OPTIMIZING MANGANESE ORE SINTER PLANTS: PROCESS PARAMETERS AND DESIGN IMPLICATIONS

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ABSTRACT

In its most basic form, the process of sintering is very simple, and has been in use since the turn of the previous century. However, while the basic process is simple, control of the process relies on a number of extremely complex interdependent process parameters and requires a thorough understanding of the effect of these parameters on production capacity and product quality.

Further, as with many other processes, the process parameters and hence design details of visually similar installations are highly dependant on the specific feed materials.

While the industry trend has been towards an increase of capacity in order to lower unit production cost, typically in Iron ore sintering plants, this approach is not always possible for other commodities because of the scale of operation.

This paper seeks firstly to describe some design considerations of sinter plants; secondly, to report on results from testwork performed with a specific series Manganese ore blends; and last, to relate these results to the design of new small-scale Manganese ore sinter plants.

1. INTRODUCTION

The following report highlights the pertinent conclusions of a feasibility study by Pyromet Technologies (Pty) Ltd. for a new 250,000tpa Manganese Ore Sinter Facility in South Africa. As part of the study, sinter testwork was performed at Kumba's pilot plant in Pretoria, South Africa, on typical South African Manganese ores, as well as on some unique blends of Manganese ore, Ferromanganese baghouse dust and scrubber sludge from a local producer.

Important design considerations for a smaller scale plant are highlighted and the testwork that was performed as part of the study is described. The report also draws comparisons between the test results, literature and current operating practice. Wherever the conclusions were found to have an impact on the process design of a sinter plant, these factors are pointed out.

2. THE SINTERING PROCESS

It is assumed that not everyone who read this paper would be familiar with sintering, so a short description is given below:

The process of sintering is an agglomeration technique for fine ore that relies on heat to melt the surface of smaller particles together to form larger agglomerates. A typical sinter plant consists of a number of sequential operating units with the sinter strand at the heart of the plant. The simplified process sequence is as follows:

Raw materials such as ore fines, coke/coal, dust/sludge and in some cases slag modifiers and additives, are batched and conveyed to a blending system. The raw materials are blended in a rotating mixing drum with "Sinter Fines" and water to achieve a "Green Feed" in a process commonly referred to as "Nodulizing". The nodulized green feed is introduced to the sinter strand on top of a sized "Hearth Layer" to form the "Sinter Bed". This bed now passes through the "Ignition Hood" to initiate the reaction. Burners in the hood ignite the carbon in the green feed and the reaction is propagated by chemical reaction between the carbon and air sucked through the sinter bed by the offgas fans. The sinter burns through vertically while the bed moves horizontally towards the discharge end. The sintered material is discharged through a finger crusher onto a cooling strand, where ambient air is blown through the crushed material from below. After cooling, the sinter is conveyed to a crushing and screening station where it is sized and finally conveyed to product storage.

3. DESIGN CONSIDERATIONS

Despite all other demands which the design of a modern strand-type sinter plant possess, such as materials preparation and handling, as well as reasonably sophisticated controls and instrumentation, the sinter strand proper remains the core of the plant. Below are therefore outlined the design requirements and engineering approaches for the main components of the sinter strand. To a certain extent, very sophisticated computer software is utilised for these developments, such as Flo++ for Computational Fluid Dynamics (CFD) and MSC.Marc® for dynamic thermal stress modelling.

3.1 Pallet Cars

The pallet cars serve to convey the sinter along the strand and above the windboxes (wherein negative system pressure prevails), while the sintering process takes place.

The sinter strand can kinetically be regarded as an unlinked endless chain. The pallet cars are therefore subject to stresses resulting from:

- exposure to cyclic thermal variations due to the high temperatures experienced on the upper (sintering) strand and cooling taking place on the lower (return) strand sections,
- exposure to cyclic static loads from the mass of the green feed/sinter,
- exposure to cyclic dynamic loads from the forces imparted by the drive sprockets, as well as by the pallet cars against one another.

While the development of strand-type sinter plants and their component materials have been going on for well near a century, the fact remains that the above described arduous duty will fatigue the most suitable materials (e.g. HS Meehanite® and similar cast irons) within a limited number of cycles. The major European operators of sinter plants therefore base their pallet cost estimates upon an average service-life of 10 years, at somewhat less than 8000 hours per year.

