'The tap-hole' – key to furnace performance

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The critical importance of tap-hole design and management to furnace performance and longevity is explored through examining some of the specific matte, metal and slag tapping requirements of non-ferrous copper blister and matte converting and smelting, ferroalloys smelting and ironmaking systems. Process conditions and productivity requirements and their influence on tapping are reviewed for these different pyrometallurgical systems. Some critical aspects of the evolution of tap-hole design to meet the diverging process and tapping duties are examined. Differences and similarities in tapping practices and tap-hole management are reviewed. Finally core aspects of tap-hole equipment and maintenance are identified that are considered important to securing improved tap-hole performance and life, so pivotal to superior furnace smelting performance.

Keywords: Tapping, Tap-hole, Ironmaking, Ferroalloy, Non-ferrous, Matte, Slag, Blister.

Introduction

The sheer diversity of tapping configurations used on industrial pyrometallurgical operations is at first bewildering, from: historical no-tap-hole tilting furnaces, to modern eccentric bottom tapping (EBT) tilting and/or bottom slide-gate electric arc furnaces; to classical single tap-hole multiphase tapping (e.g., metal/matte and slag), to dedicated phase tap-holes (e.g., dedicated metal/matte-only and slag-only), to dedicated phase multi-tap-hole configurations (up to 8 metal/matte-only tap-holes and 6 slag-only tap-holes); to more esoteric metal/matte-only siphons and slag overflow skimming (e.g., Mitsubishi Continuous Process [BM10]). This can be further complicated by periodic batch tapping; to consecutive tapping on a given tap-hole; to alternating tap-hole practice tapping; to near continuous slag-only tapping, with discrete batch matte/metal tapping on higher productivity, but low metal/matte fall (<20% by mass feed) Co and Ni ferroalloys and precious group metals (PGM) matte furnaces; to near-continuous tapping achieved through batch tapping of individual tap-holes, but opened consecutively [BF29,20]; to fully continuous tapping on coupled multi-furnace cascades [BM10].

This is largely a consequence of differing processing conditions (process temperature, superheat (ΔT) and Prandtl number, $Pr = \mu C_p/k$, where μ = dynamic viscosity, C_p = specific heat content and k = thermal conductivity, and resulting heat flux). But this can also be influenced strongly by industrial operating philosophy ito. furnace design for campaign life longevity (i.e., greater capital spend for longer, say 20-30 year life) versus furnace productivity (i.e., number of heats/campaign to provide the greatest possible dilution of fixed costs per unit of commodity produced). This may not even be consistent within a given commodity; all ironmakers (blast furnace (BF) campaign life-based) supply downstream steelmakers (who use heat/campaign-based converters and/or electric arc furnaces).

However, regardless of the specific tap-hole configuration or operating philosophy, due to the addition of dynamic (often periodic) and more intense process conditions (exposure to higher temperatures leading to accelerated corrosion; greater turbulence, and elevated rates of mass and heat transfer) and higher concomitant thermo-mechanical forces (from thermal or flow shear stresses), furnace performance and longevity is intimately linked to tap-hole performance. For good reason Van Laar [BF22] titled his paper 'The tap-hole: The heart of the blast furnace' in the 2001 Symposium entitled 'The tap-hole – the blast furnace lifeline' [BF21], while the title of the 2010 Coetzee and Sylven [FA6] contribution 'No tap-hole – No furnace' and the staging of this very Tapping Conference in 2014 suggests continued criticality and relevance.

By first comparing and contrasting some of the process conditions and resulting tap-hole and tapping requirements of different commodities, an attempt will be made to identify key elements of: tap-hole design; physical tapping practices; equipment; monitoring and maintenance practices characteristic of superior tap-hole management and required to secure prolonged tap-hole performance and life.

Commodity-specific process and operating conditions

To provide some context on the range of tap-hole designs, operating and maintenance practices adopted for different commodities, it is instructive to make some comparison of key process physico-chemical and operating conditions prevailing.

Table I. Indicative[1] Process Limits, Properties and Operating Conditions per Tapped Commodity

	Iron-making	**Cr ferro-alloy**	**Mn ferro-alloy**	**Ni ferro-alloy**	**Cu blister /matte**	**Ni Matte**	**PGM matte**
Furnace	BF	SAF/ DC-arc	BF/ SAF	Circ/6iL EF	FF/ TSL	6iL/TSL/ FF	6iL/Circ/TSL
M + S Tap-holes	1-4	1-3, 1-2+1-2	1-2, 2+2	2+4-6	2-8+2-6	2+2	2-3+2-3
$T_{metal/matte}$, °C	1480-1530	1500-1650	1300-1450	1430-1550	~1170-1320	1150-1300	1300-1500
$\Delta T_{metal/matte}$, °C	~350	50-100	50-150	20-350	100-250	50-300	400-650
T_{slag}, °C	1480-1530	1600-1750	1350-1550	1550-1630	1170-1350	1200-1400	1450-1600
ΔT_{slag}, °C	~200	<50	50-100	50-150	50-100	50-150	50-200
$q_{average}$, kW/m^2	25	5	5	50-100	20-100	20-50	30-100
$q_{peak\ tap\text{-}hole}$, kW/m^2	>200	>15	>15	>200	>300	>200	>300
$\rho_{metal/matte}$, t/m^3	6.7-7	~6.7	~5.5	~7.5	~5-7.5	~4.5	~4.2
ρ_{slag}, t/m^3	2.6-3.1	2.7-3.2	2.7-3.3	2.8-3.2	3.5-4	2.8-3.2[i]	2.8-3.2
$\mu_{metal/matte}$, Pa.s	0.004-0.007	~0.007	0.005	~0.006	0.002-0.005	0.003 (0.05[i])	0.0025
μ_{slag}, Pa.s	0.1-0.5	~0.5	0.7-1.5	~0.5	0.03-0.07	0.3	0.3
$k_{metal/matte}$,[ii] W/m°C	50	~20	~14	~30	~5-160	17[i]	17[i]
k_{slag},[ii] W/m°C	~0.5	~0.2	~0.2	~0.7	~2-8	0.8 (8[i])	~0.8
$C_{p,metal/matte}$, MJ/t°C	0.8	~0.9	~0.9	~0.5	~0.5	~0.7	~0.8
$C_{p,slag}$, MJ/t°C	~1	~1.7	~1	~1.2	~1	1.25[i]	~1.3
$\beta_{metal/matte}$, /°C	8 x10^{-5}	7 x10^{-5}	-	8 x10^{-5}	1 x10^{-5}	1 x10^{-4}	1 x10^{-4}
β_{slag}, /°C	-	-	-	-	-	3 x10^{-4}[i]	3 x10^{-4}
$Pr_{metal/matte}$	0.1	0.3	0.5	0.2	0.01	0.13 (2.1[i])	0.12
Pr_{slag}	~500	~4000	~5000	~850	~15-450	470 (47[i])	~450-500
$H_{metal/matte > MTH}$, m	0.5-2	0.3-0.6	0.3-0.6	0.15-0.3	0.25-0.4	0.25	~0.3
$H_{metal/matte\text{-}STH+Top}$, m	1-2	(0.3+) ~1	(0.3+) ~1	0.6-1+ 0.4-1	0.2-0.4+ 0.2-0.4	0.2-0.4+ 0.2-0.6	0.5+ 0.6-0.9
$P_{top\ of\ liquid\ level}$, bar	5	>1[iii]	>1[iii]	>1[iii]	~1	~1	>1[iii]
$d_{metal/matte\ tap\text{-}hole}$, m[iv]	0.04-0.08	0.07-0.2	0.04-0.1	0.04-0.1	~0.05	~0.07	0.04-0.07
$v_{tapping}$, m/s	5 (to 8)	~4	~2-4	~2-4	~2-4	~2-4	~2-4
$\dot{m}_{metal/matte}$, t/min[v]	2-8	~1-4	1-2.5[vi]	~1.5-3	1-3	~2.5	0.5-1.5[vi]
Metal/matte fall	60-75%	35-50%	35-60%	5-20%	~40%	30-40%	10-25%

[1] Some operations may operate quite far from these generically indicative values.

	Iron-making	Cr ferro-alloy	Mn ferro-alloy	Ni ferro-alloy	Cu blister /matte	Ni Matte	PGM matte
Tap-hole repair, w	4	>12	>26	1-2/8	4	3-9/26	1-4/12
Tap-hole life, y	10 (12)	2-6	2-6	1-4	1-4	1-3	1-2
Furnace life, y	15-20	12	20	20	6-12	30	12

[i][BM9]. [ii]At process temperature; Mn solid at 727°C. [iii]Operate with significant charge burden. [iv]Non-HM tap-holes often start ~40 mm diameter. [v]FA and non-ferrous instantaneous batch mass tapping rate. [vi]Higher value also typical $\dot{m}_{slag}$.

Notable features include:

- Shear metal fall and productivity of ironmaking BFs >10 000 t/d hot metal (HM), achieved through near continuous tapping at more than double the rate and velocity of, but through tap-hole diameters not too dissimilar to, other commodities.
- High pressure of tapping liquids of ironmaking BF (up to 5 bar blast pressure at tuyeres, to add to already high hydrostatic pressure of comparatively thick slag and thick and dense metal).
- More limited accessibility of smaller circular blast and electric furnaces (EF) (up to 22m diameter) to multiple tap-holes, than larger rectangular six-in-line (6iL) furnaces (up to 36 x 12m).
- Low comparative temperatures and superheats of (often near-autogenous) copper smelting
- Relatively low superheats of ferroalloys (FA) in DC-arc and submerged-arc furnaces (SAF).
- Higher viscosity (and Pr number), but lower thermal conductivity and density of slag than metal/matte.
- High thermal conductivity of liquid blister Cu.
- Extreme superheat (ΔT) of PGM matte [BM3,4].

Slag Freeze-Lining Versus Matte/Blister Copper 'Hit' Potentials

A striking industrial observation is the ease with which slag freeze linings can be formed and maintained (almost 'self-healing') from even superheated slag, provided cooling is adequate. It is also quite remarkable how effectively just a thin accretion layer of slag (a couple of millimetres thick) can provide a sufficient thermal resistance to appreciably lower critical lining and copper hot-face temperatures.

By stark contrast, especially in PGM matte and blister Cu processing, equivalent matte/metal accretion formation often seems near impossible to achieve, to the extent that operation of copper coolers on blister Cu requires 'demonstrated ability to maintain a protective accretion coating' [BM15]. Or stated another way in the PGM matte industry: operation of copper coolers unprotected from direct contact with superheated liquid matte is simply not tolerated.

With regards to the heat transfer conditions applicable to successful implementation of a water-cooled composite copper lining, four key criteria can be defined when considering the influence of process heat flux, $q = h_b\Delta T$ into (where, $\Delta T = T_B - T_f$ and h_b = convective heat transfer coefficient from bulk process liquid of temperature T_B, to accretion freeze lining of temperature T_f [2]), and out through, the composite cooling system. The latter is described for the simplest one-dimensional case by:

$$q_C = (T_f - T_C)/(x_f/k_f + x_R/k_R + 1/h_I + x_C/k_C + 1/h_C)$$

where, q_C = composite cooler heat flux, T_f = effective accretion freeze lining temperature in contact with process liquid (be it metal/matte or slag); T_C = bulk temperature of cooling fluid; x_f and k_f are thickness and thermal conductivity of accretion freeze lining, respectively; x_R and k_R are thickness and thermal conductivity of residual refractory, respectively; h_I = convective heat transfer coefficient at cooler hot-face; x_C and k_C are thickness and thermal conductivity of cooling element, respectively; and h_C = convective heat transfer coefficient of cooling medium (e.g., air or water).

Following the example of Robertson and Kang [T17], some relevant limiting conditions for such a heat transfer system can be described as: Condition 1) for accretion to (sustainably) freeze, q must be less than q_C; Condition 2) the cooling system hot-face temperature (be it refractory or copper) must be less than T_f of the specific accretion in question (be it metal/matte or slag); Condition 3) the copper hot-face temperature must not exceed copper's melting point (or

[2] $T_{liquidus}$ is commonly used to describe the real freeze lining temperature T_f. Recently, Mehrjardi et al. [T13], proposed a mechanism that supports that the temperature of the interface of stationary steady state freeze-lining deposit (T_f) can be lower than the liquidus temperature (but no lower than $T_{solidus}$) potentially facilitating operation with freeze-linings at temperatures below the liquidus.

copper's long-term service limit of < 461°C [T17]); and Condition 4) usually, unless specifically designed for, the boiling point of the cooling medium should not be exceeded (as defined by the prevailing coolant operating pressure).

Somewhat paradoxically, despite the significantly higher Pr number of slag [T17] (Table I) and its positive contribution to both natural and forced convection heat transfer Nusselt numbers through correlations[3]: $Nu = hL/k \propto (GrPr)^{1/4}$ and $(Re^{1/2}Pr^{1/3})$, respectively, effectively when the k_{matte} ~20 times higher compared to k_{slag} is accounted for, estimates of h_{matte} remain ~20 times higher than h_{slag}.

Considering the first condition, compared to slag, superheated matte of potentially four times greater superheat (ΔT_{matte} up to 650°C) and ~20 times the convective heat transfer coefficient delivers far greater incident heat flux than slag ($q_{matte} = h_{matte}\Delta T_{matte} \sim 80 q_{slag}$) and so is capable of up to a couple of orders of magnitude greater thermal 'hit' of the cooling system (Condition 1). This higher heat flux of matte compared to slag leads to higher temperatures of critical lining hot-faces (e.g., refractory and copper cooler – Conditions 2 and 3), which are then (Condition 2) all too easily above the unusually low T_f of matte, due to its unusually low solidus (850°C) and even liquidus (950°C) temperatures.

In such a situation a copper cooler unprotected by any alternative thermal barrier (e.g., refractory/slag) is significantly at risk to any superheated matte/blister Cu 'hit' that can rapidly lead to hot-face temperatures rising to where the cooler copper simply melts (i.e., 1085°C). Yet for most slag systems these conditions are rarely violated; stable slag accretion freeze linings prevail, supported additionally by a high viscosity slag 'mushy zone' adjacent to T_f [T27], to protect the composite cooling system.

