JOM, Vol. 70, No. 11, 2018
https://doi.org/10.1007/s11837-018-3041-7

# Variables Applicable to Benchmarking of Tap-Hole Life-Cycle Management Practices in Coke-Bed-Based Ferroalloy Production

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Benchmarking is a tool available to furnace operators to evaluate their tap-hole life-cycle management practices against those of their peers. It allows furnace operators to challenge their own practices in order to increase furnace utilization. To facilitate the benchmarking process, it is necessary to define the variables to be considered and how they relate to one another. This article develops, from the literature and industry interviews, a holistic conceptualization of the variables that form part of tap-hole lifecycle management and performance. Specifically, the article focuses on the variables related to coke-bed-based processes (FeCr, SiMn, and HCFeMn) applying SAF technology of circular design.

## INTRODUCTION

In pyrometallurgical furnaces, tap-hole life-cycle management aims to reduce the operational and financial risks associated with tap-hole failures,[1] while simultaneously maximizing furnace utilization. The tap-hole life cycle typically consists of four functions: operation, relining, maintenance, and repair. Management practices associated with each function typically form part of day-to-day furnace operations. A benchmarking study aimed at tap-hole life-cycle management in platinum group metal (PGM) and nickel matte smelting was reported by Nolet.[2] Nine plants participated in the project and four aspects of furnace tapping were compared namely: tapblock design, tapblock monitoring, tapblock maintenance, and tapping practices. Another example of a benchmarking study specifically aimed at tap-hole life-cycle management was reported by Nelson et al.[3] Their study touched on the relining function by focusing on the effect of furnace design parameters on tap-hole integrity.

South Africa has a large ferroalloys industry with primary production facilities for ferrochromium (FeCr), silicomanganese (SiMn), high-carbon ferromanganese (HCFeMn), ferrosilicon (FeSi), and silicon (Si) alloys. Submerged arc furnace (SAF) and direct current (DC) arc furnace technologies are employed. Technology- or commodity-specific benchmarking exercises will allow for improved tap-hole life-cycle management in the South African ferroalloys industry.[1] Further benefit could be attained by expanding these exercises to other countries utilizing similar technologies or producing similar products. The results presented here formed part of a study aimed at developing and testing a methodology for benchmarking tap-hole life-cycle management practices in coke-bed-based ferroalloy production (FeCr, SiMn, and HCFeMn) utilizing SAFs of circular design.

## METHODS

The context for this research was SiMn production using SAF technology in South Africa. The research was executed in two phases: (1) identification and (2) validation.

During the *identification* phase, the goal was to identify an initial list of dependent and independent variables to be considered. The dependent variable chosen was tap-block life. The independent variables were chosen to be related to tap-hole life-cycle management and were required to directly or indirectly affect tap-block life. The independent variables were collated through a review of the literature and through interviewing key operating

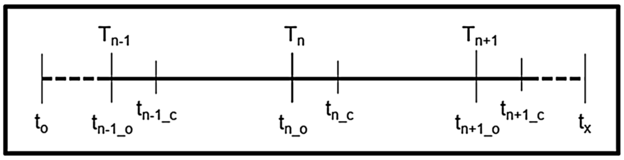

Fig. 1. Timeline describing discrete tapping events according to their tap numbers ($T$) and the time intervals ($t$) at which they occur indicating when the tap-hole is opened ($t_o$) and when it is closed ($t_c$).

personnel at producers of SiMn, HCFeMn, FeCr, and PGM matte (one site each). The key papers identified during the review were Nolet,[2] Nelson et al.[3,4], and Steenkamp et al.[1]

During the *validation* phase, the goal was to validate the list of independent variables for the context of SiMn production using open SAF technology. Personnel were interviewed on site and included the production manager, two production superintendents, and one production engineer. They were asked to review the initial list and suggest any shortcomings/omissions in the data. The final list was then updated based on their recommendations.

