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FOREWORD

Innovation and research into mining technology is necessary to position Africa as a world leader in minerals production and beneficiation. The Young Professionals Council is pleased to host a unique, three-day online conference that will showcase a broad range of emerging research and innovation from young professionals in the metals and minerals industry. Presentations will focus on new technology, tools and techniques relevant to exploiting Africa’s mineral resources safely, competitively and sustainably.

T.M. Mmola
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An Investigation into the Possible Use of an Existing Rotary Kiln for the Pilot-Scale Investigation of the PREMA Process

M B. Sitefane,1* J D. Steenkamp1,2 and P J A. Bezuidenhout1

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2School of Chemical and Metallurgical Engineering, University of Witwatersrand

PREMA (Pre treatment of manganese ores) is a European Union (EU) Horizon 2020 Programme that was funded under the CE-SPIRE-03-2018 Open Call. The main aim of PREMA is to demonstrate the feasibility of utilising industrial off-gases and solar thermal energy, to reduce energy consumption (~25% reduction) and CO₂ emissions (~15% reduction) – based on predictive computational modelling – in the manganese ferroalloy production process. To this end, the project has a total of seven work packages (WP). Each WP focuses on a different aspect of the project. Under WP4, the main aim of Task 4.1 is to demonstrate, at a pilot-scale, the feasibility of integrating a preheater to a submerged arc furnace where ore has been preheated to 600°C. The campaign will be undertaken by Mintek, using its upgraded 300 kVA AC furnace utilised for smelting, which has been integrated with a suitable rotary kiln utilised for preheating. One of the kiln options considered was an existing kiln colloquially named Bushpig. Assessment of its suitability for the pilot-plant campaign is reported here. The assessment criteria were: kiln dimension, ability to adjust feed rate, ability to achieve nominal design feed rates of between 200-250 kg/hr, and the ability to preheat manganese ore from room temperature (around 25°C) to 600°C. Following the assessment, the Bushpig kiln was found to meet all the requirements barring one: the ability to pre-heat the manganese ore to 600°C. Modifications to the existing kiln were recommended. The modifications would entail adding heater boxes on both sides of the cold zones, in order to improve the manganese ore discharge temperature. An alternative solution would be to evaluate another rotary kiln with improved specifications.

INTRODUCTION

PREMA is funded by the European Union (EU) Horizon 2020 Programme under the CE-SPIRE-03-2018 Open Call. The foremost aim of PREMA is to demonstrate the feasibility of using novel energy systems i.e. smelter off-gases and solar thermal energy, during the production of manganese (Mn) ferroalloys. This invention is predicted to reduce the overall energy consumption and CO₂ emissions by 25% and 15% respectively (Mintek, 2019). To effectively manage the main aim of PREMA, the project was subdivided into seven well-defined work packages (WP). Each WP focused on a different aspect of the project. Under WP4, Task 4.1 aims at demonstrating on pilot-scale, the technical feasibility of integrating a preheater to a submerged arc furnace (SAF) where ore has been preheated to 600°C.

The nature of the proposed pilot-scale work for WP4 necessitated that a smelting furnace (in this instance the upgraded 300 kVA AC furnace located at Mintek), be integrated with a pre-heating unit. The idea being that the pre-heating unit would preheat the manganese ore (Mn-ore), which would then be fed hot to the furnace. For practical and financial reasons, it was decided to use a rotary kiln for this
To this end, a suitable kiln was sought. One option available at Mintek was an existing kiln – said to have last been operated in the 1990s. This kiln was colloquially named Bushpig, and assessed for its suitability for the upcoming campaign.

The assessment criteria are stated alongside the four research questions below. It should be noted that the Bushpig kiln could only be deemed suitable for the campaign if the answer was ‘yes’ to all four of these research questions.

