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Tap-hole opening: Advances and improvements

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In pyrometallurgy, thermal lances are commonly used to open furnaces tap-holes. Despite their routine use, lances have undergone a process of innovation in design and assembly which has resulted in lances capable of maximizing the generation of thermal energy and of working in different operation conditions; that is to say, with a variety of mud plugs, molten materials, furnace temperatures, as well as different oxygen pressures. To achieve a safe and efficient tap-hole opening, now it is possible to choose the right thermal lance for each process. In this paper, different ways of tapping furnaces are explored with an emphasis on how to choose the appropriate lance for a specific task. Guidelines for troubleshooting of common problems in furnace tapping are also given.

INTRODUCTION

As is well known, opening tap-holes is one of the most dangerous and crucial activities carried out on a furnace. Dangerous because workers are daily exposed to high temperatures and fumes; and crucial because failure in this activity means delays during furnace operation, and in the worst-case scenario, a shutdown.

From the beginning of pyrometallurgy, and throughout several centuries, tapping was performed using hand tools (hammers and crowbars). From the final years of the 19th century and the beginning of the 20th century, different kinds of tools, such as stopping tools, drills, and oxygen pipes (still in use), began to be employed (Dienenthal, 2014).

In this paper, we explain how new tools have been developed (and efficiently applied) considering previous mistakes and omissions; and how tapping becomes a safe and efficient routine when the right tools are chosen and correctly operated.

TECHNOLOGICAL EVOLUTION

Tap-hole Evolution

The tap-hole is a fundamental part of the furnace, because it retains the molten product inside the furnace, but also in turn is the passage through which this material is removed. Over time, many resources have been invested to develop a variety of tap-hole types to extend the useful life and optimize opening processes (Dienenthal, 2014).

Tapping before Drills and Oxygen Pipes

Until around 120 year ago, tapping was carried out with very basic tools such as crowbars and sledgehammers, and with great human effort (Figure 1).

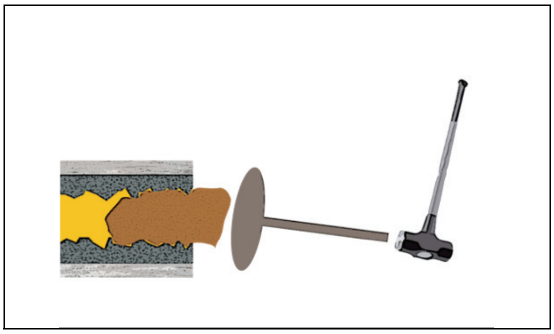

Figure 1. Sketch of tap-hole closure with sledgehammer.

Blocking the tap-hole once the furnace was emptied used to be one of the most complex tasks in this operation. This complexity arose from the irregular shape that the passage took when opened with manual tools, with many cracks and prominences. A great amount of time and human effort was required to put the mud plug into the tap-hole and make it flow into in every crack, sealing the passage (Dienenthal, 2014).

Clay Gun Evolution

Until 1895 the stopping process was carried out manually. After that, a stopping apparatus was developed (Wiley, 1896) (Figure 2).

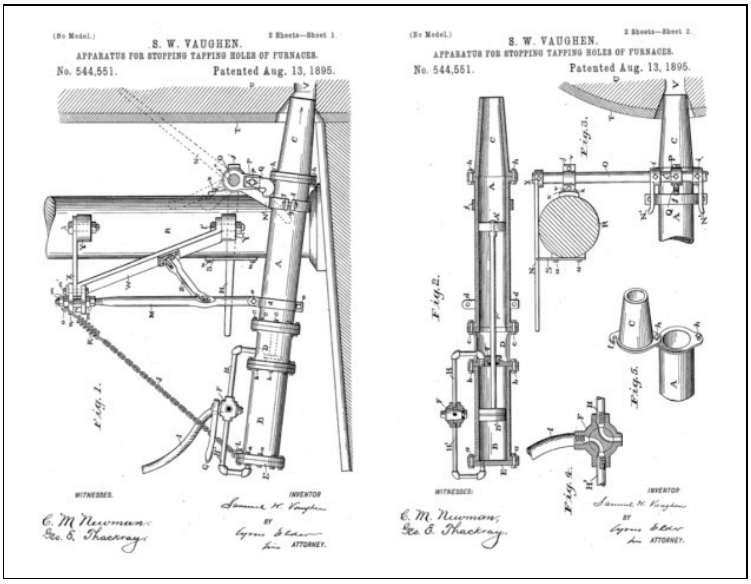

Figure 2. Apparatus for stopping tap-holes by Samuel W. Vaughen (Vaughen, 1895).

Drilling Machine Evolution

Drilling machines were the first solution developed by the industry to replace crowbars or sledgehammers (Figures 3 and 4). They reduced the effort required by the operator and allowed a more regular shape of the passage. This equipment was able to perform openings resulting in smoother walls and a well-defined, even diameter along the full length of the passage.

Although drills meant an improvement in the quality of perforation, they presented a drawback: they could not open the tap-hole completely, and the process had to be finished using an oxygen pipe or another tool.

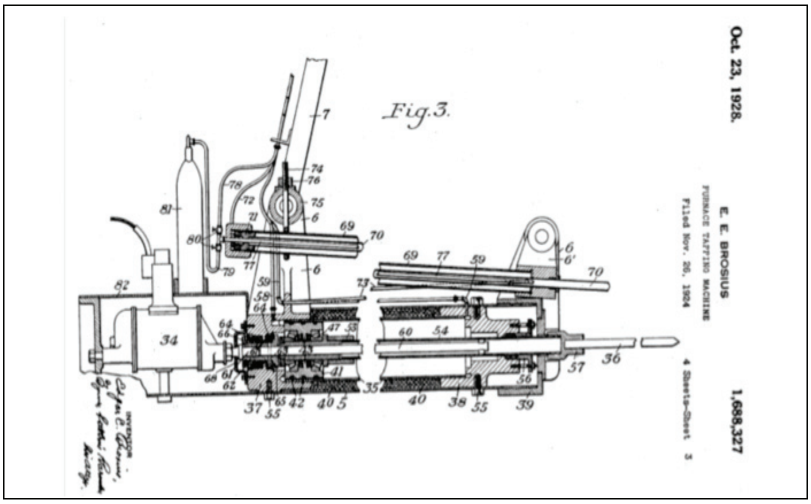

Figure 3. The first record of a tap-hole drilling and lancing apparatus, by E.E. Brosius (Dienenthal, 2014).

