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The Exact Art and Subtle Science of DC Smelting: Practical Perspectives on the Hot Zone

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Increasingly, sustainable smelting requires technology that can process metallurgically complex, low-grade, ultra-fine and waste materials. It is likely that more applications for direct current (DC) technology will inevitably follow in the future as DC open-arc furnaces have some wonderful features that facilitate processing of a variety of materials in an open-arc open-bath configuration. A DC open-arc furnace allows for optimization and choice of chemistry to benefit the process, rather than being constrained by the electrical or physical properties of the material. In a DC configuration, the power is typically supplied by an open arc, providing relative independence and thus an extra degree of freedom. However, if the inherent features of the technology are misunderstood, much of the potential may never be realised. It is thus important to take cognisance of the freedom an operator will have as a result of the open arc and ensure that operating strategies are implemented. This extra degree of freedom hands an operator a very flexible tool, namely virtually unlimited power. Successful open-arc smelting is about properly managing the balance between power and feed, and practical perspectives on the importance of power and feed balance are presented to highlight this aspect as the foundation of proper open-arc furnace control.

INTRODUCTION

Direct current (DC) open-arc furnaces have some wonderful features. These furnaces are good at processing fine feed materials (because of the open bath) and are also very good at treating feed materials with complex compositions. The power is generally supplied by an open arc, providing relative independence in respect of power input and thus an extra degree of freedom. Open-arc operation allows a choice of chemistry to benefit the process, rather than being constrained by the electrical or physical properties of the materials (e.g., resistance heating). The freedoms and features of an open arc, however, mean that operational strategies are critical to success. Mintek's involvement in development and testing of a variety of DC smelting technologies is well established with more than 30 years of experience operating pilot DC furnaces.[1–6] Through this work Mintek continues the evaluation of DC furnace technology for a variety of diverse metallurgical applications and has developed an in-depth understanding of the features as well as the subtleties of operating these furnaces. In light of this experience, some aspects of these insights are presented in the form of a practical overview, primarily reflecting on the intention of the open arc while highlighting the basic operating principle that is required to adequately leverage the power of lightning.

Enthusiastic pyrometallurgists are interested in the thermodynamics and engineering of high-temperature processes; however, many fellow pyrometallurgists will agree that some aspects of smelting fall within the realm of the "subtle arts"; some may even say aspects of smelting belong in the realm of magic. Quoting Rowling, the author of *Harry Potter and the Philosopher's Stone* may seem whimsical, but the following extract reflects the essence and the passion of pyrometallurgy and bath smelting, and the intention of this paper, quite well. In the quote, Professor Snape introduces young magicians to potion-making, which in the opinion of the author may as well have been written as an introduction to operating an open-arc, open-bath smelter.

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"You are here to learn the subtle science and exact art of potion-making. As there is little foolish wand-waving here, many of you will hardly believe this is magic. I don't expect you will really understand the beauty of the softly simmering cauldron with its shimmering fumes, the delicate power of liquids that creep through human veins, bewitching the mind, ensnaring the senses…".[7]

For those of us ensnared by the beauty of the simmering open-arc, open-bath cauldron, this paper aims to facilitate reflection on the nuances and principles of operating an open-arc DC smelter. The purpose is not to negate the need for science and engineering or good furnace design but to reflect on the practical challenges often misunderstood or underestimated. Unfortunately, no furnace design, whether it consists of the most advanced cooling systems, or fancy instrumentation and control systems, can overcome poor operating strategies. It is unfortunate that many operations do not understand the true nature and intention of DC open-arc smelting and hopefully this paper will provide some insight into the art and science of DC smelting.