The choice of materials and shapes of the components of the pallet cars is further governed by the following requirements:

- minimal pressure drop through the grate bars,
- maximum abrasion resistance of the grate bars,
- maximum ductility and abrasion resistance of the cheekplates in respect of sliding motion of green feed and sintered material against same,
- quick exchangeability of worn or otherwise unserviceable components by unskilled labour.

3.2 Sinter Strand Drive

The (non-linked) pallet cars are pushed along the top strand of the machine's frame by the drive sprockets, which are fitted with shrink-discs on a common shaft. The sprockets are equipped with replaceable tooth segments, precision-cast from special steel. The teeth impart a rolling action upon the inner wheels of the stub axle assemblies, of which four are attached to each pallet car. Note that the outer wheels of the stub axle assemblies serve to guide the pallets at their return points, i.e. at the drive and discharge stations, while the inner wheels carry the static and dynamic loads as the pallets are pushed along the strand.

The drive of the sinter strand is normally not located at the discharge end of the strand, for reasons of heat and serviceability. Prime mover options are:

- electro-mechanical, with Variable Speed Drive (VSD).
- electro-hydraulic, with variable displacement pump or motor.

Dual or single drives can be fitted. The main considerations in the choice of drives and drive arrangements are given to:

- reduction of overhung loads, by use of shaft-mounted planetary gear-boxes,
- speed range,
- serviceability.

3.3 Take-Up Mechanism

This serves to compensate the differential thermal expansion between the moving pallet cars and the machine frame with the rails and windboxes, while maintaining adequate pressure to avoid separation of the pallet body faces. Take-up mechanisms are generally automatic by means of counterweight/pulley systems, or hydraulic.

The benefits of a hydraulic system are:

- minimum pressure can be dialled-in to reduce frictional wear between the pallet body faces,
- replacement of single pallet assemblies (opening the strand) is facilitated by the use of a double-acting cylinder (or cylinders).

While some suppliers have in the past for very valid technical reasons provided large strands, where the take-up station is located at the discharge end of the strand, for smaller machines it is more feasible to provide that facility at the cold drive end. In either case, the respective station must be designed as a mobile unit, either mounted on a wheel/rail arrangement, or suspended from it. An accurate guiding mechanism, which allows alignment of the drive station on the centre-line of the strand, is essential.

3.4 Crash-Deck and Finger Crusher

The crash-deck serves to guide the sintered material, as it is discharged out of the pallet cars, into the finger crusher. As the crash-deck is subject to severe impact and abrasion, it is heavily lined. In one case at Sidmar in Belgium, on a 5,8 m wide machine of about 8 million tpa capacity, the crash-deck is lined with ceramic cubes of 300 mm square cross-section, 500 mm high. The life span of these liners is quoted to be one year – i.e. the duration between the yearly scheduled plant maintenance periods. For plants of smaller capacity (in the range of several 100 000 tpa) the lining of the crash-decks with hardwearing plate (Hardox®, Ti-Hard), or even cast (e.g. Titanium Carbide alloys) is normally adequate.

The finger crusher reduces the lumps of sinter cake to a size smaller than 150 mm, in preparation for cooling and secondary crushing. As the sinter cake retains a temperature of about 850 degrees C upon leaving the strand, the finger crusher operates in a very hostile environment.

This fact is addressed with the following design features:

- exchangeable fingers/finger-wheels,
- shielded bearings,
- water-cooled shafts (on larger machines),
- quick exchangeability of complete shaft assembly, incl. fingers, bearings and bearing shields. This necessitates the facility for easy removal of the dust canopy, as well as easy disconnection of the crusher drive. On some existing plants, the operation is performed in a couple of minutes with the help of an overhead crane.

3.5 Ignition Hood

Ignition hoods can be described as refractory lined steel boxes, in which two or more horizontally opposed burners are arranged. Any kind of fuel, like fossil fuels or furnace off-gas can be used as heat source. Vertically operable doors shut off the faces of the ignition hood down to the top level of the green feed, in order to minimise heat losses. The duty of the ignition hood has been explained above.