Comparing k_{matte}, k_{FA}, k_{HM} and $k_{blister\ Cu}$ of 17, 10, 50 and 160 W/m°C and resulting Pr_{matte}, Pr_{FA}, Pr_{HM} and $Pr_{blister\ Cu}$ = ~0.2, ~0.2-0.5, ~0.1 and ~0.01, respectively (Table I); ratios of convective heat transfer relative to PGM matte can be estimated as $h_{matte}:h_{FA}:h_{HM}:h_{blister\ Cu}$ = 1:~1.5:~2:~5, respectively. Relative to matte, convective heat transfer coefficients of HM and blister Cu are greater. Maximum superheats $\Delta T_{PGM\ matte}$, ΔT_{FA}, ΔT_{HM}, $\Delta T_{blister\ Cu}$ of 650, 150-350, 350 and 350°C, respectively, will tend somewhat to help balance the resulting process heat fluxes, $q = h\Delta T$. So it would appear that it is low T_f (listed here at it solidus lowest extreme) of T_{matte}, T_{FA}, T_{HM}, $T_{blister\ Cu}$ of 850, >1250, 1130, and 1065°C that most limit ability to form a protective accretion freeze lining, and so render copper coolers ultimately more prone to thermal 'hit' by (PGM) matte/blister Cu.

Integrated tap-hole and tapping system management

Key aspects of tap-hole design and tapping operation, maintenance and monitoring will be presented separately for sheer convenience of presentation layout. However, lest this be misleading, it should be re-iterated that all aspects need to be considered as part of an integral system, which must be managed as such for success. Overly focussing on one component at the expense of another (e.g., tap-hole clay optimisation, without due consideration for mudgun and drill capabilities) is unlikely to yield optimal results. A *'chain only being as strong as its weakest link'* adequately describes the role of integration of all aspects of the tap-hole and tapping into a holistic system for sound management.

Types of tapping systems

Tapping systems can be conveniently categorised according to the product phases being tapped and the process conditions prevailing: primarily temperature, ΔT (versus solidus or liquidus), k and Pr number.

Slag-only Tapping

With its high Pr number and elevated melting properties (Table I), provided slag is kept free of metal/matte/bullion, this potentially represents the simplest liquid for which to design an effective tap-hole system, comprising merely a high-intensity water-cooled copper slag tapblock, protected by an accretion freeze-lining of product slag. A significant advantage to slag-only tapping is that downstream it facilitates direct treatment of slag by either traditional water granulation [BF35,FA21], or increasingly, 'dry' air atomisation (sometimes with energy recovery) to useful slag products amenable to handling and sale in ironmaking, steelmaking and Ni and SiMn ferroalloy applications [FA17,21].

Dedication of the tap-hole to slag, is particularly effective for handling corrosive slags (especially acidic slags >50% SiO_2 that are fundamentally incompatible with basic and some other refractory oxides), because there is no chemical potential for reaction with a frozen slag essentially of the same composition. Thus retention of a protective freeze lining reverts to a more predictable issue of designing for thermal equilibrium thickness, and adoption of suitable safety factors to provide some protection to deviations therefrom.

[3] Where, Grashof number, $Gr = g\beta\Delta TL^3/(\mu/\rho)^2$, Reynolds number, $Re = \rho vL/\mu$, where g = gravitational acceleration, β = volume expansion coefficient, ΔT = surface to bulk liquid temperature difference, L = characteristic length, μ = dynamic viscosity, ρ = density, v = fluid velocity, h = convective heat transfer coefficient and k = thermal conductivity.

On many industrial furnaces a combination of level measurement and phase separation is more than adequate to tap slag free of metal/matte. Nishi *et al.* [FA23] report on the importance of designing the height of the slag tap-hole to avoid Mn ferroalloy discharge through it. This is also a typical requirement of more quiescent EF or slag cleaning furnace (SCF) processes of low (< 20%) metal/matte fall (effectively 'slag-making' processes, that may even be subject to near-continuous slag tapping, such as Co and Ni ferroalloys and base and PGM matte smelting). On other matte flash furnace (FF) to TSL converting processes (e.g., blister Cu to PGM matte, respectively), it is typically necessary to equip them with downstream FF settling and/or SCF processes, for further recovery of pay metals from slag, especially oxidic losses that require recovery through reductive processes.

Theoretically, the critical height for entrainment (h_e) of a two-layer liquid through an orifice of diameter (d) is related to $\alpha d Fr^{0.4}$, where α depends on the density difference and which phase is being withdrawn (typically $\alpha < 0.625$ when lower viscosity phase withdrawn; $\alpha \geq 0.8$ when upper more viscous layer is withdrawn). And where $Fr = v/(dg\Delta\rho/\rho)$ and v is the discharge velocity, $\Delta\rho$ is the density difference between heavier and lighter liquid, and ρ is the density of the lighter liquid [T7,28]. Using assumed physico-chemical properties and tap-hole conditions (Table 1), h_e can be predicted of the order of 0.12 m for copper FF settler and PGM EF smelting (and theoretically even ironmaking BF conditions). Not too surprisingly therefore, the dedicated slag tap-holes located up to 1 m above the metal/matte tap-holes of the relevant industrial furnaces, coupled with tight metal/matte level control (to a maximum height of 0.25-0.4 m above matte tap-holes on blister Cu and PGM matte furnaces – Table I), permit slag tapping substantially free of metal/matte from its interface with the bulk slag, and entrained specifically through tapping (ignoring entrained and unsettled metal/matte droplets from other sources).

Similar two-phase liquid entrainment and initial declination of the slag interface towards the tap-hole as tapping commences, followed by a switch to initial inclination and even 'pumping' out of the tap-hole later in the tap, has been modelled on BFs by CFD [BF41,43,44,45]. However, He *et al.* [BF39] in the modelling of BF tapping, caution that the metal should not be maintained at a depth too low above the tap-hole for risk of entraining process gas by 'viscous fingering' during tapping, especially when the slag viscosity is high, or in the presence of a permeable bed of solids through which to tap (e.g. coke bed).

The efficacy of intense copper cooling (predominantly in a circular slag tapblock configuration) is clear (Figure 1 and Figure 2). These elements directly impart a thicker protective freeze lining compared with the alternatives of: just top lintel copper blocks; or 'inverted-U' square copper blocks and circular block water-cooled copper pin designs [BM11, FA5] (the latter choosing rather to try to moderate freeze-lining thickness). These latter designs all avoid the presence of water below the tap-hole. It is a moot point if this is indeed universally a safer situation, especially if control of furnace operating levels is adequate, simply because of the less desirable trade-off of imparting an inherently thinner protective freeze lining with less cooling.

Concerns frequently articulated of overly cooling copper coolers [T2, BM11, FA5] are: extravagant cost; fear of preventing easy tap-hole opening; or freezing of a tapping stream. Even with the least intense top lintel or shallow-cooled (i.e., water circuits outside the furnace) copper and refractory-lined slag tapblocks, problems associated with the latter two operational aspects can occur, and generally coupled with undesirable increased copper slag tapblock wear rates. Szekely and DiNovo [T23] in a modelling study of the critical factors for tap-hole blockage of a molten stream (e.g., during tapping), determined that nozzle diameter was most critical, followed by metal superheat, with the extent of preheating (or in this case cooling) of the nozzle walls less significant. Effectively, this implies: enlarge the tapping channel diameter if the slag tapping stream is freezing.

Figure 1. All 3 slag tap-holes open with near-continuous slag tapping on a PGM matte furnace. Notice hood extraction.

Figure 2. High-intensity water-cooled slag tapblock with solidified slag freeze-lining core through which slag is tapping at 1659°C.

It is again a moot point whether reduced cooling intensity, including removal of water circuits from beneath the tapping channel, indeed universally represents the safer option, if the consequent sometimes inadequate protective freeze-lining thickness results in increased copper hot-face temperatures that will reduce long-term integrity of the copper block itself (i.e., requires sustained temperatures below 461°C [T17]). Furthermore, if the tap-hole is still prone to 'slow tapping' even with less intense cooling, it may suggest that an alternative operational tapping strategy is appropriate.

Some of the larger ferroalloy furnaces for Mn and DC Cr alloys production also operate separate slag tap-holes, which assist enormously in separating post-tap-hole metal and slag handling logistics. In many instances, the separate slag tap-holes are merely refractory graphite/microporous carbon/carbon tapblocks (usually the former two due to improved resistance to wetting and lower corrosion by slag). Increasingly, deep-cooled (i.e., water-cooled copper extends inside the furnace) copper lintel or 'inverted-U' blocks are used to promote cooling of such refractory slag tap-holes.

Combined Metal/Matte and Slag Tapping

This is decidedly the norm, but it also often presents the greatest design challenge due to the different nature of the slag and metal and their chemical incompatibility with linings selected as suitable for the other phase. Traditionally, refractory tapblocks (refractory oxide or carbon-based) were adopted for combined metal/matte and slag tapping. With few exceptions, the refractory oxides are relatively resilient to metal- and matte-only tapping. Carbon-based tapblocks risk C dissolution and/or oxidation (e.g., by dissolved $\underline{O}$) in service with (carbon-unsaturated, so less likely on HM) metal/matte. Corrosion of both carbon-based and oxide refractories is invariably accelerated by slag, even to the extent of the corrosion being catastrophic, e.g., if acidic slags contact basic refractories (e.g., magnesia). Depending on the specific slag system amphoteric (alumina) refractories can also be susceptible to both acidic (e.g., high silica) or basic (e.g., high lime) slags.

Refractory-lined overflow launders are used in continuous tapping of copper matte and slag from the Mitsubishi Continuous Process smelting furnace, and certain corrosion challenges are presented (addressed largely by fused cast magnesia-chrome). Somewhat remarkably, unlined water-cooled copper tap plates are routinely fitted onto the furnace exterior for combined matte-slag tapping elsewhere in the copper industry, such as on top sumberged lance (TSL) furnaces. This presumably is possible only owing to the comparatively low temperature (< 1200°C – Table I) and relatively low copper matte superheat, in combination critically with slag that has potential to freeze (even if only as a thin layer, a couple of millimetres thick) as a protective accretion on copper tapping surfaces.

Most combined metal-slag tap-hole processes are characterised by lower slag-metal ratio around 0.4-1.5 t slag/t metal (metal fall ~35-60%, in the case of Cr and Mn ferroalloys - Table I), or significantly lower 0.2-0.4 t slag/t HM in ironmaking BFs (metal fall ~65% - Table I), to near slagless tapping in Si (and alloy) processes. A striking feature of the ironmaking BF is its sheer productivity (> 10 000 t/d) coupled with complex internal process structures ('deadman' and tap-hole 'mushrooms'). Even with multiple tap-holes, these process structures would complicate attempts to control hot metal and slag levels adequately and to the extent necessary to permit effective dedicated metal- and slag-only tapping. Good mixing of liquid metal and slag in the tap-hole and runner in combined tapping is also suggested to help de-sulphurise the HM [BF41]. So as with the majority of older ferroalloy SAFs and BFs, deep-cooling is generally not contemplated, with limited water-cooled elements only being applied more judiciously.

Dedicated Metal/Matte Tapping

Provided that metal/matte can be tapped substantially slag-free, configuration for dedicated metal/matte tapping is possible. Theoretically it can be calculated that separation of slag to at least 0.07 m above the metal/matte tap-hole should facilitate matte tapping without slag entrainment (α drops to 0.625 for tapping of the denser, less viscous phase [T7]). Efficiently separating metal/matte from slag already in the furnace, decidedly simplifies post-tap-hole handling and associated logistics.

Emergency/Drain Tap-hole

Some furnaces are equipped with emergency/drain tap-holes [BM16,17,19], used in emergency when the furnace does not drain from operating tap-holes [BF36], or to effect bath drainage to a lower level than normal operating tap-holes for safer repairs. A contrary view of some operators, is to avoid such tap-holes, for fear that they potentially increase risk by: tempting non-emergency/non-drain use, and presenting another weakened region of furnace lining (at still higher pressure head) for unplanned drainage.

Tap-hole design

Tap-hole and Tapping Channel Heat Transfer

On a large furnace crucible wall, bath heat transfer can reasonably be approximated as 1-dimensional. In the simplest configuration of a long circular tap-hole, heat transfer from a now faster flowing hot tapped liquid is dominated by radial heat loss in passage down the tapping channel. Even with a reasonably fast water cooling flowrate of $6m^3/h$, it can readily be estimated using $q = Q/A = (\dot{m}\, C_p)\, \Delta T$ that for just a 1°C rise in water temperature, the equivalent tapping channel (tapblock or faceplate) heat flux (q) exceeds 0.5 MW/m^2.

In a real tapping channel, in addition to the tapping channel heat transfer, heat transfer from the contained furnace bath also exists, resulting in a 3-dimensional heat transfer situation that is more extreme than almost any other region of furnace crucible. The tap-hole specifically is invariably subjected to the most arduous of conditions [BF2,5]:

- highest liquid (metal/matte and slag) velocities, affected by the degree of radial or peripheral flow and total flow that converge on the tap-hole to achieve productivity setpoint
- highest turbulence (increased by gas entrainment and even blowing under pressure, and associated enhanced mass and heat transfer from both stream tapping and through the action of any tap-hole clay flash devolatilisation and subsequent 'boiling' at the back of the channel)
- wildly fluctuating and periodic thermal loads (from cool dormant condition, heating rapidly when opening the tap-hole with oxygen, or hot liquid tapping, and with tap-hole clay 'boiling' and gas bubble-driven circulation upon tap-hole closure)
- high dynamic loads (action of opening and closing tap-hole).

Tap-holes are also prone to gas leakage, especially when operated under pressure in a BF, which may result particularly in the case of ironmaking or ferroalloys adopting carbon-based refractory, to continuous threat of exposure to and reaction by CO (risk of carbon deposition), oxidation by injected oxygen, air or steam (especially if water leak), slag and maybe even SiO(g), and reaction with volatile gas species such as alkalis and zinc (leading to refractory attack) [BF2,22,38] (Table II).

Tap-hole 'Refractory' Design

Clearly to be successful, tap-hole designs need to cater not only for average, but peak, process heat flux conditions. Van Laar [BF3] suggests, that in BF tap-holes, peak heat fluxes exceeding 1 MW/m^2 have been detected, considerably in excess of the normal average heat fluxes measured (25 kW/m^2 – Table I). This would not be inconsistent with a 1.4 MW/m^2 event involving metal encroaching on the lower zone of a copper waffle cooler recorded in Co ferroalloy production [FA16].

Nearly all tap-holes are designed with a length that exceeds the adjacent sidewall thickness. Unfortunately, this provides only short-term protection against tap-hole area liquid breakout, because the tap-hole length will at best rapidly recede to its thermal equilibrium dimension.

Use of several refractory types (Figure 3) in BF tap-holes and their environs is reported [BF1,2,13,21,22,28,35] including:

- 100% alumina (most 'insulating', k = 1-5 W/m°C)
- pitch-impregnated [BF27] carbon/alumina
- large carbon blocks (k ~14 W/m°C)
- hot pressed small carbon or semi-graphite bricks (lower iron content of latter, to reduce CO disintegration [BF1,38])
- microporous (potential advantages of less metal infiltration if maximum pore size < 1μm [BF1,14,38]) large carbon or semi-graphite blocks
- thermally conductive graphite (k ~140 W/m°C, frequently applied as 'safety' tiles glued to the steel wall in the immediate tapblock vicinity [BF2,34,35])
- sometimes graphite with high-alumina silicon carbide castable in the centre (favoured for reasons of: improved tapping stream dissolution and erosion resistance over graphite in the event of the latter's loss of freeze lining or protective baked tap-hole clay inner annulus, somewhat improved tolerance to oxygen lancing over graphite, provision of some heat storage for tap-hole clay baking, and possibly some improved tolerance to microcracking induced through mudgun and drill impact forces).