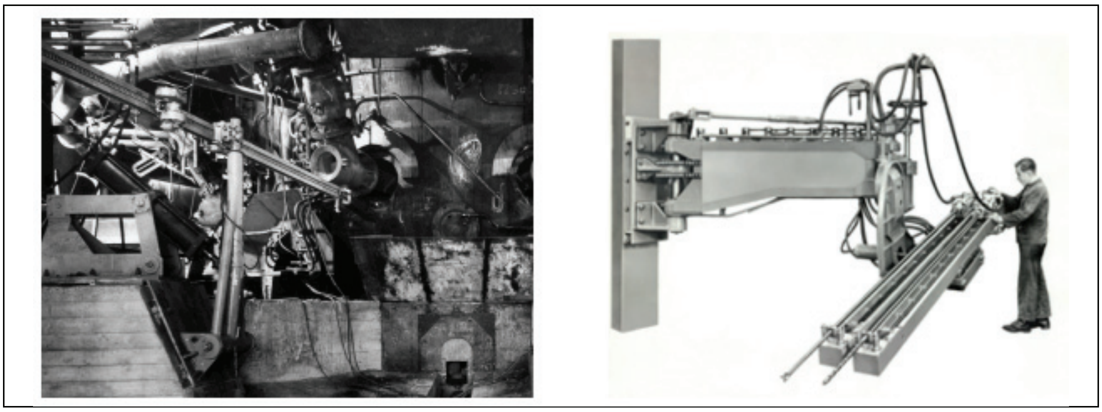

Figure 4. The first stationary tap-hole drills, 1950-1960 (Dienenthal, 2014).

Figure 5. Modern tap-hole equipment by TMT (Dienenthal, 2014).

THERMAL LANCE EVOLUTION: SUCCESS AND FAILURE

Thermal lances and oxygen pipes have prevailed through time; although they have not been without problems. The following sections describe the evolution of the lance, highlighting achievements and shortcomings.

Discovery of the Oxygen Pipe as a Tool to Perforate Tapholes

In 1901, Dr Ernst Menne, a German chemist and specialist in blast furnaces, tried for the first time to put a steel pipe carrying oxygen into the furnace through the tap-hole (Almqvist, 2003). He discovered that the mud plug melted, allowing the pipe to penetrate the passage. The oxygen pipe burned in the same way that such pipes they do today.

In search of improvements to the tap-hole opening process, Dr Menne continued with investigations that led him to patent different devices. In 1902 he presented a patent for a thermal lance that worked with both oxygen and with oxyhydrogen – the most powerful fuel at that time (Figure 6). The patent description mentioned that Dr Menne heated the tap-hole to the ignition point using oxyhydrogen, then cut the hydrogen supply and continued heating with only oxygen gas. Although he obtained only a small flame; the heat from the reaction was sufficient to melt the slag. In this way, he discovered that the lance produced thermal energy capable of melting slag and other hardened masses. Although Dr Menne's inventions were patented, they were not adequate for the operation, so only oxygen pipes continued to be used.

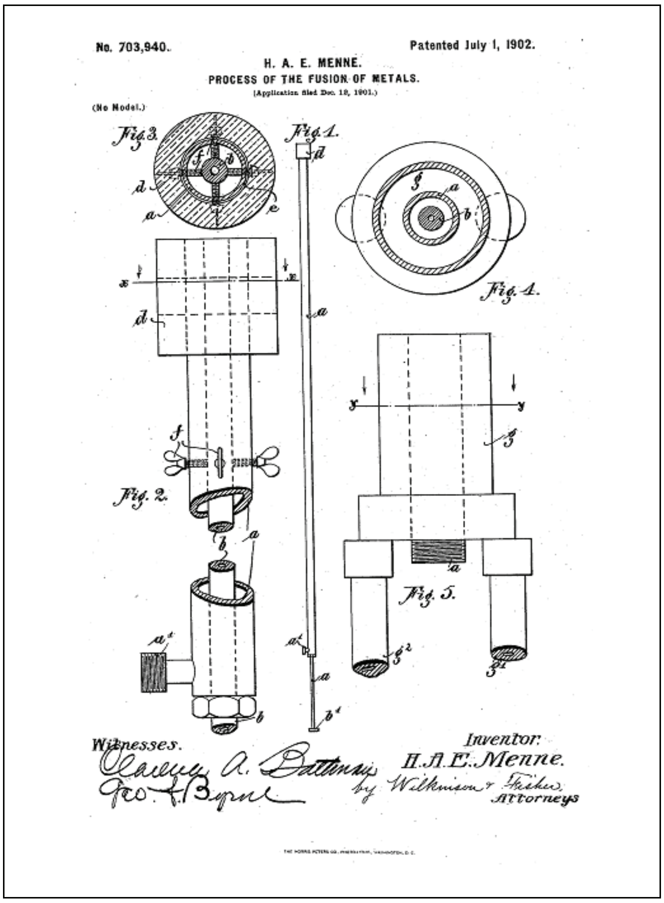

Figure 6. The first thermic lance, invented by Ernst Menne in 1902 (Menne, 1902).

Current Situation

Efforts to improve tap-hole opening technology focused on mechanical devices. However, since drills are not 100% efficient for opening the passages, a large number of thermal lances have been designed, most of which for one reason or another have not surpassed the traditional oxygen pipes in performance. Certain aspects of the performance of thermal lances were only superficially studied, or not studied at all, for many years.

For example, the failure of the lances patented by Dr Menne was due to two facts:

(a) They used gaseous reaction fuels
(b) They could not concentrate the energy.

In addition, Dr Menne did not pay attention to the origin of the energy or its relation to volume, nor did he consider that the iron reacts in the solid state.

Beginning of a New Era

Considering the performance of the thermal lance (an oxygen lance with rods) and the results obtained by Dr Menne, investigation were driven by the need to develop a lance that could generate more energy than an oxygen pipe of the same diameter (cross-section), and to control the energy released in the reaction.