It was found from the literature review, plant visits and correspondence with leading authors in the field that specific terminology may be interpreted differently in different furnace environments. Having a common definition and mathematical description of independent variables are thus crucial for a scalable benchmarking study that can be expanded to other plants, commodities or countries. The validated variables list presented in this research will be used as the foundation for a future benchmark study in SiMn production.

## RESULTS AND DISCUSSION

The definitions of the validated independent variables were based on the concepts and variables defined in Figs. 1, 2, 3 and 4.

### Operations

The typical independent variables associated with the operations function are listed and defined in this section. Where applicable, the way in which these variables are quantified in a plant environment is also described.

1. $P$: Instantaneous power input (MW).
2. $p$: Furnace pressure (Pa).
3. $X\%$: concentration of individual components in alloy or slag (mass.%) determined by bulk chemical analyses of tapped alloy or slag.
4. $M_{\text{alloy}}$: mass of alloy per tap (tons) preferably determined by load cells, alternatively inferred by operating personnel from production data.
5. $M_{\text{slag}}$: mass of slag per tap (tons) preferably determined by load cells, alternatively inferred by operating personnel from production data.
6. $T_{\text{alloy}}$: temperature of alloy (°C) preferably determined by a dip thermocouple at the tap-hole outlet, or by a pyrometer, or inferred from production data.

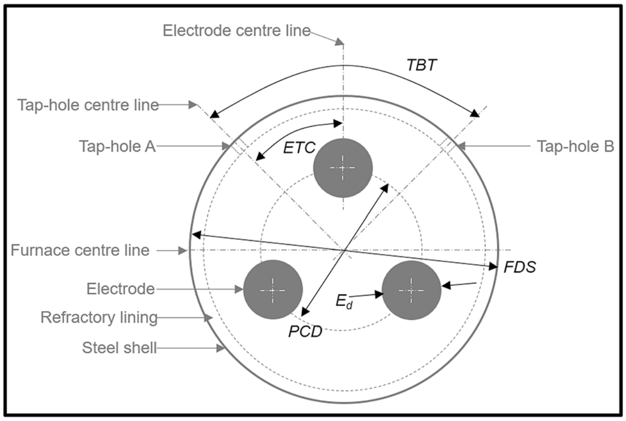

Fig. 2. View in plan of a typical three-electrode, circular furnace with furnace components, and associated lines and text, indicated in gray. Variables described and used to define other variables below, and associated lines and text, indicated in black.

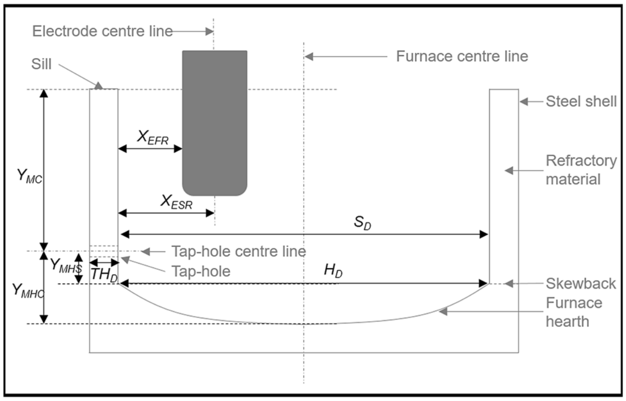

Fig. 3. View in elevation of a typical circular furnace with furnace components, and associated lines and text, indicated in gray. Variables described and used to define other variables below, and associated lines and text, indicated in black.

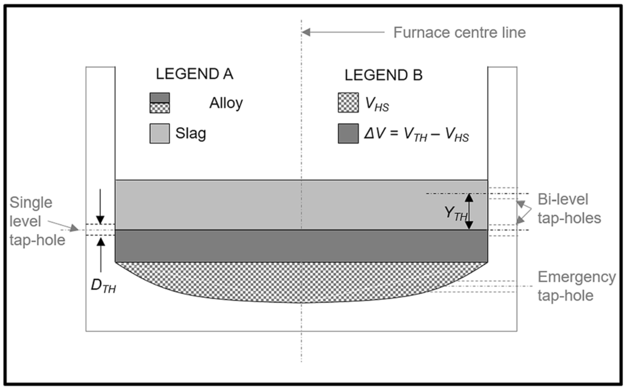

Fig. 4. View in elevation of a typical circular furnace with different tap-hole configurations indicated as well as the typical liquid phases present in the furnace.