To meet these requirements, the ignition hood must be equipped with the following features:

- the burner flames must operate with low velocity, to avoid disturbance of the green feed bed,
- a flat flame shape is beneficial for fast and even ignition of the green feed,
- adequate provision must be made for the controlled supply of cooling air to the burners, so that the requisite flame temperature can be dialled-in,
- the operation of the burner controls must be easily understandable,
- all controls must be fail-safe,
- pilot flames must be reliable, e.g. if the burners are operated run with gas of low and/or fluctuating calorific value, like furnace or coke-oven gas, it is recommended that the pilot flames be operated on Liquid Petroleum Gas (LPG).

4. SINTERING TESTWORK

Generally speaking, the testwork goals were threefold; firstly to confirm certain pre-selected process parameters (based on existing Manganese-Sinter producing plants), secondly to assess the recipes in terms of production capacity of the envisioned plant, and finally to obtain design information specific to a new sintering facility.

Changing parameters such as % Coke addition and to a lesser extent also % Water addition is normally used to reach an optimization point for a set of operating parameters. If the set of conditions are chosen adequately close to target, optimization is judged by the Sinter Fines Ratio (weight of fines generated / weight of fines returned to green feed) that needs to be as close to 1 as possible (a sinter is considered to be “in” if the ratio is between 0.95 and 1.05).

If water and reductant variations fail to converge the sinter fines ratio, it can only be further optimized by changing the Sinter fines input[1] to the green feed mixture for a set bed depth and (suction) pressure drop.

4.1 Process Parameters

The following process parameters were initially identified and set at the indicated, pre-selected values:

- Pressure Drop = 800 - 900 mm Water Gauge (WG)
- Bed Depth = 250 mm
- Ignition Time = 1.5 min
- Ignition Temperature = 950°C
- Hearth Layer = 30 mm
- Return Fines = 25% of Sinter

Some of the selected parameters for the tests were based on information from existing plants while others were based on information obtained from literature.

4.2 Recipes

The recipes were chosen based on projected operating requirements of a local Ferromanganese producer.

Summarized they consisted of the following:

- the “Base Case”, containing ore but no dusts or sludges,
- the “11DSF Unpelletized”, with 11% dust and sludge added to the ore fines, and
- the “11DSF Pelletized”, with 11% dust and sludge addition, but this time pre-pelletized prior to mixing with the ore fines.

5. RESULTS AND DISCUSSION

The following discussion is based on a mixture of information obtained from existing operations, a thorough literature review, observation and analysis of the raw data as reported after each test. A table indicating results of all the tests is included in Table 2.

5.1 % Water Addition

Water is added to the sinter mixture for a variety of reasons, the most important being the propagation of agglomeration of fine dust onto the larger particles during the nodulizing process. This together with nodulizing time plays a pivotal role in the control of the permeability of the sinter mixture and consequently the sinter cake.

However, it also influences the quality of the sinter cake (cold strength) and the production rate, yield and sinter fines ratio. Literature references and existing operators emphasize the importance of moisture control for these reasons.

From the limited literature available on sintering of manganese ores, typical water addition rates are very high (7 to 14% of the feed)[3][4] compared to those used at existing operations (3,5 to 5%). Since the ores used in the reported testwork are very similar to those used at the existing plants (successfully) the tests were started on 4% water addition.

This parameter was quickly optimized during the tests and stabilized at 3.8%, 4.4% and 4% for the Base Case, 11DSF Unpelletized and 11DSF Pelletized respectively.

It should be noted that water addition is a parameter that can be easily further optimized during commissioning of a full-scale plant and is not considered as critical per se. However, control of the optimum water addition definitely is critical for stable operation and adequate provision for this should be made during design.

5.2 % Coke Addition

The sintering reaction is propagated by smelting of the surface layer of individual particles and fusing them together. The heat (energy) available for this reaction is controlled by the reaction between carbon added to the mixture and oxygen from air sucked through the bed. The interaction between these two parameters is complex and plays a big role in determining the process outputs i.e. yield, production rate, sinter fines ratio and quality for a given set fixed process parameters.

