The future of Ni–Cu smelting in Botswana: the choice between flash-smelting and top-submerged lance furnaces

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Abstract

The BCL furnace is scheduled to restart operations after being placed on care and maintenance in 2016 due to depressed nickel prices. The decision to start operations after such a stoppage ought to be led by a techno-economic evaluation of process options to make operations more resilient. For BCL, the decision lies between using the existing flash-smelting furnace (FSF) or a top-submerged lance (TSL) furnace. Available studies show that the FSF combined with other converting technologies is cheaper to operate; however, such studies are based on flowsheet simulation results of single copper concentrates and therefore do not provide a full scope of practical capabilities based on smelter operator skills.

Using a t-test on normalized prior operational data from three Cu FSF and two Cu TSL, it was found that the only statistical differences between the operating costs of the FSF and TSL technologies are in the coal use for heating the feed blow and number of rebuilds: the FSF consumes coal to heat the feed blow and the TSL requires 2.4 rebuilds during a course of a single FSF campaign. A summative operating cost comparison over the existing BCL FSF 11-year life shows that BCL can decrease operational costs by some BWP 55.5 million if the operation were to change to the newer TSL technology. The savings derive from reduced coal use, which is normally associated with heating the blow when using the FSF. Despite the TSL carrying added costs of 2.4 rebuilds during a life time of one FSF furnace campaign, the cost associated with the TSL rebuilds of approximately BWP 1.3 million is minimal compared with the overall operational expenditure decrease that BCL will incur on using the TSL technology. In terms of the technology, BCL can have higher Ni–Cu recoveries at lower operational costs by elimination of Ni–Cu losses and eliminating the slag-cleaning furnace by converting to a TSL furnace.

Keywords

BCL smelter, Outokumpu flash smelting, top submerged lance furnace, Ni–Cu smelting

Introduction

BCL Limited is a nickel–copper (Ni–Cu) mining company owned by the government parastatal Minerals Development Company of Botswana. The mine has operations in Selebe-Phikwe in northeastern Botswana. As part of its mining operations, BCL owns a flash smelter capable of treating 900 kt/a of concentrate (Botswana Chamber of Mines, 2017).

In October 2016, all BCL Group mining operations were placed under care and maintenance due to depressed nickel prices, amongst other reasons. The nickel price had steadily dropped over a period of two years from January 2014 to just below USD 4/lb. Since 2016, the nickel price has increased to ~USD 12/lb in 2023. This means that, in theory, BCL can restart operations; however, restarting operations after such a stoppage is often accompanied by technical changes to operations so as not to suffer the same fate should the metal price fall again (Fichani & Mabentsela, 2019).

Fichani and Mabentsela (2019) have shown process option routes worthy of further study to improve processing of the low-grade Ni–Cu ore and concentrate available in Selebi-Phikwe and neighbouring mines. With regards to smelting, the authors recommended that a trade-off study be done to assess the benefits of switching from the current flash-smelting furnace (FSF) to a top-submerged lance (TSL) furnace. This recommendation was not based on techno-economic considerations, but rather on global trends in the copper smelting industry, which show that TSL furnaces had increased in popularity to comprise some 50% of all new copper smelter installations in 2004 (Schlesinger et al., 2021). In a neighbouring country, Zambia, a copper smelter operator in 2003 chose to upgrade from an electric furnace to a TSL furnace over an FSF (Ross, 2005). The FSF was excluded on the basis of technical complexity for the Zambian environment, not being suited for retrofitting into existing furnace equipment, and high capital cost (Ross, 2005). The TSL was chosen because of low capital costs, low operating costs, and relative ease of operation (Ross, 2005). It must be pointed out that the above study did not serve as a comprehensive comparison between the two furnace technologies, but rather as a high-level review of each technology. As such, the results of Ross (2005) cannot be used for the BCL case.