1. Size assessment: Does the kiln fit in the limited space available at the pilot plant?
2. Feed rate variation assessment: Does the kiln allow for adjustment of its feed rate?
3. Nominal design feed rate assessment: Can the kiln achieve the design nominal feed rate of 200-250 kg/hr?
4. Discharge temperature assessment: Can the kiln achieve a discharge temperature of 600°C, especially at the design feed rate?

The remainder of the paper describes the theory evaluated relating to this work, the methods adopted in performing the evaluation of the suitability of the Bushpig kiln, and the findings and discussion stemming from said activities. A final conclusion along with a few recommendations are presented at the end of the paper.

**THEORY**

**Manganese ferroalloy production**

South Africa has the largest land-based manganese resource in the world, at 74%, but only 32% of the reserve (USGS, 2020). The resource is estimated at 13 billion tons and the reserve in 2020 only at 260 million tons i.e. a significant amount of ore is low grade. Because of the local availability of raw materials at low costs, and historically low prices and stable supply of electricity, South Africa has significant installed capacity to produce manganese ferroalloys (Steenkamp et al., 2018). Unfortunately, due to significant increases in the prices of manganese ores mainly due to demand in China and increases in the price of electricity (Van Zyl, Bam, and Steenkamp, 2020), only two of five South African plants are currently in operation.

Two primary alloys of manganese are produced from manganese ores and 90% of the manganese alloys produced are utilised in the production of steel (Olsen, Tangstad, and Lindstad, 2007). High Carbon Ferromanganese (HCFeMn) typically contains 76% to 82% Mn (ASTM, 2009) and Siliconmanganese (SiMn) contains 65% to 68% Mn (ASTM, 2010). To produce these alloys, carbothermic reduction processes are applied in which carbon from carbonaceous materials, i.e. coal or coke, reacts with the oxygen in the ores to produce alloy, slag, and an off-gas rich in CO which turns into CO$_2$ on combustion (Olsen, Tangstad, and Lindstad, 2007). Only the alloy is a high value product with the slag and off-gas either sold as low value product or treated as a waste product.

For manganese alloys, the process is net endothermic, and significant amounts of energy have to be supplied in order to sustain the reduction processes. HCFeMn is produced in alternating current, submerged arc furnaces (SAFs), where energy is supplied by electricity, or blast furnaces (BFs) where the combustion of coke provides the process energy required (Olsen, Tangstad, and Lindstad, 2007). Around 90% of HCFeMn is produced in SAFs (George et al., 2015). For SiMn production, only SAF technology is applied. The energy requirement for HCFeMn is typically between 2200 and 3900 kWh/ton alloy (Olsen, Tangstad, and Lindstad, 2007) and for SiMn between 3500 and 4500 kWh/ton alloy (Tangstad, 2013). The amount of CO$_2$ produced per ton of alloy ranges between 1.3 and 1.4 ton (Lindstad et al., 2007). If the electricity is supplied by coal-fired power stations, the amount of CO$_2$ associated with the production of the alloys increases 6 to 8 fold. A study by Tangstad et al. (2015) showed that by preheating the ore to 600°C, both the electrical energy required in the SAF and the CO$_2$ emissions from both the SAF and the coal-fired power stations will be significantly reduced.
Rotary kilns

Rotary kilns are cylindrical tubes, with a typical length of 50 000-22 000 m and a diameter of 2-6 m at full-scale applications, used in the high-temperature processing of materials (Kritzinger and Kingsley, 2015). They are inclined, rotate to foster movement of material, have various zones, and are fired to promote the desired chemical reactions (Gordon and Nell, 2013). Firing can either be by direct or indirect heating. Direct heating implies that the heat source is in contact with the material (typically gas-fired), whilst indirect heating implies that the heat source is not in contact with the material (electrically or gas-fired). In either case, the heat transfer phenomena encompasses radiation, convection, and conduction in varying degrees (Arad and Arad, 2013).