It is important to note that none of the different process parameters (pressure drop, yield, production rate, ignition temperature, carbon addition etc) are totally independent from each other. However, the amount of carbon added to the green sinter feed is possibly the most critical to control since it determines the behaviour of the bed during sintering and also influences the cooling properties to some extent.

Typically, with too much carbon in the mixture, the bed is fused too far and starts to close up, preventing air flow through the bed for a fixed pressure drop. This in turn leads to long sintering times and low production rates. In contrast, too little carbon in the mixture prevents adequate sintering and increases the amount of fines from the process, at the same time lowering the yield.

During testwork a set of parameters is chosen based on the best available data for the specific green sinter mixture. The amount of coke added to the feed is varied and the effectiveness of sintering is judged by the amount of fines (< 5 mm fraction) produced by the process (essentially unsintered materials). Depending on the ratio of input to output fines, the amount of coke is adjusted.

In the test campaign it was found that the sinter fines ratio on the 250mm bed did not converge on any of the conditions tested even though the coke addition was increased from a low of 4.0% up to a maximum of 7.25%. For the Base Case, the closest value obtained for a pressure drop of 900 mmWG was 0.92 with a coke addition of 6.3% after which it began to drop again. Similarly for the DSF conditions, at 900 mmWG, the highest value for Sinter Fines Ratio was 0.864 at a coke addition of 5.85%.

From these observations, it was decided to lower the pressure drop to attempt to further optimize the process.

5.3 Pressure Drop

As stated before, propagation of the sintering reaction is controlled by the amount of carbon and air in the system, providing the energy for reaction. On full-scale production plants, it is difficult and impractical to control the airflow through the bed and as a consequence, pressure drop is controlled rather than airflow. The amount of air sucked through the bed is dependant on the permeability of the mixture for a specific pressure drop and therefore may vary along the length of the strand due to changes in permeability.

Pressure drop through the system is kept constant at a predetermined level by suction of the gas cleaning system fans. Control of individual suction boxes is possible online but not necessary, save for those under the ignition hood. Ignition takes place at about 180 mmWG, largely independent of the bed depth, but sintering pressure drops are linked to bed depth.

Since no convergence of sinter fines ratio was reached at a 900 mmWG pressure drop with increasing amounts of coke, the pressure drop was lowered first to 700 and subsequently to 550 mmWG. Slight improvements were observed both on the Base Case conditions (max 0.94 ratio at 5.3% coke), and on the 11DSF conditions (max 0.93 ratio at 5.85% coke) at a pressure drop of 550 mmWG.

However on these conditions the production rate and to a lesser extent also the yield were negatively affected. It was therefore clear that another parameter needed to be changed to force convergence of the sinter fines ratio while still maintaining acceptable production rates and yields. The only other option available was to change to a deeper bed.

5.4 Bed Depth

Practically, there are a multitude of sinter plant configurations possible for any given production rate. Varying the width, length or depth of the bed has slightly different impacts though[5]. Existing South African plants use fairly deep beds, as do most of the references in literature[3][4].

The major effect of a deeper bed stems from the relationship between surface area and volume of sinter produced. With increasing bed depth, the ratio of volume to area increases and less unsintered surface fines can be expected. This should impact on yield and sinter fines ratio, but not necessarily production rate.

As a rule, provided that the pressure drop is adjusted, production rates are not affected because at a fixed vertical sintering velocity (speed of burn through the bed), it requires a proportional amount of time for differing bed depths. However, it may impact on the horizontal speed of the sinter strand since the burn-through point would shift with sintering time.

For the test campaign, the effect of a deeper bed (at 380 mm) was immediate and extremely effective. Due to time constraints and based on previous results, only the 11DSF Unpelletized mixture was tested on the deeper bed. On the very first test with the deeper bed the sinter fines ratio was considered to be "in" at 1.05. Conditions for this test were the same as for the last of the 250mm bed test at 5.35% coke, 4.4% water and 550 mmWG.

Because of the slight overshoot of this convergence, it was decided to test the limits of the condition at a higher pressure drop to increase the production rate. The optimum conditions were easily found at 650 mmWG, 5.25% coke, and 4.4% water.

5.5 Ignition Time

Ignition of the green sinter feed is by burners fired on conceivably any source of fuel. Ignition time is not considered to be a critical parameter as long as the coke in the top layer is sufficiently ignited to propagate the reaction further through the bed.