Use of higher conductivity silicon carbide [BF18] in conjunction with carbon surround and alumina tapping channel hot face bricks has also been reported [BF8]. In some instances, heat removal is further enhanced by addition of water-cooled iron or copper tap-hole notch channels, or even water-cooled copper inserts/plate coolers [BF21,22].

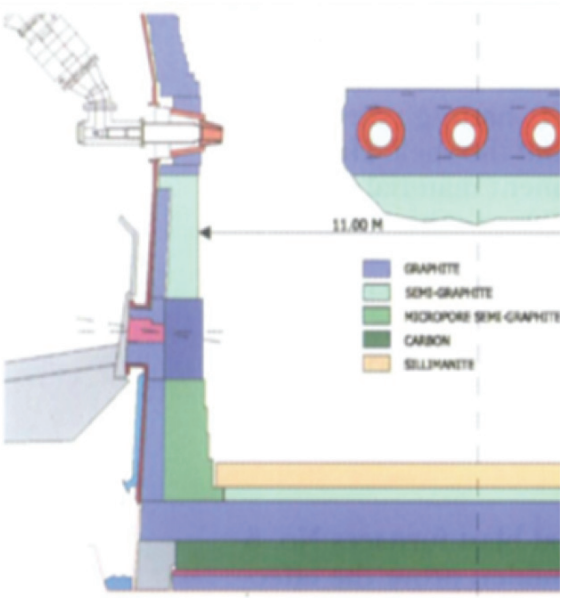

Figure 3. Tap-hole and environs equipped with refractory of various thermal conductivities and integration into BF lining (after Stokman et al. [BF1]).

Table II. Carbon-based refractory and onset of key wear and attack mechanisms ([BF2, BF38])

Thermo-mechanical and chemical attack mechanisms	Onset Temperature* °C
Alkali and zinc#	400
CO deposition	450
Stress cracking	500
Oxidation (enriched, or air)#	600
Steam oxidation	700
CO_2 oxidation	1050
Liquid penetration, corrosion (e.g., by carbon dissolution, or by slag) and ensuing erosion#	1150 # Especially in tap-hole region [BF14]

* Depending on specific refractory type; oxide- or carbon-based, calcined anthracite or graphite aggregate, or binder-derived [BF38] (binder more prone to attack than aggregate) and associated trace impurity catalysts (e.g., Fe).

In all instances involving use of composite refractory types, especially when water-cooled components are included (Figure 3), a critical design requirement is to cater for differential thermal expansion properties that can easily differ by an order of magnitude, with potential to cause gaps, stresses and strains, thus increasing the potential for liquid infiltration [BF3]. An experience reported [FA2] of furnace campaign life reduced from 14 to just 3 years when switching from a design where 'the original furnace had forced air cooling in the bottom, but no additional (water) cooling for the furnace walls' (and by inference attempt at freeze-lining in, or at least near, the tapblock) may well illustrate this. Moreover, the additional requirement for freeze linings of guaranteed effective operation always around thermal equilibrium, has led Singh *et al.* [FA3] to state with justification: 'but in the present Indian scenario with process parameters not stable … it is difficult to maintain the conditions inside the furnace desirable for a true freeze lining', so failing to 'give the expected lifetime of over 25 years'.

For adoption of any freeze lining concept, 'half-measures' are entirely unacceptable. Achievement of just a 'partial' and/or 'periodic' freeze lining will prove unsuccessful, and present a considerably more dangerous operating condition, than on a traditional insulating tap-hole design concept.

The first technique crucial to tap-hole refractory longevity is the ability to create and retain protective accretion freeze lining or 'skull' [BF5], as tap-hole performance is greatly compromised by operation in the partial, or substantial, absence of a stable accretion freeze lining; also described as 'no skull' condition [BF1]. Accretion freeze lining thickness has already been shown to be enhanced by higher conductivity refractory in actively cooled furnace lining systems, with the resulting colder refractory presenting more resistance to attack by a number of wear mechanisms, depending on the temperature of onset of thermo-mechanical or chemical attack by a given mechanism (Table II).

Role of Tap-hole Clay 'Mushroom'

The second crucial feature, specific to ironmaking BF tap-hole design, is the active development and continuous renewal of a tap-hole clay (also described as mud) 'mushroom' to provide some hot-face protection on the back of the tapping channel [BF5,12,13,29,35,36,47,48,49,50,51,52,53,54,55] (Figure 4). The 'mushroom' requires tap-hole clay for its development and consists additionally of incorporated slag, iron and coke. Tsuchiya *et al.* [BF19] hypothesise that a necessary condition for development of a 'mushroom' is that the tap-hole length can be extended only when the holding space for injected tap-hole clay is effectively realised, so that the major part of the tap-hole clay surface is covered by the coke column (Figure 5). It is further hypothesised [BF54] that the tap-hole clay is 'extruded in the furnace like strings' and these 'strings accumulate in the coke free spaces by folding together with solidified iron and/or slag'. Other conditions required for increase of the tap-hole length to develop the 'mushroom' then include sufficient tap-hole clay sintering time in the holding space and the specific characteristics of the clay during and after heating and sintering. 'Mushroom' stability can be adversely influenced by 'floating' of an ironmaking BF 'deadman', especially if

it is physically connected to the back of the 'mushroom' [BF22]. Water leaks are also reported to cause 'mushroom', frozen skull and lining damage [BF2,22].

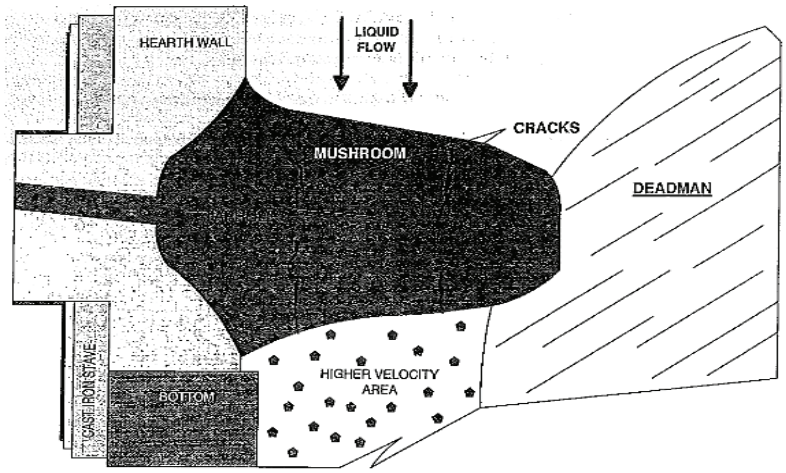

Figure 4. 'Mushroom' connection of tap-hole hot-face and 'deadman'. Diversion around 'mushroom' of descending liquid depicted. In tapping, this combines with peripheral liquid flow around the 'deadman' to yield higher velocity liquid flow below the tap-hole and lining hot-face, with potential for hotter flow conditions and enhanced wear (after Van Laar [BF22]).

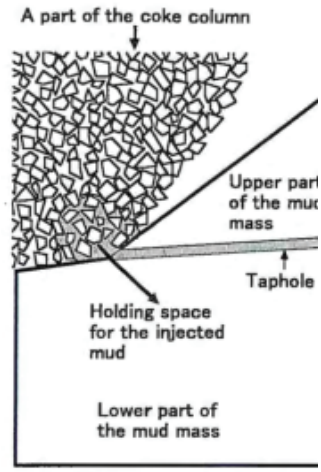

Figure 5. Schematic drawing of holding space for injected mud into the BF (after Tsuchiya et al. [BF19]).

The necessary condition of a 'holding space covered by a coke column' may well explain why a protective tap-hole clay 'mushroom' is only routinely reported for ironmaking BFs. In non-ferrous processing coke is absent (or substantially absent), so the necessary requirement of a coke column to cover tap-hole clay in the holding space is missing. Moreover, as will be described later, certainly in electric smelting of PGM mattes, matte superheat is so high (up to 650°C –Table I) that tap-hole clay injected into matte appears to near-instantaneously react with gas release and extreme turbulence, so that a tap-hole clay-based 'mushroom' cannot be stabilised.

While a coke bed is a well-reported feature of ferroalloys smelting [FA14], it remains local to the electrode tips. Extension of the coke bed to the furnace tap-hole - a necessary condition according to the proposed mechanism of 'mushroom' development - would almost certainly result in a condition too conductive for effective electric power input. A genuine 'mushroom', at least in the equivalent sense to that of an ironmaking BF, therefore seems improbable. At best, some extent of tap-hole clay 'self-lining', but not a 'mushroom', is depicted in ferroalloy SAFs [FA11].

Ferroalloy Tap-hole Design

The ironmaking BF tap-hole refractory list fairly represents the experience in Cr, Mn & Si ferroalloys, of an increasing general trend towards use of materials of increasing thermal conductivity, and to what is colloquially known in the industry as 'freeze-linings'. With the traditional insulating (especially large) furnace designs, just 2-6 years furnace lining life on Cr and Mn ferroalloys are reported common [FA1,4,6,12], with a single slag tap-hole life reported as short as 2 months [FA4]. However, longer 10-15 year furnace lifetimes have been achieved on traditional insulating linings in Japan. Generally, Cr and Mn ferroalloys SAFs have made use of only refractory alumina tapblocks, silicon carbide tapblocks surrounded by alumina, carbon, or microporous carbon blocks.

This supports progression from more insulating refractories (refractory oxide castable and brick, carbon-based ram or Söderberg paste), to intermediate thermal conductivity carbon blocks and even more thermally conductive semi-graphites and graphites. The latter designs have delivered in excess of 20 years lining life on some large Mn ferroalloys furnaces [FA4,7].

An emerging trend is of an additional composite refractory variant involving use of a thermally conductive graphite sleeve inside an insulating carbon tapblock (Figure 6). This intriguingly, is converse in concept to placement of insulating refractory oxide inside graphite, reported as a preferred option for ironmaking BFs.

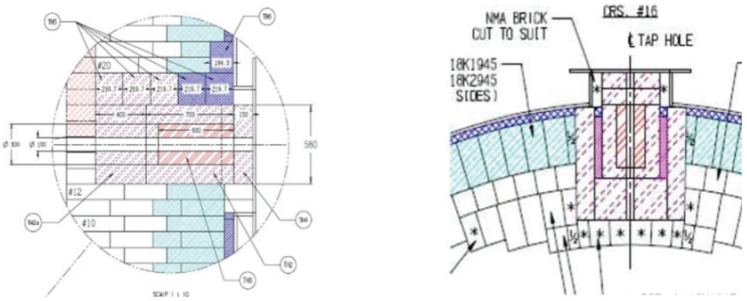

Figure 6. Latest ferroalloy tap-hole design to be incorporated into SAF 'freeze lining', incorporating replaceable carbon 'mickey' brick on cold face, replaceable graphite sleeve inside 2-piece carbon tapblock, carbon rammed against side carbon tapblocks, with carbon block hot-face at the back of the tap-hole (after Duncanson & Sylven [FA2]).

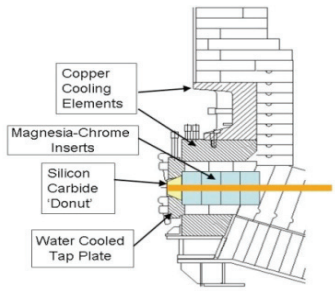

Figure 7. High-intensity composite water-cooled and refractories tapblock for blister copper (after George-Kennedy et al. [BM12]).

Hearn *et al*. [FA7] best describe the reasons for this as follows. The end hot-face of graphite insert is protected by a carbon tapblock, while the cold-face is protected by a removable carbon 'mickey' block, that can be replaced if damaged by either drilling or oxygen lancing activities, to secure a flat mating surface for the mudgun to more effectively close against without excessive tap-hole clay bypass. During tapping, the graphite absorbs the tap heat, which the outer annulus carbon tapblock of lower thermal conductivity cannot transmit as effectively, so ensuring a hot tap-hole with improved flowrate. The heat retained in the graphite sleeve after tapping and immediately following tap-hole closure by mudgun, aids tap-hole clay baking. At the next tap, a 45 mm diameter hole is drilled through the baked tap-hole clay core, to create a tap-hole clay annulus inside the graphite sleeve that affords some protection against its direct contact by the molten tap stream. Obviously the tap-hole clay can erode with time. During planned removal of the front 'mickey' carbon block, the graphite sleeve can be core-drilled out and both items replaced to effect a tap-hole repair. An additional tap-hole repair design feature involves splitting in two and gluing the carbon tapblock (that contains the graphite sleeve), with carbon paste rammed to close the gap to adjacent furnace sidewall lining, to allow for easier removal with less peripheral lining damage during replacement in planned maintenance [FA2,6,12].

Some Mn [FA11], DC-arc Cr [FA18] ferroalloy furnaces make use of inserted water-cooled copper components on both metal and slag tapblocks, ranging from top lintel to 'inverted-U' designs, to cool graphite (advantage of less wetting by slag) and microporous carbon tapblocks (if metal tapping stream dissolution and erosion of graphite prove too aggressive).

High-intensity Water-cooled Tapblock Design

Quite different though, are the more intensely cooled tapblock designs on: blister Cu [BM8,11,12,15,16,17,18,19], and non-autothermal processes requiring electric smelting such as: Ni and Co ferroalloy [FA5,13,15,16,17,19, BM16,17], as well as base and PGM matte furnaces [BM2,3,4,5,6,16,17]. These almost universally adopt water-cooled copper tapblocks of rectangular shape: 3-sided (inverted 'U-shape', so absence of water-cooled copper below tapping channel), 4-sided 'dog box' [FA13] (Figure 9), or high-intensity one-piece waffle cooler copper tapblock designs (Figure 7 and Figure 8). Some are equipped with pin-cooling (with 'inverted-U' water passages [FA5] – Figure 9).

These copper coolers are lined internally with a square configuration of surround bricks, usually made of magnesia (graphite was also apparently successfully trialled in nickel matte smelting [BM2], but was reported discontinued), containing internal tapping module refractory bricks through which the tapping channel runs (Figure 7, Figure 8 and Figure 14). The latter comprise refractories that vary with commodity: almost exclusively pitch-impregnated magnesia in Ni ferroalloys [FA13, BM16,17]; magnesia-chrome in blister Cu or matte [BM2,6,12,16,17], or alumina-chrome in PGM mattes [BM6,16,17]. Both graphite and silicon carbide have also been trialled in matte smelting [BM2].

