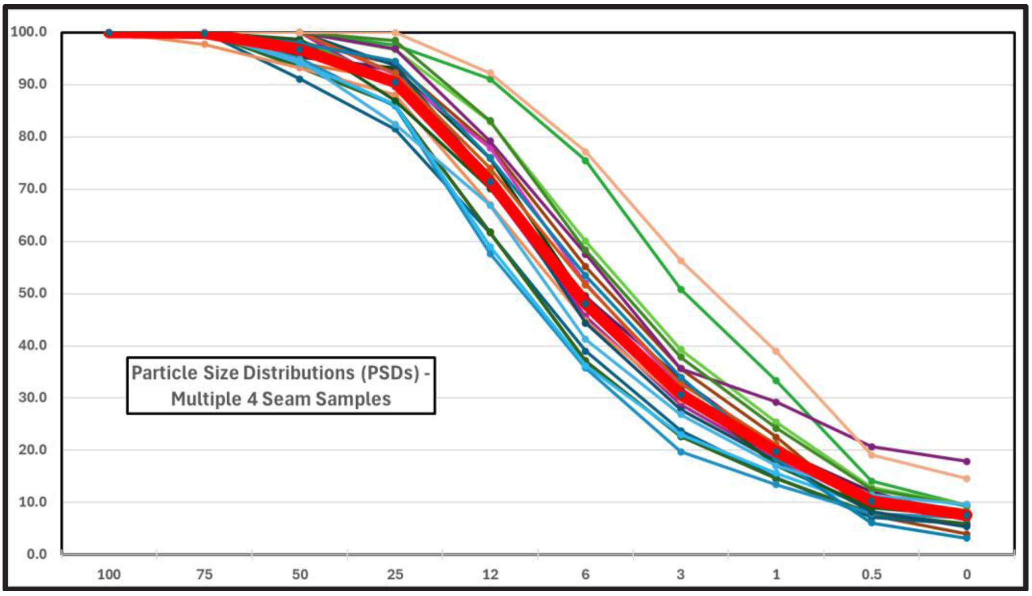

Fig. 5. Particle size distribution (PSD) based on multiple sources

3 LIMN simulation flowsheets

Flowsheets have been developed to represent the equipment configurations to be studied.

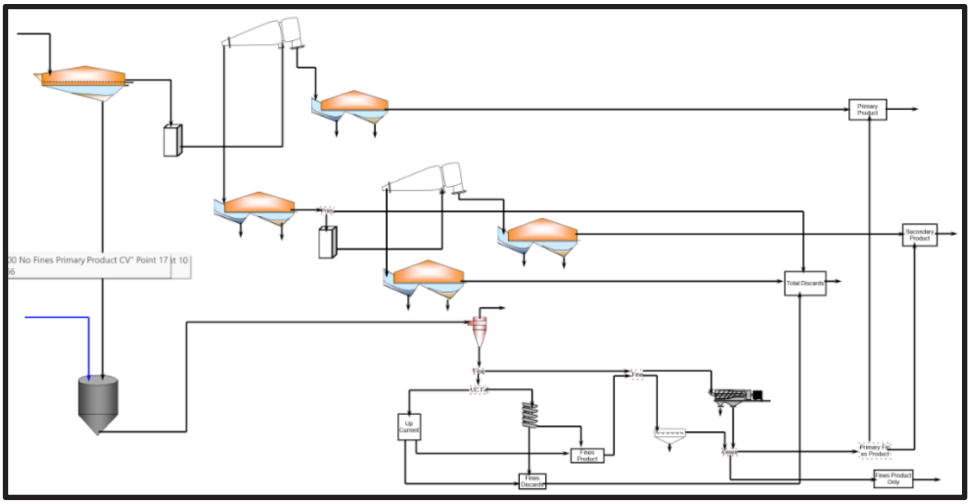

Fig. 6. Full LIMN flowsheet

The flowsheet in Fig. **6**, shows every option that can be chosen, it has:

- Desliming at 1mm.
- Single or Two stage Dense Medium Cyclone (DMC) which can treat the desliming screen overflow, +1mm. (Only 1 stage of DMC is used for this study.)
- The desliming screen underflow, -1mm, is fed to classifying cyclones which cut at a nominal 0.15mm.
- The classifying cyclone overflow is discarded
- The classifying cyclone underflow can either be:
    - Discarded raw
    - Treated in spirals or Up Current Classifier (UCC)
    - Dewatered using High Frequency (HF) dewatering screens or in a fines centrifuge.

Choice boxes are used to direct process flows to change the simulation flowsheet configuration. The advantages of this method rather than simulating separate specific flowsheets is that each piece of equipment will have the same efficiencies assigned to it and the feed to the plant will be identical and less liable to input errors.

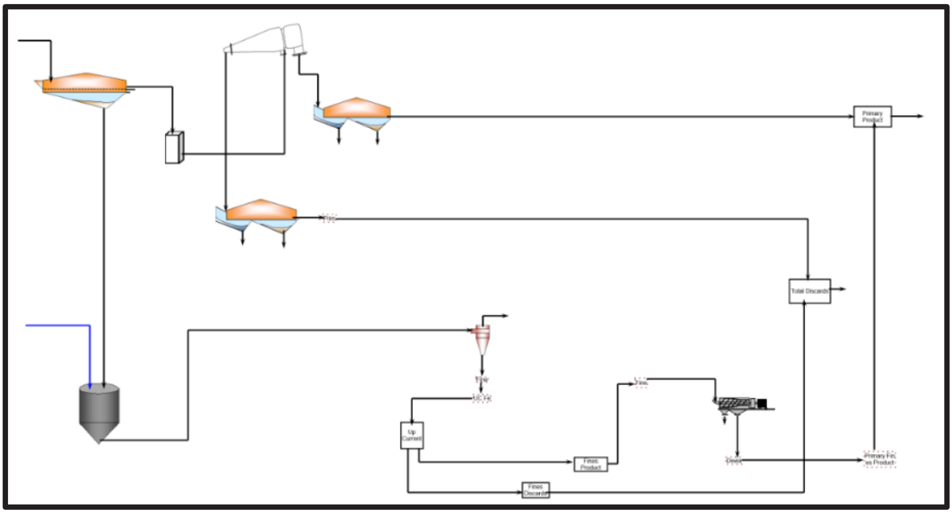

Fig. 7. Flowsheet set up as single stage DMC, UCC and fines centrifuge

Sub-circuits, displayed in Fig. **7** and Fig. **8**, are shown as examples, but other configurations are also used. Each piece of equipment is simulated using efficiencies and performance characteristics based on actual plant data as far as possible.

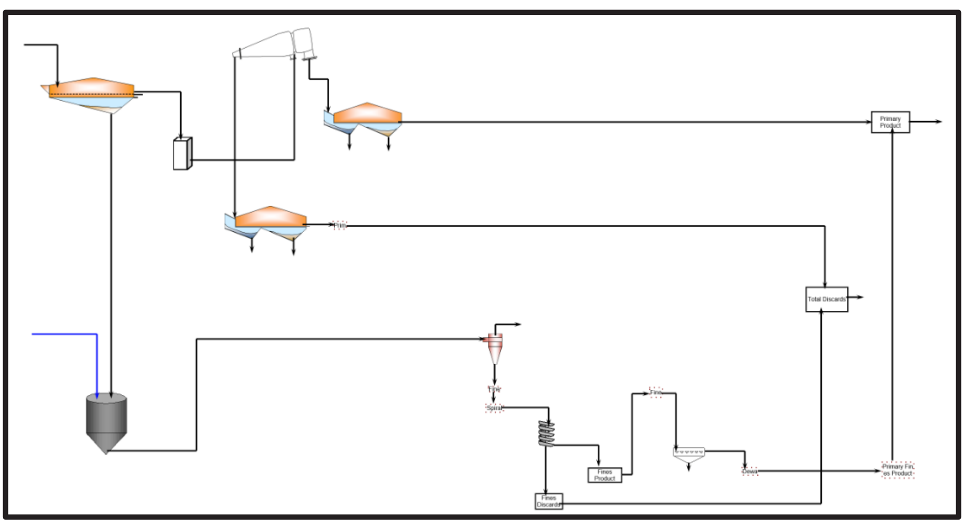

Fig. 8. Flowsheet set up as single stage DMC, spirals and HF dewatering screen

3.1 Dense medium cyclone (DMC)

Fig. **9** shows EPM values per size range based on multiple plant efficiency tests.