The cement and direct reduction of iron ore industries, which apply direct heating, are the largest users of rotary kilns (Kritzinger and Kingsley, 2015). Other pyrometallurgical processes that utilise the kiln include the calcination, pre-heating, and pre-reduction of nickel laterites, ilmenite, manganese, and chromite ore (Keskinkilic, 2019; Lobo, Kolbeinsen, and Seim, 2013; Gordon and Nell, 2013; Van Staden et al., 2018).

One of the advantages of using rotary kilns is seen in the ability to easily adjust parameters such as the kiln length, diameter, inclination angle, and rotational speed, for process optimisation purposes (Kritzinger and Kingsley, 2015). In the case of the Bushpig kiln used for this study, only the kiln inclination angle and rotational speed could be adjusted. In addition to this, the feed rate to the kiln could also be adjusted. This was because the kiln was fed using an external vibrating feeder. The three parameters, namely: kiln inclination angle and rotational speed, and vibrator speed, could thus be adjusted in order to possible vary the feed rate.

METHODOLOGY

Overview

The procedures discussed in this section are those adopted for Bushpig size analysis, the material preparation, and the pilot-scale testwork. The pilot-scale testwork is further divided into the cold and hot test procedures.

Bushpig size analysis

Bushpig size analysis was prompted by the need for Bushpig to fit into the limited space available at the pilot plant facility. Figure 1 presents a 2-D schematic diagram of the pilot-plant layout. The diagram was constructed using Fusion 360, a computer-aided design program. The top level (level 3) represents the feeding section where hoppers are stationed. The bottom most level (level 1) is where the 300 kVA submerged arc furnace will be stationed. The middle level (level 2), represents the available space for Bushpig. According to the diagram, for Bushpig to fit in the available space, its height must be 2200 mm or less. There was more leeway in terms of the longitudinal dimensional requirements. The Bushpig kiln dimensions were taken using a Stanley PowerLock measuring tape.
Material preparation

The main raw material used for the testwork was Mn-ore obtained as lumps (> 20 mm) from a local ferromanganese producer. The chemical composition of the ore, determined by Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES), as obtained from the producer is shown in Table I.

Table I. As-received chemical composition of the Mn-ore analysed by ICP-OES (SD ‘standard deviation’ from three measurements; components do not necessarily reflect the true mineralogy of the sample)

<table>
<thead>
<tr>
<th>Components</th>
<th>Mn</th>
<th>Fe</th>
<th>Al₂O₃</th>
<th>CaO</th>
<th>MgO</th>
<th>SiO₂</th>
<th>P₂O₅</th>
</tr>
</thead>
<tbody>
<tr>
<td>%</td>
<td>29.20</td>
<td>5.50</td>
<td>0.25</td>
<td>21.51</td>
<td>3.22</td>
<td>4.84</td>
<td>0.056</td>
</tr>
<tr>
<td>SD</td>
<td>0.37</td>
<td>0.07</td>
<td>0.04</td>
<td>0.15</td>
<td>0.03</td>
<td>0.05</td>
<td>0.01</td>
</tr>
</tbody>
</table>

The size distribution of the as-received ore necessitated that crushing and screening be undertaken to meet the +6-20 mm size fraction that was required for the campaign. Crushing was undertaken using a Schmersal 1747 laboratory jaw crusher. Screening was undertaken manually using a 19.6 mm (large) and 5.6 mm (small) sieve. The crushing and screening process was undertaken in two sequential steps. Step 1 entailed crushing the ore, and then manually screening, using the large sieve (this was the only screen available closest to 20 mm). All the over-size particles from this step were re-crushed and re-screened, while the undersize particles were taken to step 2. Step 2 entailed further screening the ore using the small sieve (this was the only screen available closest to 6 mm). The oversize particles from this step were kept and used for the testwork, while the undersized particles were bagged and stored. A sample size of 50 kg was obtained in this manner.