THE ROAD LESS TRAVELLED

DC furnaces have been successfully implemented for a variety of commercial applications. However, the technology is often still thought of as the new kid on the block, but perhaps the true story can be best described as the road less travelled. The original DC furnace concept predates alternating current (AC) furnace technology evidenced by the work of Sir William Siemens.[8] Siemens first used a DC arc furnace with a vertical graphite cathode to melt material in contact with a water-cooled bottom anode in 1878. The first AC electric arc furnace (invented by Paul Héroult) was patented and first operated in 1900.[6] Thus, technically, DC furnace technology is the older brother of AC furnaces. Electric furnace technology became almost entirely AC-based because of the use of AC for efficient power transmission from large central power stations. DC implementation only really became viable once low-cost high-power solid-state semiconductor rectifiers became available. Since the mid-1980s, the technology has been widely implemented for steel-scrap melting and, in addition, metallurgical processes like ferrochromium and ilmenite smelting.

Descriptors like "unproven" or "high-risk" are still used to describe DC technology. Contributing towards this reputation is the fact that the some DC furnace installations were marred by difficulties during start-up and experienced design challenges. Barnes et al.[9] described a variety of factors that contributed towards the Chambishi DC furnace's operational challenges. The Barnes paper references the well-known McNulty curves[10] to evaluate the Chambishi project in the context of the classifications developed by McNulty. The paper provides some insight into managing risks, and, although we know that no start-up will ever be perfect, the success or failure of a project is all about mitigating risks. The four types of projects identified by McNulty are briefly summarized as follows to highlight the types of risks:

- Type 1: Mature technology, used elsewhere, scale similar to or smaller than prior applications of the technology, and thorough pilot testing completed.
- Type 2: Prototype technology (early or first implementation), incomplete pilot testing, and severe operating conditions (e.g., high temperatures), innovative parts of technology work, but auxiliary and support systems not tested or designed to suit.
- Type 3: As for Type 2. In addition, limited piloting was done and/or feed variability is common. Design flaws in simple systems, e.g., feed systems may contribute, and often engineering was "fast-tracked".
- Type 4: As Types 2 and 3, but with more complex flowsheets. A lack of understanding of chemistry, product quality or raw material characteristics is often an issue. Inadequate training of staff also adds to the difficulties and delays.

Flowsheet complexity, variability, design flaws in simple systems and fast-tracked projects are clearly significant contributors to delays, and all of these can contribute towards project failures. These characteristic mistakes are not unique to DC projects. New or novel applications are often selected specifically to address properties of the raw materials (ores are increasingly complex, lower in grade and non-standard). Despite rational views and facts, new technology is also measured against a higher standard, and failures reflect poorly on the reputation of the technology, even if the root cause is not directly related to the technology. In order to minimize risk, it is critical that operators understand the technology they are implementing. Training of new plant teams is therefore critical, yet, even with the best of intentions, it remains a tremendous challenge to get new teams up to speed. Although it is of course extremely important to fully appreciate and understand new technology (through piloting), even if the technology is not really that new, it is usually new to the plant teams responsible for commissioning and eventually operating the furnaces.

Mintek's test facilities have indeed been used quite successfully to demonstrate DC smelting for many applications. The smelting step is often tested thoroughly but usually in isolation and quite early in the project development phase. Upstream and downstream integration is seldom demonstrated at pilot scale. This can result in poor or inadequate designs for simple auxiliary systems like feed or off-gas systems. However, smelting is more than just the technology and the equipment, and furnaces are designed successfully all the time without integrated testing. Equipment is, however, operated by people, and operating an open-arc furnace requires a different operating approach often not intuitive to operators. Unfortunately, while Mintek's metallurgists and operators continue to gain practical experience in the exact art of operating DC furnaces, knowledge transfer to new plant operators has been much harder to achieve. Some of the most successful implementations of DC technology committed early funding to send their new plant teams to Mintek to operate a DC furnace for an extended period, prior to commissioning the industrial furnace. It is not, however, always practical or affordable, but it is a good example of addressing a high-risk item head on.

A BRIEF HISTORY OF DC SMELTING IMPLEMENTATION

Ferrochromium alloy smelting in a DC open-arc furnace for direct processing of ore fines has come of age over the past 30 odd years.[11] South Africa's chromite resources are well known for their friable nature, and during the early 1980s, Mintek and Middelburg Steel and Alloys (now incorporated in Samancor) jointly developed the DC open-arc process for the production of ferrochromium with the objective of exclusively smelting chromite ore fines. DC application to ilmenite smelting followed shortly after, via the first installation of DC smelting for Anglo American at Namakwa Sands (now incorporated in Tronox).[6,12] Both DC operations initially endured the pain of "being first", but are still successfully operating their furnaces.

