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METHODS OF EXTENDING A BLAST-FURNACE CAMPAIGN*

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As before, the main trends in blast-furnace smelting in the Twenty-First Century are decreasing coke consumption, increasing furnace productivity, and lengthening of the furnace campaign. In the last few decades, the focus has increasingly been on extending the campaign through various technical, technological, and organizational measures. This article surveys the work done in these areas and analyzes the results of research performed by the world's largest producers of pig iron.

As previously, the main priorities in blast-furnace smelting worldwide in the Twenty-First Century remain reducing coke consumption, increasing furnace productivity, and lengthening the campaign of the furnace [1–3]. In recent decades, it has become a point of special emphasis to attempt to extend the campaign through the use of various technical, technological, and organizational measures.

This article presents an overview of these efforts and analyzes the results of studies performed by large producers of blast-furnace pig iron.

Shown below are data [1] compiled over several decades in Japan to determine the main reasons for the shutdown of blast furnaces to perform capital repairs:

Wear of the lining	1975–1985	1986–2000	2001–2005
Top, shaft, bosh	43	22	–
Bottom	11	3	–
Hearth walls	29	47	4
Other reasons	0	6	–

During the period 1975–1985, blast furnaces in Japan were shut down mainly due to wear of the lining in the top, shaft, and bosh.

In the 1980s, factories began installing thin-walled shafts and boshes in blast furnaces with the use of efficient vertical slab-type coolers and special SiC and SiC–C refractories (which are resistant to abrasion and the penetration of liquid smelting products). The plants are also using horizontal slab coolers in combination with graphite blocks and silicon-carbide brick arranged in alternating layers ("sandwich" structure). Intensive heat removal through the graphite blocks keeps the SiC refractories in a uniformly heated state throughout their thickness [4]. The design profile of the furnace is created by a layer of refractory concrete that is applied by guniting and is periodically restored during brief (48–72 h) planned outages of the furnace. The use of new refractories in the shaft and bosh, a new lining technology, and an efficient cooling sys-

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tem has lifted previous limitations on the duration of the campaign. The campaign is now 15–20 yrs, and it has proven to be even greater on individual furnaces [5]. One example of the use of this approach is 1543-m^3 blast furnace No. 2 at the Whylla, Australia plant of the company OneSteel. The lining in that furnace lasted 23.4 yrs, and the furnace smelted 16961 tons/m^3 furnace volume with an average productivity of 1.983 tons/(m^3·day). Beginning in 1986, the furnace was periodically banked 48–72 h for guniting of the shaft. A total of 43 such guniting operations were performed during the campaign [6].

During the period 1986–2005 (see above), wear of the furnace lining took place mainly on the walls of the hearth and the bottom. This pattern is the same that has been seen repeatedly in Europe and North America [7–9]. The problem of improving the durability of these elements of blast-furnace linings has yet to be fully resolved, and at present it is the life of the lining of the hearth and the bottom that determines the campaign of a blast furnace with a modern lining and cooling systems.

In addition to using high-quality refractories and improving the design of the hearth, the service life of the lining of the heart and bottom can be increased by instituting certain organizational and technological measures. In particular, blast-furnace shops should use crust-forming materials introduced into the furnace along with the normal charge or injected through the tuyeres with the use of special equipment.

Technological measures to extend the service life of the lining of the hearth and bottom. Two stages can be discerned in the period from the moment a blast furnace is blown in until the end of its campaign. In the first stage (lasting 5–10 yrs after blow-in when standard carbon blocks are used [8]), no special measures need to taken to protect the lining, regardless of the unit productivity of the furnace. The furnace lining undergoes a small amount of wear during this period as a result of its oxidation and erosion, as well as due to the deposition of alkalis and sooty carbon. The thickness of the lining in the hearth region during the first period does not decrease to below the allowable minimum (500 mm). However, one important step that must be taken during this period – and especially the next period – is to provide constant monitoring of the temperature of the lining of the hearth. Such monitoring is needed to find temperature peaks, which could be an indication that the slag crust is increasing or decreasing in thickness, temperatures are rising, and the walls are being subjected to larger aggressive loads. Such changes in temperatures and loads result in wear of the lining.