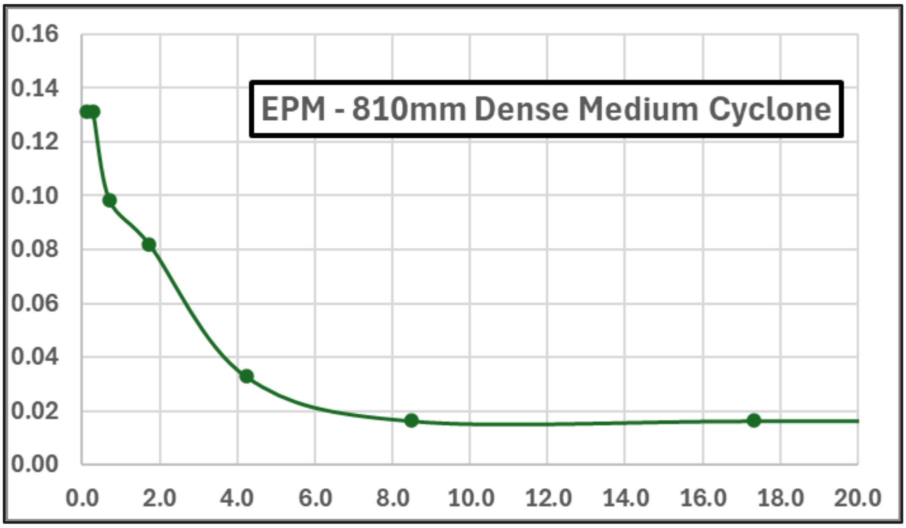

Fig. 9. Efficiency curve for 810 mm dense medium cyclone

The medium SG range is set between 1.35 and 1.85 for this study, which is a cutpoint range between approximately 1.48 and 1.9 due to the density shift in the DMC.

3.2 Spirals

Spirals tend to have a lowest cutpoint of 1.75 to 1.8 based on testwork when treating high-near-dense, difficult-to-treat, Southern African coals. For these simulations a fixed cutpoint SG of 1.8 and EPM of 0.15 is used for all sizes. The advantage of spirals is that they are relatively cheap.

3.3 Upward current separators (UCC)

UCCs are adjusted using density and water upflow rates, the efficiency and ease of adjusting cutpoint is better than for spirals. Cutpoints can be adjusted easily down to approximately 1.5. The cutpoint has been kept constant across the size range and the EPM used is shown in Fig. ***10***.

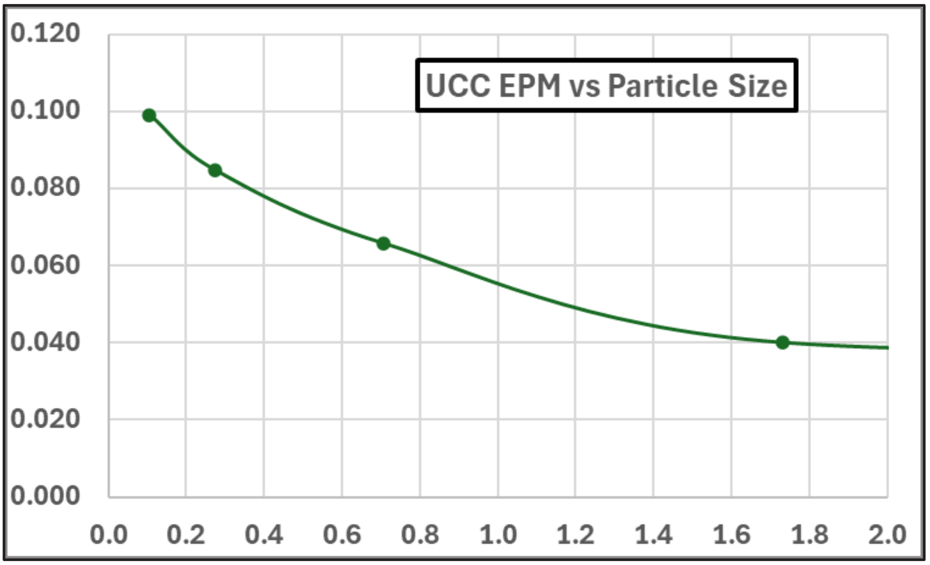

Fig. 10. Efficiency curve for UCC

3.4 Dewatering equipment

The fines can be dewatered on a HF dewatering screen or in a fines centrifuge.

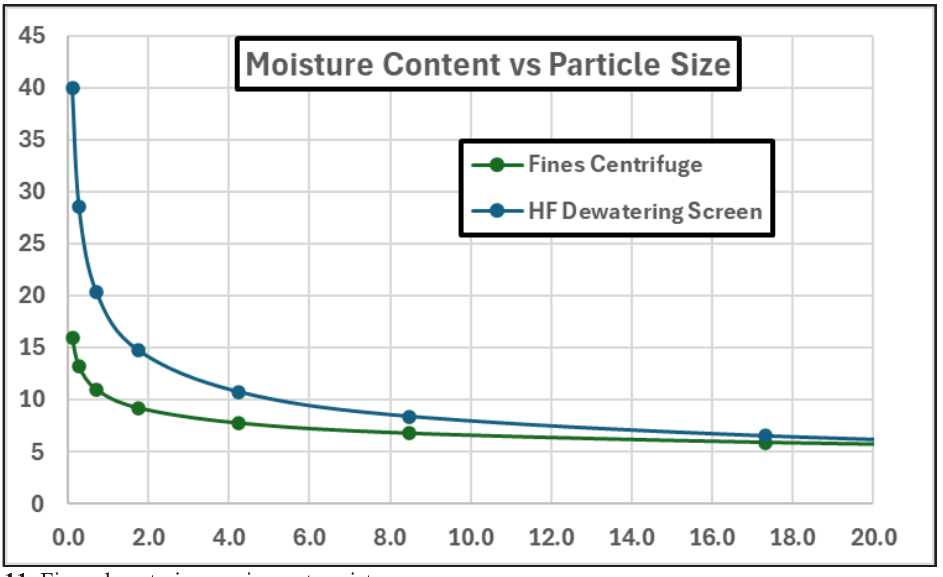

Fig. 11. Fines dewatering equipment moistures

Fig. **11** shows the moistures that can be expected per particle size for fines centrifuges and HF screens. The total moisture is calculated by weighting the particle size distribution with the moistures. Typically, a HF dewatering screen product is approx. 25% and the product from a fines centrifuge is of the order of 13% moisture. For this case, the coarse coal, 50 x 1mm, discharged from the drain and rinse screens is set at 7% moisture. The product moisture is the weighted composite of the coarse coal and the fines moisture produced by each particular configuration.

4 What can be produced?

The simulation is run to identify the "best product" that can be produced over the Life Of Mine. Additionally, should we treat the fine coal, -1mm, and how? NCVAR for coal is calculated using the formula:

NCVAR = (ADCV - (0.212 * Hyd) - (TM * 0.0245)) * (100 - TM) / (100 - IM) * 238.84
NCVAR = Net Calorific Value As Received in Kcal / Kg
ADCV = Air Dried Caloric Value in MJ/Kg
Hyd = Hydrogen, which has been set at 4%
TM = Total Moisture %
IM = Inherent Moisture %

It can be seen that the total moisture of the product is critical, as NCVAR depends on ADCV and Total Moisture. Each period the washability is run through the mine plan will feed coal onto a desliming screen, the fines and ultrafines extracted, and the oversize beneficiated in a DMC. The DMC and fines product is combined, and the DMC medium SG is controlled to produce the overall product NCVAR target quality.

The target qualities are: NCVAR 6000, 5700, 5400 and 5100. 4800 was looked at briefly but a single stage plant on this feed will not produce down to this quality, so a second stage could probably be used to produce a middlings product.

4.1 Price

Obviously, coal pricing is a moving target, but for this study, the pricing being used is shown in **Fig. 12**.