Early adopters of technology often feel the need for secrecy, wishing to maximize the benefit from lessons learnt for themselves. This is also true for DC smelting. A glaring lack of data and publications in the public domain and on DC operations speaks to this point, further complicating the matter of knowledge transfer among users. The art of DC smelting is rarely captured in publications. The DC "user group" is still a relatively small community if truth be told, and the tendency to protect know-how and experience has thus resulted in the dissemination of information more in the form of operational lore than through scientific publications. As DC technology matures, more data will hopefully be published and perhaps DC-specific sessions at major conferences may become a reality in the near future.

Thus far, the story of DC is a story of paradox. Some operations are extremely successful and continue to expand and thrive, while others have struggled and even failed. Although proper furnace design and addressing the risks associated with project complexity contribute to successful implementation, there is something else at play, namely how quickly an operation learns to understand the constraints and the power of the open arc.

THE MORE WE CHANGE THE MORE THINGS STAY THE SAME

The intention of a reductive smelting process is of course to separate the valuable metals from the gangue by selective reduction. If the desired balance is maintained and managed, the open-bath open-arc DC operation achieves phenomenal results (recovery and throughput). DC smelters are generally intended to be high-intensity units. Just because one can achieve high throughput, this does not mean that this is a free ride. An interesting feature of the early adopters of DC technology is that the intended products and metallurgy were actually quite well known. From a metallurgical perspective, there is no cause to believe that smelting in a different type of furnace should significantly alter the process. Ferrochromium production in a DC furnace focused primarily on treating fines directly, and the subsequent metallurgical benefits were not a direct objective. The benefits associated with DC ferrochromium smelting are as a result of the freedom to adjust the slag composition to achieve metallurgical objectives, and in this case the DC furnace is a metallurgical enabler, allowing yield or grade optimisation unparalleled in the ferrochromium industry. Despite the perceived differences, the basic metallurgy is not different (the properties of the well-mixed open-bath enables the operations to operate closer to equilibrium). Ilmenite smelting is another good example where one could argue that DC furnaces are not that much different from the original technology (as used by Richards Bay Minerals in South Africa, for example). Richard Bay Minerals uses the process technology originally developed by Quebec Iron & Titanium (QIT), namely rectangular six-in-line graphite-electrode furnaces in open-bath mode with AC open-arc operation.[6] High-titania slag, the primary product from ilmenite smelting, is highly conductive, and there is no alternative but to operate with an open arc, regardless of the type of furnace technology.

The two examples intend to illustrate that, despite application of a new furnace technology, the principal chemistry and process parameters were actually not that new. However, at implementation, the operations needed to learn how to run these furnaces to achieve the benefits associated with this technology or, with a more negative slant, to avoid destroying their furnaces.

Initially, DC technology was strongly associated with feeding via hollow electrodes as it was the belief that the magic of the hot arc is only accessible if the feed is fed directly into the plasma arc. Generally, feed arrangements for DC furnaces have shifted towards maximizing throughput and reducing the cost of electrodes, and Mintek rarely operates or recommends a hollow electrode feed arrangement. Feed is still, however, fed into the furnace engine room, the hot spot or arc attachment zone where the arc supplies the power. In order to maximize the benefits of the open arc, feed should be presented to the hot zone, although some feed can be accommodated towards the sidewalls to assist with shielding the roof from radiation from the bath (if operating with an open-bath, the majority of radiation is from the hot surface of the slag). Arc stability can be negatively impacted if feed rates are not well controlled, however, as slug (intermittent, variable feeding) feeding into an arc or even the hot zone is obviously undesirable. The aim should always be to provide feed to the hot zone in a controlled manner, as an unstable arc can quickly result in poor outcomes.

SO YOU HAVE AN OPEN ARC?