The transition to the second stage of hearth operation takes place when it is discovered that some regions of the lining have undergone excessive wear. Such regions are a particular problem when they form near the iron notches. When these regions are found, measures are introduced to return the lining to its original condition or increase the thickness of the protective slag crust (by closing the tuyeres or replacing burnt coolers). In critical situations, sometimes repairs are made to the side walls of the hearth on banked furnaces without removal of the salamander [9]. However, to extend the life of the hearth lining during this period, it is necessary to resort to the following technological and organization measures:

- adhere to the tapping schedule and tap the same amounts of smelting products through the different notches;
- lower the smelting rate;
- minimize the number and duration of furnace stoppages;
- improve the efficiency of cooling of the hearth and the bottom;
- charge or inject materials which contain elements that will form high-melting carbides in the furnace, these carbides then settling on the walls of the hearth and forming a protective crust.

The tapping schedule affects the rate at which pig iron flows into the hearth. The rate of flow of the smelting products can be decreased and hearth drainage improved by shortening the period between taps on furnaces with one notch or by alternating taps (in a circular pattern) on furnaces with several notches. To minimize the rate of flow of the smelting products into the hearth, the furnace should be tapped continuously and the iron notches should be lengthened [10, 11].

The technological measures that can be taken to **lower the smelting rate** can be divided into measures that lower the smelting rate locally or in the furnace as a whole, which in turn leads to a reduction in the quantity and rate of flow of smelting products in the hearth.

A local reduction in smelting rate is achieved by measures such as closing the tuyeres in the sectors with a high hearth-lining temperature, installing tuyeres of smaller diameter, and controlling the quantities of fuels injected through the tuyeres. All of these measures lead to a decrease in the temperature of the hearth lining and an increase in the thickness of the slag crust in certain regions of the lining [6, 7].

Lowering the overall smelting rate means reducing the productivity of the furnace. As is known, high furnace productivity is often achieved by enriching the blast with oxygen. This raises the temperature in the hearth and thus shortens the life of the lining. In this case, the length of the furnace campaign depends heavily on the design features of the furnace and the smelting practice that is employed. Western European blast-furnace specialists [9] think it is critical that the unit productivity of the furnace be roughly 2.6 tons/(m^3·day).

The results obtained from the operation of furnaces Nos. 1 and 2 at the plant operated by the company Rautaruukki (Finland) serve as typical examples of the effect of smelting rate on the condition of the lining in the hearth and bottom of a blast furnace. The chosen periods of furnace operation were characterized by a high unit productivity (about 3.72 tons/(m^3·day), and the furnaces were repaired after these periods ended. Furnace No. 1 was shut down in 2002 due to the high temperature of the lining near the iron notches, while furnace No. 2 was shut down in 2004 because of the poor condition of the hearth coolers and wear of the lining at the junction of the hearth and the bottom. The same reasons caused the shutdown of blast furnace B operated by the firm Cocrevill Sambre in Ougree, Belgium [7]. Such instances are far from unique [9, 12].

However, some of the statistical data for European, Japanese, and South Korean blast furnaces on the unit productivity and unit production of pig iron over a campaign (tons/m^3) is not indicative of the clearly negative effect of high smelting rates on the furnace campaign [13, 14]. Some blast-furnace specialists believe that despite the adverse effect of high smelting rates on the campaign, this problem is more than offset by the associated reduction in operating costs [10].

Minimizing the number and duration of furnace stoppages reduces lining wear from thermomechanical stresses. Fluctuations in lining temperature caused by furnace shutdowns lead to the creation of additional stresses in the lining, the formation of cracks, or even the lining's fracture. The number of shutdowns and the variations in operating regime lead to contraction of the brick lining (and expansion of previously formed cracks), enlargement of the salamander in the sump portion of the furnace (due to repeated blow-ins), and eventual fracture of the courses of the lining that are close to the bottom. These fractures can reach the shell of the furnace itself. The longest furnace campaigns are obtained when the number of shutdowns is minimal [9].

The cooling of the hearth and bottom can be made more efficient by *washing* the existing cooling system and arranging for *additional cooling* at hot spots. Such additional cooling can be provided by flooding the exterior of the furnace in those regions or by installing a water jacket.