7. $T_{\mathrm{alloySH}}$: extent to which alloy was superheated (°C) calculated in Eq. 1:

$$T_{\mathrm{alloySH}} = T_{\mathrm{alloy}} - T_{\mathrm{alloyLIQ}} \tag{1}$$

where $T_{\mathrm{alloyLIQ}}$: liquidus temperature of alloy (°C).

8. $T_{\mathrm{slag}}$: temperature of slag (°C) preferably determined by a dip thermocouple at the tap-hole outlet, or by a pyrometer, or inferred from production data.
9. $T_{\mathrm{slagSH}}$: extent to which slag was superheated (°C) calculated in Eq. 2:

$$T_{\mathrm{slagSH}} = T_{\mathrm{slag}} - T_{\mathrm{slagLIQ}} \tag{2}$$

where $T_{\mathrm{slagLIQ}}$: liquidus temperature of slag (°C).

10. $R_{\mathrm{S/A}}$: slag-to-alloy-ratio (dimensionless) calculated in Eq. 3:

$$R_{\mathrm{S/A}} = \frac{M_{\mathrm{slag}}}{M_{\mathrm{alloy}}} \tag{3}$$

Tapping practices related to process conditions can be evaluated in terms of the independent variables calculated below.

11. $t_{\mathrm{tap}}$: tap duration (min) calculated as indicated in Eq. 4:

$$t_{\mathrm{tap}} = t_{n\_\mathrm{c}} - t_{n\_\mathrm{o}} \tag{4}$$

where $t_{n\_\mathrm{c}}$: time tap-hole is plugged with clay (min) as defined in Fig. 1; $t_{n\_\mathrm{o}}$: time from first liquid observed (min) as defined in Fig. 1.

12. $\mathrm{TR_A}$: average alloy tap rate (tons/min) calculated in Eq. 5:

$$\mathrm{TR_A} = \frac{M_{\mathrm{alloy}}}{t_{\mathrm{tap}}} \tag{5}$$

where $t_{\mathrm{tap}}$: tap duration (min) calculated in Eq. 4.

13. $\mathrm{TR_S}$: average slag tap rate (tons/min) calculated in Eq. 6:

$$\mathrm{TR_S} = \frac{M_{\mathrm{slag}}}{t_{\mathrm{tap}}} \tag{6}$$

where $t_{\mathrm{tap}}$: tap duration (min) calculated in Eq. 4.

14. TOT: tap-to-tap time (h) calculated in Eq. 7:

$$\mathrm{TOT} = \frac{t_{n\_\mathrm{o}} - t_{n-1\_\mathrm{o}}}{60} \tag{7}$$

where $t_{n\_\mathrm{o}}$: time from first liquid observed for tap (min) defined in Fig. 1; $t_{n+1\_\mathrm{o}}$: time from first liquid observed for following tap (min) defined in Fig. 1.

15. $P_{\mathrm{A}}$: Tap-hole productivity in terms of alloy produced over a 24-h period (tons/day, per tap-hole) calculated in Eq. 8. Tap-hole productivity in terms of slag produced over a 24-h period can be calculated in a similar fashion.

$$P_A = \sum_{n=1}^{x} M_{\mathrm{alloy}}(T_{n-1}) = M_{\mathrm{alloy}}(T_0) + M_{\mathrm{alloy}}(T_1) + M_{\mathrm{alloy}}(T_2) + \cdots + M_{\mathrm{alloy}}(T_x) \tag{8}$$

where $T_{n-1}$: tap number (where $n > 0$, natural number).