The flipside of the flexible independence provided by the open arc requires that tight control of the mass feed rate is required in order to balance out the very stable, high-intensity power input attainable via the DC open arc. Best practice conversations for operating a DC furnace starts with one word, namely *balance*, which is easier said than done. Electrical input (arc stability and power) is usually very accurate and controlled, while feeding a furnace as accurately is not as easy nor simple. The arc attachment zone and the surrounding hot zone is where most of the magic happens in an open-arc furnace. If one considers the sheer quantity of energy generated by the arc (in a single hot spot, centrally located in the furnace), the importance of providing the hot zone with stable, continuous fresh feed seems obvious. The hot zone can be both a blessing and a curse. The key to sustainable smelting is to manage the power-to-feed balance in the engine room (the hot zone). This key unlocks the benefits of a DC furnace, yet it is often ignored or underestimated. Unfortunately, the lesson is then learnt the hard way, either through damage to equipment as a result of a furnace failure or poor production outputs. Optimization and refinements are part of any process, but it is difficult to improve a process if the basic principle is not in place. The power-feed balance should always be at the top of the agenda, regardless of the maturity of an operation. Operating a DC furnace without a sound strategy is "furnace suicide". With great power comes great responsibility. The phenomenal ability of a DC open-arc furnace to provide power to the hot zone comes with a great responsibility to feed the furnace properly, in order to match or balance the power. If the power-to-feed balance of this high-intensity machine is neglected, trouble will follow.

"IT'S COMPLICATED"

All operations have, of course, a range of variability, either naturally (from the earth) or due to engineering or control limitations. "Tight control" is relative, of course. In order to get the best control possible, it is thus important to understand the process variability, equipment limitations and the metallurgical boundaries very well and this should be incorporated into the control strategy. Once these are quantified, the impact of equipment constraints and variability on the longevity of the furnace should be quantified. Variability always comes with a price tag. It could be compromised temperature control or poor product quality, or low availability or restricted throughput, or all of the above. If, due to feed composition variability, the furnace needs to be operated at a higher temperature than suited, it may, for example, require more frequent tap-hole replacements. Due to the nature of high-temperature processes, the cost of process input variability is often throughput or integrity issues. Many risks can be mitigated, especially if the operators fully appreciate the power of the open arc and if proper controls are put in place to manage the impact of the variability. Many high-temperature processes are operated within fairly narrow metallurgical boundaries, primarily determined by the nature of the material being processed, or the product grade being targeted, or even simple economics. A DC smelter can be a powerful tool that can overcome some typical constraints (like direct processing of fines), but it is obviously not really a magical creature that can be allowed to roam free. DC arc furnaces are by no means a solution for all metallurgical problems, and the technology is not able to overcome poor control, unreliable feed systems or complete lack of feed composition control.

High-temperature processes are by their very nature unforgiving, but while a DC furnace is a very strong, well-defined muscle, we (the operator/plant metallurgist/furnace designer) need to provide the brains to curtail the brawn.

THE DARK SIDE OF THE FORCE

The multi-phase multi-component systems involved in smelting processes have so many variables that it is often difficult to pick out the most important relationships, or even to identify the cause or causes of a "disturbance in the Force" as the Jedi Master Obi-Wan Kenobi eloquently and famously said in *Star Wars*.[13] In keeping with George Lucas' *Star Wars* analogy, the Force is strong with DC furnaces. However, the Force needs to be in balance (the Dark and the Light). It is the job of the operator to bring balance and to achieve the desired outcomes. Imbalance will result in unwanted consequences, and either too much power or too much feed is of course undesirable. In order to achieve balance, both sides of the Force are required, neither can exist without the other. The mythology of the *Star Wars* story thus provides some sage and practical guidance as well as a cautionary tale, namely to heed the temptation of the Dark Side (power). Operators of furnaces are under tremendous pressure to meet throughput targets, and, in the short term, it is easy to succumb to the Dark Side (operating with excess power). It is usually easier to operate a smelting operation at a slightly higher temperature than design. Tapping difficulties are generally overcome by increasing the temperature; "the show must go on" principle. Seldom will you find a plant where the operators run the furnace slightly cold by choice. Systematic excess energy input will, of course, have long-term negative impacts on refractory and tap-hole life, yet in the short term the temptation to use this power remains within the operator's reach.