Pilot-scale testwork

The aim of the pilot-scale testwork was twofold:

1. To assess the attainable Mn-ore feed rates (called ‘cold tests’). The already concluded detailed engineering design indicated that the kiln selected must be both flexible in the feed rates achievable, and also be able to produce nominal feed rates between 200 to 250 kg/hr. Thus, cold tests were performed to assess the feed rates using Bushpig. Various tests were conducted by varying the kiln inclination angle, rotation speed, and feeding pan vibrating speed.

2. To assess the discharge temperature at various ore feed rates (called ‘hot tests’). The Bushpig kiln needed to achieve a preheating temperature of at least 600°C, especially at the nominal feed rate.
Figure 2 presents a fully labelled schematic diagram of the Bushpig rotary kiln used for the cold and hot tests (constructed using Fusion 360). The kiln mainly consisted of a feeding hopper (where Mn-ore was fed through and connected to the vibrating pan), heater box (where indirect electrical heating took place), 304 steel tube, support structure, feed discharge pipe (where Mn-ore was discharged), and metal collector drum. Thermocouple 1 and 2 in the diagram were only used to measure the discharge temperature during the hot tests. The tube had a diameter of 0.16 m. The heater box is coloured in different colours to reflect the different zones within this heated section: zone 1 (green), zone 2 (orange), and zone 3 (red). Each zone had its own control thermocouple. The thermocouple was fixed in one position (centred in each section), located outside the tube, and connected to the controller. The exposed tube sections on either side of the heater box were not heated i.e. cold zone. The feed zone is on the left in the diagram and the discharge zone is on the right.

Figure 2. Labelled 2-D schematic diagram of Bushpig kiln used for pilot-scale testwork.

The procedures adopted for both the cold- and hot-tests are separately described below.

**Cold tests**

Cold tests were conducted by initially bucket loading cold Mn-ore into the hopper. The hopper used gravity to trickle Mn-ore onto the vibrating pan, which then used its vibration motion to feed material into the tube. As a result of the tube inclination, combined with the rotational action of the tube, Mn-ore was gradually moved from the feed-section, passed through the heater box zone, and lastly through to the discharge end from where the material was collected in a drum. Cold tests were conducted at various combinations of inclination angle, rotational and vibrator speeds. Table II summarises the combination of parameters applied. The inclination angle and rotational speed were measured using a Masterlevel Box Pro Laserliner inclinometer and a Hellermannityton tachometer, respectively. The vibrating speed was manually adjusted on the instrument.

All Mn-ore feed rates were determined by collecting the ore in a drum over a set time (between 3-5 minutes). The hourly feed rate was then extrapolated from this exercise.
### Table II. Summary of adjusted parameter values for cold tests (* means deviation not calculated)

<table>
<thead>
<tr>
<th>Kiln inclination (°)</th>
<th>Rotational speed, in 10 intervals (rpm)</th>
<th>Vibrator setting, in 0.5 intervals</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5°</td>
<td>10 – 90</td>
<td>1 – 9</td>
</tr>
<tr>
<td>1.64 ± 0.04</td>
<td>10 – 90</td>
<td>1 – 9</td>
</tr>
<tr>
<td>2.56 ± 0.08</td>
<td>10 – 90</td>
<td>1 – 9</td>
</tr>
<tr>
<td>4.52 ± 0.25</td>
<td>10 – 90</td>
<td>1 – 9</td>
</tr>
</tbody>
</table>

### Hot tests

Hot tests entailed firstly heating the cold Bushpig kiln to 800°C (as per controller setting). A heating profile was deduced from this by recording the time taken to raise the temperature in each zone in 100°C steps. Once the controller temperature reached 800°C, a temperature profile of the empty tube hot zone was undertaken. This was done by inserting a long, K-type thermocouple into the tube, and then moving the thermocouple across the kiln’s hot zone, in 10 cm intervals. Once the profile was completed, Mn-ore preheating tests were conducted using the same method described above for the cold tests. The only change was that the Mn-ore discharge temperature was measured.