In all furnace conversions implemented by TSL companies to date, none have involved the conversion from FSF to TSL (Errington et al., 1997). As such, it is not easy to decide whether or not BCL will be advantaged or disadvantaged with respect to operational cost (OPEX) if it were to make such a conversion. Further, lack of detailed operational data in literature on Ni–Cu TSL furnaces worldwide makes it difficult to compare FSF and TSL furnaces for smelting Ni–Cu concentrates.

Available direct comparisons between FSF and TSL technologies are based on single-point process flowsheet models to calculate environmental impact of copper to blister smelting technologies in the form CO_2 production (Alexander et al., 2021; Coursol et al., 2010) or OPEX (Bujaku et al., 2019). In all comparisons, FSF smelting in combination with Peirce–Smith converting or FSF in combination with a flash-converting furnace proved to be most environmentally friendly due to lower CO_2 emissions resulting from the use of fossil fuel to generate heat (Alexander et al., 2021; Coursol et al., 2010). Further, the FSF in combination with a flash-converting furnace proved to be operationally less expensive (Bujaku et al., 2019). Modelling for the OPEX comparison was based on a single copper concentrate grade (Table I) and concentrate feed rate of 1.2 mt/a. The applicability of the results of Bujaku et al., (2019) is not known because the study used a single high-copper concentrate grade (see Table I). In comparison, the BCL smelter feed contains 5% Ni, 3% Cu (Legg et al. 2009). Further, a single idealized data point was used by Bujaku et al. (2019), as opposed to data drawn from practice at several smelters. Whether the BCL smelter will be better off, economically and technology-wise, by switching to the newer TSL technology or continuing with the current FSF technology remains unknown, despite these studies.

The objective of this paper was thus to conduct a techno-economic comparison of FSF and TSL technologies, with the aim of establishing whether BCL would be advantaged with respect to both OPEX and technical capacity by using the existing FSF or implementing a newer TSL furnace.

Methods

To prove that TSL technology can treat the BCL low Ni–Cu concentrates, available literature information on past operation of Ni–Cu TSL furnaces is quoted and compared with most-recent BCL operation.

For the techno-economic comparison, a t-test was used on normalized prior operational data from three Cu FSF (PARSA Leyte, Sumitomo Toyo, and Hibi Kyodo Smelting Co.) and two TSL (Mount Isa and Mufulira) to determine whether there is a statistical difference in operational performance with respect to consumable usage between FSF and TSL for copper smelting. A two-tailed t-test (Equation [1]), assuming non-equal equal variance at 95% confidence, is used for trans-technology comparison in each normalized consumable category (Cressie & Whitford, 1986). In this regard, the results of this study are based on practical experience, as opposed to the single-point simulation reported by Bujaku et al. (2019). The null hypotheses of the t-test is that both technologies use the same amount of consumables in each category:

$$t = \frac{(\bar{x}_1 - \bar{x}_2)}{\sqrt{\frac{{s_1}^2}{n_1} + \frac{{s_2}^2}{n_1}}}, \qquad [1]$$

where $\bar{x}_1$ is the sample mean of normalized consumables for the three Cu FSF smelters, s_1 is the standard deviation of the normalized consumables for the three Cu FSF furnaces, n_1 is the number of Cu FSF furnaces considered, $\bar{x}_2$ is the sample mean of the normalized consumables for the two Cu TSL smelters, s_2 is the standard deviation of the normalized consumables for the two Cu TSL furnaces, and n_2 is the number of Cu TSL Cu furnaces considered.

Table I

Copper concentrate grade (mass %) used in a prior copper smelting technology operating cost study (Bujaku et al., 2019)

Cu	Fe	S	SiO_2	CaO	MgO	Al_2O_3	Other
27	26	31	8	1	1	3	3

The results of the t-tests were altered where necessary to give information for the Ni–Cu case of BCL. Where there was a statistical difference in the operational usage of consumables between the FSF and TSL, the sum difference in OPEX between the two furnace technologies was taken with respect to conclusions drawn. The three Cu FSF and two TSL were chosen because their operational data are most complete in the open literature. Relative OPEX data for the Cu smelters were back-calculated for the lower Ni–Cu concentrate grade, where necessary, and conclusions are drawn from relative summative results for OPEX consideration.