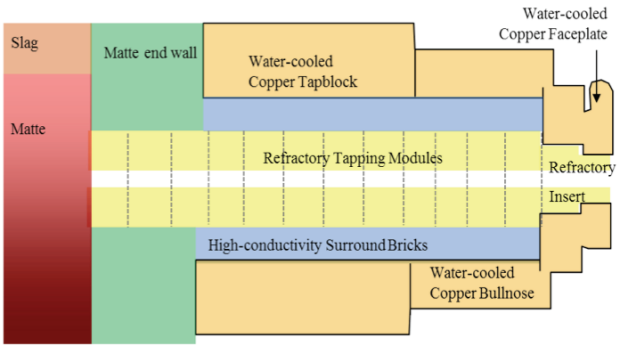

Figure 8. Schematic of a high-intensity water-cooled copper matte tapblock system, with water-cooled copper bullnose extension and water-cooled copper faceplate both outside of furnace. Only copper faceplate has 'inverted-U' water passages, so absent on the underside of the tapping channel.

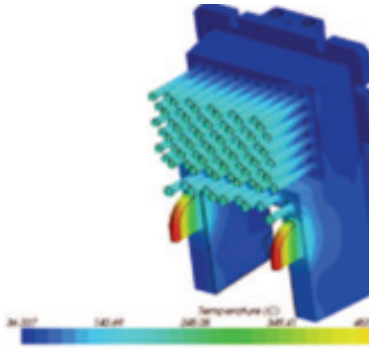

Figure 9. Water-cooled copper pin and 'inverted-U' metal tapblock design (after Henning et al. [FA5]).

For Pb bullion (temperatures of 800-1100°C tapping, with 700°C drossing [BM1,16,17]) and PGM matte processes [BM3,4,6,16,17], process superheats are high (Table I). Specifically for the latter, process temperatures are even elevated to the extent that the potential for corrosion by PGM matte of magnesia chrome refractory above 1500°C has recently been investigated [T26]. Good evidence of expected significant matte penetration, and signs of FeO and MgO corrosion products have been found, but as yet not CrS product suggested by any proposed mechanism. This suggests potential for high refractory wear rates with exceptionally high matte superheats (approaching 650°C – Table I).

In Pb bullion smelting [BM1,16,17]; blister copper [BM8,16]; and PGM matte Amplats Converting Process (ACP) TSL converting [T9, BM17], circular copper tapblocks have also been used, with both annular graphite and silicon carbide inserts; silicon carbide, high alumina, or graphite tapping module bricks.

So while ironmaking BF superheats of 350°C may seem challenging to copper-cooled operations, they are only half the matte superheats experienced on the highest intensity non-ferrous operations. Consider also the significantly lower melting temperatures of many mattes (< 950°C – Table I) and this effectively makes it impossible to develop any protective matte freeze lining, even when using even higher cooling water flow rates (but still short of those legislated for designation as pressure vessels). Notwithstanding this, Ni and PGM mattes also have a greater solubility for copper, than iron and steel, blister copper and copper mattes, so additionally have a greater chemical dissolution driving force for reaction with, not merely melting of, copper.

As already described, in such a harsh pyrometallurgical processing environment the consequence of a superheated matte/blister Cu 'hit', or lancing a water-cooled tapblock [BM12] and tap-hole failure is extreme, and can occur with near-identical sequence of events and rapidity, regardless of furnace size [T9], with potential for catastrophic cooler failure and/or furnace refractory break-out [BM18,19] to occur within the order of a few minutes … most commonly following mudgun closure [BM4]. This has even prompted one PGM producer to resort to drilling and lancing, but with tap-hole clay closure manually using stopper rods rather than mudguns [BM13].

Faceplate and Refractory Insert Design

External faceplates are important to provide: a 'perfectly' flat vertical mating face for the mudgun to engage the tapping channel (for an accurate quantity of tap-hole clay to be injected into the tapping channel; ensuring minimal bypass); coupled with a refractory insert, a mechanism to help secure tight joints along the length of the tapping channel to minimise infiltration and gas leakage [BF5]; and a means to help prevent the entire tapping channel lining dislodging and 'tapping' out of the furnace lining due to internal furnace pressure (comprising both internal operating and any blast pressure and hydrostatic head). The latter type of incident has apparently been experienced in the past on a Ni matte EF.

Thermal fatigue cracking or direct matte attack of water-cooled copper faceplates typically associated with matte splashing during tap-hole plugging, presents risk of water leaks. Sacrificial refractory or metallic cover plates have been used to address this risk [BM2], with introduction of 'inverted-U' water-cooled pipe arrangements, to secure the absence of water-cooling directly below the tapping channel to better mitigate against the risk of matte contact with water.

Tap-hole Inclination and Active Hearth Sump Design

Tap-holes are normally designed with a horizontal or vertical (e.g., EBT) orientation. The notable exception is of near universal implementation of inclined tap-holes (~10°) on ironmaking BFs [BF51]. The action of inclined tap-holes,

coupled with longer tapping channels and deeper hearth sumps (minimum sump depth 20% of the hearth diameter – [BF13]) that drain liquid deeper in the furnace (further from the sidewalls), has been modelled to lower liquid velocities (and resultant wall shear stress and wear), both below the tap-hole and at the wall periphery (that otherwise lead to undercutting and so-called 'elephant's foot' wear) [BF1,5,10,11,13,20]. The former localised higher velocities are attributed to liquid draining down past the 'mushroom' (Figure 4 - [BF22]). The latter higher peripheral velocities are more a function of draining through and around a 'deadman' [BF11,13,29,40,41]. Optimum tap-hole inclination was modelled as 15° [BF11]. Tapping conditions are further noted to distort fluid flow to the extent that towards the end of tapping, the slag is lowest in the vicinity of the draining tap-hole, inclined to its highest on the opposite side of the BF [BF20,29]. The authors are also aware of at least one high carbon (HC) Cr ferroalloy furnace equipped with a declined tap-hole.

Modelling has similarly motivated deepening the metal bath of a circular HC Mn ferroalloy SAF (but still with a horizontal tapping channel, presumably in part because of the absence of anything equivalent to a 'sitting deadman') by removal of a full carbon block course, to reduce the peripheral liquid flow velocity along the wall to a draining tap-hole [FA11]. Coupled with uprating of the transformer capacity to permit simultaneously increase of the electrode current by 25kA to raise the average power load at night by 2.3MW, and operation with a higher coke loading to allow approach to metal carbon saturation (so limiting wear by dissolution of the carbon lining), the reduced peripheral flow induced by deepening of the hearth led in operation to metal tapping temperatures on average lowered by 40°C (to 1350°C). Deepening of another Japanese HC Mn ferroalloy furnace gave benefits of marginally increased power input, faster tapping and increased productivity [FA23]. On Si ferroalloy SAFs [FA24], where metal drains through a porous bed of solids to the tap-hole, crater pressure and bed permeability significantly influence the rate of drainage of metals to and through the tap-hole.

In the largest rectangular 6-in-line (6iL) PGM matte smelting furnaces, the matte inventory can exceed 600t, with contained metal value exceeding R¼ billion. Clearly furnace deepening comes at a more significant cost. Fortunately with a combination of periodic and low volume matte tapping (< 20% matte fall) through an endwall of an inverted arch hearth design, from a rectangular furnace configuration, furnace tap-hole wear has recently proven predictable even at operation exceeding 60 MW power input [BM4]. With a circular furnace configuration more conducive to development of circumferential flow around the sidewall to a draining matte tap-hole, especially when the matte tap-hole is located almost on the top of skew line of the hearth invert, it is not inconceivable that conditions for accelerated matte tap-hole wear could develop, even at far lower power input.

Tap sequencing

A variety of strategies are adopted largely dependent on productivity requirements, number and layout of tap-holes and process conditions. For single tap-holes processing dual metal-slag mixtures, total reliance is placed on the availability of the sole tap-hole. Such tapping systems are especially common in Cr and Mn ferroalloy SAFs, which may emphasise the importance of tapping stream superheat (average-to-maximum heat flux 1-10 kW/m^2 [FA1] – Table I) over absolute temperature in describing an onerous process condition.

Having said this, a still impressive 5 700 t/d HM in a campaign life of 13 years duration at the time of reporting, was achieved from a single tap-hole BF operation [BF24]. Similarly the Mitsubishi Continuous Process for copper relies on continuous hot liquid flow down heated launders from smelting, to slag cleaning, to converting to anode refining furnaces, this being effected through a combination of furnace overflow, skimming and siphon tapping arrangements, at overall availabilities exceeding 92% [BM10]. These illustrate what is possible with superior tap-hole management and tapping practices.

Consecutive Individual Tap-hole Tapping Practice

Consecutive tapping on an individual tap-hole is a common traditional tapping practice on several ironmaking BFs [BF16,36], ferroalloy, and matte smelting operations. Even on 2-tap-hole BFs, tapping campaigns of 4 days to 3 weeks are reported [BF16]. Matte tap-hole thermal trends in Ni matte smelting [BM2] (Figure 10), clearly demonstrate the accumulation of heat in the tap-hole refractory when taps are in close succession. Similar rising temperature trends with tapping have been observed in PGM matte smelting [T3] (Figure 11). With an ironmaking BF interpretation, this could possibly be considered desirable to promote tap-hole clay baking and sintering. However, in the more intensely superheated matte-only tap-hole environment, this is rather interpreted to imply that a resting or recovery period of no tapping is called for, to help lower refractory temperatures and re-establish improved accretion, as evidently occurred on the tap-hole on the former furnace.

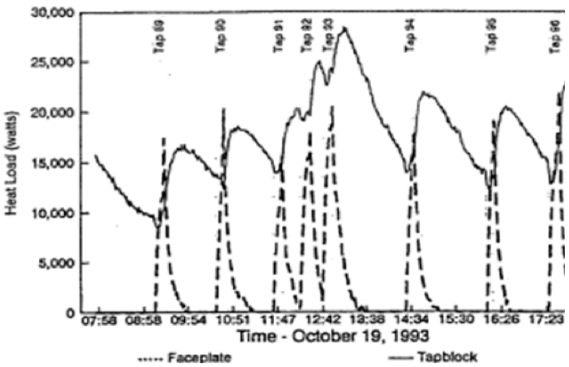

Figure 10. Typical heat load and accumulation of heat with taps in close succession (after Cameron et al. [BM2]).

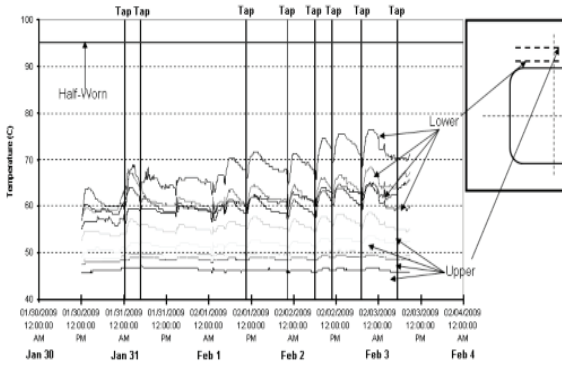

Figure 11. Trend of tap-hole temperature rise with consecutive tapping on a tap-hole (after Gerritsen et al. [T3]).

Alternating Tap-hole Practice

This variant, also described as 'side-to-side' casting [BF7], appears the norm to achieve the highest of productivities, through optimal tap-hole condition, consistent operability and reliable availabilities, and best supports preventative tap-hole maintenance. This is true of 2-tap-hole [BF7] and tap-hole pairs on 4-tap-hole ironmaking BFs [BF16,23]; 2-8 metal-only and 2-6 slag-only tap-holes on blister Cu and ferroalloy furnaces [BM12,15,16,17,18,19, FA13,15,16]; and up to 3 matte- and 3 slag-only tap-holes on base metal and PGM matte EFs [BM6,16,17, T9]. It includes ironmaking BF variants described as 'back-to-back' or 'mother-daughter' tapping [BF21,36] where a pair of taps is made before alternating tap-holes. In the case of the ironmaking BF, such practice of a pair of taps is usually in response to suboptimal conditions, such as inadequate draining or persistent taps of short duration.

One detrimental feature reported for alternating tapping on BFs where a zone of low permeability exists between tap-holes, is of potential for the slag level to rise due to excessive pressure loss, so disrupting bosh gas flow [BF40,41,43,44,45]. Slag levels could conceivably fluctuate on SAFs similarly, due to the presence of less permeable zones. Iida *et al*. [BF40] recommend enlarging the tap-hole diameter (~10%) as the best remedy to alleviate this issue.

While operating at a still impressive HM superheat, $\Delta T \sim 350°C$, the focus on the BF is largely HM productivity-driven, with up to 75% metal fall and daily targets exceeding 10 000 t HM/d, so demanding the most effective and efficient tapping with reliable operability. Most operators appear to seek to operate somewhere close to a 'dry' hearth condition [BF25], whereby hot metal and slag levels in the hearth are kept as low as possible [BF2,3], but without escape of hot gas [BF12,29]. By contrast, the requirement on the multiple tap-hole, lower metal/matte fall (<20%) Ni ferroalloy and matte furnaces [BM16,17], is primarily to secure maximum tap-hole and furnace reliability. This is especially true of high-intensity PGM matte furnaces, with their onerous matte superheat, $\Delta T \sim 650°C$, that imposes integrity challenges on even the most intensely water-cooled refractory-lined copper tap-holes.

On the highest-intensity of these operations, even with less frequent matte tapping events, the practice generally is to alternate tapping between the available tap-holes, in order to provide the tap-holes maximum 'recovery' time to lower tap-hole temperatures between taps. This is reported [BF5,15,31, BM2, T3] and has been modelled on the BF [BF4]. Merits of such an approach, originally diagnosed from scrutinising well-instrumented copper tapblock and cooling water temperature tapping trends, will be presented later using the latest fibre-optic temperature measurement trends available in PGM matte smelting.

At first glance an alternating tap-hole practice would appear to complicate timing of minor routine monthly planned tap-hole maintenance activities [BM6]. However, it should be appreciated that despite such diligent monthly repairs and essentially slag-free tapping, process conditions remain so onerous, that all but the hot-face matte tapping module bricks have to be replaced on a roughly quarterly basis to secure safe tapping, tap-hole condition and ultimately furnace integrity and longevity. And to perform such a deep tap-hole repair, tap-hole temperatures and safety dictate that the furnace power needs to be lowered for the duration of the repair. So in fact a simultaneous repair of all matte tap-holes by a team of masons on a furnace at lowered furnace power, actually minimises the impact on overall furnace utilisation.

