Productivity enhancement of an integrated steel mill by employing innovative tapping systems

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Lastly, and most importantly, I wish to thank my parents and my girlfriend for all their love and support. To them I dedicate this thesis.

Affidavit

I declare in lieu of oath, that I wrote this thesis and performed the associated research myself, using only literature cited in this volume.

Michael Skorianz

Leoben, June 15th 2009

Abstract

Increasing worldwide demand for steel products requires permanent improvements in all different areas in the steel production process. Within this thesis the increase of capacity and productivity of an integrated steel mill by improving parts of its processes is discussed. In order to meet these targets, a series of structural changes and improvements of process is essential. The task is to raise effectiveness and maintain high product quality. After preliminary field trials carried out by the partner company and performing productivity studies within this thesis, an integrated steel mill was assisted in the decision to implement a novel converter taphole changing system. Implementation, influences on process, availability, quality and maintenance are discussed. Further more a description of the productivity and profitability enhancement is carried out.

Kurzfassung

Durch die steigende weltweite Nachfrage sind permanente Verbesserungen des Stahlerzeugungsprozesses unabdingbar. Thema dieser Arbeit ist eine Erhebung und Bewertung von Kapazität und Produktivität eines integrierten Hüttenwerkes durch Prozessoptimierung. Zur Erreichung dieser Ziele müssen Struktur und Prozesse verändert werden. Die Herausforderung ist es, Schwachstellen im Prozess zu finden, zu optimieren oder diese zu ersetzen, ohne die Produktqualität zu beeinträchtigen. Nach Vorversuchen, die von der Partnerfirma durchgeführt wurden und Bewertung dieser im Rahmen dieser Arbeit, wurde ein integriertes Hüttenwerk in der Entscheidung unterstützt, ein neuartiges Konverter-Abstichsystem zu installieren. Inbetriebnahme, Einflüsse auf Prozess, Verfügbarkeit, Qualität und Instandhaltung werden diskutiert, um diese zusammenfassend in einer Produktivitäts- und Wirtschaftlichkeitsanalyse zu bewerten.

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List of abbreviations

Acronymes

ASI	Algoma Steel Inc.
BOF	Basic Oxygen Furnace
CAS-OB	Composition Adjustment by Sealed argon bubbling-Oxygen Blowing
CFD	Computational Fluid Dynamics
CIS	Commonwealth of Independent States
DRI	Direct Reduced Iron
DSPC^{TM}	Direct Strip Production Complex
EAF	Electric Arc Furnace
EU	European Union
HBI	Hot Briquetted Iron
iTAP	Intelligent Tapping
JIPM	Japan Institute of Plant Maintenance
LMF	Ladle Metal Furnace
NAFTA	North American Free Trade Agreement
OEE	Overall Equipment Effectiveness
TBD	Taphole Breakout Device
TPM	Total Productive Maintenance
IISI	Internationial Iron and Steel Institute
RHI AG	Radex-Heraklith Industriebeteiligungs AG
BBG	Böhler Baugeräte GmbH

Formula Symboles

[_]	dissolved in liquid metal
{ _ }	gaseous
(_)	in the slag
$A_{(x)}$	flow cross-section at level x
$\dot{m}$	mass flow
ρ	density
g	force of gravity
x	level for a respective flow cross-section
h_l	effective height of bath above entry of tapping pipe
h_k	length of tapping pipe between pipe entry and discharge
d	diameter at discharge
S	slope of the tapping channel
r	radius of the pipe cross-section at discharge

1 Introduction

Because of its versatile properties and its recycling possibilities, steel is the basic material for permanent development in the modern industry. It is used in almost all important sectors of industry, such as manufacture facilities and machinery, transport industry, steel-framed building construction, bridge building, power and environmental engineering, to name just a few. The world crude steel production increased from 40 million tons in 1900 to more than 1,3 billion tons in 2007 (fig. 1). Despite recession in 2008/09 steel will continue to be the number one material in this century with the best price/performance ratio.

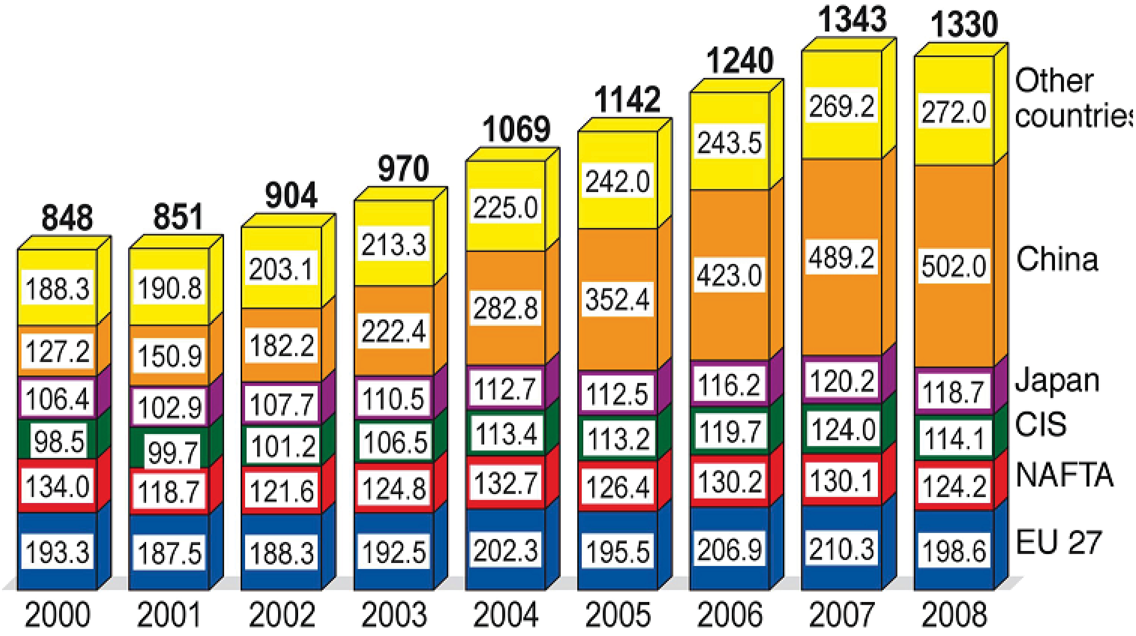

fig. 1: World crude steel production (in million tons)[1]

Increasing worldwide demand for steel products needs permanent improvements at all different areas in the steel production process. Within this thesis the increase of capacity and productivity of an integrated steel mill by improving parts of its processes is discussed. One of the main targets of a steel company is the raise of procuction, the improvement of steel-quality and the minimization of costs per ton of steel, in terms of their competitive ability. In order to meet these targets it is necessary to accelerate and optimize the processes.

For the development of capacity, a series of structural changes and improvements of processes is essential. The challenge in this connection is to find, optimize or remove

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[1] Cf.: IISI (2009)

the weaknesses in process and the bottle-necks. Also the quality of process and product may not suffer from this but has also to be improved.

The key production stage in an integrated steel mill is the Basic Oxygen Furnace (BOF) shop and establishes the basis for all following process steps. This area can highly influence the purity of the steel and, concerning time and money-consuming repairs, also the operating economy.

One important factor of increasing process and productivity is to optimize the availability of the Basic Oxygen Furnaces (BOF)-vessels. To establish background knowledge in the process of steelmaking, the layout and operation process of an integrated steelplant – especially the BOF shop with the BOF-process - is shown at the beginning (chapter 2).

With this knowledge, the tapping process and requirements are explained in the next step (chapter 3). Therefore a chronological patent study was carried out to show the development of tapping procedures and taphole layout (chapter 3.1) including the latest taphole innovations based on flow dynamics (chapter 3.2). After discussing the taphole characteristics, the matter goes into the taphole changeout process and –equipment, comparing the common way of process and a novel taphole changeout process (chapter 3.3).

For the installation of the novel system in an integrated steel mill in Canada, productivity requirements are elevated in chapter 4. Chapter 4.1.1 and 4.1.2 gives a description of the theory of productivity, efficiency and effectivity. On the research into this matter - with a detailed inspection and analysis of cycle time and performing a delay study (chapter 4.2) - it is demonstrated, that the tapping procedure and its maintenance-chain is a significant weak point in the BOF-steelplant, especially concerning process-time and turndown performance. Additional an example of the Overall Equipment Effectiveness (OEE) of a representative steelplant was established to mention the importance of availability and the big losses in BOF process (chapter 4.1.3).

In order to employ the so called iTap-system, preliminary taphole performance field trials, carried out by RHI, were used for studies (chapter 4.3.1). A mathematical model is created to figure out the optimum taphole start diameter based on a decided tapping time window and start tapping time in dependence on vessel refractory thickness and ferrostatic bath height over a vessel lifetime. This model is a tool, which enables a simple calculation of the optimum taphole layout within a converter lifetime. Summarizing the results of the productivity elevations and preliminary taphole trials, a justification study for the implementation is carried out (chapter 4.3.2).

In chapter 5 the implementation (chapter 5.2) and results (chapter 5.3) are discussed and compared to the situation before (chapter 5.3.1). With these results a description of the process- and productivity optimization is carried out concluding in a profitability calculation (chapter 5.3.2). The disposition of the thesis is shown in fig. 2.