Depending on the ore source, the ignition time may vary from 0.5 to 2.0 minutes, but from experience, an ignition time of 1.5 minutes was considered sufficient.

All the tests used a fixed ignition time of 1.5 minutes and were not considered necessary to optimize further.

5.6 Ignition Temperature

Contrary to ignition time, ignition temperature can be considered as critical. The temperature during ignition controls the quantity of the top layer[4] and as a consequence also the yield of final product from the strand[2].

In addition it may also influence the quality of the final product (strength), product yield and production rate. On some plants it has been observed that thermal shock from too high ignition temperatures leads to crack formation across the sinter bed where short-circuiting of airflow is experienced. In areas adjacent to these cracks, incomplete sintering is experienced; considered to be the major cause for lower yields, lower production rates and poor quality sinter.

For this test campaign an ignition temperature of 950°C was used throughout, based once again on experience. While existing operators use slightly higher temperatures, 950°C seemed to work well and no adverse effects were experienced with slight variations at this level.

As a side note, it should be said that the temperature of ignition and energy required for ignition are not the same and should not be confused with each other. Further, these two parameters should ideally be individually controlled which is very often difficult on a sinter plant. For those who are sceptical about this statement, consider the following:

A propane flame from a cigarette lighter may reach a temperature of around 2500°C. However, to ignite a bed of 1.2m width with a single lighter will require a very long (ignition) time and slow down your strand to an imperceptible crawl. Added to this, is the fact that you must cool down the flame to 950°C by cooling air to prevent thermal shock, thereby increasing the volume of combustion offgas. (Note that the energy content is the same in both cases, but that the energy density and temperature of the pure propane flame offgas is much higher than that of the cooled gasses).

Now in order to speed up your strand to more reasonable speeds, just use a larger lighter while applying the same principles.

5.7 Hearth Layer

The hearth layer (or grid layer) has essentially one, non-critical function – to prevent damage to the pallet cars and grid bars caused by sintering of the cake to the hearth. It has been reported in literature that some mixtures made from specific low-grade iron ores do not even require a hearth layer. This is however not applicable to the Manganese case.

The thickness of the hearth layer chosen for the tests was based on the original design specification and practical experience of existing operators (at 30 to 50 mm).

From experience, using 10kg of hearth layer for each sinter test (somewhere between 30 and 50 mm) seemed reasonable for the application and was used throughout the campaign successfully.

Slight effects of hearth layer thickness and size distribution on the permeability of the sinter cake can be expected but remain insignificant for all practical purposes.

One concern raised during the tests and confirmed by the raw data is that there may be a problem with the continuity of supply of the recirculating hearth layer. In most tests there were not enough particles of the correct size range to supply the hearth layer for the next test. It should however be noted that the test procedure for handling the sinter is only a simulation of what is expected and the case for each plant will differ depending on the crushing circuit downstream of the sinter process.

5.8 Yield

The yield of a sintering process is expressed in logical terms as the amount of sinter produced versus the amount of raw material you feed into the process.

Depending on the battery limit of the calculation, (strand end or final product) the result of the calculation may be different. The first will therefore only indicate losses due to LOI and dust sucked through to the offgas while in the latter the total fines fraction (<5 mm) is subtracted prior to calculation.

The "LOI yield" for the optimized case at 380mm bed depth was 78.19 and by subsequent calculation the "product yield" was found to be 76.27%. From an analysis of the input materials, an LOI of around 20% is expected which correlates well with the calculated figures.

5.9 Production Rate

The production rate or production index has become the norm by which the capacity of a sinter plant is judged and is usually expressed as the mass of sinter produced per square meter of active hearth area per 24 hours.

Some confusion concerning the definition of active hearth area as well as the battery limit of this calculation (strand end vs. final product) has led to much speculation on the actual production capacity of some sinter plants. It is therefore prudent to define these terms before continuing:

Firstly, the battery limit for the mass of sinter produced is after the final product screens. It therefore excludes those fines which are recycled to the green sinter feed and ignores the hearth layer fraction, which is considered to be a continuously recirculating load.