To understand how a thermal lance works, it is necessary to bear in mind that iron (Fe) reacts with gaseous oxygen (O_2) in the tip of the lance. This is an exothermic and heterogeneous reaction (Figure 7), for which Fe requires activation energy (an ignition temperature of 1143.15 K (Conway and Kirshenbaum, 1954) and that, when in contact with oxygen, it releases a great amount of energy.

The principal reactions involved in combustion process and their enthalpies of formation are shown in Equations [1] to [5] (Perry, 1934).

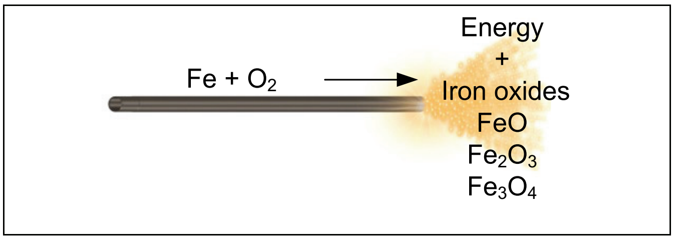

Figure 7. Reaction scheme of combustion between Fe and O_2.

$$Fe_{(s)} + \frac{1}{2}O_{2\,(g)} \rightarrow FeO_{(l)} \qquad \Delta H^{\circ}_{\mathbf{combustion}} = -270.376\ \mathrm{kJ/Fe\ mol} \qquad [1]$$

$$FeO + \frac{1}{6}O_{2\,(g)} \rightarrow \frac{1}{3}Fe_3O_{4(s)} \qquad \Delta H^{\circ}_{\mathbf{combustion}} = \mathbf{-101.868\ kJ / FeO\ mol} \qquad [2]$$

$$FeO + \frac{1}{4}O_{2\,(g)} \rightarrow \frac{1}{2}Fe_2O_{3(s)} \qquad \Delta H^{\circ}_{\mathbf{combustion}} = \mathbf{-138.619\ kJ/FeO\ mol} \qquad [3]$$

$$Fe_{\,(s)} + \frac{3}{4}O_{2\,(g)} \rightarrow \frac{1}{2}Fe_2O_{3(s)} \qquad \Delta H^{\circ}_{\mathbf{combustion}} = -408.995\ \mathrm{kJ/Fe\ mol} \qquad [4]$$

$$Fe_{\,(s)} + \frac{3}{4}O_{2\,(g)} \rightarrow \frac{1}{2}Fe_2O_{3(s)} \qquad \Delta H^{\circ}_{\mathbf{combustion}} = -372.245\ \mathrm{kJ/Fe\ mol} \qquad [5]$$

The products of the combustion of iron with oxygen are iron oxides. Their formation depends on the physical conditions in which this reaction takes place. It is therefore difficult to establish the exact amount of energy released in different scenarios. However, thanks to a variety of empirical studies, it has been possible to determine with great accuracy the performance of the lance. At the same time, progress has been made in verifying these behaviours theoretically. The Chilean company Trefimet has allocated resources to research and improve the performance of its thermal lances.

For a better analysis and understanding of the combustion process of a thermal lance, the amount of energy released by the reaction will be shown in terms of the amount of energy per gram of Fe oxidized. Thus, according to Equation [4], the maximum energy released by the lance is 7.365 kJ /g Fe. It is important that the ratio be expressed as kilojoules per gram of Fe, since it is then possible to compare and analyse important concepts for understanding thermal lances. For example, Table I shows the difference between the heats of formation of different fuels and energy per unit volume, which is a very important concept for the operation of the thermal lances, given that within the tap-hole passage the workspace is very limited. This table shows the enthalpy of formation per cubic metre of different fuels in comparison with Fe.

Table I. Enthalpies of formation of solid and liquid fuels.

Name	Chemical Compound	ΔH°c (kJ/g)	Unit	Molecular weight (g/mol)	Density (kg/m3)	ΔH°c (kJ/m^3)	Mass (kg)
Iron	Fe*	7.365	kJ/g Fe	55.845	7800	57 447 000	7 800
Hydrogen	H2	-141.786	kJ/g H2	2.016	0.0838	-11 882	0.084
Methane	CH_4	-35.011	kJ/g CH_4	16.043	0.656	-22 967	0.656
Propane	C_3H_8	-50.000	kJ/g C_3H_8	44	2.01	-100 500	2.010

* For this paper, the iron combustion energy used is that from Fe_2O_3.

The above information can be depicted graphically for ease of understanding (Figure 8).

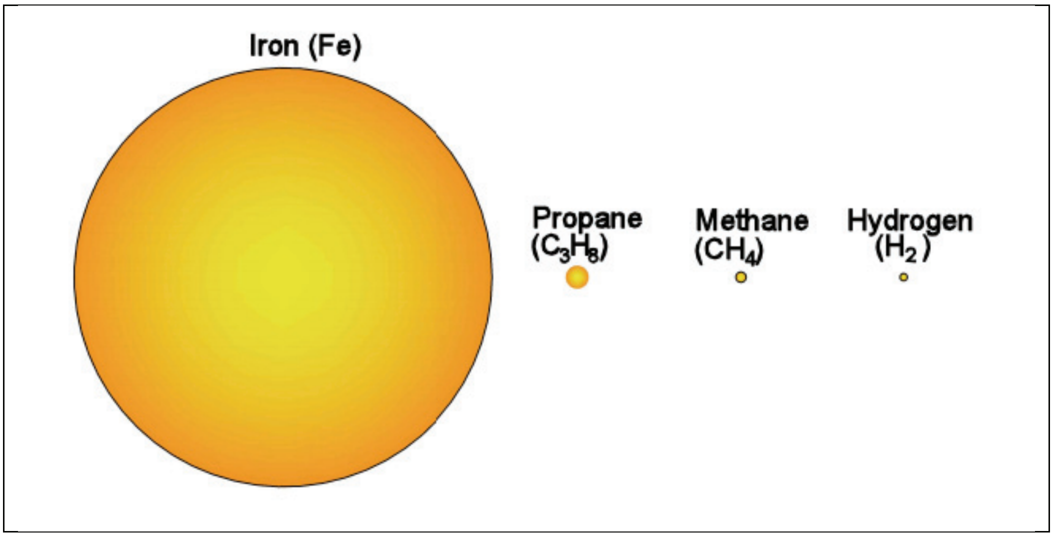

Figure 8. Graphic representation of enthalpies of formation-volume of different fuels.