Also it should be clarified that in high-intensity PGM matte smelting the 'as low as possible' liquid matte and slag levels of BF 'dry hearth' operation is definitely not sought, nor considered desirable. Considering first overall liquid level, generally too high a pressure head is not sought, because of its influence on increased rate of tapping, and potential for matte infiltration of the furnace lining. Specifically too high a matte level is also not sought, for fear of exposing the effective slag-line water-cooled copper waffle coolers to potential for contact by superheated matte.

While the waffle cooler design reportedly [T2,15] caters for metal contact of copper waffle coolers in Ni [FA13] and Co [FA16] ferroalloy processing, contact by matte, especially superheated matte, can rapidly lead to catastrophic failure.

However, this still does not warrant seeking the lowest possible matte level. This is because the matte-only tap-hole is especially configured to be refractory oxide-lined, with generally good corrosion resistance to matte, but with decidedly poor corrosion resistance to acidic slags (> 50% SiO_2 content). Indiscriminate lowering of the matte level would therefore expose not only the tap-hole to the risk of 'slagging' by hotter slag, but would accelerate refractory lining corrosion and ultimately wear. Thus a target minimum matte level is simultaneously sought with matte operated below the maximum matte level permissible.

Considering the slag level, the absolute minimum furnace slag level is controlled by its interface with matte. Operation around slag tap-hole, located typically ~1 m above the matte tap-hole (Table I) represents the lowest overall pressure head condition on the matte, which has benefit. However, at the highest smelting rates with <20% matte fall, slag make becomes significant requiring near continuous tapping compared to periodic batch matte tapping. And with slag level only at the slag tap-hole level, the pressure head is simply inadequate for slag tapping rates to be acceptable (see later). So a practical minimum operating slag level exists above which slag tapping rates, are adequate to achieve an efficient rate of slag drainage (even if multiple slag tap-holes are open).

Finally, the maximum permissible top of slag level is designed relative to the slag tap-hole. This is primarily to ensure that superheated slag does not rise above the zone of sound crucible containment below the top of the copper coolers, but also to limit excess pressure head at both the slag tap-hole and the underlying matte tap-hole.

Slag Tapping

Where consecutive tapping practice has indeed found non-ferrous application, is during 'slow' slag tapping on both Ni ferroalloy and PGM matte smelters. The slag tap-hole has a tendency to open fast and then decline in tapping rate with time. In situations where the number of slag tap-holes available is limited (e.g., due to planned maintenance), an effective solution involves closing on lazy flowing slag with the mudgun, and then shortly re-drilling open the slag tap-hole again (exposure of drill bits to slag only, is far less aggressive than metal/matte). This can easily redouble the initial tapping rate on a 'slow' slag tap-hole.

Closure on flowing slag is key, because it secures easy re-drilling of tap-hole clay only, to open the slag tapping channel. In the event where flow of a slag tap-hole has been allowed to stop, even with attempted mudgun closure, an adequate plug of tap-hole clay to the inner hot-face cannot be secured. When re-drilling is attempted, solidified slag is quickly encountered, that has the potential to impede the drill and cause skew drilling … potentially towards a water-cooled copper cooler! So somewhat paradoxically to be safer, oxygen lancing with its ability to 'cut' open, and so straighten, the solidified slag tapping channel, then becomes necessary to re-open the slag tap-hole.

Tap-hole opening

It is essential to be able to 'quickly and certainly open the tap-hole whenever required' [BF29].

Discounting the most primitive past practices of 'pricking' or 'excavating' the tap-hole open, a wide range of tap-hole opening methods are adopted [BF24] including:

- manual oxygen lancing (suggested near universally to be minimised, to < 1% of taps [BF13]; or for 'emergency only' on ironmaking BFs [BF24]; leading directly to reported blister tap-hole failure and resulting explosion on at least one site [BM12], and yet still adopted as the primary means of tap-hole opening on 36% of PGM matte furnaces [BM6])
- automated/robotic oxygen lancing [BM5, T25]
- soaking bar technique[4]
- conventional pneumatic drilling open (air)
- improved pneumatic drilling open (nitrogen and/or water mist bit cooling)
- hydraulic drilling open (nitrogen and/or water mist bit cooling), and
- combination pneumatic drilling without opening, and deliberate lancing of the last remaining metal/matte plug.

[4] Soaking bar practice found favour in iron BF tapping as an emerging development to replace taphole drilling in the '80s. It involved pushing/hammering a 50 mm bar through the mud in the tapping channel. This promised to provide improved thermal conductivity from the inner hearth up the tapping channel to better bake and sinter taphole clay. To open the taphole, the bar was reverse hammered out of the tapping channel, now of well-defined dimension, and with the promise of no risk of skew drilling or oxygen lancing damage. However, the practice had fallen out of favour by the '90s, for reasons of requiring time-consuming pre-drilling to assist with soaking bar insertion, difficulty in accurately assessing the all critical drill depth and matching it to optimal taphole clay addition, shorter taphole clay curing times with increased risk of taphole re-opening, and other taphole and "mushroom' damage induced by hammering in bar installation and removal [BF9,13,23,24,31,33].

It is worth noting, that to avoid iron or other contaminants, metallurgical grade silicon tapping requires a variety of alternative tools for tap-hole opening and maintaining the metal flow. This includes an electric stinger (connected to a bus bar system from the furnace transformers), a kiln gun [T18], steel and graphite lances, wooden poles, and graphite bott tools [FA20].

Tapping Rate

A primary requirement of tapping is to secure reliably the desired rate of furnace products. Thus, establishing the factors influencing tapping rate are important. Guthrie [T19], applying Bernoulli's equation, provides a useful estimate of tapping rate, $\dot{m} = \rho C_D(\pi d^2/4)(2gH)^{½}$ through a tap-hole of diameter (d); where, C_D is a discharge coefficient (~0.9), g is gravitational acceleration and H is effective liquid head of the phase being tapped of density, ρ.

Mitsui *et al*. [BF15] combined Bernoulli's and Darcy-Weisbach's equations, for estimating iron BF tapping rates, as $\dot{m} = \rho(\pi d^2/4)\{2(P/\rho + gH)/(1 + \lambda l/d)\}^{½}$ so including a correction for tapping channel length (l). This yields typical iron blast furnace tapping rates of 7 t/min (~10 000 t/d HM on a near continuous tapping basis), and liquid tapping velocities of 5 m/s, in tap-holes of 70 mm diameter by 3.5 m long.

Both approaches show that tap-hole condition strongly influences tapping rate (with velocities of up to 8 m/s recorded [BF26,35]) primarily through tap-hole diameter, while the latter approach further suggests tap-hole length as the next most significant influence.

In the case of Si ferroalloy SAFs [FA24], where metal must drain through a permeable bed of solids to the tap-hole, metal height influences onset of gas breakthrough to the tap-hole and associated sudden drop in tapping rate, but exerts less influence than crater pressure and bed permeability on the initial tapping flow rate.

Tap-hole Wear Mechanisms

Given a dominant influence of tap-hole dimensions on tapping rate, it is instructive to consider factors contributing to tap-hole wear (Figure 12), which are elegantly summarised by three sequential steps (Figure 13 - [T12]):

1) Penetration; 2) Corrosion; 3) Erosion.

The first step to refractory wear involves penetration of refractory, the rate of which, u_{pen}, can be described by a capillary force driven flow according to $r\gamma\cos\theta/4\mu l_p$; where, r is capillary (pore) radius, γ is surface tension, θ is the contact angle, l_p is penetration depth and μ is liquid viscosity. The latter property is inversely related to process temperature.

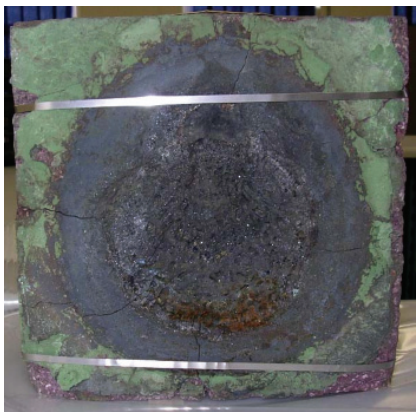

Figure 12. Matte tapping module brick with matte core; no evidence of tap-hole clay annulus; penetrated dense brittle zone annulus inside brick.

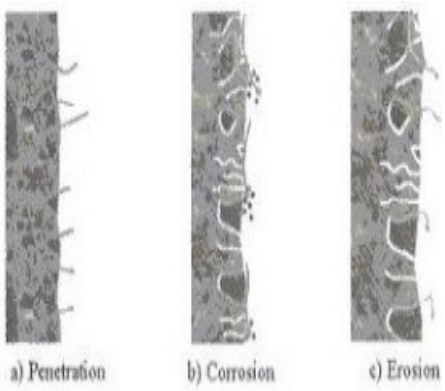

Figure 13. Representation of refractory wear mechanisms (after Campbell et al. [T12]).

Once a liquid has penetrated refractory, reaction with infiltrating liquid becomes possible through corrosion. Campbell *et al*. [T12] describe corrosion as a 'cooking time' to illustrate that its rate relates to how long a penetrated refractory has been at a temperature that supports reaction. Furthermore, as corrosion rate is described by Arrhenius' law, an exponential (as opposed to linear) type of temperature scaling is required to predict the increase in rate of corrosion with temperature.

Once a refractory has been penetrated and further weakened by corrosion, erosion becomes possible if the shear stress, $\tau = \mu(dv/dy)$ induced by liquid flow is sufficient to remove refractory. Again process conditions can influence liquid viscosity through temperature, while the rate of tapping affects the velocity gradient (dv/dy). Given estimates of

tapping velocities of 1-5 m/s, suggests that the applied shear force is a few orders of magnitude lower than the hot modulus of rupture of most refractories. So it is well-argued that tap-hole refractory erosion cannot occur until the refractory structure has somehow first been weakened by liquid penetration and corrosion [T12].

In PGM matte tap-holes, an annulus of tap-hole clay does not appear to persist to line the tapping module refractories (Figure 12). However, the same (low) velocities may possibly provide a shear force that is in excess of the hot modulus of rupture of poorly baked/sintered tap-hole clay. So in operations that critically depend on a 'maintainable' baked and sintered annulus of tap-hole clay to line the tapping channel to protect the tap-hole refractory (e.g., especially if combined tapping more corrosive slag, like on ironmaking BFs), far more attention should be given to the issue of tap-hole clay sintering and erosion properties [BF15].

Generally, the bigger potential adverse influences of suboptimal tapping velocities (than erosion) are:

Too slow: limits tapped production; delays liquid drainage, which may potentially be unsafe if critical furnace levels are threatened (e.g., matte encroachment to near vicinity of copper coolers, or slag overflow over the design maximum crucible containment height).

Too fast: induce loss of control and thus unsafe tapping and post-tap-hole conditions; followed by (in the extreme only) tapping channel and furnace lining erosion.

Drilling Open Practices

Due to the potential for oxygen-induced lancing damage to tap-holes, the vast majority of operations seek to drill open the tap-hole. This typically entails sacrificing the drill bit and potentially the drill rod. In at least one Japanese Mn ferroalloy operation, to conserve costly drill bits the drills are withdrawn as soon as metal is encountered, refitted with a sacrificial crimped steel pipe, and then drilling is resumed to open the tap-hole. This protects the drill bit condition enough to permit re-use.

Combination Drilling and Plug Oxygen Lancing Practice

On most metal-only and matte-only tap-holes operated in the substantial absence of any tap-hole hot-face 'mushroom', a combination of deep drilling followed by plug oxygen lancing is practised deliberately. The aim is to drill through the tap-hole clay as (consistently) deep as possible (700-1200 mm, depending on tap-hole design length), until drill resistance is encountered owing to a 'plug' of metal/matte/residual entrained slag. Experience dictates that attempting to drill further through this plug often leads to unintended skew drilling; especially hazardous in a water-cooled copper tapblock configuration. And often results in the drill simply getting stuck in the tapping channel. Even with reverse percussion hammering [BF37], it may become impossible to free a stuck drill bit and rod, requiring the tapper to resort to oxygen lancing to remove the obstruction.

In combination practice, the drill is then withdrawn, the drill length accurately (but manually) measured with a gradated drill-T, which simultaneously verifies that the drilling was not off-centre. Once the drill hole is positively confirmed as straight, oxygen lancing of the (short) remaining tapping channel plug is then performed to open the tap-hole. This usually requires a minimum of lancing (less than one lance pipe). In this way there is also lower risk that tappers lose the skill to safely use oxygen lances due to infrequent practice.

The rationale behind this practice is driven by a decided requirement not to overfill tap-hole clay, through addition of a metered amount of tap-hole clay, which permits operation with a consistent short (as possible) tapping channel 'plug' to lance, as will be described later.

Tap-hole Drilling Requirements

The requirements to control and optimise the rate of drainage to the tap-hole (to lower liquid velocities and wear of the furnace lining) and associated tapping rate through it (controlled liquid tap with stable post-tap-hole conditions), impose a need to maintain a constant and optimal tap-hole length and smooth shape [BF9]. This usually is as long as practicably achievable, while maintaining a near-cylindrical channel shape of defined diameter. In reality some extent of fluting towards the hot-face (conveniently modelled as a cone [BF12,29]) with erosion at the hot-face (conveniently modelled as a paraboloid, to represent a zone for 'mushroom' development [BF12,29]) has been inferred from tapping channel temperatures, drill depths and their distributions [BF12,15,29].

In ironmaking operations with lower metal fall (high slag ratio of lower density), it is argued that 'the decision for diameter and tapping practice must be focused on slag' [BF28]. This highlights a role of reliable drilling, as it represents the primary means to control tap-hole diameter.

Tap-hole Drilling Equipment and Control

Due to excessive risks of skew drilling (directly promulgating similarly skew oxygen lancing in combination drilling and plug lancing practice), especially to operations with water-cooled copper tapblocks, practice typically requires the

accurate alignment (to surveyed tap-hole centre/s [BF30]) of mudgun/s and drill/s to be checked and, if necessary, re-calibrated at the start of each shift [BF21]. Tap-hole centering notches are also reported, to locate and indent the tap-hole clay to help keep the drill from 'walking off' from the centre of the tap-hole [BF30].

In addition, guided and stiff drill rods are essential to reduce excessive drill flex and secure a straight centred tap-hole. Guide systems include automatic travel to within limits, followed by a hydraulic pin (colloquially sometimes called 'antlers' [BF27]) being physically positioned down into latch hooks. For drilling 4 m long ironmaking BF tap-holes (requiring 6 m long drill rods), additional hydraulic rod devices are fixed to the drills to prevent bending of the drill rods and drilling off the tap-hole axis [BF24]. The undesirable consequence of using a less precise suspended rock drill for tap-hole drilling has been reported previously for a 4-piece water-cooled copper Ni ferroalloy tapblock operation [FA13] (Figure 14 and Figure 15).