Secondly, the "active hearth area" is defined as the total area available for sintering from the start of the ignition hood inlet to the burn-through point. (Note that if a specific type of ore burns through quicker than another on the same strand, it does not automatically mean that the production rate will be higher.) The strand speed needs to be adjusted to push the burn-through point to the end of the strand in order to increase the active strand area, this in turn increasing the production rate.

From the test campaign, the burn-through time (or sintering time) was typically in the region of 8 to 10 minutes with a pressure drop of 900 mmWG on a 250 mm deep bed. This related to a production rate of around 28ton/m^2/24hr. However, reaching this point after only 9 minutes on average meant that to utilize the total strand length (to increase the active area), the strand will need to run at approx 2.8 m/min for a production capacity of 250 000 tpa.

With a pressure drop of 550 mmWG, the sintering times increased to around 11 minutes on average. Corresponding figures of approx 24ton/m^2/24hr and 220 000 tpa were typical but strand speed did not improve.

However, with the deeper bed (380 mm) at a pressure drop of 650 mmWG, the optimized case delivered figures of approx 27ton/m^2/24hr and 250 000 tpa for a strand speed of only 1.5 m/min. This speed is much more reasonable and in terms of the current design delivers much more flexibility for control.

5.10 Sinter Fines Ratio

A lot has already been said about the sinter fines ratio in the preceding sections since all the optimization routines were judged by this parameter.

It may be prudent to add that the ideal is to aim for a ratio of 1 at which point the amount of fines generated is equal to the amount returned to the green feed and the process is in equilibrium. On full-scale plants the sinter fines ratio is usually allowed to vary between 0.95 and 1.05, necessitating the need for buffer storage.

The testwork never reached these limits with the 250 mm bed but were easily controlled between these limits with a bed depth of 380 mm on suctions of 550 and 650 mmWG.

6. CONCLUSION

Table 1 indicates the design implications realized from the test campaign. The different options are all arbitrary permutations of a basic design and are meant to be used for comparison of design parameters. The list is by no means exhaustive. Option X indicated in the last column represents Pyromet's interpretation of an ideal configuration for a compact Mn-ore sinter plant capable of 250,000tpa.

Several improvements to existing designs are possible if due consideration is given to the fact that the feasibility study called for a fairly small plant (compared to Iron Sinter Plants) with a specific Manganese ore in mind. Not all of these can be randomly applied to any sinter plant and any ore mixture. If anything, the testwork highlighted the necessity of designing every sinter plant around the specific feed materials.

Table 1. Comparison of design parameters and capacities.

	Units	**Base**	**Option A**	**Option B**	**Option D**	**Option F**	**Option G**	**Option H**	**Option C**	**Option E**	***Option X***
No of windboxes	**off**	12	13	13	13	13	14	14	15	15	***11***
Active Length	**m**	23.31	25.26	25.26	25.26	25.26	27.20	27.20	29.14	29.14	***22.00***
Strand Width	**m**	1.2	1.2	1.2	1.2	1.5	1.2	1.5	1.2	1.5	***1.5***
Grate Area	**m^2**	27.97	30.31	30.31	30.31	37.88	32.64	40.80	34.97	43.71	***33.00***
Bed Depth	**mm**	250	250	250	380	380	380	380	380	380	***400***
Sintering Time	**min**	9.95	9.95	9.95	16.6	16.6	16.6	16.6	16.6	16.6	***17.47***
Strand Speed	**m/min**	2.34	2.54	2.54	1.52	1.52	1.64	1.64	1.76	1.76	***1.26***
Spec. Prod. Rate	**$t/m^2/24h$**	24.17	24.17	24.17	27.12	27.12	27.12	27.12	27.12	27.12	***25.7***
Disch. Capacity	**tph**	28.17	30.52	30.52	34.25	42.81	36.88	46.10	39.52	49.39	***35.34***
Availability	**%**	81%	81%	90%	90%	90%	90%	90%	90%	90%	***81%***
Annual Capacity	**tpa**	199884	216562	240625	269994	337492	290787	363484	311538	389422	***250741***
Capacity Increase	**%**	0%	8%	20%	35%	69%	45%	82%	56%	95%	***25%***

The most important conclusion to be drawn from the tests is that the ore mixture performed noticeably better with the deeper bed and implementation of this design (say up to 400mm) on future plants is recommended. Sinter fines ratios and strand speeds for the deeper bed were much more acceptable (in fact in line with the most modern plants) while maintaining the required production capacities. An added benefit of the deeper bed is in the coke consumption, which dropped from approx 120 to 100 kg/ton sinter.