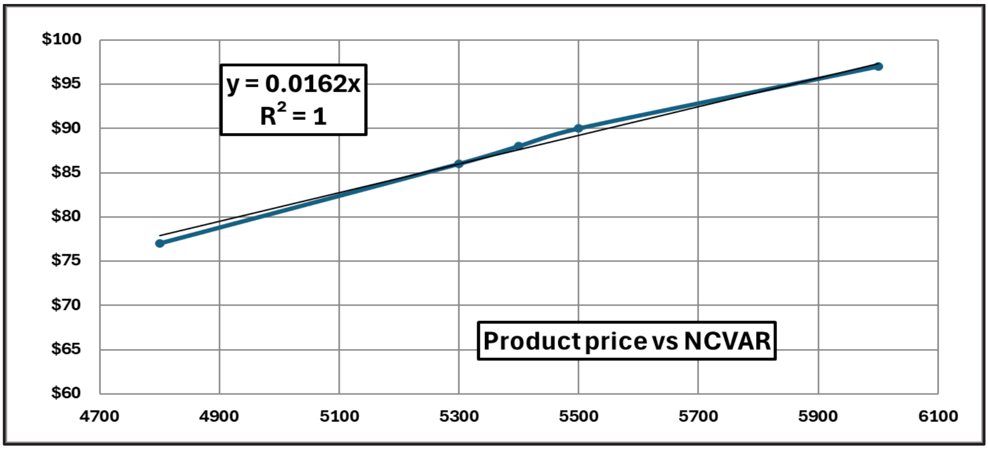

Fig. 12. Product price (US$/T FOB) vs NCVAR

5 Life of mine (LOM) runs

The same LOM will be beneficiated in the simulation using these configurations:

- No fines added back to the product

- Spirals treatment and HF dewatering screen
- Spirals treatment and fines centrifuge
- Up Current Classifier (UCC) and fines centrifuge.

The total product qualities specified are targeted but because the UCC cutpoint density can be changed, then each quality will also be targeted using UCC cutpoints of 1.5, 1.6, 1.65, 1.7, 1.75 and 1.8.

Within Limn it is relatively easy to size all the equipment "on the fly". Fig. **13**, shows the approximate plant feed tonnes per hour from the mine plan and the number of 810mm DMC cyclones required. Different size cyclones as well as screens, magnetic separators can be sized and a relative capital cost for each scenario can also be determined to enable a financial analysis against revenues.

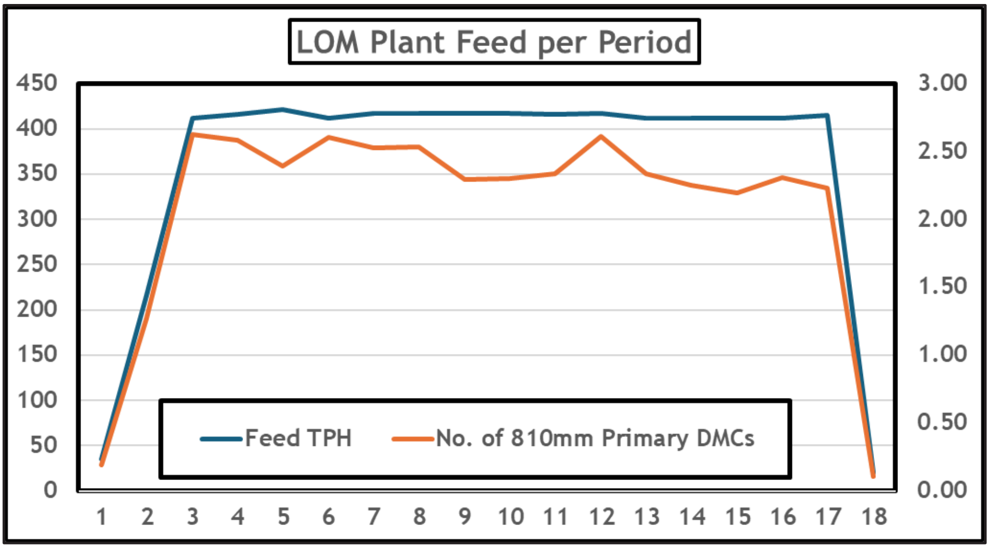

Fig. 13. Plant feed TPH and number of 810mm DMCs required

5.1 No fines added back to the primary product

This simulation is run with all fines being discarded. It should be noted that the 5 100 and 4 800 NCVAR product cannot be achieved in any period as the maximum cutpoint density of 1.9 is limiting.

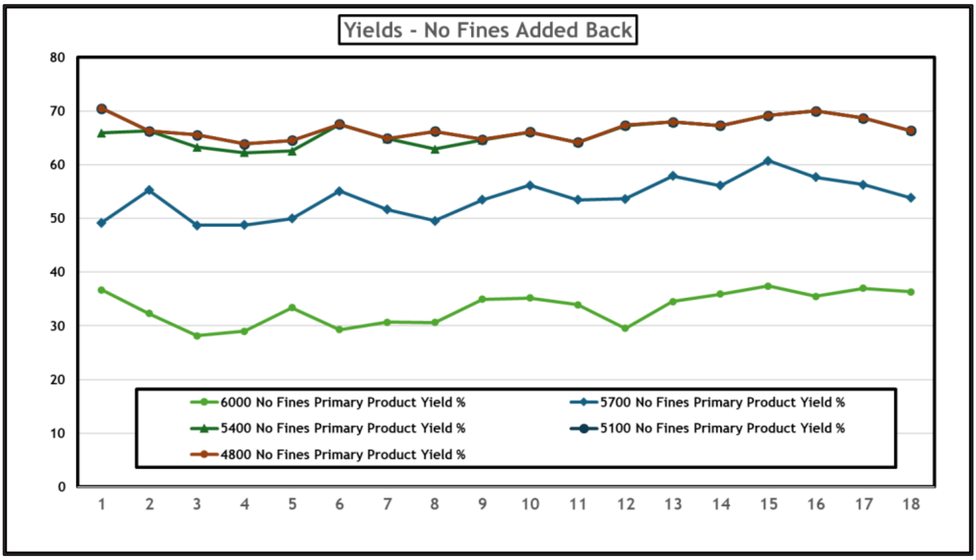

Fig. 14. Yields - no fines added back

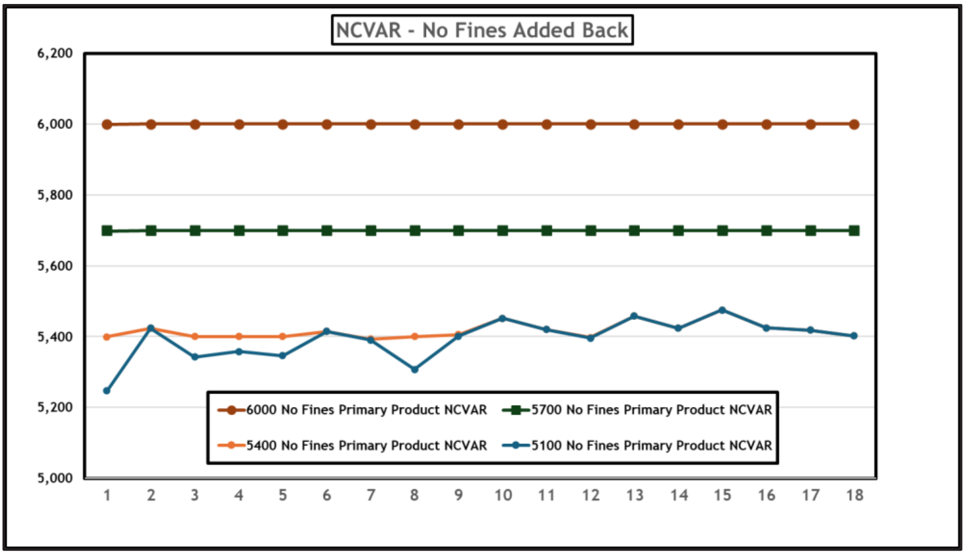

Fig. 15. NCVAR - no fines added back

Fig. **14** and Fig. **15** show that the yield for 6 000 is half that of some of the other qualities and that 5 100 and 5 400 cannot always be made. Fig. **16** shows the DMC cutpoints required for the LOM which shows the 5 100 product is too low for the reserve and stays at the maximum cutpoint, with same happening for the 5 400 product some of the time. Also, because of the maximum DMC cutpoint being reached, the results are identical to the 5 100 products.