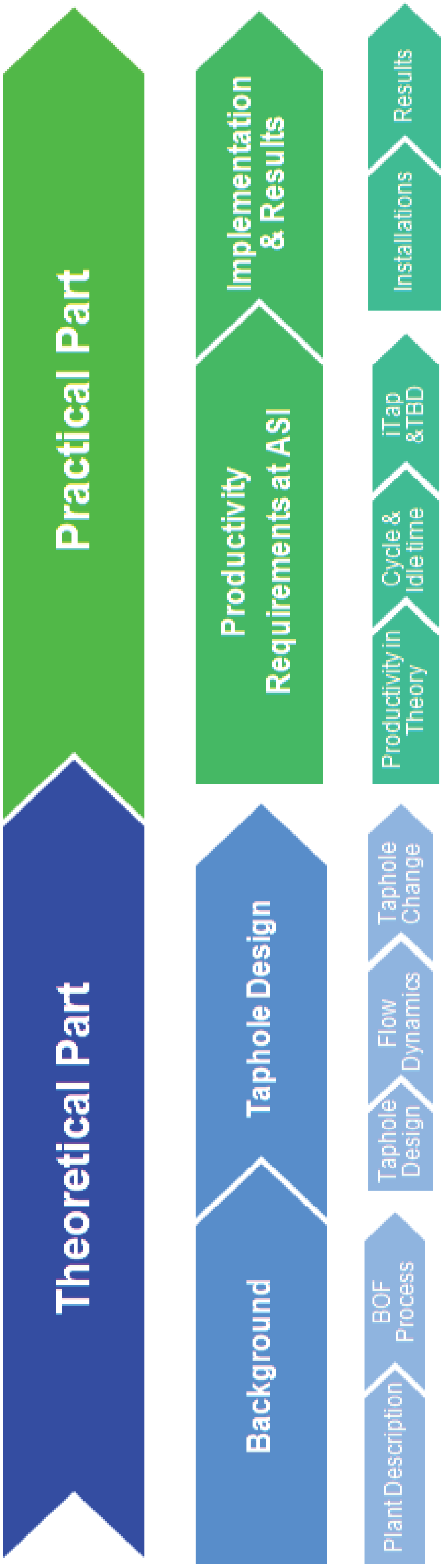

fig. 2: disposition of the thesis

2 Background

2.1 Plant description

2.1.1 Integrated steel mill

An integrated steel mill produces steel of iron ore, coal, and lime, and typically supplies a full range of products, especially rolled carbon steel, strip and plate. It operates one or more blast furnaces, coke oven, gas facilities, converter (and Electric Arc Furnace “EAF”) steelworks, casting facilities and rolling mills. Sometimes a plant for directly reducing iron ore is joined, to be less dependent on external scrap. The production capacity of an integrated steel plant ranges from two million tons to over 5 million tons per year. The layout of such a mill is - within the frame of this thesis - discussed on the basis of the company ESSAR STEEL ALGOMA in Sault Sainte Marie, Ontario, Canada (fig. 3 and fig. 4).

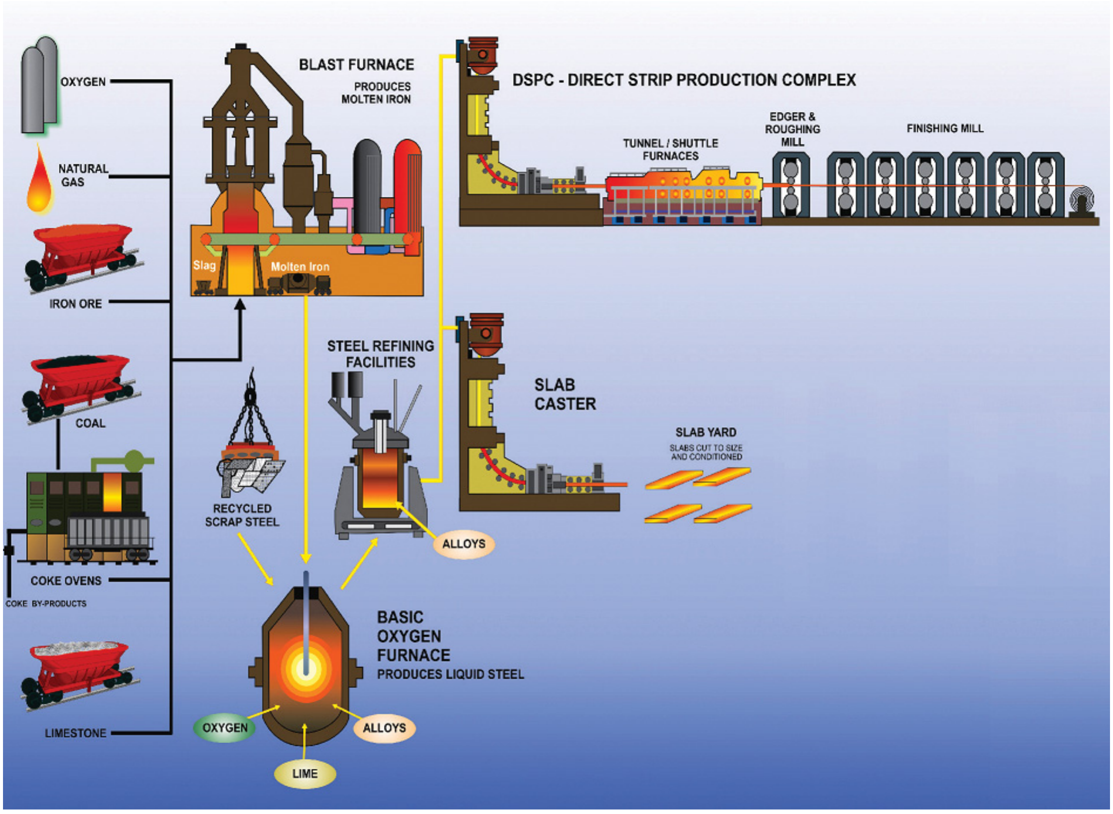

fig. 3: flow chart of an integrated steel mill [2]

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[2] Cf.: ASI (2008)

Algoma Steel Inc. (ASI) is a fully integrated mill, that began producing steel in 1902.[3] Today, ASI is Canada’s third largest steel company, with a raw steel capacity of approximately 3 million tons/year. In the last few years, many activities have been taken to increase production further up to 4.0 million tons/year in future. The flow chart shows the line of production. Primary operations feature three coke batteries, two blast furnaces, a BOF shop with two 240-metric-ton BOF vessels, a twin-station ladle metallurgy and a CAS-OB chemical reheat ladle metallurgy station.[4]

The liquid steel is processed in two casters, a slab caster and a Direct Strip Production Complex. The DSPC™ is a modern continuous slab caster coupled with direct hot rolling and positions the company as one of the leading suppliers of high strength and light gauge steel. A full range of high quality heat treated products, first stage configured blanks and large profile welded beams round out the product offering.

Today the revenues are primarily derived from the manufacture and sale of hot and cold rolled sheet and plate. Algoma´s size and diverse capabilities enables it to deliver customers in the automotive, construction, energy, manufacturing, tube and steel distribution industries.

fig. 4: location Sault Ste. Marie [5]

The plant recieves commodities and ships products to and from the steelworks in Sault Sainte Marie by rail, transport and vessel. The plant is serviced by the Canadian Pacific Railway, TransCanada Highway, USA Interstate 75 and the St. Mary´s River (port directly on steelplant), which leads via Lake Huron and Lake Erie to the Atlantic Ocean (fig. 4).

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[3] Cf.: ASI (2009)

[4] Cf.: Hilderley, Iron and Steel Technology, Vol. 3 (2006), pp. 31-35

[5] Cf.: Superior Robotics (2009)

ASI is certified with ISO 9002 (standard for quality assurance), ISO 14001 (standard for environmental management) and QS 9000 (standard for special requirements of the automotive industry) and recognized as an Industrial Energy Innovator – continuously improving energy efficiency throughout the operation including the efficient use and recycling of water.

In order to achieve the production targets, a range of improvements in primary and secondary steelmaking has to be realized. In 2008 a second blast furnace was added to the process. The increase in hot metal availability shows the importance of bottlenecking activities. To meet the new production targets several improvements in the BOF shop operation procedures and process technology have to be studied and modified based on a delay study (chapter 4.2).

Blowing practise, process control, slag practise, tapping operation and taphole maintenance, furnace maintenance, relining strategy and furnace preparation practise have to be modified to meet the demands. The productivity potential of the existing facilities were analized and it was discovered that it is the most economic way to use the benefits of capacity gaps instead of installation of new greenfield capacities.[6]

To understand the process and the procedure of the BOF shop and especially the tapping system with the tapping process, the theory and processes of the BOF and the tapping system have to be discussed in the next step. With this knowledge and after an economical introduction, the impacts on process, quality, maintenance, capacity, delay and productivity can be examined.