A DC furnace is just a very (*very*) large welding machine. If you don't add the flux and move the welding arc accordingly, you will burn a hole and ruin your work. This balancing principle (feeding the hot zone) is true no matter what scale of open arc you have. Regardless of whether it is an arc welder or a mega-scale DC furnace, you must balance the hot zone with the "cold" feed. The hot zone is where most of the balancing should happen or you are going to find yourself in a lot of trouble.

POWER-TO-FEED BALANCE

The specific energy requirement (SER) of a smelting process can be simply expressed as MWh per metric ton of total feed or power (MW)/feed rate (ton/h). SER is the energy required to transform the feed materials at 25 °C into the product streams at the desired temperatures at which they leave the furnace. SER is thus inherently the power-to-feed ratio we strive to achieve, and regardless of how a plant opts to express this ratio, it remains the fundamental starting point. Operators sometimes forget that the theoretical SER changes quite significantly if the chemical composition or temperature of the raw materials deviate from the theoretical baseline. A controlled feed and energy ratio is critical for reductive smelting processes, as the product quality relies on achieving the desired degree of reduction and separation at the target temperature. Variances in the feed recipe impact product quality and the energy balance (often both). Acknowledging the impact of feed composition variability is important, yet we cannot compensate for all variances, some of which are due to natural feed variability, while others may be due to poor feed control or equipment deficiencies. Again, as long as we understand the impact of compositional variances and provide the operators with guidelines to deal with these, the power-to-feed balance can be managed.

DIFFERENT STROKES FOR DIFFERENT FOLKS

Ilmenite smelting is a good example of a smelting process where poor carbon control can lead to both product quality and operability issues. The carbon balance is fundamentally built into the SER. Ilmenite concentrates are generally fairly homogenous (less natural variance in the feed to deal with than other ores). However, as a result of poor reduction (too little carbon), not only is the product quality compromised but excess energy (not consumed to reduce iron oxide) can increase the slag temperature. The slag, with increased concentration of iron oxide, is naturally more fluid, and an excursion with poor carbon control can easily result in hotter, more aggressive slag. Frequent poor carbon control can compromise the slag freeze-lining. On the other hand, excess carbon and/or poor temperature control can cause slag foaming. Although intentional foaming practices are used quite widely in industry, an uncontrolled foaming event is obviously undesirable. Slag cleaning processes are generally not as sensitive to variability in the carbon addition, mainly because the primary product, the metal phase, is a small proportion of the total feed. The degree of reduction is then not quite the "the knife's edge" balancing act of ilmenite smelting. Slag-intensive furnaces are basically a slag rejection mechanism, and the bulk of the energy input is used to increase the feed to the desired operating temperature to separate the valuable metals from the gangue. A relatively small portion of the total energy input is related to the reduction reaction. Slag-intensive processes are thus more like balancing on a gymnastic high-beam. Note, however, that it remains a balance between power and feed, and the sensitivity to variability depends on the process.

NAVIGATION AND FURNACE CONTROL

Carbon control and fluxing variability obviously impact slag composition, slag properties and the energy balance and cannot be ignored when managing the power and feed balance. Assuming, however, that the process is well understood and the impact of feed composition is taken into account in the power-to-feed balance, managing the feed-to-power input ratio can be quite well described through navigational principles. An operator requires information to manage a furnace, much like a pilot needs flight instruments to navigate a plane from one point to the other. The sophistication of flight instruments vary greatly, with some advanced aeroplanes virtually flying without the need for a pilot. Yet, generally, planes have some instrumentation to indicate direction and altitude. In the same way, mass fed and power information is needed to operate a furnace, and this is especially true for an open-arc furnace. A basic mass balance is, of course, also important—what goes in must come out—but in order to at least have a chance of success, it is important to start with the basics, namely input. Successful operations invest resources to improve measurement and/or estimation of input and output data. If the quality of the information improves, so does the control efficacy.