16. $\mathrm{TH_{cf}}$: tap-hole cycle frequency (taps per tap-hole/min) applicable when more than one tap-hole is in operation in any given period and calculated in Eq. 9:

$$\mathrm{TH_{cf}} = \frac{\sum_{n=1}^{x} T_{n-1}}{t_x - t_0} \tag{9}$$

where $\sum_{n=1}^{x} T_{n-1}$: total number of taps in given period (taps) calculated in Eq. 10; $t_x$: time when period ends (min) defined in Fig. 1; $t_{\mathrm{o}}$: time when period starts (min) defined in Fig. 1.

$$\sum_{n=1}^{x} T_{n-1} = T_0 + T_1 + T_2 \cdots + T_x \tag{10}$$

where $T_{n-1}$: any tap number in sequence (dimensionless) defined in Fig. 1; $T_x$: final tap number in sequence (dimensionless) defined in Fig. 1.

Tapping practices related to the ways in which the tap-hole is opened at the beginning of the tap ($t_{n\_\mathrm{o}}$ in Fig. 1) and closed at the end of the tap ($t_{n\_\mathrm{o}}$ in Fig. 1) are:

17. Whether or not a drill was used to open the tap-hole.
18. Drill duty measured in number of tap-holes serviced/drilled as a drill can service more than one tap-hole (typically in the same vertical position) when mounted on a rail.
19. Drill support configuration where drills can be mounted either hanging from rails or fixed in position using a pedestal.
20. Drilling frequency, measured in tap-holes drilled/tap, which is the number of times a drill was used to open tap-holes. This is typically only calculated for a large number of taps.
21. Drill depth per tap (mm).
22. Drill rod length (mm).
23. Drill rod diameter (mm).
24. Drill bit diameter which could be differentiate between alloy and slag if applicable (mm).
25. Drill bit consumption per ton alloy or slag (number of bits/ton alloy or slag produced).
26. Lance consumption (number of lances used/-tap).
27. Type of gas used when lancing tap-holes (typically oxygen).
28. Type of lance used, either in terms of material used for manufacturing or design of lance or both.

29. Length of metal lances used for lancing (mm).
30. Internal diameter and external diameter of metal lances used for lancing (mm).
31. Reaming of tap-hole during tap, whether or not tap-hole is opened during tapping to increase flow.
32. If reaming techniques are applied, the type of equipment used, i.e., lance rod (with or without oxygen applied) or steel bar.
33. Steel bar diameter and length (mm) where steel bars can be applied in reaming practices or for other duties, i.e., general cleaning of the tapping launder during tapping.
34. Steel bar consumption per tap (bars/tap).
35. Whether or not claygun was used to close tap-hole.
36. Claygun equipment supplier, brandname, and model number.
37. When claygun is rail mounted, number of tap-holes serviced per claygun.
38. Claygun press-on pressure which is the pressure applied by hydraulic (or pneumatic) system to ensure a proper seal between claygun and cold face of the tapblock (MPa).
39. Claygun nozzle duty (tons alloy or slag tapped/nozzle).
40. Clay capacity of claygun barrel (kg or $m^3$ or L).
41. Claygun holding time at tap-hole which is the time (min) that the claygun is held in position at tap-hole and nozzle pressure is applied.
42. Clay injection rate (kg or L/s) which is the rate at which clay is injected into tap-hole.
43. Claygun energy supply which is the source of energy applied in claygun operation and can be hydraulic, pneumatic, or electric.
44. Methods used to ensure perfect mating between tap-hole and claygun and include mechanical alignment methods, or the application of ceramic or clay gaskets to create a seal and prevent clay from being extruded from the claygun at the cold-face of the tap-hole.
45. Whether or not manual plugging method is applied.
46. If a manual plugging method is applied, state type of manual plugging method applied, including supplier, brand name, and product code for tap-hole clay.
47. Whether or not tap-hole clay is preheated prior to being used and when preheated, what method is used to preheat tap-hole clay and to which temperature (°C) is tap-hole clay preheated.
48. Type of aggregate used to manufacture tap-hole clay.
49. Type of binder used to manufacture tap-hole clay.
50. Moisture content of tap-hole clay.
51. Workability index (measure of plasticity) of tap-hole clay.
52. Tap-hole clay consumption which is the amount of tap-hole clay used to close tap-hole per tap (kg/tap).