Figure 8 underlines the importance of the energy concentration. The high density of Fe allows a large amount of energy to be concentrated at the tip of the lance, which does not happen with gaseous fuels, which require a greater volume to deliver the same amount of energy. The energy-volume concept is not always understood; for example, Dr Menne, who is considered the inventor of the oxygen pipe, patented a lance to melt metals and open passages with the use of gaseous fuels, which did not succeed at the time.

From this concept, one might think that the best lance is the one that has more iron to react, from which the idea of a tube full of iron rods was born. However, this is not always the case when working within a tap-hole because the bounce heat raises the external temperature of the tube, causing reactions that consume oxygen before the gas reaches the tip of the lance. This is literally an oxy-fuel cutting effect that 'burns' the external tube, preventing the oxygen from flowing to toward the tip of the lance and leaving the wires exposed. Consequently, the lance burns without the possibility of being ignited again (see Figure 9).

Figure 9. Thermal lance with rods used to open a tap-hole.

The latest-generation thermal lances developed by Trefimet consist of an external tube and internals tubular profiles of different transverse geometrical shapes (inserts). This configuration allows multiple internal ducts to conduct oxygen through the lance, increasing the oxygen contact area (Figure 10). So, when the iron in the ignited tip reaches 1143,15 K, it reacts with the oxygen, generating more energy per unit cross-section than the simple oxygen pipe; and preventing the lance from burning out when the external tube is consumed due to the reflected heat effect. In addition, this configuration allows a homogeneous transversal burning of the thermal lance within the passage.

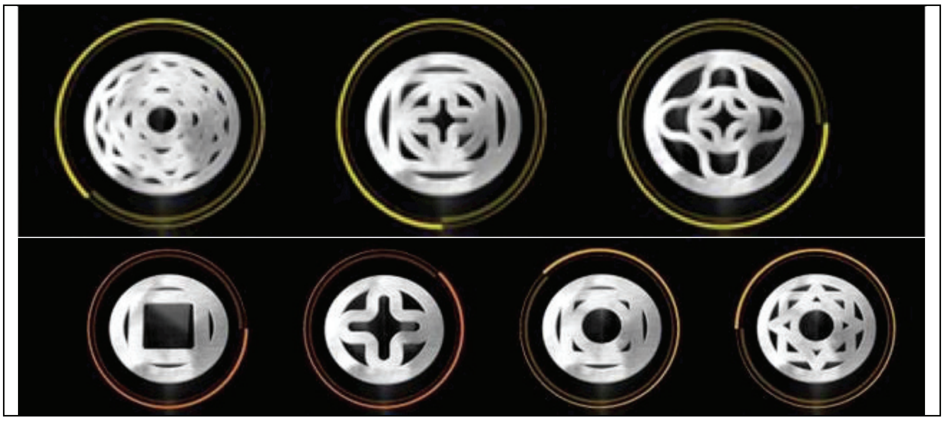

Figure 10. Profiles of Trefimet thermal lances.

Thermodynamics of Thermal Lances

The energy employed by the state-of-the-art thermal lances is released from the combustion of Fe and O_2. In this reaction, iron reacts in the solid state and oxygen in the gaseous state, *i.e.* this is a heterogeneous reaction.

Combustion consists of the oxidation of Fe at high temperatures, where the released energy is given by the enthalpy of iron oxide formation. In the process, the electrons jump from one orbital to another, changing their energy level, so when the bond is generated, the electrons release the remaining energy to establish themselves in a unique orbital. To understand how this energy is transmitted it is necessary to introduce concepts of quantum mechanics. In radiative processes, the emitted energy is understood as photons, which are emitted by electrons that jump from a higher energy to a lower energy orbital (Figure 11).

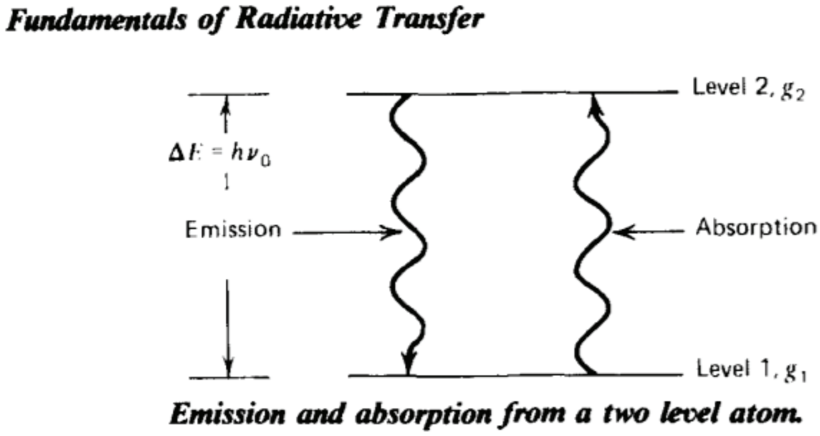

Figure 11. Energy emitted from an electron jump (Rybicki and Lightman, 1979).

These photons do not have a unique direction, so when they are emitted from a point source, the energy flow is spherically distributed. To calculate the energy flow at a point at distance r, it is necessary to consider that point as being located in a spherical shell with surface$4\pi r^2$ (Rybicki and Lightman 1979).

From this, it is possible to formulate the energy flux that the passage material receives according to the distance to the tip of the lance and the caloric energy of the lance. This relationship is governed according to Equation [6]. (By passage material, we mean the material to be melted inside the tap-hole).

$$Energy\ flux\ received\ by\ passage\ material = \frac{Caloric\ energy\ on\ the\ tip\ of\ lance}{4\pi r^2} \quad [6]$$

r: Distance from tip of lance to the material to be melted

It is evident that the amount of energy received by the passage material decreases as the square of the distance. For this reason, increasing the distance of the lance from the material to be melted reduces the amount of energy it receives. An important difference between the latest-generation thermal lances and those used previously is the way, and effectiveness with which, this energy is used. (For simplicity, the convective processes that can generate oxygen are neglected.)