Furnace navigation starts with attempting to accurately balance raw material feed rates with furnace power input, or at least continuously aiming to improve or correct this ratio. The feed into the

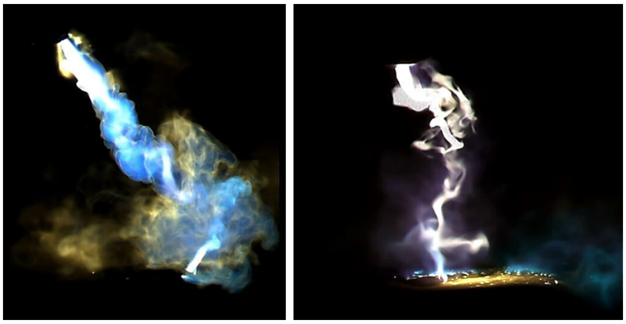

Fig. 1. High-speed photographs of DC arcs: the power of lightning (photographs by Reynolds, Mintek, 24 May 2012).

furnace is generally controlled from hoppers or storage bins integrated with a mass loss system to monitor and adjust the feed rate and feed ratios to the required levels. Mintek uses continuous, accumulative calculation and manages the power-to-feed balance ratio throughout any given feed period (expressed as how closely the actual power-to-feed ratio is relative to the desired process ratio, i.e. net energy in/mass fed). While the aim is to be perfect at all times, this is obviously never true. This practice can be described via navigational principles applied by pilots. The basic control philosophy described is applied by pilots and furnace operators alike: implement corrective action by evaluating progress against target (Figs. 1 and 2).

Figure 3 graphically depicts navigational outcomes via four simplistic scenarios. The pilot in each case aims for the mountain, while the diagrams illustrate the outcomes of four scenarios. In scenarios (a) and (b) no action is taken, while (c) and (d) illustrate outcomes due to intervention.

Scenario (a) shows a "perfect" outcome. It is a wonderful day with no wind, and the pilot can just point the aeroplane in the direction required. This is the only situation in which heading and course stay the same throughout the flight. Our furnace operator's job is to aim the furnace (target feed rates, power input), and all works out perfectly and every measurement is accurate and no interventions are required, but this is not a likely scenario.

Scenario (b) shows what would happen if a constant crosswind impacts the aeroplane after the pilot set the heading and took no further action (until the aeroplane runs out of fuel). The aeroplane very definitely will never arrive at the destination. If left unchecked, the furnace will not achieve the desired outcomes either and there is always a crosswind when operating a furnace.

Scenario (c) illustrates a case where the pilot adjusts the direction regularly (comparing the actual progress relative to the destination) and over time a change in heading occurs. The aeroplane is not actually flying a "straight course", but rather a funny curved path. At least the aeroplane will arrive at the desired destination, even if not completely efficiently. If drift occurs, the furnace

Fig. 2. Tapping the cauldron (pilot furnace) at Mintek (photograph by Geldenhuys, Mintek, 16 April 2004).

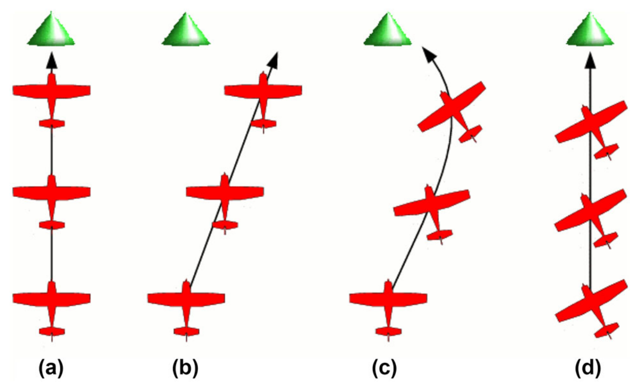

Fig. 3. Navigation (a) with no cross wind, (b, c) with crosswind. Reprinted with permission from Ref. 14.

heading may need adjustment; however, as with the flight path illustrated in the diagram, the ultimate efficiency may not be ideal; this is quite a good approximation of the majority of furnace control. A furnace has a memory, however, as it remembers what you did to it (the good, the bad and the ugly). If the influence of a non-ideal parameter is not proactively managed, the path travelled may have some consequences that needs managing. To use the flight analogy, the aeroplane will need more fuel to reach the destination if the response to drift is not managed regularly or timeously. Although not perfect, this type of corrective control is common, especially if the information (instrumentation) is less sophisticated or delayed. Commonly, we receive slag analysis and temperatures retrospectively, i.e. we've already drifted due to a crosswind and thus requires a heading adjustment as per this example.