Figure 14. Water-cooled 'dogbox' with minor cracks in surround bricks around tapping module brick with '+-shaped' crack, and off-centre drill hole [FA13].

Figure 15. Tapping module brick 4 after 219 taps. Multiple drilling of tap-hole off-centre, coupled with skew lancing [FA13].

An encoder that measures the drill position can be correlated with drill torque (hydraulic systems – [BF13,35]) or drill air pressure forward drive (pneumatic systems – [BF9]), and drill speed, to automatically determine the start and end of the tapping channel and hence the all-important tap-hole length [BF5,9,10,13,29,34]. Drill time sigma [BF27] and tap-hole length [BF13] are regarded as benchmark statistics and, with application of statistical process control (SPC), measures with which to quantify and effect tap-hole improvements.

Drill rod and bits

Drill bit shape and material (carbide [BF27,29,31] or heat-resistant Cr-Ni alloy [BF35] tips being preferred) has been the subject of intense investigation, especially in the ironmaking BF application [BF9,24,27,28,30,31,35]. The ability to retain a sharp cutting edge to cut, rather than hammer, through the tap-hole clay plug, is paramount with the bit cutting face presented to a debris- and dust-free face to drill [BF30]. Drill bit diameter is usually controlled within a range of 33 mm [BF29] to 45-65 mm [BF23,35]. Where hammering is considered important, an inside bit face that is

totally flat, to maximise transmission of impact energy is reported [BF29], coupled with transition from spherical to semi-spherical carbide shapes.

Air scavenging is typically used to achieve a cleared hole, additionally providing some cooling of the drill bit to help prolong its life [BF9]. Further improvement has involved progressively improving drill bit cooling (from air, to nitrogen, to water mist) on ironmaking BFs [BF5,7,9,10,21,23,24,25,27,34], where mist water cooling rates are in the range of 2-5 L/min and typically 4 L/min [BF29]. Water mist cooling systems are reported to have undergone still further development to overcome disadvantages of increased risk of drill equipment corrosion [BF9].

In ferroalloy and matte operations, especially those equipped with any potentially hydratable magnesia-based refractories, use of any water would be taboo (in fact even to the extent that dew point condensation associated with liquid nitrogen cooling to accelerate tapping channel repair is sometimes a concern). The short drill bit life is largely overcome when applied to drilling only tap-hole clay (i.e., deliberately not metal/matte/slag), in both metal/matte-only combination drilling, and slag-only drilling open tapping practices.

Two opposing effects of drilling on control of tapping channel diameter are reported. With premature bit wear a tapping channel negative fluting (diameter decreasing evenly down to the drill rod diameter towards the hot-face) has been reported [BF9]. Side-cutting designs capable of cutting during both forward and reverse drilling have been developed to limit the influence of drill bit wear on resulting drilled diameter [BF9]. More frequently though, a bit that fails to retain it cutting edge tends to wander, causing positive fluting (enlarging the hole to the hot-face) [BF12,15,29], or a 'mushrooming' effect [BF30,34]. Traditional rock drill bit designs provide some increased resistance to this, and are often preferred [BF30], despite still requiring drill bit replacement every tap on an ironmaking BF. This warrants further clarification on ironmaking BF tap-holes, the ability to open with 'one drill bit for every attempt' is regarded as an achievement [BF30], with only a 50% success rate reported [BF50] on one site, or an average 1.2 drill bits per tap reported on another [BF35]. Progression from threaded, to bayonet, drill rod couplings is reported [BF30] to limit the incidence of drill rods jammed tightly in couplings.

The direct consequence of a smooth straight tapping channel is a consistent smooth tapping stream and controlled post-tap-hole logistics. By contrast, a tapping channel that has an inner corkscrew shape is reported to induce a rotating and spraying tapping stream [BF9]; the latter condition exacerbated by any gas tracking on a pressurised BF operation. 'Softer drilling' (feed forward pressure < 3 bar), together with instructions to the operator to 'let the drill do the work' and so not try to force the tap-hole open using maximum force that can bend the drill rod, and produce a corkscrew condition, is reported to have lowered its incidence [BF9].

This is remarkably akin to the requirements of successful oxygen lancing; a good tapper tends to use the hot burning lance tip (> 2000°C) to progressively cut the tap-hole open in a series of small precessing actions to guide ever deeper the lance to make a straight tapping channel. While an inexperienced tapper tends instead to try to force burn the tap-hole open by pushing hard on a thin, long and flexible lance pipe, which readily causes it to deflect off course and cause damage.

Finally it is quoted that 'a rotating drilling method for opening the tap-hole, without hammering, … is expected to give an improvement of the tapping process' [BF9]. Similarly, many local ferroalloy and PGM matte tap-holes are indeed opened by drill rotating action alone without hammer action, despite the latter's availability usually. Even on ironmaking BFs, it is suggested that 'future advancements will be directed toward drilling the tap-hole without the need for hammering' [BF30].

Tap-hole closure

It is essential to be able to 'close the tap-hole with a high degree of certainty that the desired volume of tap-hole clay has in fact been installed' [BF29], and additionally ensure that upon mudgun retraction unplanned tap-hole re-opening will not result. Total elimination of re-opening events remains important, even given reported improvement from 10 to even 1 such event per annum by 2000 on one site [BF27].

Especially on slag-only closure, stopper bars, water-cooled 'rosebuds' and manual stopper tap-hole clay plugs remain common in the ferroalloy and non-ferrous industry. Slightly more sophisticated variants are used on some of the lower temperature and lower superheat mattes and blister Cu (e.g., 'Polish' plug comprising ceramic surrounding a cone-shaped tap-hole clay plug [BM12]). Over 25% of PGM and local Ni matte operations still practice manual plugging of tap-holes [BM6,13].

However, by far the majority of ferroalloy furnaces, 70% of PGM and local Ni matte operations [BM6] and all ironmaking BFs increasingly adopt sophisticated and powerful mudguns to effect tap-hole closure. Again, the importance of considering mudgun, tap-hole clay and tap-hole operating practice holistically as a fully integrated system cannot be under-stated [BF57] – coupling a hard new-generation tap-hole clay with an old weak mudgun incapable of properly delivering the tap-hole clay into the tap-hole, is bound to fail. Smith *et al*. [BF10] describe this

well through 'design of tap-hole clay is usually a compromise between 'equipment capability' and 'process' requirements.'

Mudgun Equipment and Operation

While manual plugging may seem at first glance seem extremely simplistic and requiring direct interface of the operator with a hot tapping stream, if incorrectly controlled, excessive tap-hole clay addition capable through automated mudguns potentially can have a destructive (but often hidden), action on a tap-hole and lining environs. It was not that long ago that one author witnessed a large ~30 m long furnace 'disappear from view', caused by excessive gas release and a concentrate blowback when a tap-hole was closed with a full 25 L mudgun load of wet tap-hole clay recently 'dug from the veld'. Other observations include both metal and matte 'boils' at the back of tap-holes, tap-hole 'blows', and even 'gas eruption from tar binder' [BF15]) caused by mudgun closure involving use of excessive tap-hole clay of high loss on ignition content (water flashes with ~1500 times volume increase at bath temperatures, and hydroxides, carbonates and hydrocarbons can react near-instantaneously and decompose, devolatilise and crack [BF36] to release CO, CO_2, H_2 and/or H_2O gases). In high-duty applications, tap-hole clay of low gassing potential is therefore a pre-requisite, and almost all operators seek an anhydrous [BF57], or 'water-free plastic mass' [BF10].

A perfectly cylindrical 1 m long tapping channel of 50 mm diameter requires theoretically only 2 L tap-hole clay to fully fill it. This increases to 5 L if worn on average to 80 mm diameter, by either positive fluting (exacerbated by any oxygen lancing and/or enlargement by bath wear of the tap-hole hot-face), or negative fluting down the tapping channel. Iida *et al*. [BF40] even suggest tap-hole enlargement typically occurs at a rate of 5.6×10^{-4} mm/s during tapping (1×10^{-3} mm/s when using 'poorer durability tap-hole mix' [BF40], the latter also modelled by others [BF41,45]). It is quite staggering to compare this quantity of tap-hole clay with the range reported for ironmaking BFs, admittedly, of 1.8-2 m [BF34,35], or more usually 2.5-4 m tap-hole length [BF21], of 'as little' as 10-20 L [BF21], to 50-120 L [BF21,35,3,12,13,36] to even 200-300 L tap-hole clay per closure, when trying to stabilise a 'mushroom' [BF5,21].

In ironmaking BFs, where tap-hole clay 'mushroom' operation is feasible, several operators report stable (consistently deep) tap-hole length and reduced tap-hole clay consumption (i.e., 'not excessive addition' [BF12,29,36], and reduced by as much as 50% to 100-120 L on a 3 m tap-hole length [BF12]) leading to generally improved overall practice [BF10,13,27,29,30,32,37,36]. This particularly when the tap-hole clay injection rates (rapid to assist with clean plugging of tap-hole clay down the tapping channel, yet with sufficient time for densification and crack sealing of the protective annular tap-hole clay tapping channel core [BF10,58]) and quantities, are controlled predictively.

Again, this can involve SPC to control tap-hole length (e.g., to 3.1 m [BF13]) by varying tap-hole clay volume (around a 100 L setpoint [BF13]); or to the extent where the operator is advised of the recommended tap-hole clay volume after 1.5 h of tapping, based on automatically measured tap-hole lengths and tap-hole diameter (the latter automatically inferred from measured blast pressure, liquid level and mass tapping rates [BF12,29]). Continuous load cells and micro wave radar level detection are used to determine hot metal torpedo and/or slag ladle filling rates, and so related mass tapping rates [BF29,36,41]. Operation usually involves increased tap-hole clay injection when the tap-hole length shortens and vice versa. Especially in consecutive individual tap-hole tapping practice, a common additional practice advocated on the other resting tap-holes, is for occasional tap-hole clay injection to maintain 'mushroom' condition, that otherwise is subject to progressive dissolution (if marginally carbon unsaturated) and wear in contact with hearth liquid [BF13,32].

Ironmaking BF experience suggests that less than ⅓ of tap-hole clay purchased is pushed through the gun. This wastage is ascribed to a combination of: incorrect storage under uncontrolled conditions of temperature, allowing tap-hole clay to become wet, or situations where tap-hole clay is stored beyond its useful shelf life. Of the remaining tap-hole clay, only 24% is estimated delivered into the tapping channel [BF10] (Figure 16). Nozzle cleaning, push out waste (used to ensure tap-hole clay is compressed in the mudgun barrel), nozzle-face tap-hole clay leakage (Figure 17 and Figure 18), mudgun clean out and 20% for 'mushroom' replacement constitute the remaining tap-hole clay usage.

Sacrificial wooden or ceramic nozzle covers (known locally as 'dinner plates' [BM7] (Figure 19)), are commonly used to limit tap-hole clay losses associated with mudgun push out waste (full nozzle cover) and nozzle-face/faceplate leakage (full or annular nozzle cover [BM7, BF5,13,25,28,30,37]). This has been reported to reduce mudgun nozzle tap-hole clay leakage events by 25% points from a poor norm of 50% [BF30].

Well-designed faceplates normally further enhance the efficacy of good mating with a flat nozzle face – common on Co and Ni ferroalloy and matte smelting operations. However, where faceplates are absent, some ironmaking BF operations have adopted tapered nozzle tips, for which better sealing against the tap-hole socket is claimed [BF23]. Upgrade to high nitride mudgun barrels is also cited to prevent wear [BF7,37].

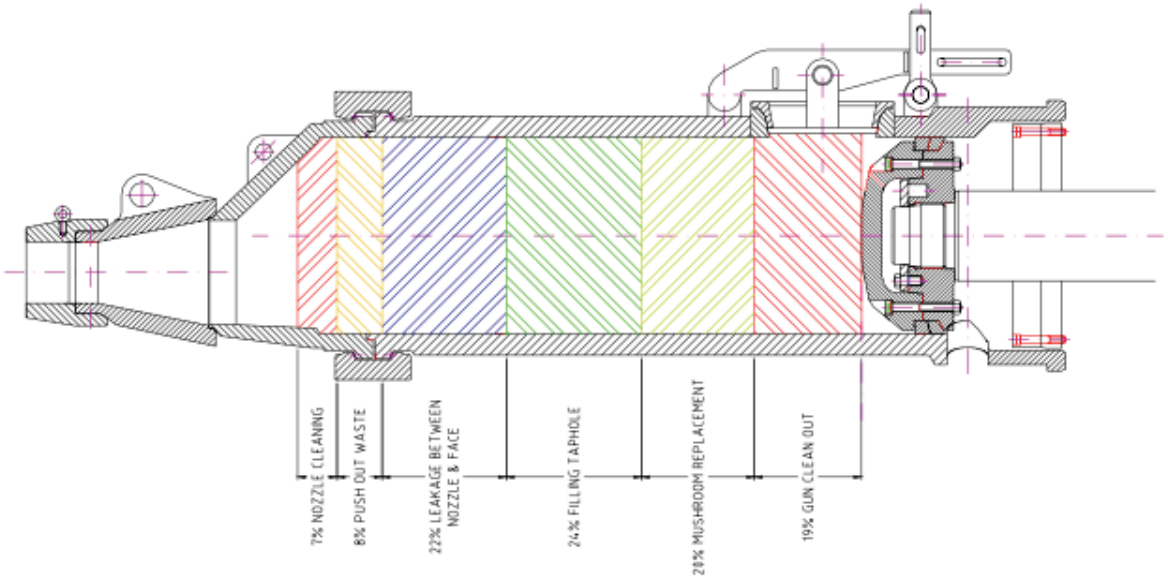

Figure 16. Estimation of tap-hole clay consumption and waste (after Smith et al. [BF10]).

Figure 17. Excessive tap-hole clay bypass [BM7].

Figure 18. Controlled dosage of tap-hole clay [BM7].

On modern mudguns, rapid and automated pressure-regulated mudgun slew is applied to further minimise damage to the mudgun nozzle, and to lower the risk of heavy impact on the tapping channel face and/or channel, that may otherwise crack or even dislodge tap-hole refractory and ironmaking BF 'mushroom' [BF10,13]. Slew pressure is usually set slightly higher relative to the mudgun barrel pressure (200-315 bar tap-hole clay pressure, resulting in a pushing force of > 60 tonnes onto the tap-hole face/faceplate, especially to push higher strength tap-hole clays [BF9,10,27,35,36]) that tend to limit the potential for bypass of tap-hole clay between the nozzle and tap-hole face/faceplate [BF5,6,13,31]. Automatic control of mudgun contact force is also preferred to limit the risk of undue mechanical damage to the tap-hole refractory; on one site achieved by a variable machine minimum pressure setpoint of 150 bar plus a variable proportion of 0.3 x plugging pressure [BF24]. In the absence of rigid faceplates, tap-hole face wear can be estimated from a relationship to cylinder stroke measured by LVDT [BF27,31].