Generally, a thermal lance is any tool of tubular shape used with Fe combustion. Once the ignition temperature (1143.15 K) is reached, the iron will react when in contact with oxygen. The output energy of this reaction will heat the iron, supporting the reaction that keeps the lance ignited.
This self-supporting capacity of the lance results in a loss of efficiency of the generated energy, since it not only raises the temperature of the inlet end of the lance up to the ignition point, but also heats the output iron oxides. In the following chemical balance (Tables II and III) the available energy to melt the tap-hole is calculated.

First, a mass balance is conducted considering:

- All the Fe of the lance reacts
- The model is governed by Equation [4] (only Fe_2O_3 produced)
- The lance has a unit weight of 1 kg/m. (unit weight for a 3/8 lance with one insert)
- That as the energy is in the tip of the lance and must proceed backwards in order to heat the iron to maintain combustion, the total mass of the lance is heated and reacts, releasing energy

- One-third of the flux of oxygen through the lance is burned, the rest flows freely without reacting.

Table II. Input data to thermal lance.

Mass Balance (Kg)		
Fe	O2	Fe_2O_3
Input		
1.00	1.31	
Output		
0	0.87	1.44

Table III. Stoichiometric molar balance according Equation [4].

Molar Balance (Kmol)		
Fe	O2	Fe_2O_3
Input		
0.018	0.041	
Transition reactions		
0	0.027	0.01
Output		
0.000	0.027	0.009

With the mass balance results, the energy balance can be calculated with following considerations:

- In order to consider the energy consumption of gases within the passage, it would be assumed that the oxygen flow is heated to 473.15 K by energy released.
- Temperature of iron oxide formation is 737.98 K.

Table IV. Energy balance of iron combustion.

ENERGY BALANCE				
	Fe	O2	Fe_2O_3	**Total**
Input				
T° (K)	298.15	298.15		
Intermediate				
T° (K)	1143.15	473.15	737.976	
Formed mass (kmol)			0.01	
$\Delta H_{Formation}$(kJ/kmol)			-810 250.00	
Energy released (kJ)			-7 365.91	-7 365.91
Heated mass (kmol)	0.02	0.08	0.01	
Cp kJ/kmol K	41.68	31.61	225.93	
Energy consumed (kJ)	640.32	452.5	2 249.41	3 342.26
Output				
T° (K)			1833.15	
Melted mass (kmol)			0.01	
Heat of fusion (kJ/kmol)			87 000.00	
Energy Consumed (kJ)			**790.91**	790.91
Total Energy				
Energy Released (kJ)			-7 365.91	-7 365.91
Energy consumed (kJ)	640.32	452.53	3 040.32	4 133.17
Total (kJ)				-3 232.74

Using the iron data input from Table II and energy balance results from Table IV, the results in Table V can be concluded:

Table V. Energy rate outputs by iron–oxygen combustion of Fe_2O_3.

Energy generated by combustion (kJ/g Fe)	-7.356
Energy consumed by self-supporting (kJ/g Fe)	4.133
Available energy for piercing by fusion	43.888%

With the appropriate limits, this energy balance can be used to calculate the number of lances needed to open a passage.

Physics of the Lance

Trefimet manufactures lances in which oxygen flow is turbulent ($Re > 10^5$). In these case, the velocity is governed in the way shown in Figure 12.

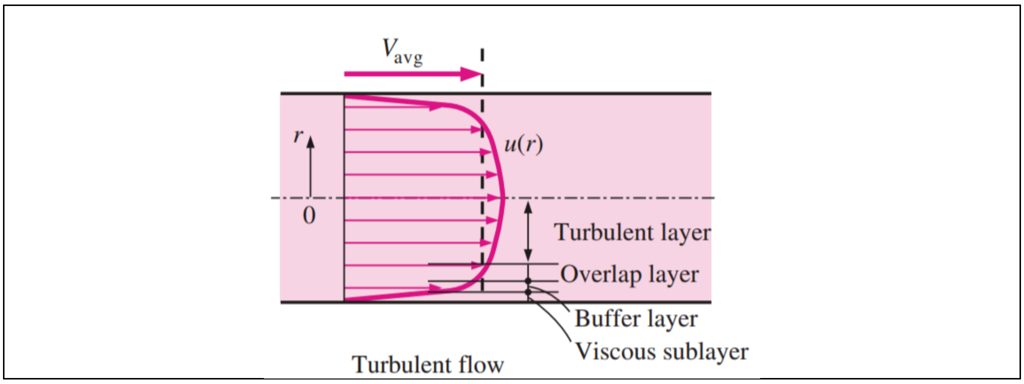

Figure 12. Velocity profile of turbulent flow (Cengel, 2006).

In fluids with turbulent flow, four layers can be differentiated: a viscous sub-layer, a buffer layer, an overlap layer, and finally the turbulent layer. For the sake of simplicity, more attention will be paid to the viscous sub-layer.

In viscous sub-layers, viscosity predominates over the inertia of the fluid; and since this is the closest layer to the wall, it is here that the friction that slows and normalizes the velocity profile of the fluid is generated. In thermal lances, the viscous sub-layer is the one that will start the reaction with the Fe in both the external tube and the insert. This layer has a characteristic thickness that depends on the physical properties of the fluid, the diameter of the tube, and the flow rate. This thickness (y) is given by:

$$y = \frac{25\mu_k\sqrt{D\rho}}{\sqrt{8v_m\mu_d}} \quad [7]$$

where
ρ: oxygen density
μ_k: oxygen kinetic viscosity
μ_d: oxygen viscosity
D: equivalent diameter where oxygen flows
v_m: average velocity.

D is the equivalent diameter of the transversal area obtained from the perimeter where oxygen comes into contact with the iron.

It is remarkable that at higher flow velocities, the thickness of the O_2 layer that reacts with the Fe is smaller.

To understand the performance of a thermal lance, it is necessary to study in detail the iron-oxygen reaction in the tip of lance. During a tap-hole opening, the lance makes contact with the passage, obstructing the oxygen flow. In the case of traditional oxygen pipes, it is necessary to exert a force on the pipe to keep it burning, obstructing the oxygen flow even more. From this situation there are three points of interest:

(a) An increase in temperature at the tip of the pipe
(b) The gas pressure increases in the tip of the lance
(c) Radial oxygen flow.