The OPEX categories considered included silica flux, oxygen, fossil fuel use to heat the feed (concentrate and blow) and holding furnaces, and furnace relining bricks during one FSF campaign life. With respect to the technological comparison, the furnace space demands were compared. Operational data for the Cu FSF were taken from Schlesinger et al. (2021); that for Mount Isa was taken from Arthur et al. (2003, 2005); for Mufulira, Ross (2005) and Burrows et al. (2012) were used. The reason for mapping the results of Cu FSF and TSL to Ni–Cu smelting is because there are no operational Ni–Cu TSL around the world to compare with the BCL smelter.

For the summative OPEX comparison, the cumulative consumable costs were calculated based on local Botswana prices in 2023. The recommendation on whether to change from the current FSF to any of the TSL technologies is based on the cumulative consumables cost of operation.

Results

Production capabilities and general operation

An FSF consists of three sections: a reaction shaft, where oxidation of the sulfide concentrate takes place to generate molten matte and slag droplets; a settler section, in which molten matte droplets fall and are allowed to separate from the slag by gravity; and the uptake shaft, from which smelting gases are drawn (see Figure 1).

In an FSF, typically that of Outokumpu's matte smelting, a single concentrate burner is used to evenly distribute dry concentrate feed and enriched air through the top of the reaction shaft (Vaarno et al., 2003). This is achieved by making use of concentric ducts. In the inner duct, enriched air (34%–38% O_2) at 260°C is blown vertically down into the reaction shaft. In the central duct, concentrate and flux, in the form of silica, fall through by gravity. At the burner tip of the inner duct, a distributer cone is installed to ensure that enriched air is horizontally blown through the falling concentrate/flux feed

(Schlesinger et al., 2021). As particles, typically < 100 µm, descend the reaction shaft, they react with the enriched air. The oxidation reaction is exothermic in nature: as the particles react, they heat up and melt, forming molten matte already in the reaction shaft and molten slag by reaction with fluxing agent (Schlesinger et al., 2021; Vaarno et al., 2003). The reactions involved are the direct oxidation of copper and nickel sulfide.

The molten matte and slag droplets reach the settler, where they are allowed to separate by gravity, giving a dense sulfide matte and silicate slag. The slag is continuously tapped while the matte is periodically tapped through separate tap holes. The smelting gases, mainly SO_2 and N_2, the latter coming from the enriched air, are drawn up from the uptake shaft. The total air requirement at the BCL smelter complex is 120 000 Nm^3/h at an enrichment ratio of 34%–38% for a concentrate feed rate of 130 t/h (Legg et al., 2009). The air is heated by steam to 260°C. The feed typically comprises 5% Ni, 3% Cu, 30% S, 45% Fe, and 8% SiO_2 (Legg et al., 2009). The process produces a matte that has 30%–35 % Cu–Ni with a Ni recovery of 92.3% (Legg et al., 2009). Although flash smelting is autogenous, using latent energy contained in the sulfide bonds, supplementary fuel in the form of pulverized coal at a rate of 52.6 kg/t of dry solid feed is added to the BCL feed to ensure operating temperatures are reached (Warmer et al., 2006).

A TSL furnace is an upright cylindrical furnace that uses a top-introduced submerged lance to introduce enriched air to a bath of molten slag (Figure 2). Cold air is fed in to form a protective skull around the lance to prolong lance usage, thus negating the need to heat the air. Concentrate and flux are fed from the top of the furnace and fall by gravity to the surface of the slag bath through separate feed holes. The lance penetrates the slag bath by a few meters; for example, only by 0.3 m in a slag with a thickness of 1.85–2 m at the Chambishi Copper Smelter in Zambia (Zhao et al., 2019). Usage of oxygen in the bath is indirect. It involves a reaction with iron oxide in the slag bath to form magnetite in the slag. The magnetite is then used inside the furnace to oxidize sulfide containing copper and nickel, resulting in the formation of iron oxide and Cu and Ni sulfide matte. In this regard, iron oxide acts as catalyst in the oxidation of Cu and Ni sulfides (Schlesinger et al., 2021; Vernon & Burks, 1997). The TSL technology is led by two companies: ISASMELT™ and Ausmelt.