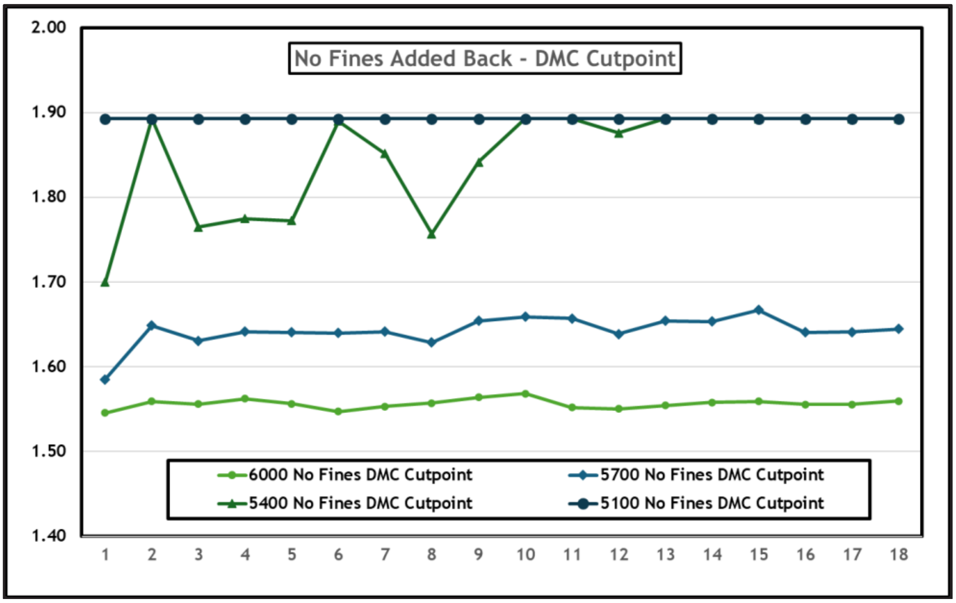

Fig. 16. DMC cutpoint - no fines added back

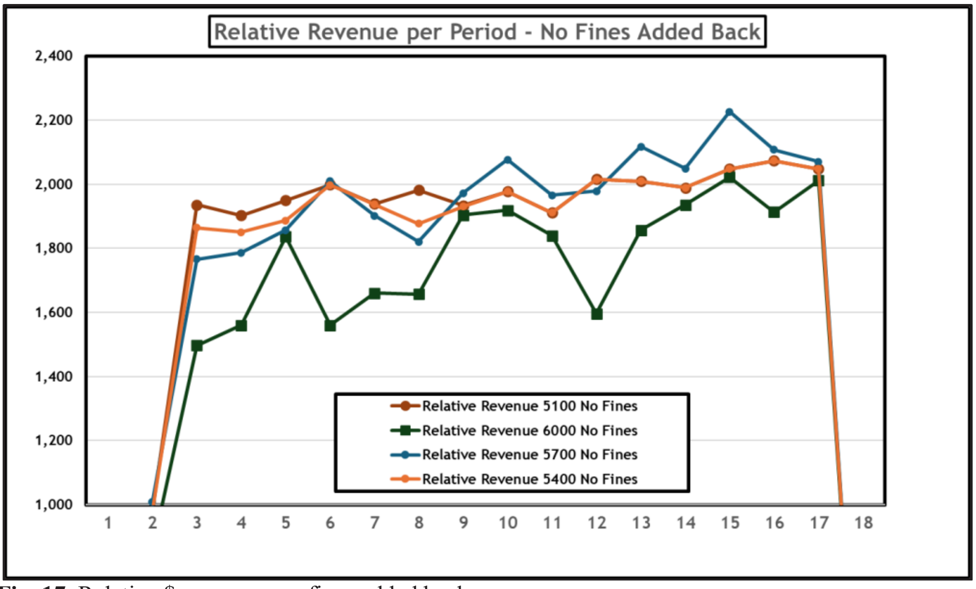

Fig. 17. Relative $ revenue - no fines added back

5.2 Spirals and HF screen

Treating fines with spirals and dewatering on HF dewatering screens is almost the default setup for South African coal washing plants. This is mostly because it is a cheap option which worked in the past and is perceived as being simple to operate. However, spirals generally cannot operate at cutpoint SGs less than 1.75 and HF dewatering screens generally produce total moistures of 25% and more. Spirals do need to be looked after as they are liable to beaching, which reduce their effectiveness.

Fig. 18 shows the fines product from the LOM plan feed, the NCVAR is approx. 4050, which means that the coarse plant must overwash to achieve the overall product quality.

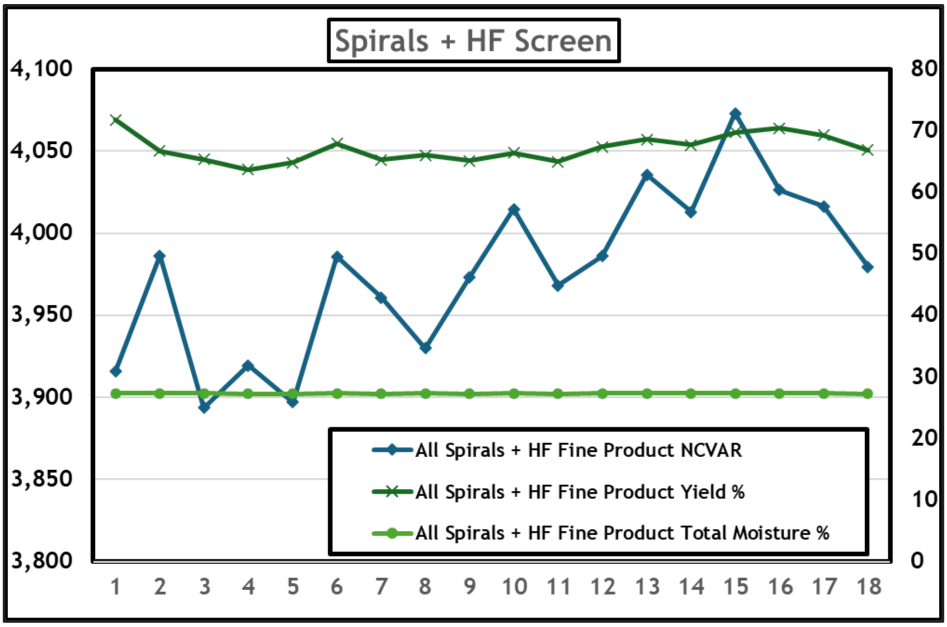

Fig. 18. Spirals & HF screens LOM fines product

Figure 19 shows the total product at multiple NCVAR total product targets. The quality only achieves specification for the 5 400 target. The 6 000 and 5 700 are not made because the ADCV required cannot be reached, and the 5 100 and 4 800 products cannot be met because the overwashing of the coarse coal increases the proportion of the fine coal to a point where the total product quality cannot be reached.