Pressing the pipe against the material of the tap-hole causes energy to be retained in the tip, which generates an increase in temperature towards the back of the pipe. This results in an increase in the sector available for ignition, generating spontaneous reactions that are distributed randomly, leaving unreacted spots (see Figure 13). At the same time, the pressure increases and a considerable pressure difference is generated between the inside and the outside of the lance, increasing the velocity of the oxygen flowing. In this way, due to radial oxygen flow, the detached fragments are dragged out of the pipe.

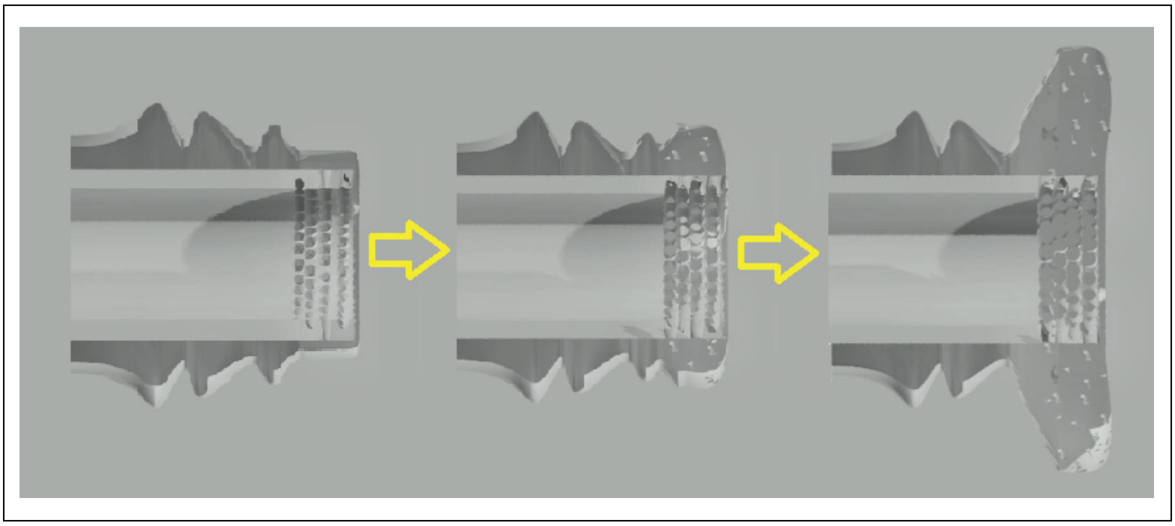

Figure 13. Sequence of radial combustion in a traditional oxygen pipe.

Taking into account this phenomenon, the fragments detached from the lance will react with the radial oxygen, generating reactions outside the edge of the lance and melting the material of the passage radially (damaging the passage). These reactions will be called 'radial reactions' (Figure 14).

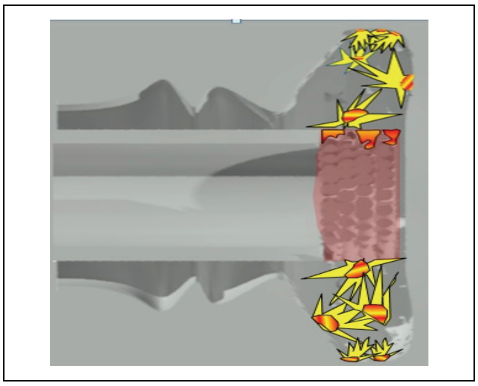

Figure 14. Sketch of iron fragments (red) reacting outside the traditional oxygen pipe and melting the walls of the passage (radial reactions).

To estimate the distance at which these reactions are generated, it is necessary to define three quantities.

$$[Velocity] \times [Burning\ time] = [d] \qquad [8]$$

Velocity: Velocity of detached fragment.
Burning time: Time required to burn the fragment dragged by the oxygen
d: Distance from the edge of the pipe at which the fragments are burned.

The velocity of the detached fragments depends of the pressure difference between the inside and outside of the lance, since this difference determines the oxygen velocity. For simplicity, it will be assumed that this is the velocity of the detached fragments.

The ’burning time’ term refers to the time when detached fragments will be delayed reacting. This term is related to the detached fragment size; a larger fragment will take longer to ’burn’.

The term *d* refers to the distance from the tip of the lance to in which the detached fragment reacts. It could be inferred that the burning time depends on both the difference in pressure between the inside and outside of the lance and the size of the fragment released from the lance. From the operational point of view, the difference in pressure will depend of the force with which the lance is pressed against the passage. But from a design point of view, another phenomenon comes into play in the process of iron combustion. Taking into account the stoichiometric balance (Equation [4]), and the density of iron oxide (5.242 g/cm^3 (Lesker, 2014), it can be inferred that the oxygen drastically reduces in volume to react with the Fe, forming local areas of low pressure around the point of reaction, a process that decrease the total pressure in the tip of the lance. From here it is possible to infer that the greater the amount of Fe available for reaction, the lower the pressure difference between the inside and outside of the lance, minimizing the term *d* and, therefore, the damage to the passage. For this reason it is possible achieve a smooth tap-hole opening by a lance with inserts, where a traditional oxygen pipe opens an irregular tap-hole.

DIFFERENCES BETWEEN TREFIMET LANCES AND TRADITIONAL OXYGEN PIPES

A comparison between a Trefimet lance and a traditional oxygen pipe of the same diameter is presented. Then, based on the information given in this paper, a scheme of the progression of a thermal lance and a traditional oxygen pipe is shown.

In the case of the oxygen pipe, the effective energy is found in the perimeter of the pipe and not concentrated in the cross-section, so a large part of the energy will be projected radially. The contact with the oxygen is only in the inner section of the tube, thus the contact area is smaller which results in fewer reactions per unit cross-section, making the self-sustaining combustion of the pipe difficult. To maintain this self-sustaining reaction it is necessary to forcefully press the pipe against the passage to increase the temperature and pressure at the tip of the lance. However, by increasing the temperature of the lance, the oxygen rebounds in the material of the tap-hole and the reactions take place on the outside of the lance, leading to combustion over a greater length within the passage. In this situation, which is exacerbated by the phenomenon of fragmentation described in ’Physics of the lance’, the released energy cannot be controlled and takes a radial direction (towards the walls of the tap-hole). This situation can generate the opening profile shown in Figure 15.