In the operational extreme of combination drilling and plug oxygen lance practice, avoiding excessive tap-hole clay delivery beyond the tapping channel hot-face (for fear otherwise of tap-hole clay boiling and ensuing damage to tap-hole hot-face), precise control of tap-hole clay input is imperative. This often involves measurement and automated control of injected tap-hole clay volume. Indeed in several instances when tap-hole clay addition has been excessive [BM4,7], it has been demonstrated that controlled reduction of tap-hole clay addition (closer to the volume predicted theoretically for a 'normal' tap-hole' dimension) has even resulted in increased drill depth (further enhanced by improved furnace operating control of allowable upper matte temperature – Figure 20).

Figure 19. Sacrificial mudgun nozzle 'dinner plate' [BM7].

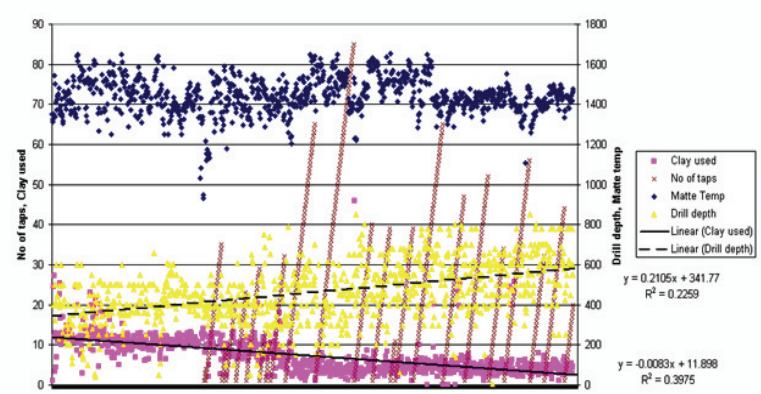

Figure 20. Reduced tap-hole clay injection (by 60%) leading to increased drill depth, even before tighter matte temperature control [BM7].

On ironmaking BF operations [BF10,24,29,37], staggered, multi-stage mudgun injection at different speeds may be practiced to achieve optimal tap-hole conditions. This may involve [BF37]: 1) First push: fast push of 45 kg tap-hole clay to displace all material from the tapping channel, followed by a slower push of another 45 kg tap-hole clay to build the 'mushroom', and a final very slow push of variable tap-hole clay mass to still further build the 'mushroom' and compact the tap-hole clay in the tap-hole; and 2) Second push: very slow push 5 minutes after the first push, with < 5 kg tap-hole clay addition to further compact tap-hole clay and close voids. To diminish the risk of tap-hole breakout, the mudgun then remains in position for 5 minutes to allow adequate tap-hole clay curing before it is removed from the tap-hole face. On another operation, with constant ram hydraulic pressure of 275 bar, a rate of tap-hole clay injection of 14 kg per second was sought [BF27].

Tap-hole clay

Tap-hole clay requirements

Typical requirements cited for tap-hole clay [BF10,24,36,47,48,49,50,51,52,53,54,55,56,57,58,59] include:

- Soft and plastic (workable) enough to inject when pushed by mudgun, but 'hard' enough to effectively displace tapping liquid and deliver a substantially tap-hole clay-only plug to the required depth in the tapping channel
- Curing to the required strength (often described as sinterability [BF57]) and without shrinkage to ensure a tight seal within the tap-hole (not prematurely in the mudgun), in the required mudgun dwell time and plug to next tap time
- Effect safe tap-hole closure (i.e., without subsequently re-opening) and without tap-hole and furnace lining damage (e.g., limited gas evolution and associated turbulence) and with 'mushroom' stabilisation (where sought, e.g., ironmaking BFs). This requires consideration of both effective tap-hole clay displacement in the injection direction [BF50,51,55], and 'good spreading ability in the direction perpendicular to the injection direction' to maintain a stable 'sedimentary deposit that is gradually and stably grown' [BF55] and exhibiting good high-temperature adhesion to the constituents already present in the tapping channel [BF54]
- Sufficiently soft to be readily drilled straight down the middle of the tapping channel without deviation, in an acceptable time (especially important where productivity constraints exist, e.g., ironmaking BFs)
- Allowing a stable, controlled tapping stream flow without surging or splash (often associated in ironmaking with blast gas tracking [BF26,56] and gas entrained with 'viscous fingering' to above the critical value that induces a deleterious splashing casting stream [BF39,46], even to the extent of slug flows [BF41,42,43,45])
- Ideally 'hard' and durable [BF57] enough to withstand penetration, corrosion and erosion by the tapped metal/matte and/or slag and so preserving a protective and adhesive annulus between the tap stream and tapblock refractory (without additional corrosive reaction with tap-hole refractory), to extend the useful tapping channel lifetime of acceptable controlled diameter, shape (i.e., minimal long-term fluting) and length.

To secure optimal paste quality, additional tap-hole clay preparation is recommended as [BF27]: stand-alone tap-hole clay storage building; maintained with a 10-day supply of tap-hole clay; with temperature controlled to 25-30°C; with an equivalent in-process controlled temperature for storage of tap-hole clay at the tapfloor [BF57]. Prolonged storage of resin-bonded tap-hole clay, especially at temperatures exceeding 40°C, is reported specifically as being detrimental to its performance [BF48]. However, especially for tar-bonded tap-hole clays, a minimum of 15 days ageing is reported as essential to secure adequate tap-hole clay loss in plasticity and increased hardness [BF59]. A tap-hole clay producer

even reports forced cooling of tap-hole clay to avoid any risk of continued undue temperature rise before final packaging of product [BF50].

Tap-hole clay aggregate and matrix

Most technical developments of tap-hole clay originate from the ironmaking BF industry, where the high-productivity (10 000 t/d HM), combined metal and slag duty, high pressure (~ 10 bar at tap-hole – [BF3]) and long tap-hole length (2.5-4 m – Table I) impose high demands on tap-hole clay quality. Mitsui *et al*. [BF15] use lowering of specific tap-hole clay consumption (kg/t HM) to outline early developments from the 1970's to 1988. These include progression from coke, to alumina, to silica and back again to pitch-impregnated alumina [BF54] and high alumina fine matrix (< 45 μm and > 50% by mass [BF49,53]) and/or coarser aggregates (~20% by mass 1-3mm [BF53]), variously with zirconia, kyanite [BF58], SiC, and silicon, aluminium and ferrosilicon metal and/or nitride matrix additions as fine powder to lower porosity, shrinkage, decrease volatiles, increase antioxidant action, lower wettability by slag and improve extrudability, corrosion, sintering and erosion performance [BF10,27,48,49,50,51,54,55,56,57,58]. Mention is also made of a trend to smaller particle size for improved compaction [BF27], improved tapping channel sealing against gas egress [BF56] and even ultrafines (< 10 μm) [BF49] for improved strength, corrosion and abrasion resistances and 'ability to go straight during gun-up instead of extending transversely inside the furnace' [BF50]. The improved corrosion resistance and higher positive residual expansion coefficient performance of pure silica and pure alumina sources compared with aluminosilicates is also reported [BF15]. A 'swelling' characteristic [BF15,36,47], is important to help seal a tap-hole subject to temperature fluctuation from the extreme of superheated tapping temperatures to cold closure conditions in water-cooled tapblocks. A somewhat more empirical approach has similarly led to convergence on use of tap-hole clays of high alumina content for high-intensity operations in the local pyrometallurgical industry.

Tap-hole clay binder

Traditionally coal tar pitch was used as the binder (~20% by mass [BF52]) for tap-hole clay. This was followed by a period in the 1990s where phenolic resin binder found favour. By 2001, it was reported that 90% of Japanese ironmaking BFs [BF21] and a Canadian producer [BF37] had moved back to tar-bonded tap-hole clay, while in Europe tar, resin and resin-tar binder combinations all continued to find favour [BF21]. By 2005, one supplier of tap-hole clay reported only two ironmaking plants in Japan were using resin-bonded tap-hole clay [BF53].

Tar-bonded tap-hole clays are generally thermoplastic, hard (often requiring pre-heating of the tap-hole clay in the mudgun barrel by gas heaters or hot water/steam to become pliable [BF24], especially for operation in colder climates) and slower curing (2h cast time is deemed insufficient for full curing and sintering [BF27], although only 20-30 min is frequently encountered in practice [BF41,43,44,51]). The latter necessitates the mudgun to remain in position for an extended time after plugging to avoid subsequent unintended tap-hole re-opening. Unlike resin binders, tar-bonded tap-hole clay is reported to have an advantage of forming a transition-free union with carbon-based refractory resulting in a monolithic tap-hole lining [BF24] and improved adhesiveness under high temperature conditions [BF54]. Radiant heating from the tapping launder may necessitate barrel protection by metal or ceramic insulating shields [BF37], or even water-cooling. Mudgun partial or full circumference, water jacket, dual heating/cooling systems are quite common in ironmaking BFs and some Cr and Mn ferroalloy operations. This is often automated to operate at a fixed temperature setpoint (e.g., constant 50-65°C [BF25,24,37,35]); or for maximum flexibility, an adjustable controlled temperature range (e.g., 25-90 °C [BF27] is provided for, and tailored specific to a given tap-hole clay type in use [BF6]). Between 10-30% reduction in tap-hole clay consumption by wastage is reported for using water-cooled mudguns [BF24,35].

Resin-bonded tap-hole clays are faster curing [BF48,51,52]; of benefit to shorter mudgun dwell time and quicker tap-hole turnaround (important in high-productivity operation, e.g., ironmaking BFs). Occasionally, though, the tap-hole clays can cure too fast, leading in hotter tap-holes to the tap-hole clay curing before injection is complete [BF13,50] or, in the extreme, to blocking prematurely in too hot a mudgun barrel with risk to delay in effective tap-hole closure. Resin-bonded tap-hole clay can be prone to greater volatility upon heating [BF52] and more undesirable gas evolution (observed in local industry) and is perceived to be incapable of effecting tap-hole closure on some high temperature and superheated Cr metal-only and PGM matte-only tap-holes. Some resin-bonded tap-hole clays have also been reported to cure too hard for acceptable drill times (<15 min.), requiring binder reformulation [BF50]. On high-intensity PGM matte operations, the risk of failing to close timeously a 'vicious' superheated tap, is considered so extreme that procedures further dictate that no matte tap-hole may be opened without availability of two fully prepared mudguns loaded with tar-bonded tap-hole clay to close the matte tap-hole.

Ballewski *et al*. [BF24] observe that generally 'the lower the temperature, the more difficult the correct choice of a binder system for mud becomes, since otherwise the front tap-hole area would extend negatively on the cold side'. Ostensibly for other reasons, just such tap-hole extension outside the furnace (colloquially described as a bullnose – Figure 8) is precisely what has tended to happen with intensely-cooled copper tapblocks.

Abramowitz *et al*. [57] reported that 'small changes (<5%)' in either light oil loss (260°C for 6h) or loss on ignition (defined by them at a temperature of 1204°C, rather than a more common 900°C, or 1000°C [BF59]) can 'change many dimensional and strength properties (as high as 119%)' of tap-hole clays. This emphasises the need for close control of conditions in manufacture of all tap-hole clays to yield a consistent quality product. Solely, using cold crushing strength (>7.6MPa) and workability (18 – 28%) as quality criteria, in the early 1980s tap-hole clay rejection rates up to 40%, or even more, were not uncommon for the tap-hole clay manufacturers. Rejection rates below 15% were suggested as acceptable.

In the local industry, variable coal tar pitch supply and quality has at times led to suboptimal 'cutting' additions of oils to overly viscous pitch, with resin additions to try to restore curing times. With typically 20% by mass binder addition [BF49], this often has led to tap-hole clays prone to excessive gas evolution and suboptimal handling and plugging characteristics; possibly suitable for less onerous slag tap-hole closure, but unsuitable for high-duty superheated Cr metal-only and PGM matte-only applications.

Health issues with tap-hole clay

Although a minimum tap-hole clay curing time of 45 minutes before re-drilling and tapping is reported to emit fewer fumes [BF30], tar binder poses health risk through release of polycyclic aromatic compounds such as benzo-pyrene that are carcinogenic [T22, BF21]; while release of similarly undesirable formaldehydes and phenols is associated with the resin binders. Molenaar [BF21] argues that benzo-pyrene particles in the air condense on dust, affording some protection by wearing a mask, which is ineffectual for protection against formaldehyde and phenol vapours.

Non-polluting tap-hole clay is therefore desirable, provided it can adequately meet the arduous duty and requirements of tap-hole clay without introducing further risk (e.g., tap-hole liquid breakout). It was reported [T22] that non-polluting single-phase binders proved unsuccessful, but that a single-phase binder A plus binder B (made of several mixtures) met comparable plasticity, high-temperature adhesivity, high thermal expansion and low erosion properties to those of existing tap-hole clays. Yet that was in 2004, and the authors were unaware of industrial adoption of such non-polluting tap-hole clay, possibly suggesting some deficiencies, until a 2014 report of a commercial tar binder of 'one thirtieth of the benzopyrene' content of ordinary coal for binders [BF55].

Tapping and tap-hole environment

Tap-hole opening (emissions associated with drilling uncured tap-hole clay, or fumes released in oxygen lancing), the act of tapping metal/matte/slag (release of process gases under pressure such as CO or H_2 especially in ironmaking BF; or SO_2, possibly even H_2S, by release or reaction especially in matte smelting, but also other trace gases such as Cl- or F-bearing species, or contained volatile heavy metal impurities, e.g. Pb, As, Cd, Zn, etc., depending on specific composition) and tap-hole closure (volatile emissions from tap-hole clay) all lead to increased environmental emissions around the furnace. Tap-hole, launder and ladle hoods (Figure 1) and even whole tapping aisle extraction systems are increasingly required to achieve the necessary and acceptable workplace hygiene and environmental abatement.

Tap-hole maintenance and life

Preventative Maintenance

Ironmaking BFs incorporate robust designs that may last for more than 10 years with little maintenance required of the castable at the front cold-face (and without mickey bricks) [BF23]. An original 4-tap-hole construction that lasted 12 years is also reported. Other BF sites report a 28-day cycle of casting tap-hole pairs [BF23], or recasting of tap-hole faces in planned maintenance scheduled every 18 weeks [BF29]. Tapblock graphite block inspection every 4 years is also reported [BF27].