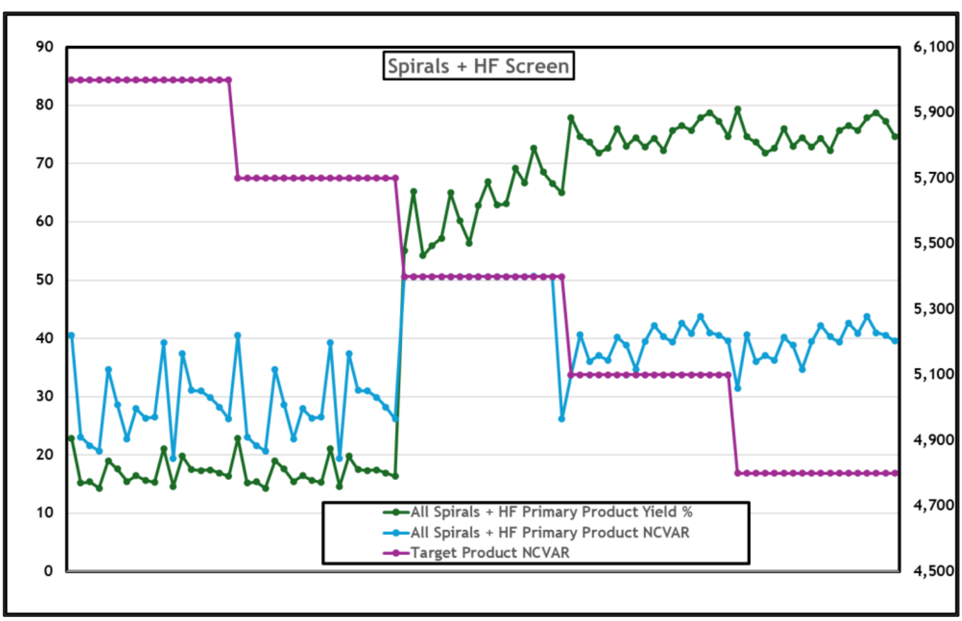

Fig. 19. LOM runs, fines treated in spirals and HF screens for 6000 to 4800 NCVAR

Fig. 20 shows the air-dry total product qualities for the LOM qualities at all the NCVAR targets.

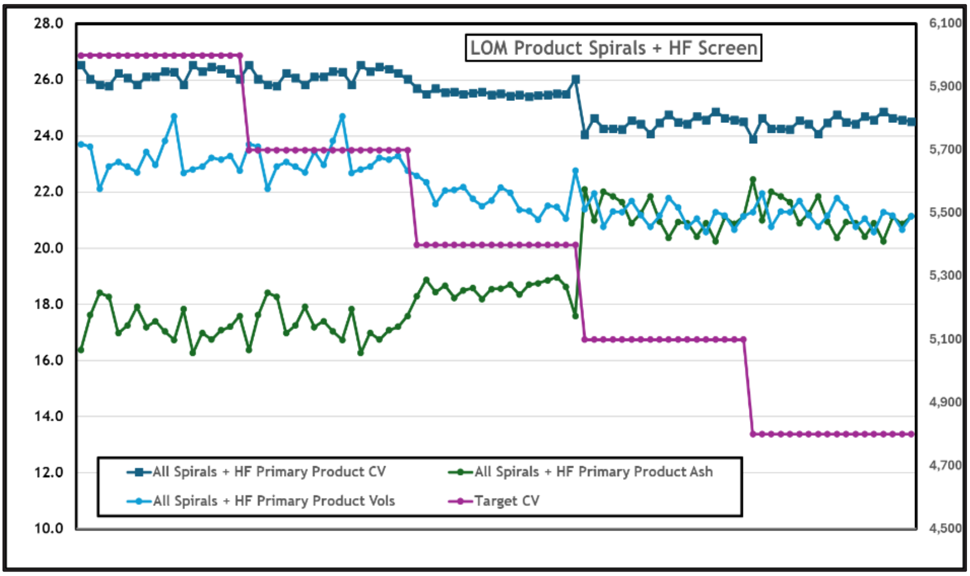

Fig. 20. LOM total product LOM air dry qualities

Fig. **21** shows the DMC reaching its maximum and minimum cutpoint SG.

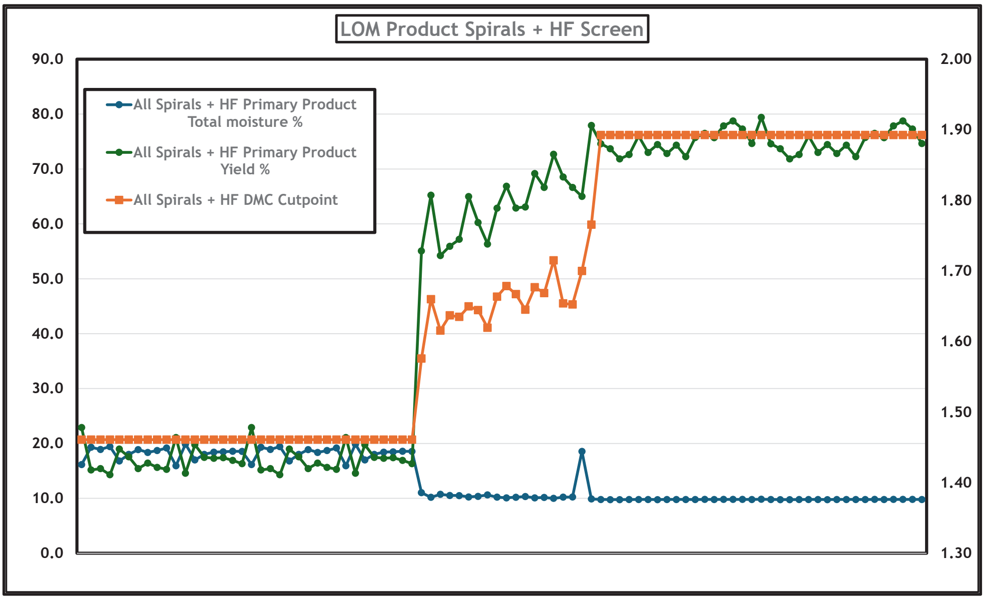

Fig. 21. LOM spirals + HF screens DMC cutpoint

5.3 Spirals and fines centrifuge

Treating fines with spirals and dewatering on fines centrifuges is often not done in South African coal washing plants. This is mostly because centrifuges are perceived as expensive and being more difficult to operate. The spirals still performs identically but fines centrifuges produce total moistures of 12 to 15% which increases the fines NCVAR, which means that the DMC circuit doesn't have to overwash as much as when HF screens are used.

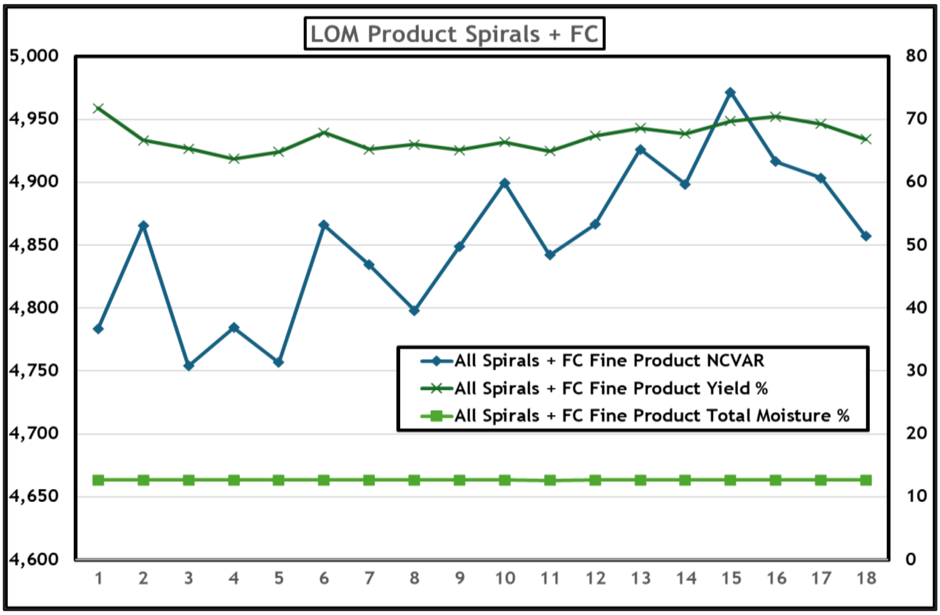

Fig. 22. Spirals and fines centrifuge LOM fines product

Fig. 22 shows the fines quality moves from around 4 050 to 4 950 because of the lower total moistures. Fig. **23** shows the 6 000 total product quality still cannot be made and the 5 100 and 5 400 products are over specification.