Owing to the turbulent environment caused by gas injection inside the furnace, the matte and slag do not separate well inside the TSL furnace, so a settler furnace is needed. Matte and slag are periodically tapped from the TSL furnace from water-cooled tap holes, in the case of ISASMELT furnaces, or continuously from a weir, in the case of Ausmelt furnaces (Schlesinger et al., 2021).

The slag and matte are tapped into a settler furnace, which allows for their separation. To maintain a molten slag and matte, the settler furnace is powered by external sources of fuel, such as electricity, where economics allow, or by fuel to balance heat losses through the settler walls. The separated matte and slag are then separately tapped from the settler furnace for further processing (matte) or discard (slag) (Bakker et al., 2009).

Apart from the energy supplied to the settler furnace, additional fuel is supplied to the TSL furnace in the form of coal or hydrocarbon fuel (Schlesinger et al., 2021).

The typical feed concentrate grade to the BCL FSF smelter is given above. The design capacity of the BCL FSF is 900 kt/a (Botswana Chamber of Mines, 2017). The matte comprised 31.7% Ni–Cu with 92.3% Ni recovery. The slag comprised 0.201% Ni and was discarded (Legg et al., 2009).

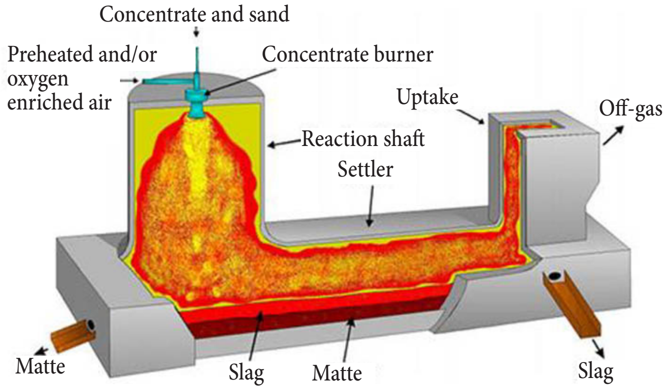

Figure 1—Cross-section through an Outokumpu flash-smelting furnace (Vaarno et al., 2003)

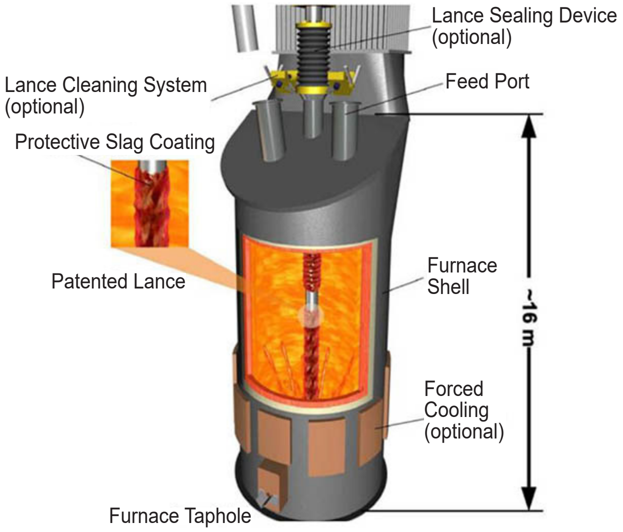

Figure 2—Cross-section through a top-submerged lance furnace (without settler furnace) (Hoang et al., 2009)