2.1.2 BOF steelplant

The purpose of the BOF process is to refine the hot metal produced in the blast furnace into raw liquid steel, which may be subsequently refined in the secondary steelmaking shop.[7] The aim is to produce highest steel quantity and quality at lowest production costs. Manufacture of steel in a modern BOF is a highly automated and efficient method.

To have an idea of the layout, fig. 5 gives an insight into a BOF-shop. Before the vessel, hot metal pretreatment, torpedo ladle, mixer and scrap yard are situated. Located above the vessel, there are several hoppers for fluxes like lime, magnesia, briquettes, ferro-silicium or HBI, the lance with connections for oxygen and cooling water, waste gas main and waste heat boiler. Beneath the vessel the slag ladle, hot metal ladle on a ladle car, and the alloying addition (added during tapping) can be found. Lateral there is an actuation for tilting the converter.

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[6] Cf.: ASI (2008)

[7] Cf.: Steeluniversity (2009)

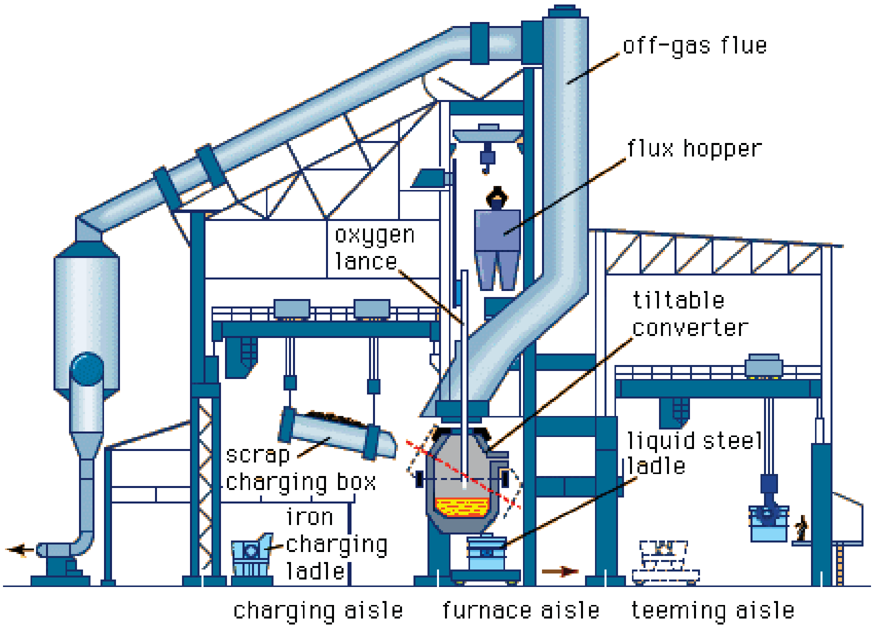

fig. 5: layout of a BOF-shop [8]

BOF vessel and auxilliary equipment

The BOF comprises a upright steel shell, which is interiorly lined with magnesite or dolomite refractory bricks (fig. 6, left).

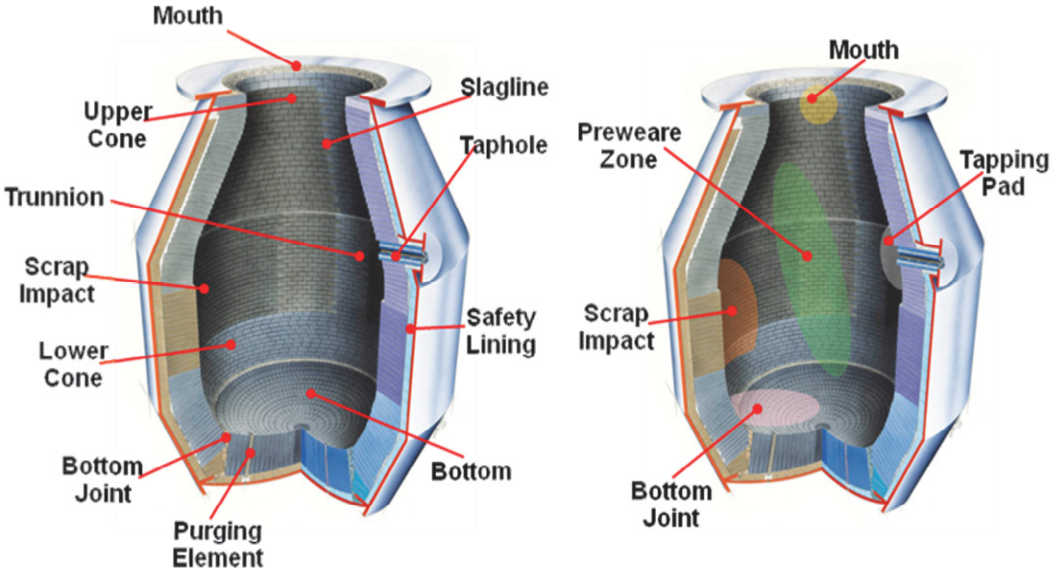

fig. 6: BOF lining concept (left) and wear zones (right) [9]

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[8] Cf.: Encyclopedia Britannica (1999)

[9] Cf.: RHI AG brochure marketing training steel (2006)

The vessel has trunnions extend outwardly from opposite sides of the shell that are contained in bearings which are mounted on a stationary part of the superstructure. The trunnions and bearings enable the vessl to be tilted horizontally.[10] The typical capacities range from 150 to 350 tons of liquid steel.

The capacity of the inner volume of the vessel is 5 to 10 times larger than that of the steel to be treated, in order to confine the major part of metal by the oxygen blast, together with swelling of the slag during the foaming periods.

Lining protection

Due to the influence of wear and hence the influence of the taphole layout (chapter 3), the wear mechanisms and their influences are discussed. The wear of refractory can be devided into three main groups: thermal, mechanical and chemical wear. The wear triangle with an overview of different kinds of lining influences is demonstrated in fig. 7. Because of different wear mechanisms, which affect the refractory, different zones of erosion can be observed (fig. 6, right). The main wear areas are the tap pad, the mouth and the charge pad (scrap impact).

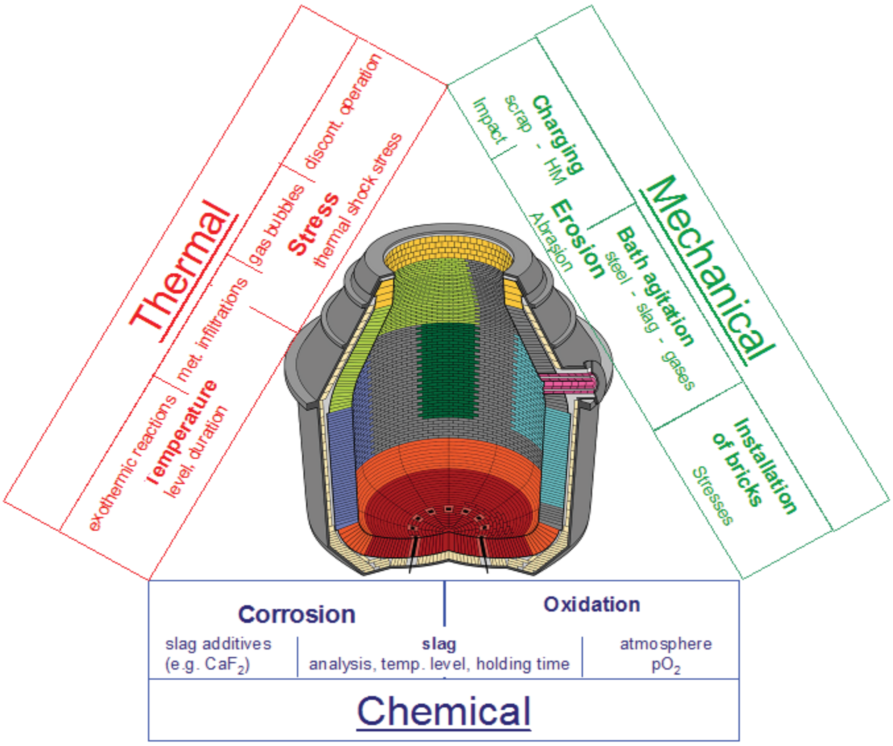

fig. 7: wear mechanisms [11]

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[10] Cf.: United States patent 4270949: Making of steel by the BOF Process (1981)

[11] Cf.: Majcenovic (2006)

Aims in BOF maintenance to avoid the most aggressive slags (chemical wear) are:

- Too high $(FeO)_n$ contents at high temperatures should be avoided (reblows are particularly damaging the refractory)
- Dolomitic lime should be used as an input material to saturate the slag in (MgO)[12]

As an example, the lining wear of a BOF during a lining lifetime is demonstrated in fig. 8:

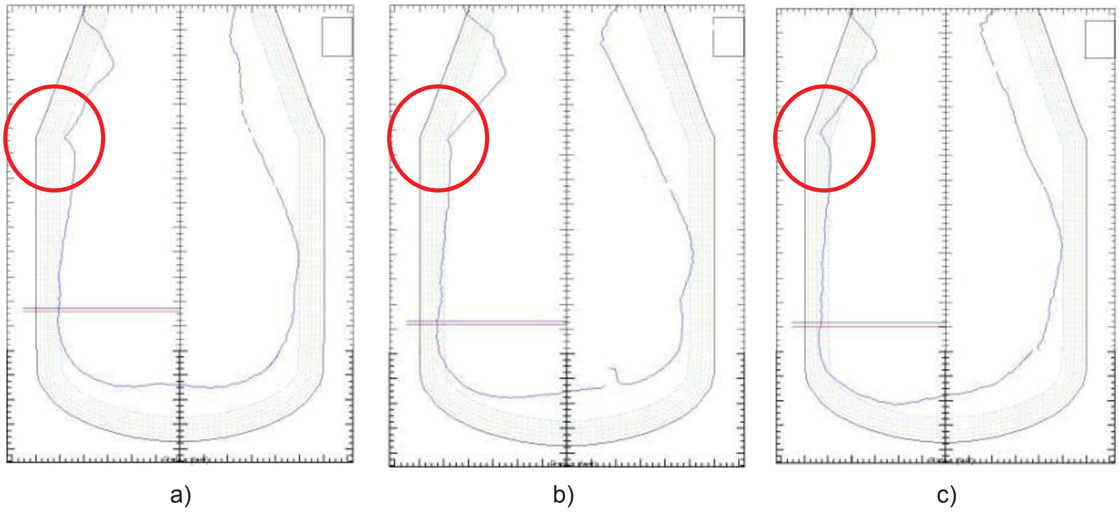

fig. 8: lining wear after[13]: a) 2978, b) 3877, c) 4877 heats

The following methods and strategies in furnace refractory maintenance are commonly practised in steelplants:

"Zero Maintenance": A zero maintenance converter achieves life span up to 2500 heats. This practise is very common in European steelplants. Maintenance is minimized and comprises only taphole changes and mouth gunning due to minimizing skull formation and facilitating mouth cleaning. This practice is often used in plants with a high productivity 2/2 or 2/3 vessel operation mode.[14]

Another maintenance strategy is "Slag Splashing". After tapping, the remaining slag in the converter is cooled down by adding large quantities of (MgO). This mixture then is splashed during a 2-5 minute period with a high-pressure nitrogen jet. Before charging scrap and hot metal, the slag is poured off. Slag splashing is a common practice in many steelplants all over the world and was developed in the USA about 15 years ago. Although this method has become more common in Europe over the last decade, the procedure differs. While in North America slag splashing is carried out after almost every heat, in Europe this practice is used only after every third or tenth heat.[15] The advantage is the increased vessel lifetime up to over 50.000 heats. The big disadvan-

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[12] Cf.: Steeluniversity (2009)

[13] Cf.: Ferrotron (2008)

[14] Cf.: Prattes, Zettl, Cappel (2008), p. 2

[15] Cf.: Prattes, Zettl, Cappel (2008), p. 2

tage is mouth skull formation and bottom build up, which causes problems with the bottom stirring elements and enourmous costs because of the reduced availability of the vessel due to maintenance acitvities.

"Slag Coating and Slag Washing" are similar practices to Slag Splashing. The difference is, that the vessel is rocked back and forth several times instead of splashing with the high-pressure nitrogen jet. The bottom area, tap pad and scrap impact are covered with a thin slag layer.[16] Before charging, the excess slag is slagged off. Also this way of maintenance includes a lot of availability losses. The Slag Coating practice is currently performed at ASI. Here Mouth cleaning caused by skull formation is one of the biggest availability factors.

By "Hot Patching" the scrap impact zone, tapping pad and bottom joint are repaired with self flowing refractory mixes. To guarantee the sintering of the repair mix, this method requires a longer period than Slag Coating and is usually practiced during planed vessel downtimes.[17]

"Gunning" is a common way to repair worn refractory in the most damaged zones with special gunning mixes by a mechanised gunning manipulator. The target is a decreased and equal wear rate. The latest development of this practise is "Super Gunning".[18] This improved gunning operation can be performed in a continous BOF operation during the short cycle breaks between tapping and charging. Therefore a special gunning machine is used and allows higher gunning speed and a more precise repair adjustment control.[19] Another advantage is the conservation of the bottom stirring elements.

2.2 BOF process

2.2.1 Charge, materials, products

fig. 9 demonstrates a scheme of charge, materials and products of the BOF process. The raw materials and ingredients charged into the converter are.[20]

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[16] Cf.: Prattes, Zettl, Cappel (2008), p. 2

[17] Cf.: Prattes, Zettl, Cappel (2008), p. 2

[18] Cf.: Prattes, Zettl, Cappel (2008), p. 3

[19] Cf.: Pudack, Lanzenberger (2007), pp. 14-19

[20] Cf.: Iron- and steel metallurgy, lecture script, University of Leoben (2006)

- **Liquid hot metal:** The BOF-process is not heated externally – for this reason it is called an autothermic process. The hot metal comes from the blast furnace after specific pre-treatments, particularly desulfurization and dephosphorization. Important factors for the following process steps are chemical composition, energy content and crude steel temperature.

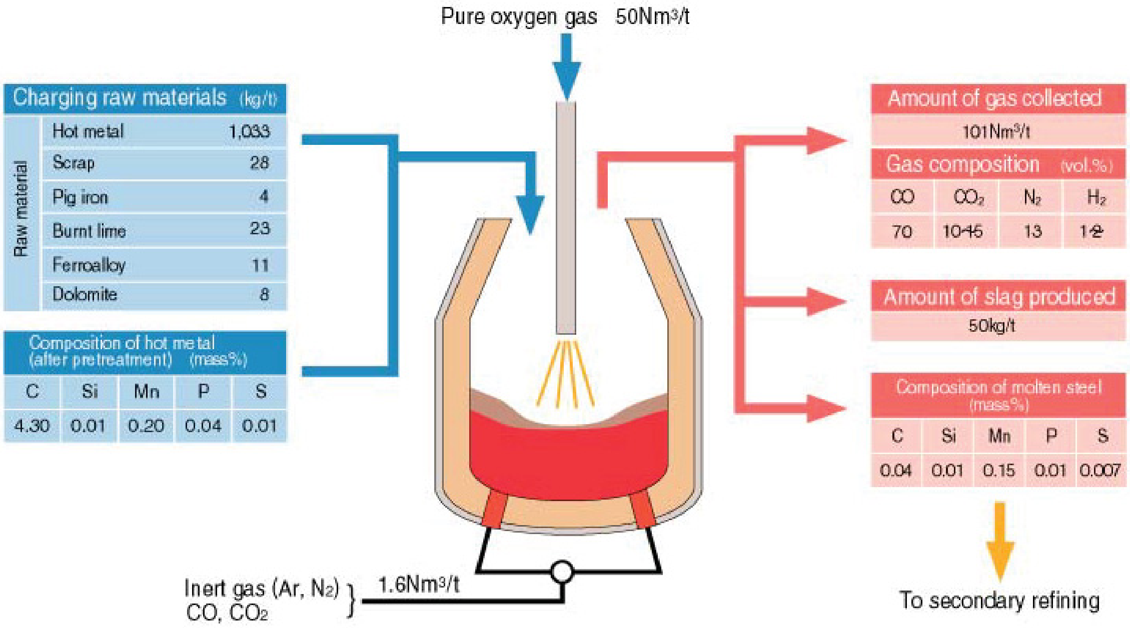

fig. 9: charge, materials and products of BOF process [21]

- **Scrap:** 10 – 30 % of the total charge is scrap. There are different types of scrap: external and plant scrap. Plant scrap has the advantage of known composition, external scrap might include unwanted elements and additions, that become part of the process, such as:
  - Sulphur (from oils and paint; hard reduction during defining due to oxidizing conditions)
  - Zinc, Lead and Cadmium (from anticorrosive coatings)
  - Nickel (from alloyed steel) and Copper (from electrical engeneering) cannot be removed during defining
  - Plastics (from organic coatings; cause corrosion of refractory and emissions)

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[21] Cf.: Kawasaki Steel

- **Slag forming additions:** typical slag forming additions are Lime (CaO), dolomitic Lime (CaO-MgO), Alumina (Al_2O_3) and Fluorspar (CaF_2) (uncommon)
- **Direct Reduced Iron (DRI) or Hot Briquetted Iron (HBI)** may also be added to the process to substitute the scrap (advantage: no tramp elements)
- **Gases**
  - Oxygen {O_2} for the refining process (through a multi-hole lance or bottom plugs)
  - Nitrogen {N_2} for purging and increase the [N] content
  - Argon {Ar} for purging

- **Alloys**: ferroalloys (FeCr, FeSi, …) and desoxidation-agents like Al, Si,.. (after blowing or during tapping)

⇒ The products of the BOF process are:[22]

- **Liquid steel (**tab. 1)
- **Offgas** is rich in {CO} (about 80-90%), recovered through the closed or suppressed combustion hood, and is often used in the burners of the reheating furnaces
- **Slag,** poured out of the vessel after tapping of steel (tab. 2)

Gas and slag are valuable by-products.