Scenario (d) is an outcome of an elegant compromise between heading and course. It requires accurate data for the direction and speed of the crosswind to achieve. Although more ideal, it is not the most likely manner of furnace control as it requires accurate, up-to-date data not readily available. We should, however, always strive to improve our "flight" instruments towards this ideal.

Navigating a furnace with advanced instrumentation and accurate, timely information is of course the ideal. At the rate technology is changing, perhaps an "autopilot" furnace may eventually become a reality. However, until science catches up with fiction, we have to rely on the best control system available to us, namely experienced operators.

DOES IT MATTER HOW YOU GOT THERE?

Generally, an operator should only implement minor tweaks (periodically) to manage drift to ensure that, at the end of a discrete period, the desired destination is reached. These discrete periods and to a degree the objective destination are optimized for each plant based on the information available to the operator. The degree of manual intervention is determined by the sophistication and accuracy of instrumentation, data, equipment and control systems. However, no control system can compensate for poor information or inadequate equipment. An experienced operator can intervene manually to overcome major deviations, as long as the principle of the power and feed balance is well understood. Too often, an operator realises shortly before a tap that the carbon or power input ratio for the past few hours has drifted out of range and then tries to correct the error in a short, intense burst just before the slag tap. Under the right conditions, this type of intervention can cause severe process instability and will not adequately address the imbalance caused by the drift. If events beyond the operator's control cause a significant deviation from the plan (i.e. major down time or major failures), adjustments or interventions may need to be more radical (e.g., either slower feed or total feed stoppages). It may be prudent to land, refuel and re-calculate a new course if completely off track. A start-up strategy and procedure should be provided to operators to catch up if the furnace experiences a significant down time; consistency is key.

When feed control is fairly accurate (and composition and temperature are relatively consistent), frequent adjustments may not be required and the path may be close to the ideal. However, in the real world, input parameters vary all the time, and controlling a furnace may become quite a challenge if the frequency (and complexity) of adjustments increase.

It is hopefully clear that an aero plane and a furnace both require some basic instrumentation. Although our objective is to reach a destination as efficiently as possible, this is not likely (ever). Operations obviously strive for perfection (or at least systematic improvement), but all furnaces are operated in the real world, with real-world limitations. Furnaces also have excellent memories; it is not just about the destination. The impact of excursions tend to add up if left unattended. Minor variances in tapping temperatures and product composition are expected and are usually due to the natural uncertainties in our system. Frequent, large adjustments to major operating targets, especially reactively, can easily lead to further unwanted complications. A hot slag tap should be taken seriously, of course, but dumping feed into the furnace after the slag was tapped will not address the problem and most likely introduce more instability (much like trying to fix the carbon balance just before a tap; it is too late to make a simple mass correction). A significant portion of the memory in the example (the slag), has "left the building". How we react to an outlier should be informed by the "what went wrong" question, as this determines the intervention required. Compensating accurately for history is not trivial, and operators unfortunately respond to some variances with a hammer when perhaps a scalpel is more appropriate.

In order to arrive at the desired destination, accurate information from the feed system and power supply is required. Although this may appear obvious, it is alarming how often this information is not available, or poor quality data are used. In the absence of accurate information, the operator is driving a car at high speed with no brakes and only manages to stay on the road through very dramatic interventions, rather than controlling the vehicle at the appropriate speed limit (SER) for the road conditions. Power input to a furnace is normally one of the most accurate inputs to the mass and energy balance. Rate of energy loss is probably the next most reliable number, especially for well-instrumented, water-cooled furnaces, and probably only marginally less accurate than the power input if the instrumentation is suitable for use. The trick is usually to determine an accurate mass fed (and feed composition), accurate power input and an accurate energy balance to allow for optimization.