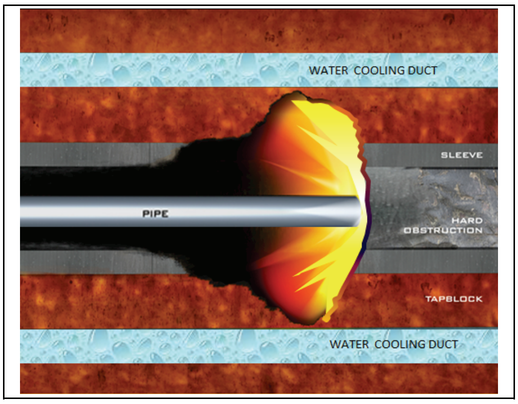

Figure 15. Schematic representation of a tap-hole opening profile with radial dispersion of energy of combustion.

The radial direction of the oxygen pipe energy melts sections of passage walls that should not be damaged. The figure depicts a tap-hole with water cooling that is about to be damaged by this action.

In contrast, the Trefimet thermal lance is made up of concentric inserts that allow a greater area of contact with the oxygen, concentrating the reaction mainly at cross-section of the lance. Consequently, the inserts react at both the outer and inner perimeter. When both surfaces are in contact with oxygen, the reaction proceeds faster, therefore when in an open space the lance inserts burn faster than the external tube. However, within passage the reflection effect and the non-combusting oxygen causes the external tube to burn at the outer perimeter, balancing the combustion between the external tube and the inserts. It is important to note that this phenomenon is subject to the amount of oxygen being adequate to maintain this balance and allow an optimized performance of the lance. Using a thermal lance in optimal operating conditions, the opening profile shown in Figure 16 would be achieved without damage to the tap-hole, even in the case of blockages.

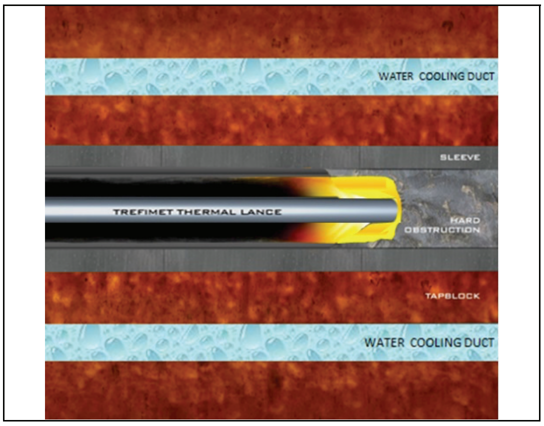

Figure 16. Ideal opening profile obtained with a thermal lance.

Using the concepts illustrated in Figure 15 and Figure 16, it is possible to establish the differences listed in Table VI.

Table VI. Differences between modern lances and traditional oxygen pipes.

Oxygen pipe	Thermal lance
Uncontrolled release of energy	Controlled release of energy in a forward direction
Does not burn outside the passage	Burns in any conditions
Irregular opening profile, with possible damage to the walls of the passage	Smooth and controlled tap-hole opening facilitates plug insertion
Low energy efficiency in axial aperture	The axial direction of energy allows a higher velocity of penetration and a smooth-walled passage
As there is no energy control, a greater oxygen flow must be used to open the passage	Optimal performance is achieved with a low oxygen flow (see Physics of the lance section), allowing use in foundries with low oxygen flow
Greater projection of incandescent material towards the operator due to the high oxygen flow used	Lower oxygen flow decreases the projection of incandescent material towards the operator

Users of Trefimet thermal lances have proven the advantages of these over the traditional oxygen pipes for different types of furnace (copper, platinum, ferrochrome, silicon, ferrosilicon, *etc*.) in many countries, including Norway, South Africa, the USA, and Chile. Among the advantages are an increase of the useful life of the passage by up three times compared to one opened only by oxygen pipes, and less generation of sparks, which increases operator safety and comfort.

THERMAL LANCES IN FURNACE OPERATIONS

An efficient lancing operation must take the following into consideration.

- **Adequate oxygen flow for a specific lance.** For good performance it is important to use the appropriate oxygen flow for the specific lance. This will optimize the consumption of the lance in operation.
- **Position of the lance in relation to the material to be melted.**
  In the previous section it was shown that the energy received by the material in the tap-hole decreases when the distance to the lance increases (see Equation [6]). Since the reaction of Fe (in the solid state) with O_2 occurs at the tip of the lance, it is important that the tip touches the material that needs to be melted.
- **Force exerted by the operator on the lance.** As discussed in the section 'Physics of thermal lances', when a thermal lance is pressed against the passage, fragments are thrown off radially, decreasing the efficiency of axial energy.
- **Working with pasty/viscous material.** Pasty/viscous materials can be encountered in the following two situations.
  - Material near the solidification point: when the temperature of a liquid material decrease and solidification begins, a process of crystallization or nucleation takes place. Elements with a high fusion point, like metals, begin to undergo a state change from liquid to solid at this fusion point. As a result, the molten material loses its fluidity and is incapable of flowing out of the tap-hole.
  - In the case of a mixture of two materials with different fusion points, where this mixture is at an intermediate temperature between those two points, the material with the higher fusion point solidifies, creating accretions in the floor of the furnace. For example, in electric smelting furnaces this phenomenon produces a viscous mixture with low fluidity that is at a high temperature.

    When opening furnaces containing materials in this condition, the solid part of the passage is not problematic for low-energy lances, but for the pasty area it will be necessary to use a robust lance to displace the material using physical force.

Choosing the Appropriate Lance

In order to choose the appropriate lance for a particular process, it is necessary to consider the following factors.

- **Available flow of oxygen in the supplying network.** This is the first factor for consideration. The greater the amount of iron, the greater the required flow of O_2 in the tip of the lance. It is important to point out that a higher pressure does not necessarily mean a higher flow.
- **Material to be melting (mud plug or other).** In order to obtain a good performance of the lance, it is necessary to know not only the characteristics of the material constituting the mud plug, but also the material being processed. In this way it will be possible to determine the technical requirements, specific heat, fusion point, thermal conductivity, and latent heat of fusion. Opening a tap-hole in a copper smelting furnace is very different to opening one in a silicon furnace.