2.2.2 Metallurgical reactions

The main functions of the BOF process are to decarburize and remove phosphorus from hot metal and to optimize the steel temperature so that any further treatments prior to casting can be performed with minimal reheating or cooling of the steel. The exothermic oxidation reactions that occur during basic oxygen steelmaking generate a lot of heat energy - more than is necessary to attain the target steel temperature.[23] This extra heat is used for heating and dissolution of oxygen, heating of the bath, melting scrap, slag formation and covering the temperature losses during the process. In the chart below the metallurgical reactions, the typical compositions and temperatures of a hot metal charge and tapped steel are shown:

---

[22] Cf.: Iron- and steel metallurgy, lecture script, University of Leoben (2006)

[23] Cf.: Steeluniversity (2009)

	Decarburization		
⇒	[C] + [O]	⇔	{CO}↑
	Slag formation with silicon, manganese and phosphorus		
⇒	[Si] + 2$(FeO)_n$ + 2(CaO)	⇔	(2CaO.SiO2) + 2[Fe]
⇒	[Mn] + $(FeO)_n$	⇔	(MnO) + [Fe]
⇒	2 [P] + 5 $(FeO)_n$ + 3 (CaO)	⇔	(3CaO.P2O5) + 5[Fe]
	Desulphurization		
⇒	[S] + (CaO)	⇔	(CaS) + [O]

	C [%]	***Si [%]***	***Mn [%]***	***P [%]***	***S [%]***	***O [%]***	***Temperature [°C]***
Hot metal	4,2 – 4,5	0,2 – 1,2	0,2 - 0,5	0,05 - 0,13	0,01 – 0,	0,0	1340-1380
Steel	> 0,02	0,0	0,1 – 0,4	0,008–0,02	0,005– 0,02	0,05 – 0,08	1620-1720

tab. 1: metallurgical reactions, compositions and temperatures [24]

The hot metal charge is refined by rapid oxidation reactions on contact with the injected oxygen.[25]

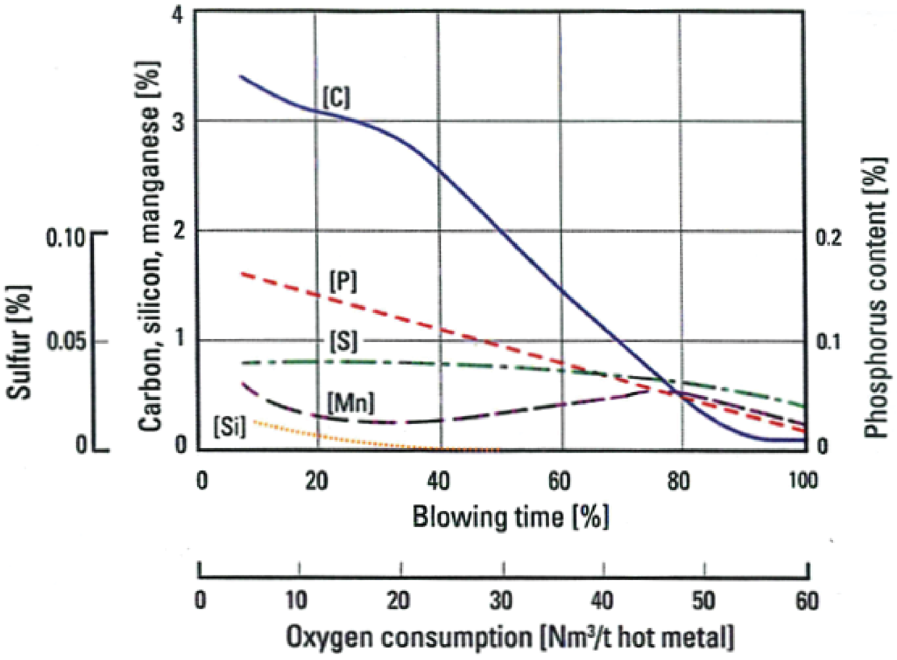

fig. 10: variation in bath composition during blowing [26]

---

[24] Cf.: Köller (1997)

[25] Cf.: Steeluniversity (2009)

[26] Cf.: Cappel, Wünnenberg (2008), p. 55

Included elements in the hot metal are „burnt“. Important: affinity of the tramp elements to oxygen in dependence on the temperature. By this reason the time course of the reactions is regulated. The most important reaction is the decarburization: oxygen reacts with [C] to {CO}.

The tramp elements react in two steps: first they are oxidized (unsoluble in liquid hot metal), then they drop out into the slag. In fig. 10 the courses of the most important elements during a blowing period are demonstrated.

Metallurgical process elements and their behaviour

Carbon is dissolved in hot metal till saturation. If [Mn] is high, Fe_3C can occur. [C] burns to {CO} and partially to {CO_2}, this reaction is the main energy supplier during the heat. The {CO}-bubble formation is responsible for the prompt de-carburisation.[27]

The oxidation of [Fe] is exothermic. Fe-slagging is necessary for the dissolution of lime. Reactions of [Mn], [P], [Si] and the formation of dicalcium silicate are also exothermic. [S] results from hot metal or scrap. The converter is suitable for desulphurisation to only a limited extend.

At the beginning of the process the [N]-content is approx. 80 ppm. During the blowing [N] is purged out by {CO}. An unintentional additional supply of [N] is caused by the dissolution of scrap, the purging gases and by contact to the atmosphere.

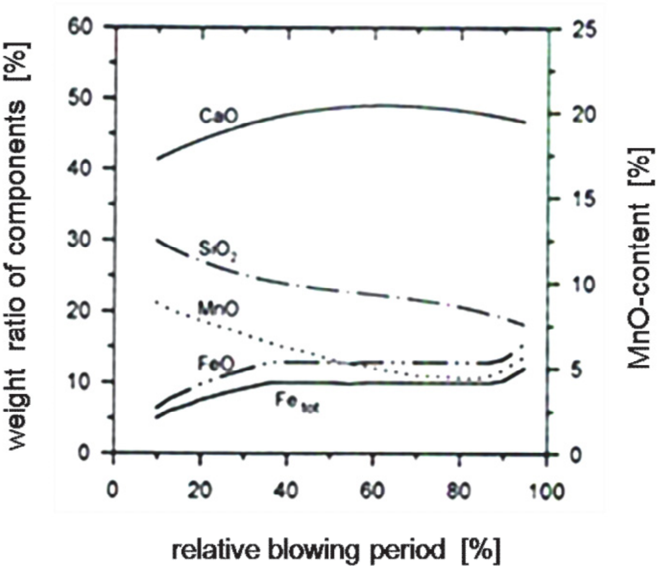

fig. 11: content of slag elements [28]

Refining slag	
(CaO)	42 – 50 %
(SiO_2)	10 – 20 %
($FeO)_n$	20 – 30 %
(MgO)	2 – 15 %
(MnO)	10 – 15 %
(P_2O_5)	0,8 – 2 %
(Al_2O_3)	1 – 2 %
basicity(CaO)/(SiO_2)	2,8 – 4
quantity	80 – 110 kg / t_{steel}

tab. 2: typical slag analysis

---

[27] Cf.: Steeluniversity (2009)

[28] Cf.: Chigwedu (1997)

Hydrogen is basically unwanted in steel. It is removed by {CO} bubbles.

The graphs in fig. 11 show the weight content of slag-elements during a complete heat. In tab. 2 the percentage of elements in the final slag is demonstrated.

Chemical reactions and energy

To show the energetic in- and outputs, the energetic contents of the reactions are listed in tab. 3. The reaction of [Si] brings the most energy imput, followed by [P], [C], [Mn] and [Fe].

Exothermic reactions									
1kg	[Si]	to	(SiO_2)	⇒	7810	kcal	=	32692	kJ
1kg	[Mn]	to	(MnO)	⇒	1780	kcal	=	7451	kJ
1kg	[P]	to	(P_2O_5)	⇒	6050	kcal	=	25324	kJ
1kg	[C]	to	{CO}	⇒	2875	kcal	=	12034	kJ
1kg	[Fe]	to	$(FeO)_n$	⇒	1174	kcal	=	4801	kJ

tab. 3: exothermic reactions and heat energy [29]

fig. 12 shows the sources of energy input and output.

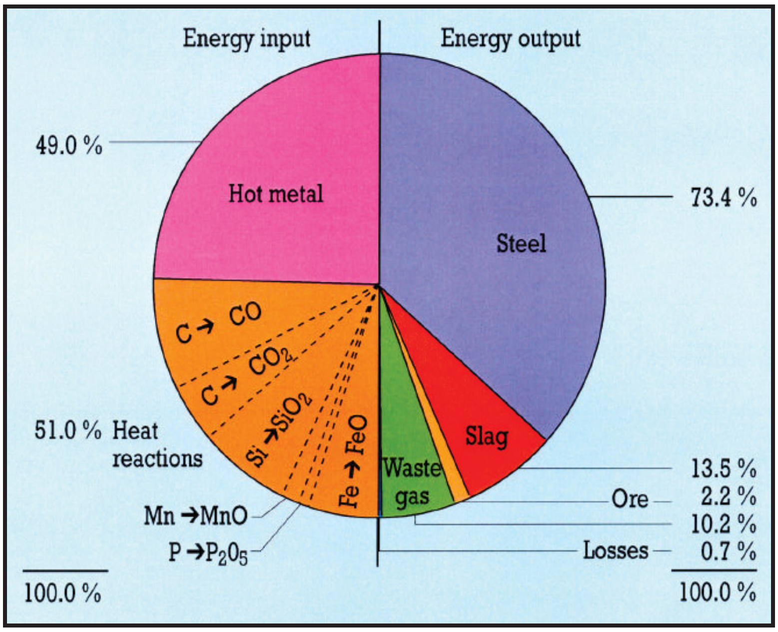

fig. 12: energy input and output of BOF process [30]

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[29] Cf.: Iron- and steel metallurgy, lecture script, University of Leoben (2006)

[30] Cf.: Köller (1997)

2.2.3 Operation sequence

Followed the operation sequence of a heat is demonstrated (fig. 13).