CONCLUSION

Optimising a smelting operation is a complex, multi-faceted adventure. If the very stable, high-intensity power input that can be attained in a DC furnace is matched by equally stable and controlled feed to the hot zone, the furnace can achieve phenomenal efficiencies. Unfortunately, feed systems are often not able to match the accuracy of power input, often leading to compromises and even failures. Sadly, a Rolls Royce furnace is often matched with a feed system resembling a used VW bug from the 1960s. It is important to address feed input as one of the primary risks when smelting in open-arc mode.

A summary of good practices or principles for DC smelting is a daunting task, and while topics like thermal efficiency, arc length management, mass balances, metallurgical control and many others should ideally be addressed as sub-topics of good practices, optimizing should start with ensuring that the operator of an open-arc furnace understands how to manage the powerful hot zone. The hope is that this paper will provide food for thought and remind furnace builders and operators of the fundamental principle entrenched in the open-arc operation. A DC furnace often allows for process optimization beyond the norm, but when things are not going to plan make sure the power and feed is balanced or else nothing else will matter.

Mentors would often start a young pyrometallurgists' induction into the world of smelting with the following sage advice: "Take care of the slag and the metal will take care of itself". Although valid advice, for a DC furnace one might perhaps rather shape the new generation through the following modified version: "If you take care of the hot spot, the slag and metal will take care of themselves."

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REFERENCES

1. N.A. Barcza, T.R. Curr, and R.T. Jones, *Pure Appl. Chem.* 62, 1761 (1990).
2. I.J. Geldenhuys and R.T. Jones, in *Proceedings of COM Pyrometallurgy of Nickel and Cobalt 2009*, ed. by J. Liu (CIM, Montreal, 2009), p. 415.
3. I.J. Geldenhuys and R.T. Jones, in *Proceedings of the Sixth Southern African Base Metals Conference*, ed. by P.A.P. Fouche (SAIMM, Johannesburg, 2011), p. 477.
4. R.T. Jones, Q.G. Reynolds, T.R. Curr, and D. Sager, in *Proceedings of Southern African Pyrometallurgy 2011*, ed. by R.T. Jones and P. den Hoed (SAIMM, Johannesburg, 2011), p. 15.
5. R.T. Jones, in *Celebrating the Megascale: Proceedings of the Extraction and Processing Division Symposium on Pyrometallurgy in Honor of David G.C. Robertson*, ed. by P.J. Mackey, E.J. Grimsey, R.T. Jones and G.A. Brooks (Wiley, San Diego, 2014), p. 129.
6. R.T. Jones and T.R. Curr, in *Proceedings of Southern African Pyrometallurgy 2006,* ed. by R.T. Jones (SAIMM, Johannesburg, 2006), p. 127.
7. J.K. Rowling, *Harry Potter and the Philosopher's Stone* (London: Bloomsbury Pub, 1997), p. 102.
8. W. Siemens, *English patents*, No. 4208 of 1878 and No. 2110 of 1879.
9. A.R. Barnes and R.T. Jones, in *Proceedings of COM New Technology Implementation in Metallurgical Processes Symposium,* ed. by CIM (CIM, Montreal, 2011), p. 111.
10. T.P. McNulty, *Min. Eng.* 50, 50 (1998).
11. I.J. Geldenhuys, in *Proceedings of the Thirteenth International Ferroalloys Congress*, ed. by M. Tolymbekov (P. Dipner, Karaganda, 2013), p. 31.
12. M. Gous, in *Proceedings of Southern African Pyrometallurgy 2006,* ed. by R.T. Jones (SAIMM, Johannesburg, 2006), p. 189.
13. *Star Wars: The Complete Saga* (*Episodes I–VI*), Dir. George Lucas, Blu-Ray, 2011.
14. Jörg Emmerich, *Flight Gear Flight Simulator (FGFS) Online Handbook*, http://www.emmerich-j.de/Handbuch/EN/B7_RNAV.html. Accessed 22 July 2016.