A total of six selected hot tests were performed – all at an angle of inclination of 4.52°. The reason for the choice of angle was that observation of the cold test revealed that this setting yielded the most widespread feed rates. All the tests were performed at a controller temperature set-point of 800°C, which was 200°C above the desired discharge temperature. The higher temperature setting was meant to compensate for the unavoidable cooling experienced in the non-heated discharge section. Furthermore, 800°C was considered a safe higher temperature to avoid possible deformation of the steel tube.

The parameters selected for the six hot tests are summarised in Table III. From the hot tests, the peak discharge temperature was obtained. The peak temperatures refer to the maximum temperature attained from the two measuring spots i.e. thermocouple 1 or 2.

### Table III. Parameters used for hot tests at an angle of inclination of 4.52 ± 0.25°

<table>
<thead>
<tr>
<th>Rotational speed (rpm)</th>
<th>Vibrator setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>4.5</td>
</tr>
<tr>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>20</td>
<td>4.5</td>
</tr>
<tr>
<td>20</td>
<td>5</td>
</tr>
<tr>
<td>30</td>
<td>5</td>
</tr>
<tr>
<td>40</td>
<td>4.5</td>
</tr>
</tbody>
</table>

### RESULTS

#### Bushpig size analysis

A 2-D schematic diagram of Bushpig, along with its corresponding labels and measured dimensions, is presented in Figure 3. From this figure, the following main dimensional features of Bushpig were observed.

- The total tube length was 4105 mm. Of this length, the hot zone constituted in the order of 45% with a total length of 1845 mm.
- The entire kiln length – including the hopper and discharge feed pipe – was 5000 mm.
- The total height of the kiln, which includes the hopper and support structure, was 2400 mm.
The above results clearly demonstrate that the height of Bushpig i.e. 2400 mm, exceeds that of the available pilot plant height by 200 mm (see Figure 1). This means that Bushpig cannot fit into the existing pilot plant space, unless structural modifications are undertaken.

![Figure 3. Labelled 2-D schematic representation of Bushpig kiln (with dimensions in mm).](image)

Pilot-scale testwork

**Cold tests**

The feed rate results for the cold tests are summarised in Table IV, Table V, and Table VI. The results presented do not include work done at an angle of inclination of 0.5°, since the ore did not travel to the discharge end at this setting. Instead, most of the ore at this angle of inclination was discharged just below the vibrating pan (reverse- or back-feeding).

A number of observations were made from the tables. These are summarised in bullet form below:

- **Vibrator settings of 1 to 4 did not yield any ore flow.**
- **Vibrator settings of 6 to 9 for an angle of 1.65 and 2.56°, and 6.5 to 9 for an angle of 4.52°, resulted in excessive back-feeding.** The levels of back-feeding were considered too excessive to apply this setting in a pilot-plant context.
- With the exception of a few cases, the feed rate was observed to be directly proportional to the inclination angle, rotational speed, and vibrator speed.
- The nominal feed rate was obtained in three instances in each of the angle of inclination settings.
- **An angle of inclination of 4.52° yielded the highest feed rate flexibility,** with a feed rate as low as 51 kg/hr, and as high as 1062 kg/hr. Such flexibility is especially crucial in a pilot-plant context where unforeseen circumstances, requiring drastic actions, are often encountered.
Table IV. Feed rates (kg/hr) obtained at an inclination angle of 1.65 ± 0.04° (*’Means excessive back-fed encountered; **’ means feed rate was within the nominal feed rate bracket)

<table>
<thead>
<tr>
<th>Vibrating speed setting</th>
<th>Rotational speed (rpm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1-4</td>
</tr>
<tr>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>20</td>
<td>0</td>
</tr>
<tr>
<td>30</td>
<td>0</td>
</tr>
<tr>
<td>40</td>
<td>0</td>
</tr>
<tr>
<td>50</td>
<td>0</td>
</tr>
<tr>
<td>60</td>
<td>0</td>
</tr>
<tr>
<td>70</td>
<td>0</td>
</tr>
<tr>
<td>80</td>
<td>0</td>
</tr>
<tr>
<td>90</td>
<td>0</td>
</tr>
</tbody>
</table>