The ISASMELT TSL furnace is able to treat low Ni–Cu concentrates. Agip's nickel ISASMELT furnace, in Australia, which was commissioned in 1991, treated 60 kt/a concentrate containing 7% Ni and 3.5% Cu to produce a matte of 45% Ni–Cu. Production at Agip was stopped due to depressed nickel prices and the smelter was decommissioned after less than six months of operation (Bakker et al., 2009). Two other Ni Ausmelt TSL smelters exist in China: Jinchuan started in 2008 and Jilin in 2009 (Andrews et al., 2013). In 2013, these were quoted to treat 1.1 mt/a and 0.27 mt/a of Ni concentrate, respectively (Andrews et al., 2013). Interestingly, Jinchuan operated an FSF from 1993 to 2006, and only in 2008 did they add a new TSL (Jinchuan Group Co., LTD., 2023). Little is published on the operation of these two TSL furnaces.

Although the Agip furnace treated a much lower feed rate, the capability of ISASMELT to treat Ni–Cu concentrates was proven and has also been proven through pilot-scale test work (Bakker et al., 2009). The Jinhaun and Jilin plants prove applicability of the Ausmelt TSL for Ni–Cu smelting. Therefore, it can be said that TSL technology can treat low Ni–Cu sulfide concentrates.

The TSL carries further advantages of:

- *Higher nickel and copper recovery than the FSF*. This is because the sulfide feed is partially roasted in the reaction chamber in an FSF. Partial roasting of the metal sulfides in the feed can be mistakenly overdone, which leads to formation of nickel and copper oxides, which are then lost to the slag and need to be recovered via a separate electric furnace (Crundwell et al., 2011). In a TSL, chance of oxidation of metal sulfide in the feed does exist via reaction [2]. However, unlike the FSF, the oxidation reaction is not the main source of heat and formation of nickel and copper oxides is self-correcting via reaction [3] (Vernon & Burks, 1997):

$$MS(feed) + 3Fe_2O_3(slag) \rightarrow MO(slag) + 6FeO\ (slag) + SO_2(gas) \qquad [2]$$

$$MS(feed) + 2MO(slag) \rightarrow 3M(metal) + SO_2(gas) \qquad [3]$$

The OPEX implication of the above is a saving for BCL if it were to run a TSL. The savings arise from not running a separate electrical slag-cleaning furnace to recover nickel and copper after the main FSF furnace.

- *Ease of smelting high-magnesium concentrate with a TSL.* With a FSF, the feed is heated by burning sulfur in the feed. This presents a challenge for high-magnesium concentrates because these produce slags with a melting point near the upper burning temperature limit within the reaction shaft (Crundwell et al., 2011). Therefore, such concentrates do not melt in the reaction shaft, which may lead to loss of nickel and copper because of being locked in solid burnt concentrate lumps. Corrective measures for this in the FSF is the use of supplementary coal to provide added heat in the reaction shaft.

In the TSL, temperature control derives entirely from burning fossil fuel or an equivalent, so is more independent of the reactions necessary to give the sulfide matte. Therefore, the reaction temperature can be increased with ease and without limits, at least within reasonable operating conditions. In this regard, the TSL can treat high-magnesium concentrates better than the FSF.

Operating cost and technological comparison

Raw data and statistical analysis

Raw operational data for three Cu FSF and two TSL are given in Table II; normalized data per furnace operator are shown in Table III. Raw consumable data was normalized per tonne of feed or per tonne of copper in the feed.

The results of the t-test are shown on the right side of Table III by way of the P-value, together with conclusions for the Cu smelting comparison. Analysis of the t-test results and their application to Ni–Cu smelting at BCL is presented in the following section. Note that the BCL figures are not taken into consideration in the t-test.