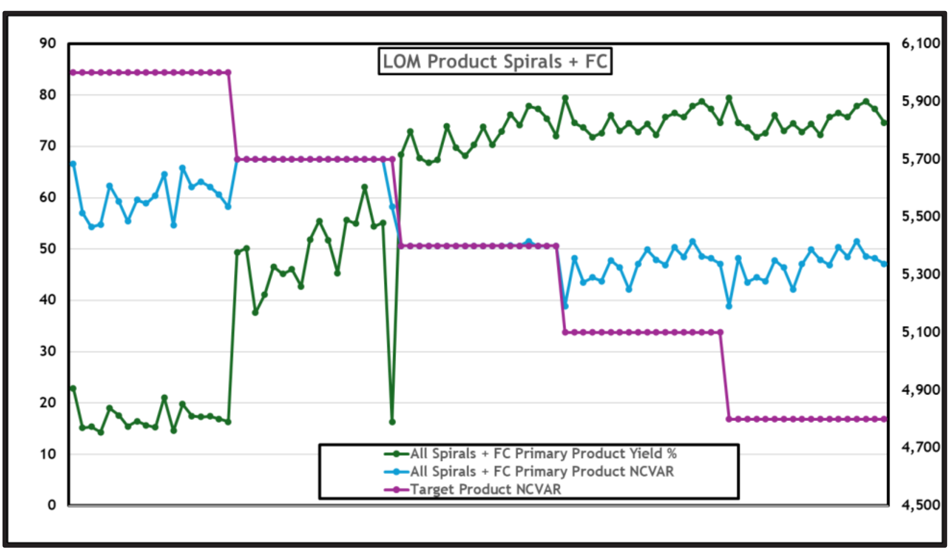

Fig. 23. LOM runs, fines treated in spirals and fines centrifuges for 6000 to 4800 NCVAR

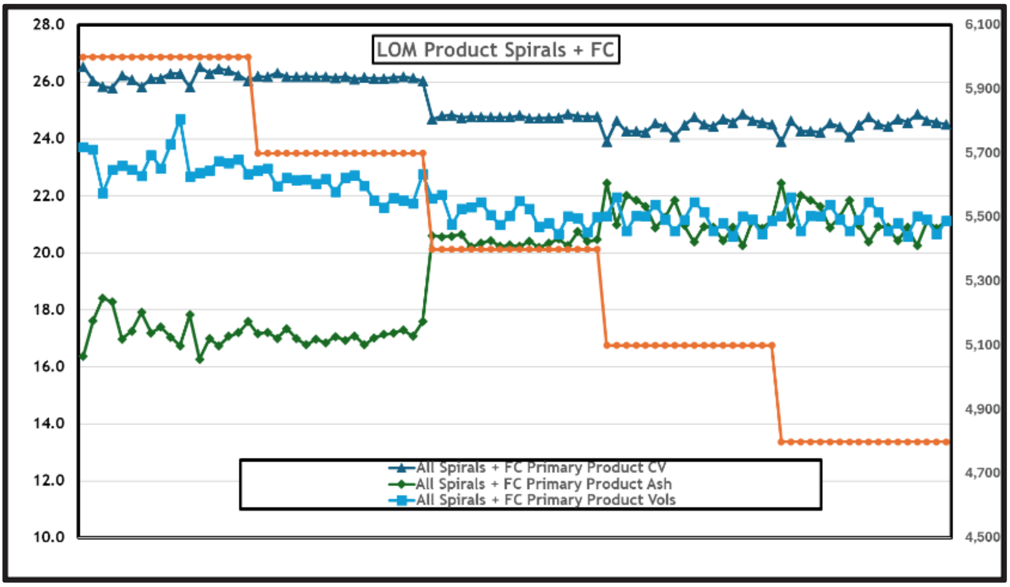

Fig. 24. Air dry qualities spirals + fines centrifuge

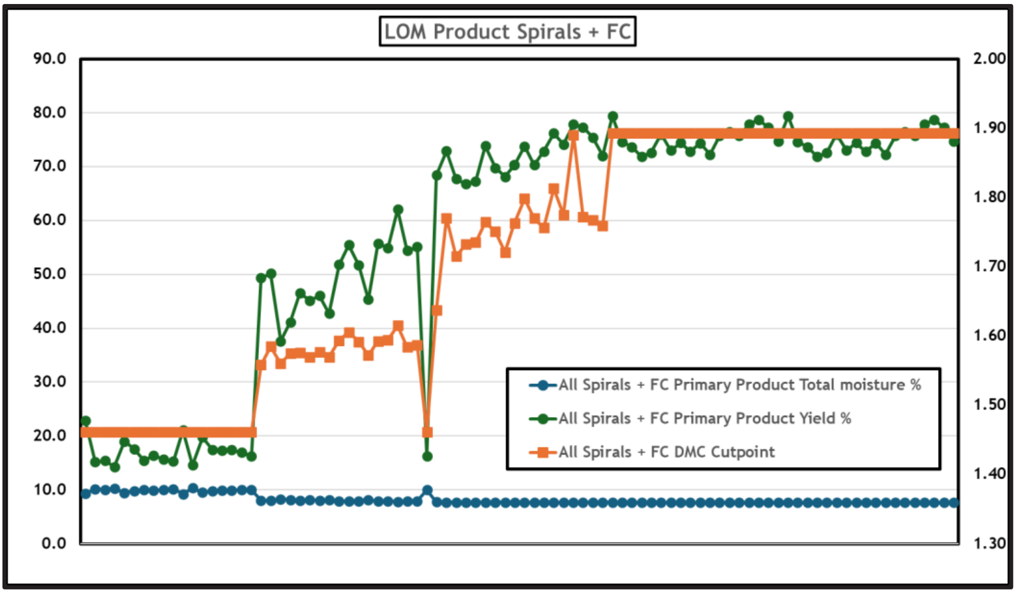

Fig. 25. LOM spirals + FC DMC cutpoints

Fig. 25 shows that because the fines product is closer to the target quality, it is easier to control the total product quality. The large difference in results from dewatered on a HF screen or a fines centrifuge shows that total moisture is critical when producing moisture adjusted product qualities. Fines centrifuges are not difficult to run if the installation is done properly and with thought. It is also important that fines are dewatered separately in their own centrifuge and not in a normal basket centrifuge together with the coarse material. Fines centrifuges are more expensive, but this can be trivial compared to the increased revenues that can be generated.

5.4 UCC and fines centrifuge

The important difference between spirals and UCC, such as Teetered Bed Separators (TBS) is the ability to change the cutpoint density by changing the bed density or upward water flowrate.

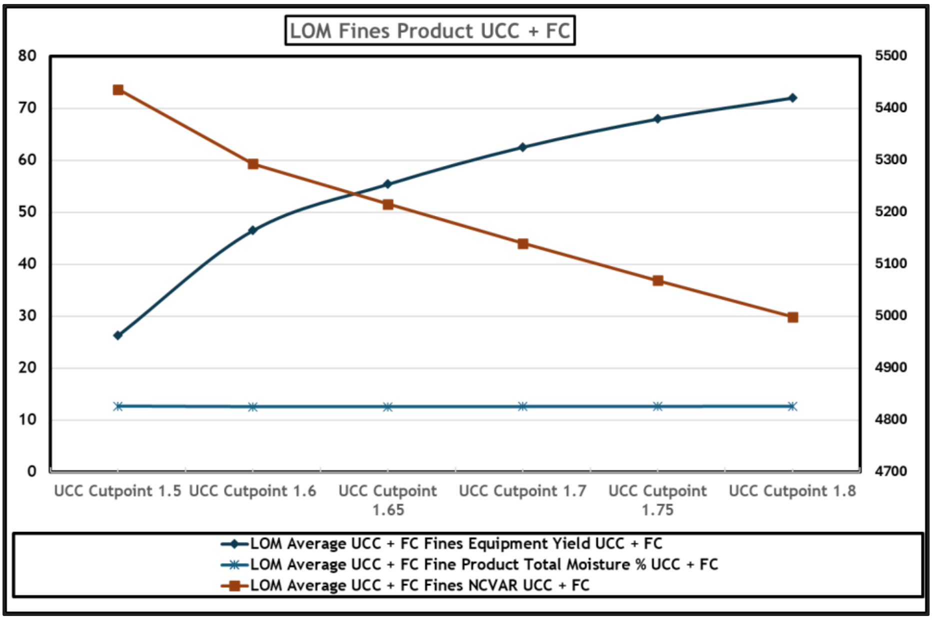

Fig. 26. UCC+ FC fine products, yield, moisture & NCVAR at different SGs

Fig. **26** shows that an UCC, if necessary, in conjunction with a fines centrifuge, can produce a fines quality in excess of 5 400, whereas spirals + fines centrifuge can only achieve 4 950.