Table V. Feed rates (kg/hr) obtained at an inclination angle of 2.56 ± 0.08°

<table>
<thead>
<tr>
<th>Vibrating speed setting</th>
<th>Rotational speed (rpm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1-4</td>
</tr>
<tr>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>20</td>
<td>0</td>
</tr>
<tr>
<td>30</td>
<td>0</td>
</tr>
<tr>
<td>40</td>
<td>0</td>
</tr>
<tr>
<td>50</td>
<td>0</td>
</tr>
<tr>
<td>60</td>
<td>0</td>
</tr>
<tr>
<td>70</td>
<td>0</td>
</tr>
<tr>
<td>80</td>
<td>0</td>
</tr>
<tr>
<td>90</td>
<td>0</td>
</tr>
</tbody>
</table>

Table VI. Feed rates (kg/hr) obtained at an inclination angle of 4.52 ± 0.25°

<table>
<thead>
<tr>
<th>Vibrator speed setting</th>
<th>Rotational speed (rpm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1-4</td>
</tr>
<tr>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>20</td>
<td>0</td>
</tr>
<tr>
<td>30</td>
<td>0</td>
</tr>
<tr>
<td>40</td>
<td>0</td>
</tr>
<tr>
<td>50</td>
<td>0</td>
</tr>
<tr>
<td>60</td>
<td>0</td>
</tr>
<tr>
<td>70</td>
<td>0</td>
</tr>
<tr>
<td>80</td>
<td>0</td>
</tr>
<tr>
<td>90</td>
<td>0</td>
</tr>
</tbody>
</table>

Hot tests

Three temperature profiles, presenting the changes in Zone 1 to 3 temperatures over time, are graphically depicted in Figure 4. Each profile reveals what transpires during the heating of the empty Bushpig kiln. What the profile mainly indicates is that heating occurs at different rates within the three zones. Zone 3 had the highest heating rate; followed by Zone 1. All zones considered, it takes about 160 minutes to get the controller temperature from room to the 800°C set-point. This observation must be factored in if the Bushpig kiln will be used for the pilot-plant campaign.
The hot-zone profile, when the controller temperatures were at 800°C for the respective zones, is presented in Figure 5. The solid line curve represents the scenario where the Bushpig kiln was empty. The dotted line curve is for a scenario when the Bushpig kiln carried a load of Mn-ore and set at 4.52°, 20 rpm, and a vibrator setting of 4.5.

An analysis of the graphs reveals the following:

- Despite a controller temperature setting of 800°C, the hot zone air temperature is mostly below the setting.
- The hot zone air temperature drops significantly when Mn-ore is introduced to the tube. This was expected, since the introduction of cold Mn-ore means that some of the available heat is utilised to heat up the ore.
- The kiln carrying load had a higher air temperature closer to the discharge end (~380°C), compared to when it was empty (~120°C). This observation points to a rise in temperature, reflecting a transfer of heat from the Mn-ore to the air. This type of heat transfer mechanism, as discussed by Arad and Arad (2012), is mainly through free convection and radiation.
The results of the peak discharge temperature for the six hot tests are shown in Table VII. The results indicated that the highest peak discharge temperature was 325°C, at a feed rate of 230 kg/hr. This was obtained at an angle of 4.52°, a rotational speed of 20 rpm, and a vibrator speed setting of 5. The remainder of the discharge temperatures were all below 300°C.