On the whole, the cooling of the hearth wall depends on the transfer of heat through the entire wall to the coolers or the cold shell of the furnace. Here, it is important to constantly maintain close contact between the hearth lining and the elements of the cooling system. Even the presence of a 0.5-mm air gap between the lining and a cooler or (in the case of external cooling) between the lining and the shell will shift the 1150°C isotherm in the lining 390 mm closer to the cooling surface [15]. Special bulk materials with a high thermal conductivity are placed in the gap to restore contact between the cooling-system elements and the lining [16].

Thus, there is a sufficient number of measures that can be taken to extend the life of a blast-furnace lining. In general, these measures increase the local or overall thickness of the slag crust on the heart and bottom portions of the lining. Another effective method is to introduce crust-forming materials into the furnace either by injecting them through the tuyeres or charging them through the top. Titanium-bearing materials in particular are suited for this purpose.

The charging of crust-forming materials through the top of the blast furnace is done fairly often as a preventive measure to help form a protective layer of high-melting titanium carbonitrides on the surface of the lining. Various materials are used for this purpose, include titanium-bearing iron ores (15–40% TiO_2), titanium-bearing blast-furnace slags (5–9% TiO_2), ferrotitanium (32–35% TiO_2), and pellets, sinter, and briquets containing relatively large amounts (2–5%) of titanium oxide [17–22]. Such materials are charged into the peripheral region of the top, which ensures that the titanium-bearing material will migrate toward the hearth walls and form a protective crust on them.

The average consumption of titanium-bearing materials is about 10 kg/ton pig. With an increase in the temperature of the lining, the quantity of titanium-bearing addition charged into the furnace is increased to 20 kg/ton. Using larger amounts of this addition can have negative effects related to a deterioration in the viscosity of the liquid smelting products

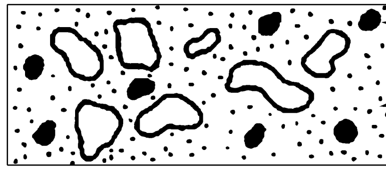

Fig. 1. Diagram of the deposition of titanium oxide and the formation of calcium titanate.

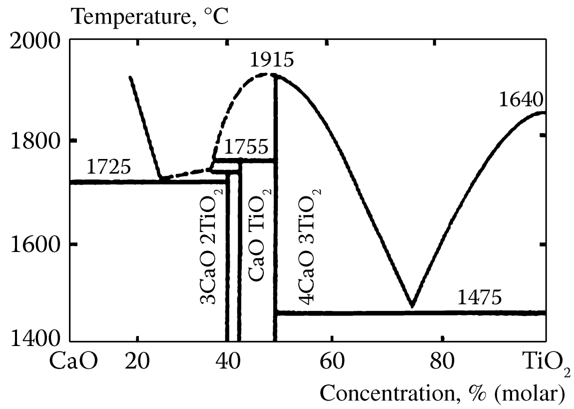

Fig 2. Phase diagram of the CaO–TiO_2 system.

[10, 17, 23]. The charging of titanium-bearing additions is usually limited by the fact that converter pig iron should contain no more than roughly 0.3% titanium. The slag should have a titanium dioxide content within the range 1.5–2.5% [23, 24].

To study the mechanism responsible for the formation of protective crusts and confirm that such a crust has formed on the hearth and bottom parts of the lining, specialists at the research centers of the companies Companhia Siderugica Naciona (CSN) (Brazil) and Corus Research (the Netherlands) performed extensive studies that included experiments in crucible furnaces, examination of the microstructure of samples taken from blast furnaces, the construction of thermodynamic models, and testing of the models for accuracy. The information that was obtained led the researchers to propose that titanium carbonitrides are formed in blast furnaces by the following mechanism [17, 23].

Entering the furnace, compounds of titanium (ilmenite – $FeTiO_3$) are reduced and become part of the liquid smelting products. Here, titanium is transferred to the primary slag in the form of an oxide. The slag that has accumulated in the well interacts with the surface of the lining, penetrating its open pores. However, due to the high viscosity of the slag, its penetration is limited to a thin layer close to the working surface (roughly to the 1350°C isotherm) and the depth of penetration is no greater than 2 mm [17]. This is related to the high crystallization temperatures of blast-furnace slags, which are characterized by high basicity and high viscosity within the range 1350–1480°C.