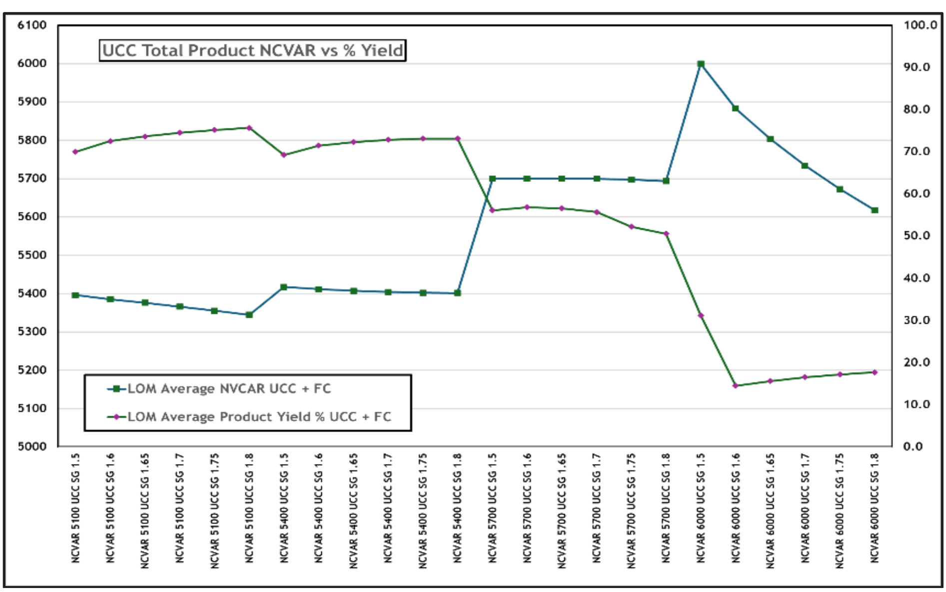

Fig. 27. UCC + FC total product NCVAR and yield at varying UCC SGs

Fig. **27** shows that the total product can be 6 000 NCVAR if the UCC is run at a cutpoint of 1.5. The lowest quality it can produce is 5 400. **Fig.** ***28*** shows the air-dry qualities that are produced using UCC and fines centrifuges.

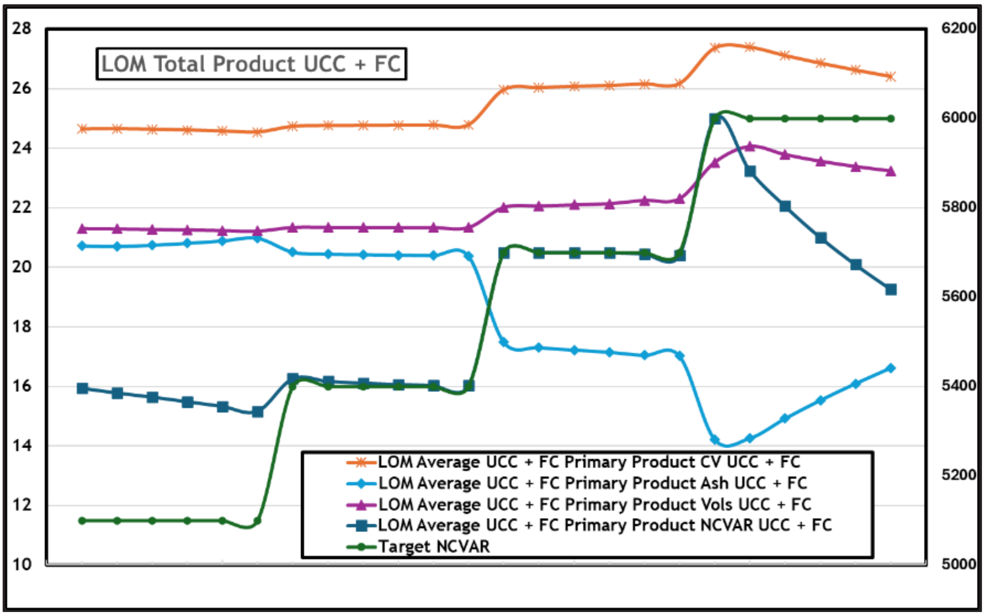

Fig. 28. Total product UCC + FC qualities

Error! Reference source not found. compares the differential revenues when aiming for varying NCVAR by varying the UCC density. It shows that aiming for a 6 000 product can be achieved but at considerably reduced revenues compared to lower NCVAR products. It also shows that the differential between 5 400 and 5 100 is small. Consequently, the higher quality should be easier to market and a 5 400 would be the favoured product.

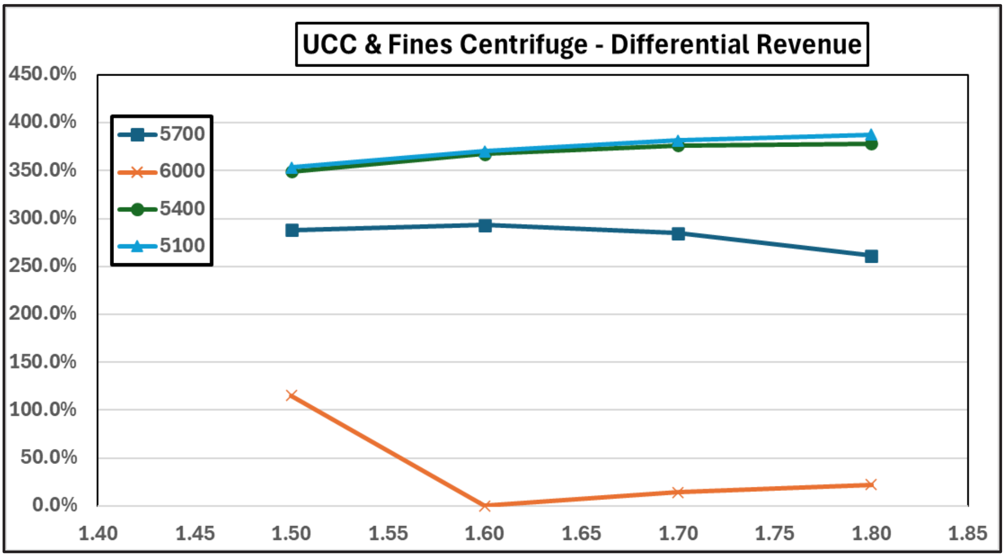

Fig. 29. UCC and fines centrifuge differential revenues

6 Comparative results

Fig. ***30*** compares spirals with UCC at varying cutpoints, with the products dewatered in fines centrifuges.

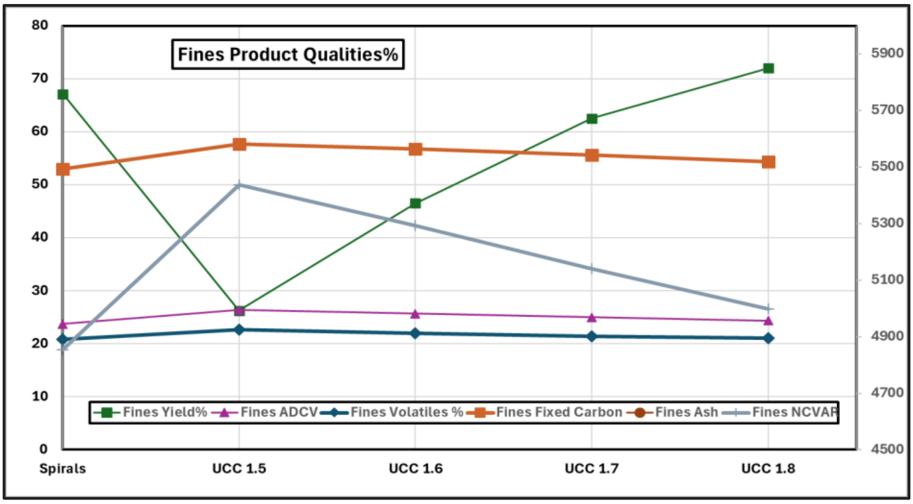

Fig. 30. Comparisons of fines only yields and qualities

The comparisons will be made using all the options:

- No fines added back
- Spirals + High frequency dewatering screen
- Spirals + Fines Centrifuge
- UCC + Fines Centrifuges 1.5 UCC cutpoint
- UCC + Fines Centrifuges 1.6 UCC cutpoint
- UCC + Fines Centrifuges 1.7 UCC cutpoint
- UCC + Fines Centrifuges 1.8 UCC cutpoint

All will be examined producing 6 000, 5 700, 5 400, 5 100 and 4 800 products.