## Reline

The typical independent variables associated with the reline function are listed and defined in this section.

1. Tap-hole configuration philosophy in plan view whether one, two, or three tap-holes per level.
2. Tap-block designs, which could include water-cooled elements (or elements cooled by other means) and/or multiple refractory components. The layout of the multiple components in the tap-block design is of importance.
3. Tap-hole vertical configuration philosophy which can be a single level or bi-level tap-hole configuration, as indicated in Fig. 2. For single-level tap-holes, both alloy and slag streams are tapped through a single tap-hole. For bi-level tap-holes alloy, having a higher density than slag, is tapped through the lower-level tap-hole and slag through the upper-level tap-hole.
4. Whether or not an emergency tap-hole to drain the furnace prior to a rebuilt (see Fig. 2) is included in the design.
5. $D_{TH}$: tap-hole diameter (mm) per tap-hole (alloy, slag, emergency), as indicated in Fig. 2.
6. $Y_{TH}$: distance between alloy and slag tap-hole (mm) in the case of bi-level tap-holes, as indicated in Fig. 2.
7. FDS: furnace diameter of steel shell (m) indicated in Fig. 3.
8. PCD: electrode pitch circle diameter (m) applicable to three-in-circle configuration and indicated in Fig. 3.
9. TBT: tap-hole horizontal configuration, indicating the distance between two tap-holes as indicated in Fig. 3 (° or mm).
10. ETC: electrode center line to tap-hole center line (°) indicated in Fig. 3.
11. $Y_{MHC}$: difference between alloy tap-hole and hearth center line (mm) indicated in Fig. 4.
12. $Y_{MHS}$: difference between alloy tap-hole and hearth skewback for a dished hearth (mm) indicated in Fig. 4.
13. $H_R$: hearth radius (m) calculated in Eq. 11:

$$H_R = \frac{H_D}{2} \tag{11}$$

where $H_D$: hearth diameter (m) indicated in Fig. 4.

14. $H_A$: hearth area ($m^2$) calculated in Eq. 12 for a flat hearth. For a dished-shaped hearth, surface area of dish shape should be calculated:

$$H_A = \pi\left(\frac{H_D}{2}\right)^2 \tag{12}$$

15. $R_A$: Ratio of alloy tap-hole depth to electrode diameter (dimensionless) calculated in Eq. 13:

$$R_A = \frac{TH_D}{E_D} \tag{13}$$

where $TH_D$: alloy tap-hole depth (m) defined in Fig. 4; $E_D$: electrode diameter (m) defined in Fig. 3.

16. $V_{TH}$: alloy sump volume up to alloy tap-hole center line ($m^3$) calculated in Eq. 14:

$$V_{TH} = \Delta V + V_{HS} \tag{14}$$

where $\Delta V$: alloy sump volume between top of hearth skew and alloy tap-hole center line ($m^3$) defined in Fig. 2; $V_{HS}$: alloy sump volume up to top of hearth skew ($m^3$) defined in Fig. 2.

17. PD: conventional hearth power density ($kW/m^2$) calculated in Eq. 15:

$$PD = \frac{1000 \times P}{H_A} \tag{15}$$

where $H_A$: hearth area defined in Eq. 12 ($m^2$).

18. $PD_{ESR:}$ electrode delta symmetry to refractory hot face power density (MW/m) calculated in Eq. 16:

$$PD_{ESR} = \frac{P}{X_{ESR}} \tag{16}$$

where $X_{ESR}$: distance between electrode delta symmetry (which is similar to PCD defined in Fig. 3) and refractory hot face (m) define in Fig. 4.

19. $PD_{LVMTH}$: local volumetric power density to alloy tap-hole center line ($MW/m^3$) calculated in Eq. 17:

$$PD_{LVMTH} = \left(\frac{P}{H_A \times Y_{MC}}\right) \tag{17}$$

where $H_A$: hearth area defined in Eq. 12 ($m^2$); $Y_{MC}$: distance between furnace sill and alloy tap-hole center line (m) defined in Fig. 4.