Calcium oxides and titanium oxides in the slag react with one another in accordance with the below reactions and form calcium titanates $CaTiO_3$ and $Ca_4Ti_3O_{10}$ in the open pores:

$$CaO_{(l)\text{slag}} + TiO_{2(l)\text{slag}} \rightarrow CaTiO_{3(s)}; \quad (1)$$

$$4CaO_{(l)\text{slag}} + 3TiO_{2(l)\text{slag}} \rightarrow Ca_4Ti_3O_{10(s)}. \quad (2)$$

The newly formed phases form a protective crust on the side walls of the hearth, reducing the rate of wear of the lining (Fig. 1). In addition to calcium titanates, it has been found that quartz (SiO_2) and silicon carbide (SiC) are also formed. The protective crust undergoes continuous wear and restoration thanks to the periodic cycles of taps.

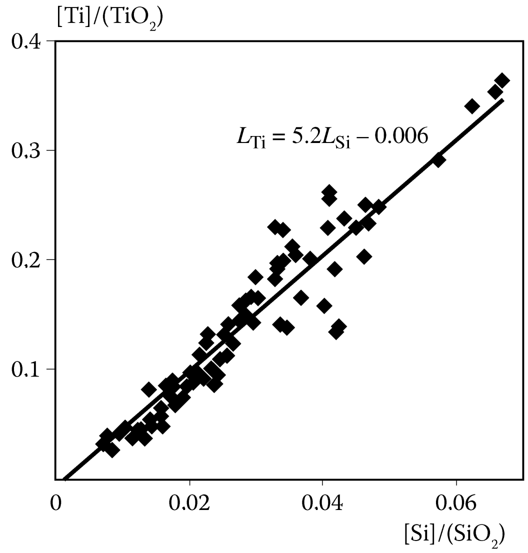

Fig. 3. Relationship between the coefficients characterizing the distributions of Ti and Si between pig iron and slag.

In accordance with the phase diagram of the CaO–TiO_2 system (Fig. 2), the titanate phases that are formed have a fairly high refractoriness (1755°C). Proceeding on the basis of the high reactivity of these two oxides, the minimal concentration of TiO_2 in the slag, and the slag's high content of CaO, it was proposed that all of the titanium oxide reacts with the calcium oxide [17].

At the slag/pig-iron interface and within the pig iron itself, titanium oxide is reduced to titanium as it continually reacts with the carbon in the coke. The newly formed titanium is dissolved in the pig iron. The overall process of reduction to metallic titanium that then dissolves in the liquid pig iron takes place by means of the reactions [23]:

$$(TiO_2) + 2C \leftrightarrow [Ti] + 2CO(gas); \quad (3)$$

$$(TiO_{1.5}) + 1.5C \leftrightarrow [Ti] + 1.5CO(gas). \quad (4)$$

The reduction of TiO_2 is also partly mediated by silicon in accordance with the reaction

$$(TiO_2) + Si \leftrightarrow Ti + (SiO_2). \quad (5)$$

This is confirmed by the linear relationship between the coefficients that characterize the distributions of these elements in the pig iron and the slag (L_{Ti}= [Ti]/(TiO_2) and L_{Si} = [Si]/(SiO_2)]. Values of these coefficients were determined by thermodynamic modeling (Fig. 3).

A mixture of carbides and nitrides of titanium is formed when metallic titanium dissolved in the pig iron reacts as follows with gaseous nitrogen and solid carbon in the coke:

$$Ti_{(l)} + 0.5N_{2(g)} \rightarrow TiN_{(g)}; \quad (6)$$

$$Ti_{(l)} + C_{(s)} \rightarrow TiC_{(s)}. \quad (7)$$

Figure 4 schematically depicts the formation of a protective crust of titanium carbonitrides.