Table VII. Peak discharge temperature for the hot tests (all tests at an angle of inclination of 4.52°; ‘*’ feed rates not changed by heating)

<table>
<thead>
<tr>
<th>Rotational speed (rpm)</th>
<th>Vibrator speed setting</th>
<th>Feed rate (kg/hr)*</th>
<th>Discharge temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>4.5</td>
<td>95.0</td>
<td>250</td>
</tr>
<tr>
<td>10</td>
<td>5</td>
<td>154.0</td>
<td>296</td>
</tr>
<tr>
<td>20</td>
<td>4.5</td>
<td>106.0</td>
<td>293</td>
</tr>
<tr>
<td>20</td>
<td>5</td>
<td>230.0</td>
<td>325</td>
</tr>
<tr>
<td>30</td>
<td>5</td>
<td>260.0</td>
<td>257</td>
</tr>
<tr>
<td>40</td>
<td>4.5</td>
<td>574.0</td>
<td>264</td>
</tr>
</tbody>
</table>

DISCUSSION

Size analysis

As already alluded to in the results section, the Bushpig is unsuitable from a size perspective for the planned pilot-plant campaign. This is because its height exceeds that of the available height by 200 mm. The question is then whether the Bushpig kiln could be modified to a height that would meet the pilot-plant height requirements.

A possible solution to this problem would be to reduce the current height of Bushpig, by removing and reducing the length of the vertical columns on the support structure. The intervention could be carried out without compromising on the required kiln weight support. Figure 6 presents a schematic diagram of the proposed modified Bushpig kiln.

![Figure 6](image_url)  
*Figure 6. Proposed Bushpig appearance (with new height dimensions) after modifications.*

The resultant modification leads to a new total height of 1800 mm, a 600 mm reduction from the previous height. This modification renders the concern that Bushpig will not fit in the available pilot plant space obsolete. The new modified kiln will fit in the available space.
Adjustment of the Mn-ore feed rate

The ability to adjust the Mn-ore feed rate is important because by their nature, pilot-plant campaigns require a degree of flexibility to be able to deal with different situations brought about by breakdowns, operational needs, safety considerations, and discoveries along the way. In such cases, the ability to adjust the feed rate in response to any of these situations becomes paramount.

Based on the feed rate results presented in Table IV, Table V, and Table VI, it can be safely concluded that the Bushpig kiln does meet the requirement of flexibility in feed rate. In the tables alluded to, the results indicated that by simply changing any of the three variable parameters investigated, the feed rate achieved can be as low as 3.6 kg/hr and as high as 1062 kg/hr. Furthermore, with the exception of the inclination angle which requires the use of a forklift for its adjustment, other parameters can be adjusted fairly easily.

Achievement of the design nominal maximum feed rate

From the initial detailed engineering design activities conducted, the maximum nominal feed rates for the proposed PREMA pilot plant lay somewhere between 200 to 250 kg/hr (Steenkamp et al., 2021). As such, the Bushpig kiln needed to fulfil this requirement in order to be deemed suitable for the campaign.

Again, looking at the feed rates presented in the results section (Table IV, Table V, and Table VI), a number of parameter combinations yielded this requirement. The combination of parameters that yielded this requirement are graphically depicted in Figure 7.

![Image](image.png)

*Figure 7. Kiln rotational speed and angles of inclination that yielded the desired feed rate ‘red line’ shows lower and upper limits of the desired feed rates. The corresponding vibrator settings are shown in the stipulated tables.*

The results on the graph indicate that the Bushpig kiln meets the maximum nominal feed rate requirement.

Achievement of discharge temperature of 600°C

The ability of the Bushpig kiln to preheat Mn-ore to a temperature of 600°C is another important consideration. The reason for this is because the premise of the PREMA project is that smelting Mn-ore, preheated to 600°C, will bring about a significant reduction in energy consumption and CO₂ emissions.
Therefore, testing this hypothesis requires a preheating unit capable of achieving the Mn-ore temperature stipulated.

Examining the preheating results presented, it is clear that none of the selected preheating tests yielded the required Mn-ore kiln discharge temperature. As quoted, the highest discharge temperature was 325°C – almost 50% below the target (at 230 kg/hr feed rate).