The second important conclusion from the testwork is that even with the increased bed height, some flexibility exists in terms of the pressure drop required through the bed.

The tests at 550 mmWG performed almost as well as those at 650 mmWG. While this could possibly be further optimized on a 400 mm bed, the specification of the offgas fan for the Pyromet design falls within this limit and should be less expensive than those specified originally at 900 mmWG prior to the tests.

7. REFERENCES

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Table 2. Raw Data from Test Results.

Test No	Coke (%)	Water (%)	Press Drop (mm WG)	Ignit Temp (°C)	Offgas Temp (°C)	Sinter Time (min)	Cooling Time (min)	Grid Layer Rec'le (kg)	Grid Layer Retain (kg)	Mass Mixed (kg)	Surplus Mix (kg)	Total Feed (kg)	Total Green Feed (kg)	Sinter Mass (kg)	Top Layer (kg)	Fines Mass (kg)	Product Mass (kg)	Sinter Fines Ratio	Coke per ton Sinter (kg)	Coke/ ton Green Feed	LOI Yield (%)	Product Yield (%)	Prod Rate (t/m^2/ 24hr)	Plant Capacity (TPA)	Strand Speed Calc (m/min)
Base Case	5.50	4.00	700	1002	429	8.48	5.42	6.32	3.68	75.00	9.22	65.78	48.35	51.03	2.87	19.60	31.43	0.78	115.12	74.83	76.35	65.00	29.45	287333	2.6
a	5.60	3.80	900	1002	450	8.93	6.04	6.42	3.59	75.00	9.59	65.41	48.08	49.32	5.53	19.34	29.98	0.70	122.17	76.19	78.38	62.37	26.61	259579	2.5
b	6.00	3.80	900	962	505	9.48	5.49	4.35	5.65	75.00	11.11	63.89	46.96	54.83	1.85	19.54	35.29	0.79	108.62	81.63	79.88	75.16	28.15	274604	2.3
c	6.30	3.80	900	989	453	9.37	5.51	3.77	6.24	75.00	10.02	64.98	47.76	54.92	0.89	17.84	37.08	0.92	110.40	85.71	76.29	77.64	29.63	289092	2.3
d	6.45	3.80	900	970	451	9.75	6.58	4.15	5.85	75.00	10.57	64.43	47.36	55.10	0.54	18.65	36.45	0.89	114.02	87.76	77.27	76.97	28.25	275582	2.3
e	6.75	3.80	900	875	467	9.67	6.50	3.12	6.88	75.00	10.41	64.59	47.48	56.86	0.84	18.86	38.00	0.87	114.75	91.84	78.68	80.04	28.96	282575	2.3
f	7.25	3.80	900	960	500	9.82	6.35	2.58	7.42	75.00	11.35	63.65	46.78	57.22	1.21	19.00	38.22	0.83	120.72	98.64	80.15	81.71	28.23	275442	2.2
g	6.45	3.80	550	981	449	13.40	11.98	3.92	6.08	75.00	11.74	63.26	46.50	53.80	1.25	17.37	36.43	0.90	112.02	87.76	77.41	78.34	20.38	198872	1.6
h	5.70	3.80	550	969	460	10.90	8.75	6.11	3.89	75.00	12.58	62.42	45.88	48.38	2.14	16.58	31.80	0.88	111.87	77.55	74.70	69.32	23.05	224893	2.0
I	5.30	3.80	550	960	432	11.45	9.33	6.85	3.15	75.00	11.16	63.84	46.92	47.81	1.92	16.07	31.73	0.94	106.62	72.11	72.96	67.63	22.46	219167	1.9
j	6.45	4.10	550	964	439	13.90	10.67	4.95	5.05	75.00	9.60	65.40	48.07	54.62	2.83	17.34	37.28	0.86	113.15	87.76	80.12	77.56	20.87	203652	1.6