Step 1: Charging scrap

For charging, the vessel it is tilted and steel scrap is dumped from a scrap wagon or a crane-supported scrap vessel into the converter through its open end. The scrap is used as a coolant. It helps to control the extremely high temperatures produced by violently exothermic reactions in the converter.

Step 2: Charging of hot metal

After dumping its load, the scrap vessel is moved away and hot metal is charged by an iron ladle. The ladle is moved to the vessel and tilted to pour its content into the vessel – about three times as much as scrap. Thereafter, the ladle is moved away from the vessel to a position wherein it may receive another charge of molten metal.[31]

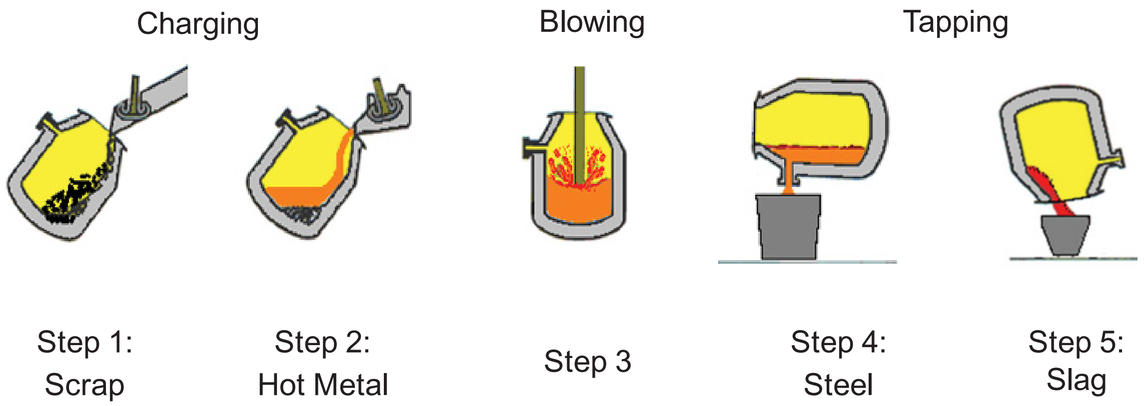

fig. 13: BOF sequence

Step 3: Blowing

After charging of scrap, hot metal and lime (for slag formation), the vessel is returned to upright position and the steelmaking process starts. A water cooled lance is retracted vertically into the converter and blows up chemical pure oxygen with supersonic speed on the hot metal (fig. 14). Due to the high velocity, the oxygen in solution is transported to the bottom of the vessel.

---

[31] Cf.: United States patent 4270949: Making of steel by the BOF Process (1981)

Within seconds after the oxygen is turned on, it is ignited by the hot metal and reaction with the impurities of the charge commences. At this point in the process, the prescribed weight of fluxes is added to the vessel.[32] Especially the [Si] content in the hot metal has a major influence on the addition of lime and therefore on the amount of slag in the converter.

At the beginning of blowing the lance is situated about 2,5 m above bath-level to ensure a quick slag formation due to increased slagging of $(FeO)_n$. This process step is called “soft blowing”. The direct decarburisation by means of oxygen is high. During oxidation of [Fe], [Si], [Mn] and [P] a low viscosity slag consisting of $(FeO)_n$, (SiO_2) and (P_2O_5) is built with the added lime. This slag is very aggressive and harmful for the refractory lining. During the blowing period the lance is lowered continuously to increase the agitation and the “hard blowing” begins. Due to the formation of {CO}, the slag begins to foam. An emulsion of liquid slag, undissolved lime, liquid metal drops and {CO} is formed. The foamy slag has a huge phase surface to the melt and short reaction time. A quick mass transfer takes place between slag and melt. Also the decarburisation effect increases in this period.[33]

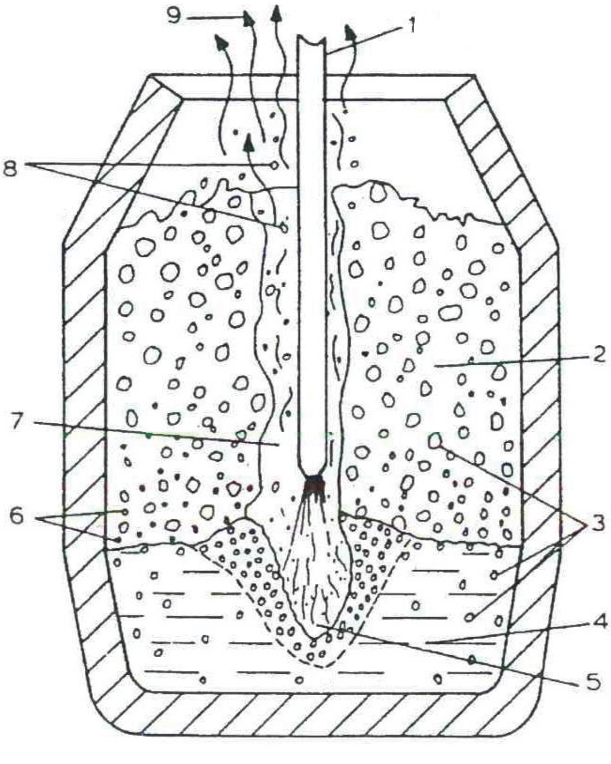

fig. 14: blowing [34]
1 blowing lance, 2 foaming slag, 3 CO-bubbles, 4 melt, 5 fire spot,
6 iron drops, 7 lance canal, 8 sprayed iron drops, 9 brown fume

---

[32] Cf.: United States patent 4270949: Making of steel by the BOF Process (1981)

[33] Cf.: Hiebler, Krieger (1992), pp. 256-262

[34] Cf.: Gudenau (2002), p. 161

The last scrap dissolves very late in the process, at about 80 % of the blowing time and provides the elements into the melt. When the blow is completed, the lance is withdrawn and the vessel is tilted to a horizontal position toward the charging aisle. A sample of the steel is obtained (manually by tilting the vessel or automatically with a sublance, which is installed inside the converter) and sent to a nearby chemical laboratory which determines the individual content of chemical elements in the steel, including carbon, phosphorus and sulphur.[35] The process now is completed and the converter is prepared for tapping.

Also practised nowadays - besides pure top-blowing with oxygen - is combined blowing, in which inert stirring gases or oxygen are additionally injected through the converter bottom.

Step 4: Tapping

In the tapping process the steel is poured through the converter-taphole into a ladle. A minimized amount of carry-over slag is benefitial for the further process (re-Phosphorization). For more details see chapter 3.

Step 5: Deslaging

After the tapping is finished, the remaining slag is poured into a slag pot and dumped in the slag yard from which it can be reclaimed. Currently, about half of this quantity gets recycled internally, either in the sinter plant or directly in the blast furnace. Valuable recovered contents are [Fe] and (CaO). The other half is used in road construction (~50 %), cement industry, landfill or agricultural purposes.

This is the end of a converter sequence. A common melting period is about 35 minutes with roughly 18 minutes of oxygen blowing.

---

[35] Cf.: United States patent 4270949: Making of steel by the BOF Process (1981)

3 Taphole design and changeout

To increase the annual output of liquid steel an important factor is to reduce the down times of every single BOF vessel in operation. Among others, taphole changing operations lead to down times. The number of changing operations, as well as the changing time itself, has to be reduced in order to decrease down times related to taphole changing procedures. To minimize the number of changing operations without influencing tap-to-tap times, the number of heats per taphole set to achieve has to be increased.[36]

The tapping system and maintenance has an important influence on the progression of the tapping times during taphole life, taphole campaign life and the related vessel downtimes. Besides maintenance, an important factor is the tapping process itself and its quality. The melt should be lead over to the ladle within a certain tapping time-period and with less $\{O_2\}$ and $\{N_2\}$ absorption.

The improvements and the aspired target veer toward an optimized tapping pipe geometry, consistence and a proper fast taphole repair system. So there are two important topics in tapping procedure. On one hand the tapping process itself and on the other hand the taphole changing procedure.

In this chapter a chronological patent study is carried out (chapter 3.1) including the latest researches into flow dynamics and the influences on tapping. After giving a short insight in the latest developments in tapping simulations (chapter 3.2) the taphole changeout process and equipment is described (chapter 3.3). On the one hand the common changeout procedure, which is practised in steelplants all over the world, on the other hand a new taphole changeout system called iTap, which is the main topic of this thesis.