Technological and operating cost comparison

This section discusses the results of the OPEX and statistical

Table II

Raw data for BCL and copper FSF and TSL used in study (Arthur et al., 2005; Arthur et al., 2003; Ross, 2005; Schlesinger et al., 2021)

	Cu FSF				Cu TSL	
	BCL (Legg, et al., 2009)	PARSA Leyte	Sumitomo Toyo	Hibi Kyodo Smelting Co.	Mount Isa	Mufulira
Fresh feed (kt/a)						
Concentrate	900	720	1 379	807	1382	821
Ni–Cu grade (%)	8[1]	26 (Cu)	28.8	29.2	23.8	29
Silica flux	–[2]	36	203	79	29.4	13
Matte						
Ni–Cu grade (%)	31.7[1]	55 (Cu)	64	63.5	57	62.5
Bath height (m)					1.5	1.5
Blast						
Feed rate (Nm^3/a)	1	0.31	0.32	0.23	0.38	0.19
O_2 (vol.%)	36	48.5	77	67	60.8	77
Temperature (°C)	260	200	200	210	< 0	< 0
Hydrocarbon feed (kt coal/a)						
Main furnace	47.3	14.5[3]	8	10	30.2[4]	13[5]
Settler furnace	–	–	–	–	–	–
Inside dimensions (m)						
Main furnace b × l or Ø	22 × 8.2	20.2 × 7.5	19.9 × 6.7	19.8 × 7	3.75	5.5
Settler furnace b × l	–	–	–		*Rotary	18 × 7.4
Furnace life (a)	8	< 11[6]	< 11	< 11	< 4.5	1.75
No. of bricks per reline (Glencore, 2022)					16 530	24 244[7]

[1] Combined Ni and Cu %
[2] Data not available in open literature
[3] Bunker oil energy content = 40 MJ/kg; coal energy content = 21.5 GJ/t
[4] Combined TSL and settler furnace
[5] Combined TSL and settler furnace
[6] General maximum campaign life. Not specific to the furnace operator
[7] Estimate based on Mount Isa value

Table III

Normalized operational data for copper TSL and FSF furnaces and t-test comparison

	BCL	PARSA Leyte	Sumitomo Toyo	Hibi Kyodo Smelting Co.	Mount Isa	Mufulira	P value	Comment
Feed								
Silica flux (t/t feed)	0	0.05	0.15	0.1	0.02	0.02	0.11	No difference
Blow demand								
Blow (Nm^3/t feed)	0.0011	0.0004	0.0002	0.0003	0.0003	0.0002	0.56	No difference
O_2 (kNm^3/t Cu-feed)	5	0.8	0.62	0.65	0.702	0.614	0.68	No difference
O_2 (kNm^3/t feed)	0.4	0.209	0.179	0.191	0.167	0.178	0.14	No difference
Coal demand								
Main and settler furnace (t/t coal/feed)	0.053	0.02	0.006	0.012	0.022	0.016	0.30	No difference
Heating blow (t/t coal/feed)	0.0132	0.0042	0.0026	0.0032	0	0	0.019	Different
Structural measures								
Space demand (m^2/(kt/a feed))	0.2	0.21	0.097	0.172	0.191	0.191	0.44	No difference
No. of rebuilds over 8 years	0	0	0	0	2.4	2.4		Different

comparison carried out on the normalized operational data for Cu smelting and its applicability to Ni–Cu smelting.

It can be concluded from Table III that, despite popular comparisons in past literature (Bujaku et al., 2019), the normalized consumables demand for FSF and TSL furnaces remain largely statistically the same. This is true for silica, oxygen, and coal demands for main and settling furnace usage. Further, despite claims for a lower footprint for the TSL, when statistically compared with FSF furnaces, the TSL furnace technology takes the same overall space when the settling furnace is taken into consideration.

The only statistical differences between the technologies, with respect to the considered items, are in the usage of coal to heat the blow and the number of relinings. The FSF uses more coal (approximately 0.0132 t/t feed for the BCL case) than for an equivalent TSL treating the BCL feed. However, the TSL would have about 2.4 more rebuilds during the time of one FSF furnace campaign. With this in mind, it cannot yet be concluded whether BCL would be better off with an FSF or TSL. A summative economic analysis of the cost of coal compared with a furnace rebuild was then carried out.