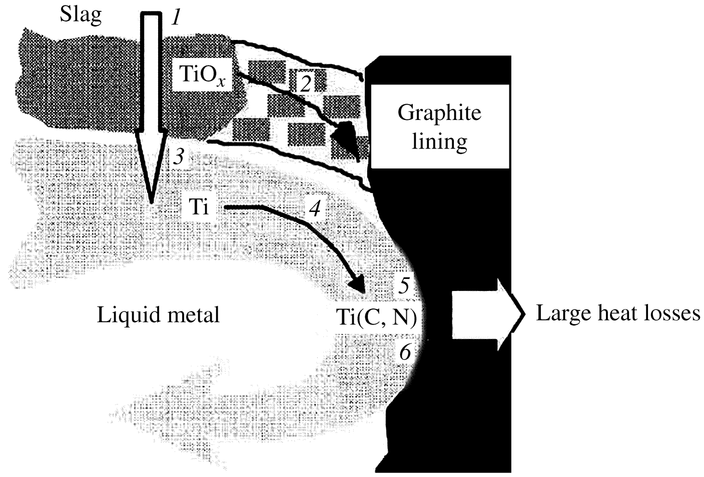

Fig. 4. Diagram of the formation of a protective crust of titanium carbonitrides on the walls of a blast-furnace hearth: *1*) dissolution of titanium dioxide in the slag phase; *2*) formation of calcium titanates and their deposition on the hearth walls (slag level); *3*) reduction of titanium dioxide and dissolution of the resulting titanium in the liquid pig iron; *4*) transport of titanium to the hearth walls; *5*) formation of titanium carbonitrides; *6*) deposition of carbonitrides on the hearth walls and growth of the crust.

To sum up, the main intensifying factors that affect the precipitation and growth of coarse titanium carbonitride crystals are:

- a reduction in the temperature of the pig iron, which helps decrease the solubility of titanium in the pig;
- the formation of stagnant zones and slowing of the pig iron's movement in the lower part of the well, in addition to the lack of mixing of the pig located in the sump. The iron in the salamander thus remains in the furnace for a long time, which facilitates the precipitation and growth of titanium carbonitride crystals in this region. The phases that are formed and mix with one another have a high melting point – about 3000°C;
- thermodynamic modeling of the formation of titanium carbonitrides has made it possible to theoretically determine the smallest amount of titanium-bearing addition (TiO_2) needed to initiate the formation of carbonitrides at a specified temperature.

It follows from Fig. 5 that the quantity of titanium-bearing material charged into the furnace per unit of pig-iron output needs to be increased with an increase in temperature in the hearth. The charging of more of this addition allows more heat to be transferred from titanium to the pig iron [17, 23].

The effectiveness of charging titanium-bearing materials through the top of the furnace is evaluated based on the reduction seen in the thermal loads on the hearth coolers and the decreases that occur in the temperature of the lining in the hearth and the bottom. Specialists from the Wuhan Iron and Steel Company (China) analyzed the results of experiments performed on blast furnaces No. 2 (1433 m^3 volume), No. 3 (1513 m^3), and No. 4 (2516 m^3) and found that the charging of 5–10 kg of titanium-bearing material per ton of pig iron reduced the thermal loads by 10–15% [25]. When the temperature of the coolers in the hearth and bottom rose on blast furnace No. 2 at OneSteel, furnace operators charged ilmenite ore at the rate of 8.5 kg/ton pig before the furnace was shut down for repairs. This measure reduced the temperature of the furnace bottom by 20% [6].

Beginning in 2003, ilmenite ore was periodically charged into blast furnace No. 2 at the plant operated by the steelmaker Siderar (Argentina). The ore was charged at a rate of 5–10 kg/ton pig as a preventive measure. The Ti content of the pig iron remained at the level 0.11%. When the temperature of the hearth lining increased further, the consumption of crust-forming material was increased to 0.15–0.18% – with the exact amount charged depending on the Ti content of the pig. It was found that the greatest effect from charging ilmenite was obtained when it was charged at the rate 20–25 kg/ton pig over a 16-hour

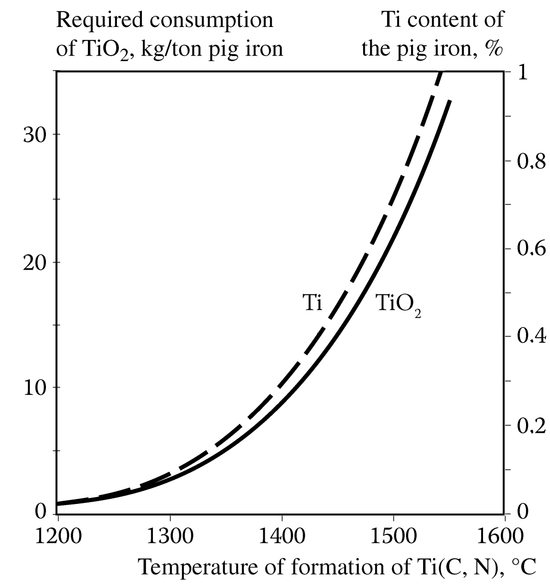

Fig. 5. Minimum consumption of TiO_2 necessary to begin the formation of a crust of Ti(C, N) at a prescribed temperature.