20. $PD_{LWP}$: local wetted perimeter power density for $^1/_3$ of slag line area ($kW/m^2$) calculated in Eq. 18:

$$PD_{LWP} = \frac{1000 \times P}{\frac{1}{3} S_A} \tag{18}$$

where $S_A$: slag line area calculated in Eq. 19 ($m^2$).

$$S_A = \pi\left(\frac{S_D}{2}\right)^2 \tag{19}$$

where $S_D$: slag line diameter (m) defined in Fig. 4.

21. $PD_{EFR:}$ electrode face to refractory hot face power density (MW/m) calculated in Eq. 20:

$$PD_{EFR} = \frac{P}{X_{EFR}} \tag{20}$$

where $X_{EFR}$: distance between electrode face and refractory hot face (m) defined in Fig. 4.

22. $PD_{LPH}$: local perimeter hearth power density of $^1/_3$ of hearth area ($kW/m^2$) calculated in Eq. 21:

$$PD_{LPH} = \frac{1000 \times P}{\frac{1}{3} H_A} \tag{21}$$

where $H_A$: hearth area defined in Eq. 12 ($m^2$).

## Maintenance

When it comes to tap-hole maintenance and repair, fairly simple activities (typically executed in less than 2 h) are considered to be maintenance activities. More complex activities (typically executed in more than 2 h) are considered repair activities. The typical independent variables associated with the maintenance function and associated maintenance plans are listed and defined in this section.

1. Tap-hole condition monitoring techniques that trigger tap-hole maintenance. In particular, the factors measured to indicate tap-hole wear and trigger tap-hole maintenance.
2. Tap-hole maintenance intervals (weeks or months), i.e., the average time between tap-hole maintenance activities.
3. Tap-hole maintenance practices which are practices executed in less than 2 h.
4. Use of reconstructive tap-hole clays: whether or not so-called ‘reconstructive’ tap-hole clays are utilized as part of furnace operations to maintain tap-holes.

## Repair

The typical independent variables associated with the repair function are listed and defined in this section. These include:

1. Tap-hole condition monitoring techniques that trigger tap-hole repairs. These include factors measured to indicate tap-hole wear and trigger tap-hole repair.
2. Tap-hole repair interval (weeks or months), i.e., the average time between tap-hole repair activities.

3. Tap-hole repair practices which are practices executed in more than 2 h.
4. Furnace lining life (years) which is the time between furnace relines.

## CONCLUSION

The goal of this research was to support the benchmarking of tap-hole life-cycle management practices in plants producing FeCr, SiMn, and HCFeMn using SAF technology of circular design. Specifically, the research output was to identify and validate a list of independent variables that affect tap-block life. The independent variables were identified based on a review of the literature and validated through interviews with plant personnel at a number of plants producing various commodities using furnace technology. The validated variables were then divided into the four functions associated with the tap-hole life cycle (operations, reline, maintenance, and repair), and reported here. Having these common definitions, and especially mathematical descriptions where applicable, will be useful for future benchmarking studies and comparative analysis studies in the field.

## ACKNOWLEDGEMENTS

Inputs received from plant personnel and Itumeleng Thobadi and Olive Makwarela from MINTEK are gratefully acknowledged. This work is published with the permission of MINTEK. Funding was provided by NIMPO (Grant No. EE58 Optimizing Furnace Tapping).

## REFERENCES

1. J.D. Steenkamp, J.J. Sutherland, D.A. Hayman, and J. Muller, *JOM* 68, 1547 (2016).
2. I. Nolet and J.S. Afr, *Inst. Min. Metall.* 116, 223 (2014).
3. L.R. Nelson, R. Hundermark, and K. Van der Merwe, *The Conference of Metallurgists—COM* (2015), p. 1.
4. L.R. Nelson, R. Hundermark, and J.S. Afr, *Inst. Min. Metall.* 116, 465 (2016).