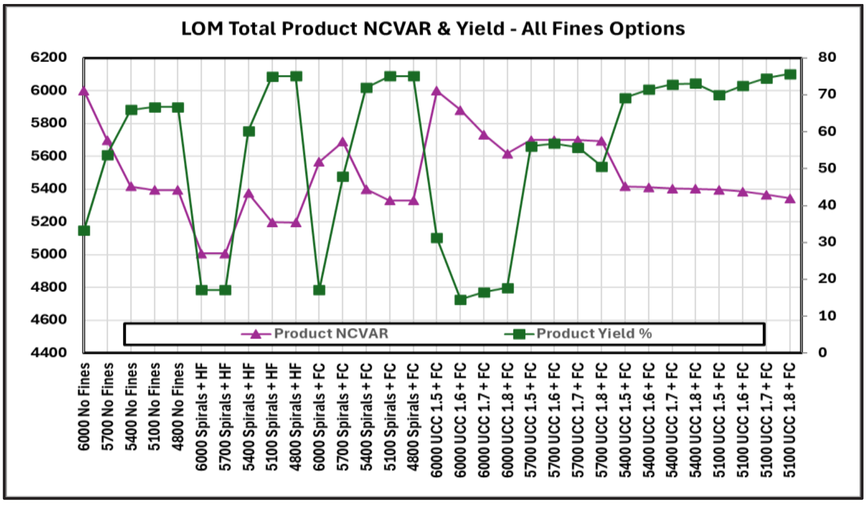

Fig. 31. All options total product yield and NCVAR

Fig. *31* shows the NCVAR and total yields for each case. Producing 6 000 and 5 700 total products are difficult, and yields are low. **Fig.** *32* shows the air dry qualities for each plant configuration.

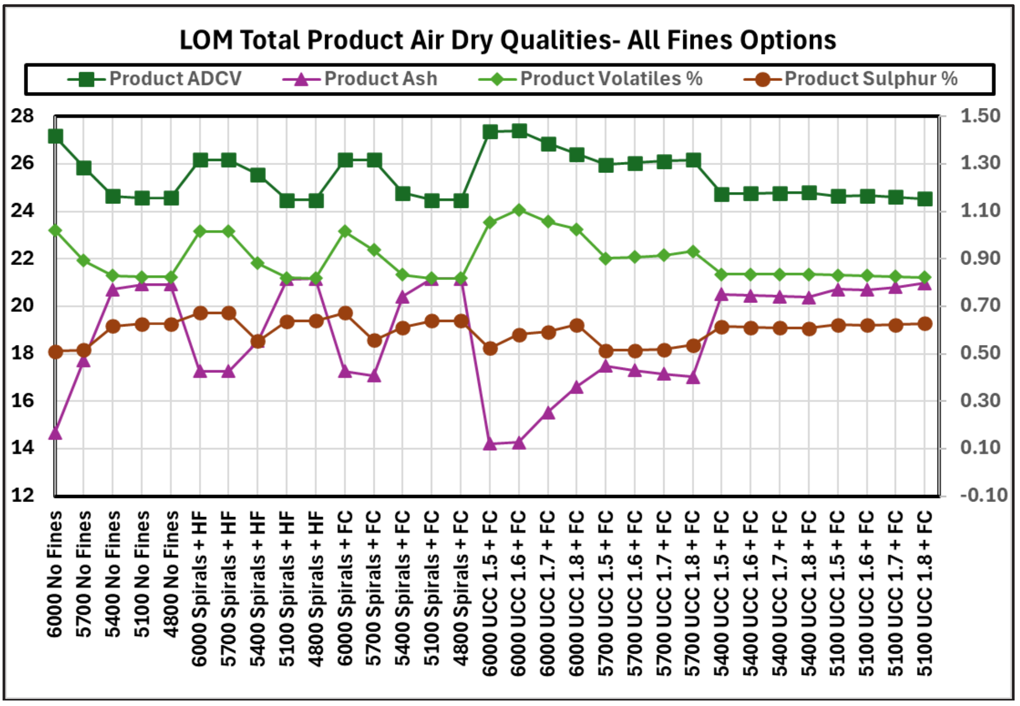

Fig. 32. Total product air dry qualities for all options

A 6 000 product can only be made if fines are discarded or a UCC cutting at 1.5 is used with similar yields. It should be noted that the revenues reported are based on the pricing graph, but the actual quality, for example 6000, may not be achieved.

Fig. *33* compares all the options and shows that the higher qualities are not economically advantageous despite the higher revenue. The comparisons are made against the lowest revenue option, which is the UCC cutting at 1.6 to make a 6 000 NCVAR product (achieved). Spirals plus HF screens is only feasible for a 4 800 or 5 100 product, which are potentially more difficult to market. Using spirals with a fines centrifuge is far better than using HF screens and makes a 5 400-product feasible even when using spirals.

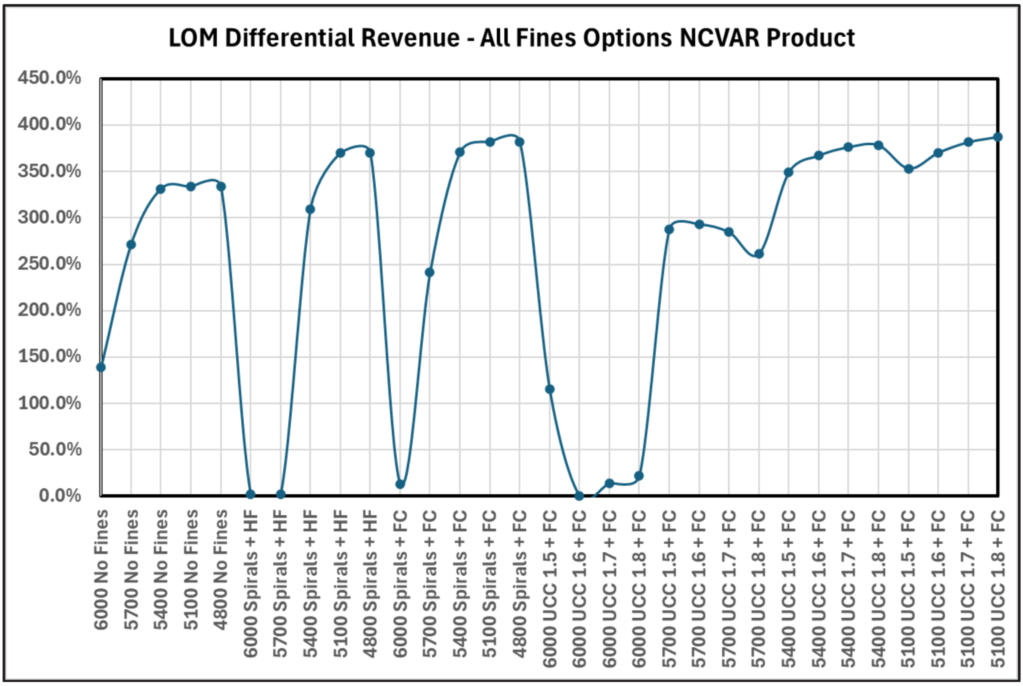

Fig. 33. LOM differential revenues for each option

7 Conclusions

The results from this specific case study show that a circuit using an UCC cutting at about 1.8 density and dewatering the fines product in a fines centrifuge to make a 5 400 product would be the best option.

It also shows that the dewatering of the fine coal is critical and that trying to save capital expenditure can result in not being able to make marketable products or at the least can result in huge reductions in revenue from the same coal. In summary, saving costs can be very expensive over the life of a reserve.

Using a simulator such as Limn:The Flowsheet Processor will result in more rigorous comparison of multiple options and help to ensure that a reserve can be exploited to its best advantage.

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