To examine whether the low discharge temperature may have been as a result of unwanted cooling along the 1400 mm cold zone after the hot zone, a temperature measurement of the Mn-ore in this area was undertaken. The same K-type thermocouple described in the temperature profiling methodology was utilised. The hot-junction of the thermocouple was placed directly on the Mn-ore, within a few centimetres after the Zone 3 hot zone. The thermocouple was left in position until such a point that the peak temperature was obtained. The peak temperature was found to be 371°C.

A comparison of the peak temperature against the final discharge temperature of 325°C for the same settings indicated that a 46°C drop in temperature occurred between these two points. While it is clear that cooling did occur along the cold zone, the 371°C reading indicated that the Mn-ore exit the hot-zone below the 600°C threshold. Two possible reasons for this observation are explored:

1. The hot zone itself was not hot enough to pre-heat the Mn-ore to the required temperature. This assertion is backed by the empty kiln temperature profile presented in Figure 5. This figure indicated that despite the controller setting being at 800°C for the three zones, actual kiln air temperatures were mostly below this setting. This is a significant observation, especially considering that convection heating plays a role in heating of materials in kilns (Arad and Arad, 2012). Two possible solutions to this problem are suggested. One would be to move the hot-zone thermocouples closer to the tube such that the control thermocouples measures the tube temperature. Another solution would be to increase the insulation of the Bushpig kiln, thus reducing heat losses.

2. Another possible reason for the low preheating temperatures could be that the hot-zone was too small to effect sufficient heating. Typical industrial kilns have a length of 50000-220000 mm, of which almost the entire length encounters some level of heating (Kritzinger and Kingsley, 2015). Although Bushpig is a pilot-scale kiln, the 1845 mm could have limited the residence time required for adequate preheating of Mn-ore to occur. This is especially so since the Mn-ore is not present in powder form. To address the shortness of the length of the hot zone, further modifications to the kiln were proposed. These were in the form of installing additional heater boxes on both opposite sides of the hot zone. Such a modification would also require alternative trunnion rollers to preserve the kiln support structure. Another consideration for the rollers was to use much thinner rollers so as to maximise the available space for the heater boxes. The modified Bushpig kiln design is presented in Figure 8.
The modifications suggested will in all likelihood improve the Mn-ore discharge temperature. Until tested, it is not known whether the modifications will be sufficient to yield the desired discharge temperature.

Putting together all the proposed modifications, the final pilot-plant layout is presented in Figure 9. When one examines the new layout, not only does the modified Bushpig kiln fit in the limited space available, but another unintended consequence has been the positive reduction of the height from the kiln discharge to the furnace. This observation meant that the intermediate cooling of the Mn-ore between the units would be reduced.

CONCLUSIONS

An investigation was conducted to examine the potential for using the Bushpig rotary kiln as a preheating unit for the upcoming PREMA campaign. Four critical criteria were considered: dimensional suitability, feed rate flexibility, ability to achieve a nominal design feed rate of 200-250 kg/hr, and the ability of the kiln to preheat Mn-ore to the required 600°C.

The testwork results indicated that the Bushpig kiln, with the introduction of small modifications, could
achieve the first three of the aforementioned criteria but could not preheat the Mn-ore to the required temperature. The reason for this was attributed both to the lower than desired temperatures in the hot zone, and low heating residence time in the hot zone. To counter this, it is recommended that additional heater boxes be installed on both sides of the existing heater box, and modifications be made to the temperature control and furnace insulation. This may resolve the discharge temperature problem. Alternatively, another rotary kiln, with better specifications, can be sourced for this application.

ACKNOWLEDGEMENTS

The PreMa project is funded by the European Union’s Horizon 2020 Research and Innovation Programme under Grant Agreement No 820561 and industry partners: Transalloys, Eramet, Ferroglobe, OFZ, and Outotec. The paper is published with permission from Mintek.

REFERENCES