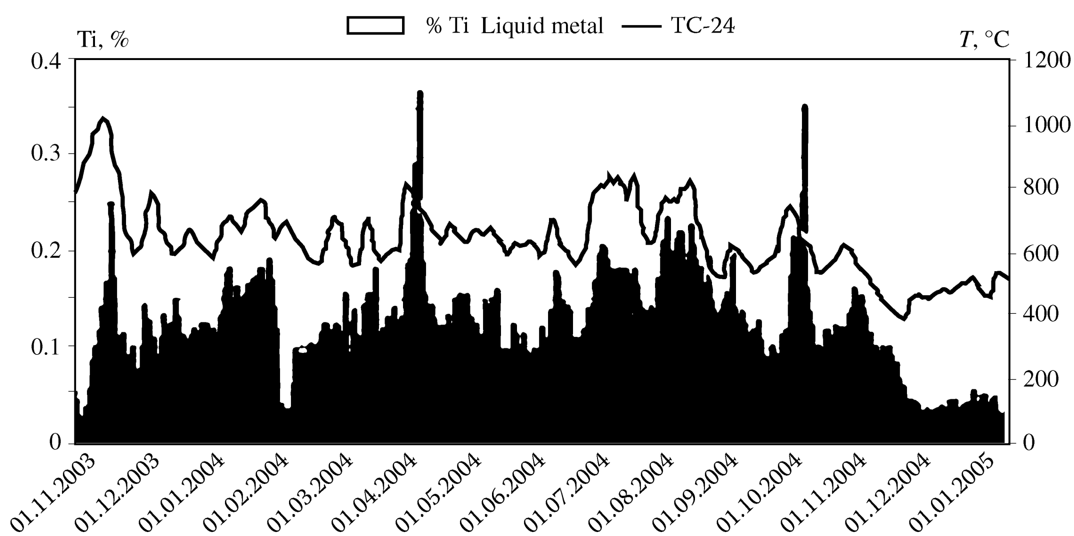

Fig. 6. Change in the Ti content of the pig iron in relation to the temperature of the lining of the hearth walls in blast furnace No. 2 at the Siderar plant.

period before shutdown of the furnace for scheduled repairs. Figure 6 shows the change in the Ti content of the pig iron (since the beginning of 2003) in relation to the temperature of the lining of the hearth walls in blast furnace No. 2. The length of the experiment involving the use of ilmenite in blast furnaces at the Siderar facility gave the company enough time to develop and implement a program to correct the temperature of the lining in the hearth and bottom of the furnaces (Table 1) [18].

A survey of numerous publications shows that the charging of titanium-bearing materials is a commonly used preventive measure for extending the life of blast furnaces and is practiced at the plants of many steelmaking companies, including Mittal Steel, Corus, Salzgitter Flachstahl, Arselor, and Severstal' [26–32].

TABLE 1. Technological Program for Correcting the Temperature of the Lining of the Hearth and the Bottom

Temperature *T* of the hearth lining (thermocouples positioned 0.6 m from the lowest part of the bottom), °C	Temperature correction		
	<5°C/day	5°C/day < increase < 7°C/day	increase > 7°C/day
<250	Normal operation without ilmenite	5 kg ilmenite/ton pig	10 kg ilmenite/ton pig Notch length <3.0 m
250–300	5 kg ilmenite/ton pig		
300–350	10 kg ilmenite/ton pig Notch length <3.0 m	10 kg ilmenite/ton pig Notch length <3.0 m	15 kg ilmenite/ton pig 15% decrease in pig-iron output Notch length <3.0 m
350–400	0 kg ilmenite/ton pig 15% decrease in pig-iron output Notch length <3.0 m	10 kg ilmenite/ton pig 15% decrease in pig-iron output Notch length <3.0 m	
>400	Ilmenite added over 16-h period n before shutdow at the rate 20 kg/ton pig	Ilmenite added over 16-h period before shutdown at the rate 20 kg/ton pig	Ilmenite added over 16-h period before shutdown at the rate 20 kg/ton pig

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