Summative operating cost comparison

This section compares the economic implications of the two identified differences in operation between the FSF and TSL (coal use for feed heating and relining). The analysis was carried out using BCL furnace conditions: a feed rate of 900 kt/a, a furnace life of 11 years, and the time period for a single FSF campaign. The TSL furnace refractory lining was assumed to be a chromite–magnesite refractory (Schlesinger et al., 2021) of ~ 220 mm length, with a brick size of 22.9 mm × 10.2 mm × 7.6 mm and density of 3.63 g/cm^3. Table IV shows the summative operational cost difference of changing from the existing FSF to a TSL furnace. All values are based on local Botswana costs.

Table IV shows that the summative difference in OPEX for BCL to change from the existing FSF to a TSL is a decrease of approximately BWP 55.5 million. This arises from savings from the lack of need to heat the furnace blow in the TSL furnace. The cost of furnace relining has minimal effect on the summative OPEX difference. This presents rather a different result from previous reports based on a single-point operation simulation (Bujaku et al., 2019).

Conclusions and recommendations

Operations that have had to undergo a stoppage due to economic reasons, such as the product price(s) not meeting OPEX, should reevaluate their OPEX for opportunities to reduce such costs. The objective of such an exercise is to ensure that such operations remain profitable during any future depressed product price. For the BCL smelter, which was placed under care and maintenance in 2016 due to depressed nickel prices, one of the choices to reduce OPEX lies between continuing to use the existing FSF technology or opting to use newer TSL technology.

Using normalized operation data from three copper FSF (PARSA Leyte, Sumitomo Toyo, and Hibi Kyodo Smelting Co.) and two copper TSL (Mount Isa and Mufulira), it was determined that the only statistically significant differences in operational consumables between the two furnace types lies in the usage of coal for heating the blow and number of relinings required during

Table IV

Comparative operational cost difference on changing from FSF to TSL for the BCL case

	Units over 11 yr	Unit cost (BWP/t)	Overall difference (million BWP)
Coal to heat blow for FSF case	130 kt	435	−56.8
Furnace bricks for TSL reline	48 929 bricks	4,100	+1.3
		Total change	**−55.5**

the furnace lifetime of one FSF campaign. The FSF requires coal for heating the feed blow; the TSL requires ~ 2.4 rebuilds in the duration of a single FSF lifetime. Other consumable and technical attributes of the two furnaces that were compared include silica flux, oxygen, fossil fuel use to heat the feed (concentrate and blow) and holding furnaces, and furnace relining bricks.

Technological comparison found that although both the FSF and TSL can treat low Ni–Cu concentrates, higher Ni–Cu recoveries at lower OPEX can be achieved by BCL if it were to convert the existing FSF furnace to a TSL. This is because the TSL technology does not involve partial roasting of the feed, which, in the FSF, poses a risk of fully roasting the sulfide Ni–Cu in the feed, which is then lost as oxides in the slag. To recover the lost Ni–Cu in the slag, the FSF operates with an electric slag-cleaning furnace to recover Ni–Cu oxides in the slag. Such an electric furnace is not necessary for the TSL because oxidation is self-correcting to yield more metal to the matte. Conversion from FSF to TSL will enable the operation to handle higher magnesium concentrates, which pose a problem for the FSF due to their high melting point. There is no statistical difference between the two technologies concerning the plant footprint if the TSL is seen as a combination of the cylindrical section and the necessary settler furnace, as has been previously suggested in literature.

A summative assessment showed that BCL OPEX would be some BWP 55.5 million lower for a TSL over a 11-year equivalent FSF life campaign. These savings originate from not needing to heat the furnace blow. The effect of TSL relining on OPEX is very minimal over this period.

In conclusion, for the considered operational consumables and characteristics of FSF and TSL based on actual performance of operating plants, it was found that the BCL smelter would be cheaper to run if it were to adopt the newer TSL furnace technology.

Despite the above, this study does not claim to be an exhaustive comparison of OPEX comparison of the two furnace technologies. OPEX related to tapping activities, tap hole changes, lance usage, and furnace availability were not considered and ought to be included in future studies.

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