11DSF Unp	4.00	4.00	700	1016	375	7.93	3.99	7.37	2.63	75.00	10.47	64.53	47.43	42.70	13.23	22.83	19.87	0.47	129.92	54.42	82.59	41.89	19.57	190919	2.8
a	4.00	4.11	700	1006	354	6.90	4.62	8.08	1.92	75.00	14.43	60.57	44.52	36.42	12.89	19.49	16.94	0.50	143.06	54.42	78.24	38.04	19.59	191116	3.2
b	4.50	4.40	900	944	505	6.53	5.14	7.37	2.64	75.00	17.28	57.72	42.42	34.65	12.11	16.31	18.34	0.54	141.62	61.22	76.45	43.23	21.65	211183	3.4
c	5.00	4.40	900	969	429	7.82	4.49	6.54	3.46	75.00	12.38	62.62	46.03	45.17	1.38	17.91	27.26	0.86	114.87	68.03	68.81	59.22	27.39	267219	2.8
d	5.35	4.40	900	950	462	7.70	5.52	6.25	3.75	75.00	13.09	61.91	45.50	46.07	0.97	18.01	28.05	0.86	118.08	72.79	69.92	61.65	28.40	277120	2.9
e	5.85	4.40	900	950	453	7.93	6.57	5.01	4.99	75.00	14.79	60.21	44.26	47.43	2.06	17.35	30.08	0.82	117.12	79.59	73.90	67.96	28.47	277808	2.8
f	5.85	4.40	700	888	472	8.67	6.31	4.20	5.80	75.00	14.12	60.88	44.75	50.31	1.41	16.68	33.63	0.89	105.90	79.59	75.43	75.16	28.89	281887	2.5
g	5.85	4.40	550	994	429	9.95	6.65	5.07	4.93	75.00	14.54	60.46	44.44	47.41	1.52	15.75	31.66	0.93	111.73	79.59	72.78	71.24	24.17	235829	2.2
h	5.35	4.40	550	905	370	9.08	6.67	5.60	4.40	75.00	12.30	62.70	46.09	49.03	1.89	17.25	31.78	0.87	105.55	72.79	74.19	68.96	27.14	264797	2.4
I	5.35	4.40	550	958	407	17.23	16.62	3.33	6.67	105.00	6.57	98.43	72.35	77.05	3.31	21.53	55.52	1.05	94.85	72.79	74.87	76.74	25.52	248961	1.3
j	5.10	4.40	650	992	421	14.53	13.55	4.87	5.13	105.00	7.77	97.23	71.47	78.88	2.53	25.18	53.70	0.93	92.35	69.39	78.45	75.14	30.08	293507	1.5
k	5.25	4.40	650	955	463	16.60	12.38	4.93	5.07	105.00	6.75	98.25	72.22	78.12	3.77	23.04	55.08	0.97	93.65	71.43	78.19	76.27	27.12	264551	1.3
Predicted	**5.25**	**4.40**	**650**	**950**	**460**	**17.47**	**13.04**	**4.93**	**5.07**	**110.00**	**6.57**	**103.43**	**76.02**	**79.21**	**3.77**	**24.25**	**54.96**	**0.98**	**98.79**	**71.43**	**75.33**	**72.30**	**25.70**	**250767**	**1.3**
11DSF Pel	6.00	4.00	550	964	451	10.27	9.50	4.89	5.11	75.00	13.51	61.49	45.19	52.34	1.29	17.22	35.12	0.88	105.04	81.63	78.91	77.72	26.30	256584	2.1
a	6.50	4.00	550	952	486	10.27	9.31	3.86	6.14	75.00	14.08	60.92	44.78	52.89	2.68	18.66	34.23	0.76	115.69	88.44	81.14	76.44	24.62	240177	2.1
b	5.50	4.00	550	982	455	10.22	8.00	4.84	5.16	75.00	12.89	62.11	45.65	48.83	2.68	18.83	30.01	0.77	113.84	74.83	74.64	65.73	21.88	213506	2.2
c	5.50	4.40	550	944	458	9.68	8.69	5.20	4.81	75.00	10.36	64.64	47.51	48.85	1.96	19.48	29.38	0.80	121.02	74.83	71.18	61.83	22.84	222885	2.3