Demands on the tapping system:

The main demand on tapping systems is to provide highest steel quality (according specifications) with highest productivity and lowest costs. Other demands are listed in a logical context to differenciate main duties, demands on process and maintenance and influences on the metallurgical conditions.

---

[36] Cf.: Berger, Cormier; (2006), p. 1

- Transfer liqid metal into steel ladle
- Main desoxidation
- Solution of at least 80 % of the alloys
- Solution of the secondary slag additions

main duties

- Maximum lifetime
- Minimum average tapping time
- Minimum repair time

→ ***process***

→ ***maintenance***

lowest possible BOF-down times,

enhancement of productivity

- Flow-optimized design of taphole channel
- Constant tapping time window
- Compact tapping stream
- Controlled stream impact
- Controlled wear
- Grade of refractory
- Minimum carry-over slag – “clean steel”
- Avoid oxygen and nitrogen absorbtion

optimum metallurgical conditions

- Maximum safety for operating personnel

Taphole maintenance: the following devices are used to minimize slag carry-over from the BOF into the ladle: prevention (ball, dart and pneumatic hammer), detection (electromagnetic system EMLI e.g., infrared e.g. IRIS). Because the whole tapping system is part of the BOF-cycle, it is productivity-determining. So for increasing productivity and quality, it is important to pay attention to these facts.

3.1 Taphole design and development

Steel produced in basic oxygen furnaces is poured from the vessel through pipelike tapholes fabricated from high temperature refractory material. These tapholes have been formed in a variety of ways, all of which have one thing in common. They can only be installed when the furnace is in a vertical reline position.[37] And also only with maintenance procedures carried out inside and outside the vessel.

---

[37] Cf.: United States Patent 3,554,523; Taphole assembly for metallurgical furnaces (1971)

A chronological patent study was carried out to show the development of tapping procedures and taphole layout. The types of taphole systems in chronological order are:

- Former types
- Pipe in pipe systems
- Stream optimized pipe systems

The latest development of stream optimized pipes is a research of applicability of computational flow dynamics, which is discussed at the end of this chapter.

3.1.1 Former types

In the earlier days, the taphole was not cylindrical and formed with angular bricks (fig. 15). Due to this fact, implementation and repairing-procedure was very complicated and took a lot of time. The erosion of refractory was high and hence the lifetime of the taphole short.

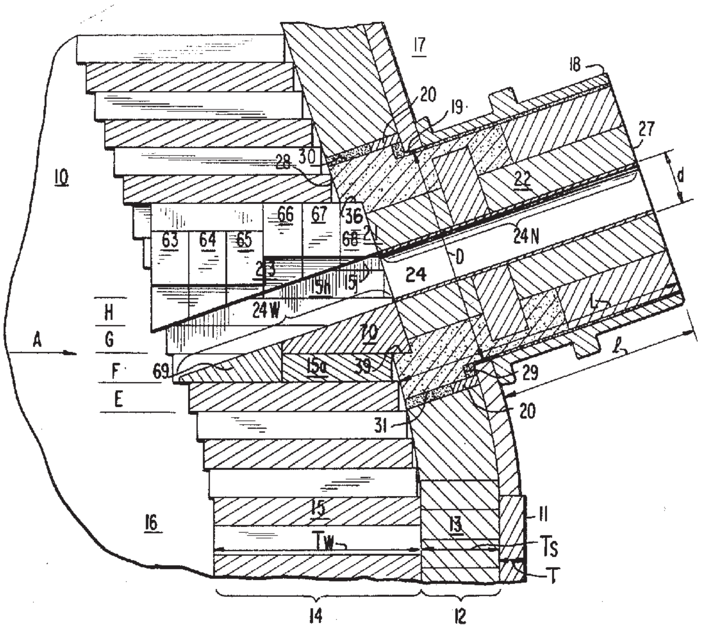

fig. 15: taphole with rectangular bricks [38]

In fig. 16, the taphole was pipelike, but it was still a hole in a block. In this matter the pouring stream and the erosion has been enhanced, but repairing-procedure could not be facilitated.

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[38] Cf.: United States Patent 3,554,523; Taphole assembly for metallurgical furnaces (1971), p. 2

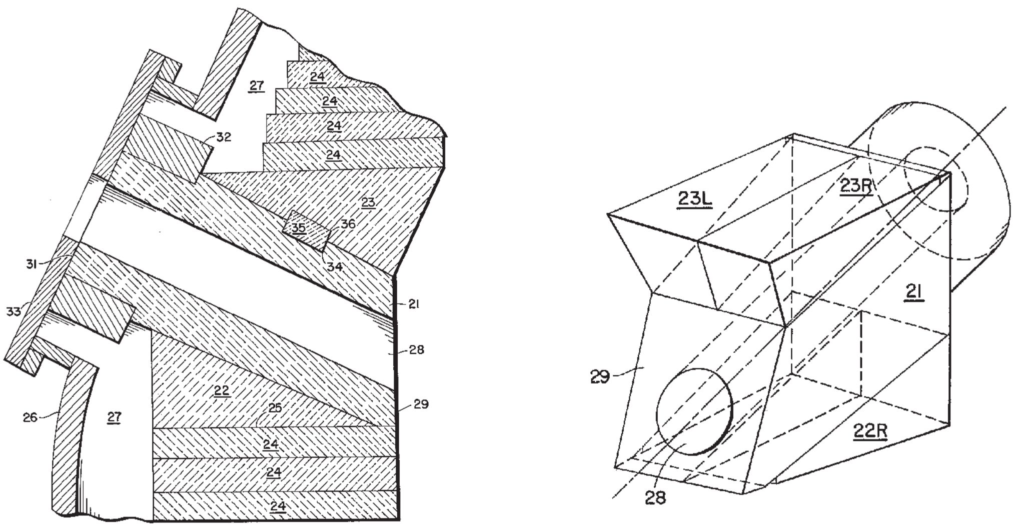

fig. 16: pipelike taphole [39]

Another idea was a taphole structure that will prevent slag entering by means of vortexing. This sould be possible with a refractory pipe which has a closed end portion extending into the vessel (fig. 17). The tubular refractory has got side wall openings adjacent to its closed end, so that the molten metal does not flow directly into the taphole. The poor flow rate and the turbulences in the tube might have been a huge disadvantage.

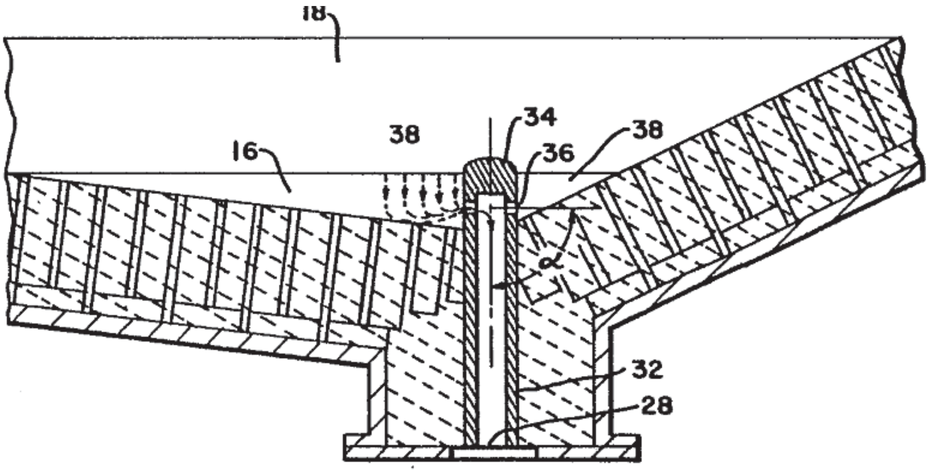

fig. 17: pipe with closed end [40]

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[39] Cf.: United States Patent 4,328,956: Taphole assembly and method of installation (1982), p. 2

[40] Cf.: European Patent Appl. 0279123A1: Taphole structure (1987), p. 4

Bit by bit the tubular tapping system with a surrounding mother block has been accomplished. In fig. 18 an isostatic pressed tapping pipe with a divided surround block in the hot face of the converter is shown. As seen from the slashed lines, the natural fluid flow is marked in this drawing.

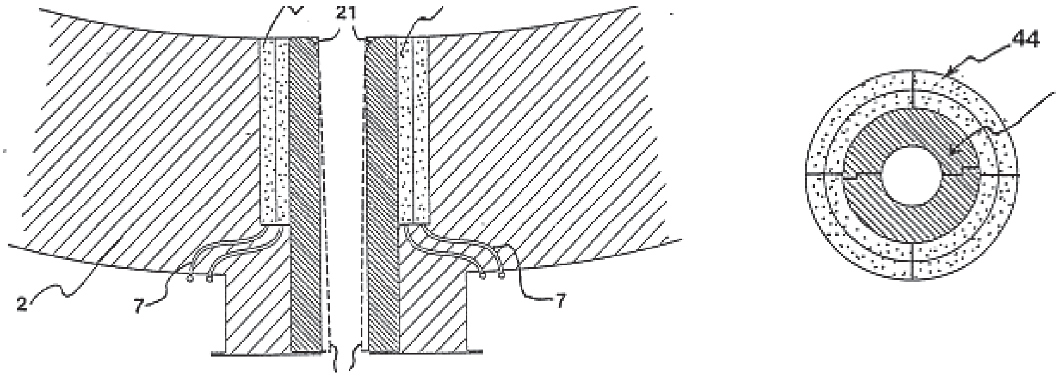

fig. 18: tapping pipe with mother block [41]

3.1.2 Pipe in Pipe system

Due to the aspect, that the repairing and taphole change procedure still has been a very difficult and time consuming issue, it was tried to invent a complete and easy "pipe in pipe system" in order not to damage the BOF lining and to avoid long vessel downtimes.