- **Temperature of process material.** Process materials with temperatures above 2000 K are very aggressive to thermal lances, since the melting point of a thermal lance is 1803.15 K (1530°C). It is necessary to distinguish two ranges of temperature when choosing a thermal lance:
  - Processes below 2000 K. The lance is selected according to the thermal requirement of the material.
  - Processes over 2000 K. The lance is selected according to the thermal requirement of the material, but in addition should have a ceramic coating to avoid or delay fusion of the lance.
- **Required diameter of the opening.** It is necessary to keep in mind the diameter of the opening to be done and the material to be pierced in order to define the thermal energy requirement and the diameter of the lance for a successful process. If the lance is chosen properly, it will be able to melt diameters up to four times bigger than the lance diameter.
  - Low thermal requirement materials. This kind of material requires a lance with a single insert (in the shape of a square or a four-pointed star). (Clay, calcium, aluminium, lead, titanium slag, and zinc).
  - Medium thermal requirement materials. As these materials require a higher thermal energy, a lance with two inserts or one with several folds will be appropriate. (Copper, alumina, and titanium slag.)
  - Materials with a high thermal requirement. Here the amount of iron inside the lance is even more important. Consequently, a greater number of inserts will be required for the lance to deliver energy in an axial direction, resulting in a clean and efficient operation. In addition, when working with this kind of material the energy must be directed forward in the direction of the lance. If the oxygen conditions (flow, pressure) allow, lances with three, four, or more inserts are used. If the oxygen supply is low, it is not possible to burn the maximum amount of iron in the lance (for example, graphite and metal carbides, tungsten, silicon, platinum, chrome, magnetite).

Common Mistakes with Thermal Lances

Regarding the Lance as a Torch

A latest-generation thermal lance and a conventional oxygen pipe burn in a completely different manner. The most important difference is that when they are inside the passage, a torch is blown out while the thermal lance remains ignited.

Figure 17. Trefimet's lance burning in a Chilean laboratory.

This is explained from the phenomenological point of view of the reaction of Fe with O_2. When these two elements react, a huge amount of energy is released in a small volume due to the density of Fe and its reaction in the solid state. The energy released is irradiated by photons emitted from iron oxide molecules. The great amount of light emanating from the tip of the lance is observed by the operators as an enormous flame. However, this is a misunderstanding, since as the reaction of the Fe is in the solid state, there can be no flame. At the same time, the reaction releases liquid iron oxides that are projected out of the lance as incandescent particles propelled by the oxygen stream. These particles are at a high temperature (over 1750 K), and due to the high light intensity, the emission point seems to be larger than it really is. A metal cutting disc in use is a good example of this phenomenon.

For these reasons, when operators see an ignited Trefimet thermal lance releasing a great amount of light and projecting material they conclude that the lance burns like a flame. Under this misconception, operators suppose that the lance must be operated at certain distance from the material to be melted, like a big torch. However, thermal lances yield their best performance when in contact with the material (see Equation [6]).

Using a High Oxygen Flow

One of the common errors in thermal lance operation is believing that the higher the flow of oxygen, the better the performance. A high oxygen flow gives the impression that the tap-hole is being penetrated faster as a consequence of the amount of material projected and the noise generated. However, as shown previously, there is an optimal oxygen flow for each kind of lance. Contrary to what is commonly thought, an excess of oxygen decreases the performance of the lance at the moment of opening a tap-hole.

Incorrect Flow of Oxygen

One of the main factors in the performance of the lance is the oxygen flow rate (m^3/s). This will always be proportional to the amount of iron in the lance cross-section. That is to say, if the mass of iron is increased, the oxygen flow must also be raised. In any cases, flow rate and pressure should never be confused.

In some facilities, oxygen networks are capable of high pressure but deliver only a low flow. This is apparent when the oxygen flow is open and the pressure drops. Typically, in smelting a 0.4 MPa pressure drop is considered a steep one. Thus, to avoid poor lance performance as result of an incorrect flow, it is necessary to control the stagnant pressure (potential energy) and the flow pressure (potential energy plus kinetic energy). This occurs because when part of the potential energy is transformed into kinetic energy, there is a pressure drop.

Pushing the Thermal Lance like a Bar or Oxygen Pipe

To keep an oxygen pipe ignited inside the passage, it must be pushed hard forward; otherwise it goes out or does not go forward. Operators who are used to working with these types of tubes usually put pressure on the lance. This is one of the most difficult practices to eradicate, because it is not necessary to exert such pressure on the tool since latest-generation lances are manufactured to be self-supporting, allowing them to burn even outside the tap-hole.

Incorrect Lance Selection

As already mentioned, oxygen pipes do not remain ignited outside the tap-hole and when lit, only a small amount of 'sparks' is seen coming out of the tip. In contrast, a modern thermal lance shows its great energy, generating distrust and fear due to the supposed damage that the energy flow can cause. These sensations can result in the following misperceptions.

- Too much energy could damage the tap-hole. This leads to choosing a lance with a low energy output, or not even running a test.
- Not allowing the use of oxygen pressure. Owing to the habit of using high oxygen flows in traditional oxygen pipes, operators do not lower the flow of oxygen when opening tap-holes with thermal lances, preventing optimal performance during the operation.
- In the case of pasty materials, the opening in the solid part of the passage is not problematic for low-energy lances. In the pasty area, however, it is s necessary to use a lance with a greater diameter, in such a way that when pushing the lance, the mechanical energy moves the pasty material. If the lance is not the correct diameter, it will be necessary to use a high oxygen flow to sweep away the pasty material.

CONCLUSIONS

Thermal lances are not necessarily the best tools to use in tap-holes. However, until a better technology emerges to completely replace the lances, it is necessary to try to inflict as little damage as possible. When a drill does not available or drilling the tap-hole open is not possible, it is best to use a thermal lance, which if selected and operated properly will provide the following benefits.

1. A passage with a smooth and straight profile is opened, which allows a good tapping of the product and efficient plugging.
2. Given the designs of thermal lances, it is possible to open tap-holes with minimal damage to the passage, which increases the useful life of the tapblock.
3. By maximizing the energy axially, thermal lances are able to open a tap-hole in less time than a traditional oxygen pipe, minimizing the exposure of operators in the high-risk area in front of the tap-hole.
4. The higher speed with which these laces open compared to the traditional oxygen pipe could also mean an increase in production due to the decreased cycle time of each tapping.

Finally, in spite of the advances in the development and operation of thermal lances, there are still points that need more attention to improve and predict their behaviour within the tap-hole.

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