Longer time-frames and operation to tap-hole breakout (usually within ~3-4 years) are also practised on many local ferroalloy furnaces, but both usually with the consequence that far more severe furnace lining damage and shortened cycle time to the next breakout results. A notable exception is campaign life of 9-12 years before first small tap-hole repair, reported on combined metal-slag tap-holes of freeze-lining design on a Cr ferroalloy furnace [FA2]. On Cr ferroalloy furnaces with water-cooled copper tapblock elements, other periodic planned maintenance may present ideal opportunities to effect annual slag tapblock and/or biannual metal tapblock repairs.

In Mn ferroalloys, typical total furnace (and by inference tap-hole) life is reported as only 6-10 years [FA1,4,7], with some early freeze-lining furnace designs giving over 20 years' life being the exception [FA4,7]. On many Mn ferroalloy furnaces periodic 'mickey' block replacement may be planned and performed as often as every 6 months, with tapblock campaign life of 3 years typical. With freeze-lining tap-hole design, life in excess of 18 months for the annular replaceable carbon block and graphite sleeve design has been reported in SiMn production [FA7]; and 400 mm (out of 870 mm) wear of tapblock hot-face in just over 3 years of service is reported in HC FeMn production [FA9].

Apparently this wear is not attributed to erosion by tapping practices alone (that involves drilling and minimal use of oxygen lancing), but it is rather suspected that standard furnace thermal equilibrium conditions do not always permit the tap-holes to remain at their design length [FA9]. On Mn ferroalloy furnaces with water-cooled copper tapblock elements, planned maintenance activities are understandably more aggressive, with mickey repairs as frequently as every 4 months.

Blister tap-holes were reported to operate 8 000 t between inner change, when flash converting furnaces were projected to deliver more than 4 years' life [BM15]. The latest furnace life estimate is now in excess of 5 years [BM12].

On Ni ferroalloy, and Ni and PGM matte furnaces, preventative maintenance may be time-based on lower intensity furnaces, but is more usually based on number of taps [BM6,16,17, FA22], rather than mass tapped, with the assumption that a 'tapping event' (comprising activities of tap-hole opening, tapping and tap-hole closing) is a more significant determinant of tap-hole wear than the mere act of tapping. As previously intimated, especially on higher-intensity superheated PGM matte operations, excessive tapping rate can also be used to trigger tap-hole maintenance.

Typical tap-hole maintenance cycles that result are: 1-4 week faceplate refractory insert and shallow tapping module brick replacement; quarterly deep tapping module and/or surround brick replacement; 1-2 year full tapping channel repair and potentially water-cooled copper tapblock replacement [BM6].

In addition, condition-based maintenance can be triggered immediately by any of: suspicion of any water leak; overly skew drilling; overly skew lancing (less easy to diagnose); excessive oxygen lance consumption; undue difficulty in tap-hole closure by tap-hole clay; damaged faceplate refractory insert; damaged faceplate (flat vertical mating surface to mudgun nozzle compromised); insert tapping channel diameter greater than a prescribed limit (practice requires this to be followed down the tapping channel, replacing adjacent tapping module bricks until the diameter is deemed within a prescribed limit); and tap-hole temperature spikes above alarm limits.

Special Maintenance

On-line repair techniques to improve tap-hole condition on ironmaking BFs include [BF8,13,24]: use of higher plasticity tap-hole clays to help seal gaps and reconstruct 'mushrooms'; use of an emergency 'nozzle can' [BF30]; injection of resin down a partially drilled (blind) tap-hole to seal cracks and reduce gas tracking; and grouting through injection under pressure of tar-bonded carbon mortars to more generally fill voids and so re-establish thermal contact and reduce gas tracking [BF34]. Details of several ironmaking BF grouting and zoned plug (blind) repairs and basic procedures are described [BF6,8,24,]. It is cautioned that great care should be exercised in grouting, using a sufficient number of open grouting points in the repair vicinity, to avoid the risk of grouting leading to excessive build-up of pressure and so leading inadvertently to refractory movement and even lining failure.

A comprehensive mudgun and drill inspection program is described with weekly, monthly, quarterly and annual activities to secure equipment reliability, early detection and prevention of possible failures [BF7]. Reliability of air supply on pneumatic drills is quoted quite frequently as a cause of poor drilling, with air accumulators and new compressors installed to address the problem [BF7].

Tap-hole monitoring

Standard Tap-hole Monitoring

Three general levels of tap-hole monitoring are identified: 1) Limited use of single thermocouples inserted into the lining, some around the tap-hole, and often associated with furnace campaign (let alone tap-hole) life under 6 years on both (historically) ironmaking BFs [BF5,13] and ferroalloy furnaces [FA1,2,4,6,7,12]; 2) Progression to more (15-50) predominantly duplex thermocouples to permit additionally heat flux calculation and monitoring display on ironmaking BFs [BF1,13,21,31] and ferroalloy furnaces [FA1], with furnace campaign life now more typically ranging between 10-20 years on both ironmaking BFs [BF2,5,13] and ferroalloy furnaces [FA1,2,4,7]; and 3) Dedicated multiple thermocouples for in-tap-hole temperature measurement [BF30], heat flux probes (equipped with thermocouples) [BF35], to the extreme of up to 30 copper thermocouples and water circuit RTDs (to determine temperatures, and water temperature rises and associated local heat fluxes) for monitoring of individual water-cooled copper tapblocks (let alone adjacent furnace lining), adopted on some high intensity non-ferrous operations.

Advanced Tap-hole Monitoring

Conditions inside the tap-hole during tap-hole clay curing can be determined by drilling a pilot hole and: inserting temporary thermocouples down the tapping channel to determine tap-hole temperature profiles with depth (e.g., on ironmaking BFs temperatures rise on average from 200 to 800°C (maximum 550 to 1200°C) from 0.25 to 1.75 – 2.2 m down the tap-hole [BF6,24,47,54,57]), thereafter reaching a plateau down the 3 m long tap-hole [BF24], and with time

(700-900°C within 30 minutes of injection [BF31]), and applicable to establishing tap-hole clay set-up times [BF6,15,24,37,54,57]; with measurement by contact thermocouple at 20 cm intervals even apparently reported in 'normal opening of the tap-hole' [BF24]; inserting nitrogen-cooled [BF31], or water-cooled [BF24] fibre-optic cameras to view internal tapping channel conditions; and core-drilling of curing/cured tap-hole clay samples for chemical and mineralogical/petrographic analysis and physical testing [BF2,41,58], sometimes on a two-year planned maintenance cycle [BF37].

In some BF stacks, ceramic rods are integrated into the lining to permit wear to be determined by ultrasonic measurement of rod length (assuming ceramic wear coincident with lining wear [BF1]). Status of the application and efficacy of this, or an alternative external non-destructive testing (NDT) acoustic emission (AE) technique [T10,BM5,20], to the more intensely cooled tap-hole region, frequently with the presence of composite refractory materials and/or water-cooled copper coolers, is uncertain.

A more recent development has been the use of an electrical resistance-based sensor (continuous along the length of the sensor, but for measurement of peak temperature only [T8]) and fibre-optic temperature sensors (either continuous sensor length peak-only, or discrete (about 25 per sensor), temperature measurements [T3,20, BM5]) to obtain more accurately a recording and better mapping of matte (and slag) tapblock temperatures in Ni and PGM matte smelting.

This development is in response to trying to avoid a 'porcupine' copper tapblock containing more conventional copper thermocouples and water RTDs than available for labelling by the alphabet! This recognises the limited range (akin to 'fishing with a rod' [BM21], so good chance of missing) of only local temperature detection by thermocouples in an intensely water-cooled copper tapblock environment (often equipped with yet a third redundant cooling circuit recessed to the cold-face; and successfully used on at least one occasion as a backup water circuit permitting safe shutdown of the furnace under controlled conditions following a cooler 'hit' and loss of primary hot-face cooling water circuit and/or furnace refractory breakout). This further recognises the more global monitoring capability, but poorer temperature resolution, of cooling water temperature rise on intensely cooled copper tapblocks (akin to 'fishing with a net' [BM21], so better capable of capturing key thermal events).

Although conventional duplex thermocouples are capable of detecting the accumulation of heat and temperature in tap-hole refractory when tapping in close succession on one matte tap-hole (Figure 10 and Figure 22), fibre-optics provide more detailed local mapping of the temperature distribution and rise associated with consecutive tapping, compared with the beneficial effects of rather resting a tap-hole to lower temperatures, as associated with alternating tapping practices (Figure 11).

Preliminary results seemed to confirm a distinct temperature rise following tap-hole closure, consistent with heat load rise following tap-hole closure observed previously [BM2]. Cooling during tapping was also reported (Figure 21). The former phenomenon has been plausibly ascribed to the significantly increased heat flux associated with tap-hole clay contact with superheated matte and associated gas bubble-driven turbulence and enhanced heat transfer. The cause of the latter is unknown.

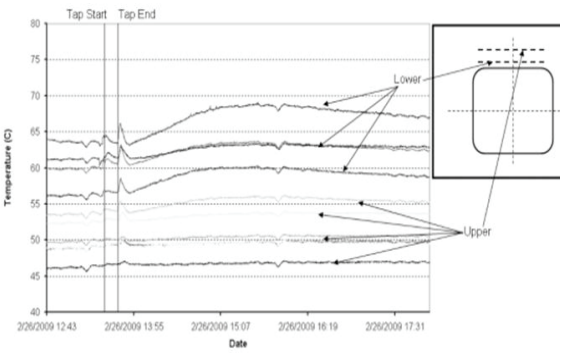

Figure 21. Close-up of tapping period showing fibre-optic temperature drop during tap (after Gerritsen et al. [T3].

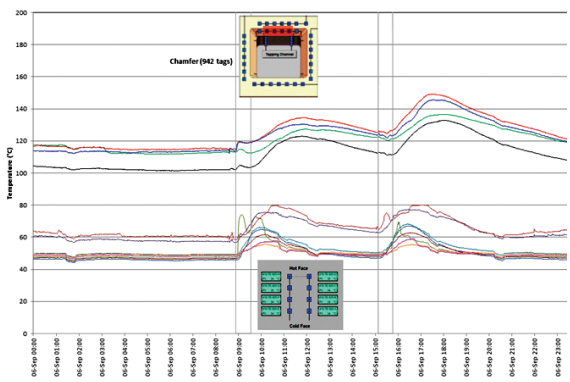

Figure 22. Recent tapping period close-up of fibre-optic temperatures on another matte tapblock (open-close shown as lines).

Recent fibre-optic temperatures, depending on whether measured at the chamfer or in the tapping channel during tapping on another matte tap-hole (Figure 22), seem to show some indications of temperature rise (and only sometimes fall) already during tapping. Temperatures at best continue on a similar trajectory, rather than with any distinct rise as may be anticipated for tap-hole clay closure (timing of which are determined from pyrometer temperature data). Moreover, while it may be tempting to ascribe apparent minor temperature dips around some tap-hole closure events to a theoretically plausible effect of tap-hole cooling by injected tap-hole clay (modelled in SiMn ferroalloy tapping

[FA10]), closer analysis suggests that the apparent dips are more likely an artefact of cooling induced periodically by the coarse temperature control of the copper tapblock water-cooling heat exchanger circuit.

Clearly still more work is required to fully understand and explain the tapblock fibre-optic temperature trends. This being a fundamental requirement prior to attempting more complex projection of possible tap-hole brick wear trends by thermal modelling, in support of advanced condition monitoring.

In response to difficulties in timeous detection of a significant tapblock temperature rise (and risks of non-detection), other more advanced monitoring and diagnostic systems have been pursued, including: principle component analysis (PCA), to try to provide some advance view of development of some abnormal tap-hole condition [T3,11, BM5,], and tap-hole acoustic monitoring (TAM), which has potential to identify the development of off-centre lancing [T10, BM5,20].

Tapping system water hazards

Given the sheer rapidity, often with very limited warning, and consequences of matte/blister Cu 'hit' of a water-cooled furnace component, it is quite obvious that refractory or accretion freeze-lining must always persist to prevent such direct interaction … somewhat analogous to the thermal shielding on the space shuttle Columbia, the loss of which was ascribed to a '*breach in the Thermal Protection system*' [T24]. The Columbia disaster involved the breaching of thermal protection tiles; analogous to the protective refractory layers in a composite copper cooling system. A final warning served on all furnace operating and maintenance personnel, is to avoid falling into the trap of complacency analogous to '*deeming damage to the Thermal Protection System an 'accepted flight risk*'' [T24]. Any decision not to investigate thoroughly a suspected matte/blister Cu 'hit', or breach of protective refractory and/or accretion freeze lining, should always be challenged with vigour!

Alternative coolants are suggested as a means to mitigate some of the risks associated with linings using water cooling in high-temperature molten bath systems [T14]. Certainly until such cooling media achieve common commercial application, effective water leak detection is a vital safety requirement for designs incorporating water-cooled linings. Monitoring for abnormal tap-hole or lining temperature drop (through cooling by water [BF13, FA16]), or abnormal temperature rise through either conversion to steam and its subsequent transport and heating effect in the nearby environs, or due to loss of freeze lining skull [BF31], is another method adopted to identify water leaks. Additional methods involve offgas analysis for increased hydrogen content (in reducing ironmaking BF and ferroalloy processes), or directly for water vapour content using hygrometers.

Water leak detection systems that require closed circuit water cooling include: monitoring frequency, and rate of change of make-up water, and stand-pipe level to detect leaks [BF13, BM5]; differential flow [T21, BM5], and multi-tier sensors involving monitoring copper and water temperatures, water flow and (periodically) water pressure [BM3,5,14, T6]. Automated pressure testing of individual cooler water circuits (at operator-selected scan rates) has proven capable of detecting even the smallest of 'drip' leaks on commercial furnaces [BM3]. The latter systems are most direct and effective, but more expensive and, for safety, dependent on coolers equipped with redundant water-cooling circuits and/or process and cooler design conditions where termination of a cooler water circuit supply for a brief period of pressure testing is without risk to conversion of water so entrapped to steam.

Conclusions

The critical importance of tap-hole design and management to furnace performance and longevity on a variety of ferrous and non-ferrous smelting processes is demonstrated. Process conditions and productivity requirements dictate specific differences and similarities in tapping equipment and practices, and in tap-hole operation and maintenance management. Operators are challenged to continually benchmark against other established best tapping practices and tap-hole management systems, to seek further incremental improvements to safety and performance.

Molenaar's [BF21] vision of the tap-hole of the future, now well over a decade old, was of a fully automated and remotely controlled environment. This effectively describes operating with personnel safely removed to the maximum extent possible from direct interface with hot liquids, hot linings and environmental containment, and tapping systems. While progress has indeed been made in this direction, further effort is required to realise such an ideal, consistent with still further improved tap-hole performance and life, and so pivotal to the safest and highest productivity furnace tapping operation possible.

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