The idea was born to assemble the tappig pipe (instead of isostatic pressed) with annular refractory bricks and a "pipe in pipe" composition, that means a complete separation of surround block and tapping pipe (fig. 19). Now it was possible to protect the lining and assemble the right taphole length in each repair period dependent on the lining thickness of the vessel.

With such a system also the taphole change could be performed easier and in a shorter time period. This was a successful way and the improvements were concentrated on this type of tapping systems.

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[41] Cf.: European Patent 0282824 A2: Device for emptying metallurgical vessels (1988), p. 5

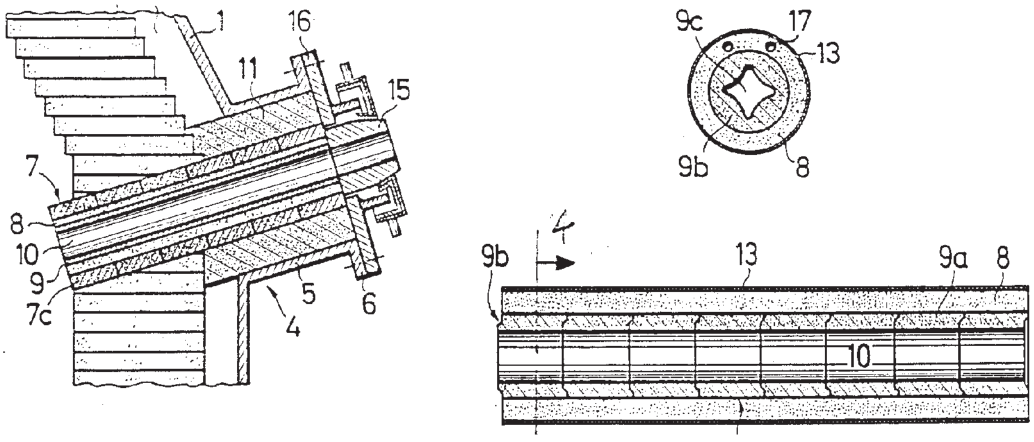

fig. 19: pipe-in-pipe-system with annular bricks [42]

In fig. 20 the tapping pipe and surround block in the vessel lining are completely separated, just centered with two toothed rings between each other with space for the gunning mass. Concerning its shape, this pipe shows already the next step in development – the step to optimize the form of the taphole by means of the stream-optimized shape.

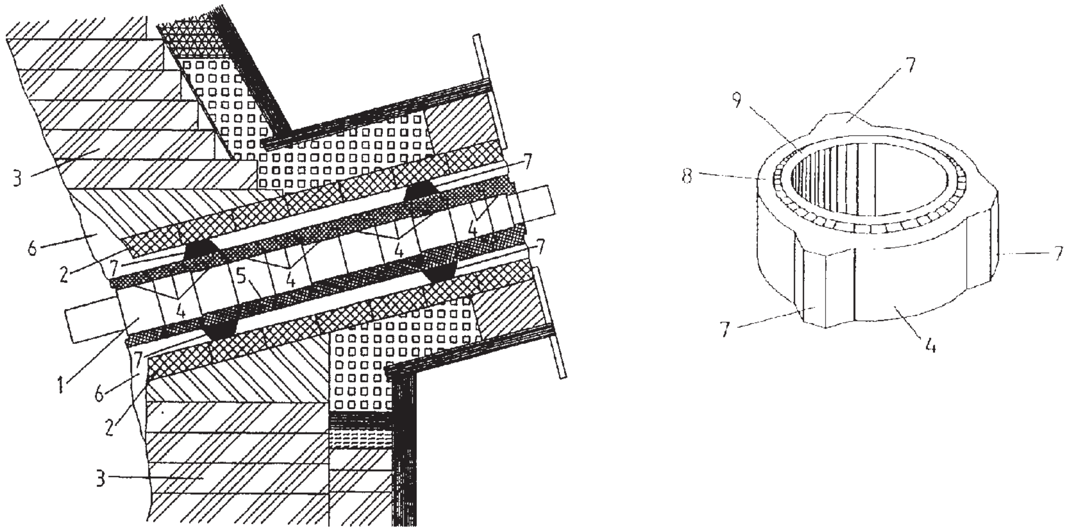

fig. 20: developed pipe-in-pipe-system [43]

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[42] Cf.: United States Patent 4,984,769: Tap spout for metallurgical vessels (1991), p. 2

[43] Cf.: European Patent Application 0414308 A1: Taphole construction (1990), p. 6

3.1.3 Stream optimized tapping pipe system

Parallel to the maintenance-based developments a new ground has been broken. In order to increasing production and quality requirements (to reduce the tapping time and increase the steel quality), the efforts were based on fluid dynamics, especially hydrodynamics (the study of liquids in motion).

As seen in fig. 21, the the natural liquid flow is not parallel but funnel-shaped. It was tried to modulate the taphole based on the flow shape, first with stepped annular and pure conical bricks, then with form-optimized refractory.

The stepped annular and pure conical bricks are arranged conical, but without considering the exact shape of the liquid flow (fig. 22). The form optimized refractory is an advancement of the conical shape and is formed due to the optimized flow shape.

Due to this facts, the company VEITSCHER established a patent (DE 4208520C2-1993 respectively US-patent 5310164-1994) related to the former patent EP 0057946B1 published by the same company in 1986.

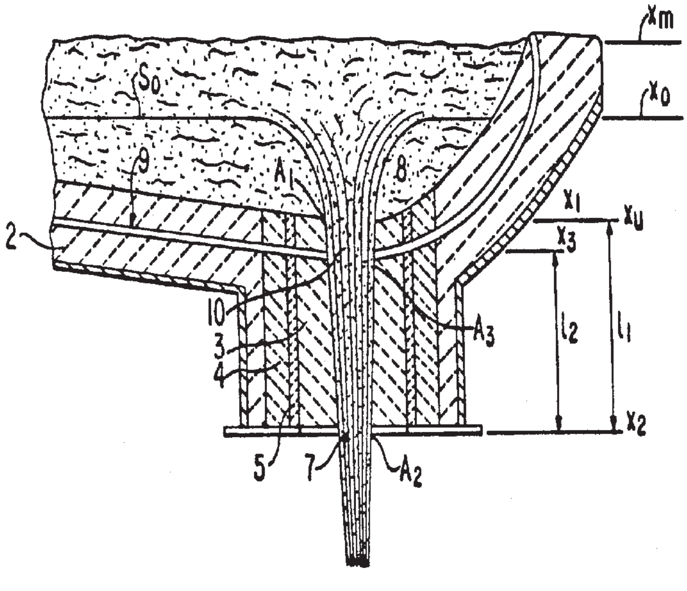

fig. 21: natural liquid flow [44]

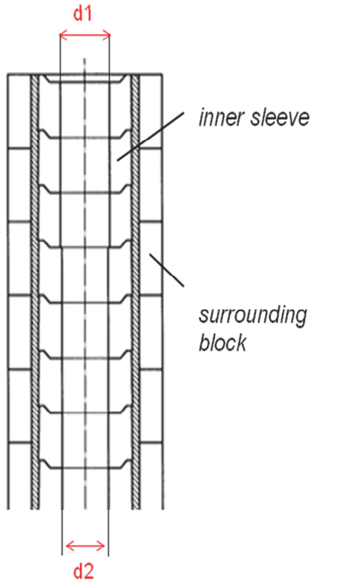

fig. 22: stepped annular bricks [45]
d1>d2

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[44] Cf.: United States Patent 5,310,164 and European Patent 0561181 A2: Tapping pipe and systemfor a converter (1993), p. 5

[45] Cf.: RHI AG (2008)

The former patent showed already, that the shape of the tapping pipe is adjusted to the flow conditions of the tapping stream. The new patent establishes an improvement concerning a new configuration of the pipe-shape with implementation of optimized flow and the trial to provide an identical tapping-time-period for the whole lifetime of a pipe. It describes the flow cross sections of a fluid in dependence on the bath height of the melt.

As described in the patent EP 0057946B1, a pipe has flow cross sections, or cross-sectional areas, which (at the level of a discharge zone of a tapping pipe) are less than at levels closer to the inside of the converter. Here the flow cross sections taper in steps from a feed zone closer to the inside of the converter toward the discharge zone of the tapping pipe.

When a tapping pipe wears, the flow resistance decreases and so the tapping time – starting from the maximal bath level of the melt to its minimum bath level – changes accordingly. This is a disadvantage, because the tapping time affects the temperature of the melt in the following vessel. As a result, a prolonged tapping period will cause in lower temperatures in the ladle. To avoid the resulting metallurgical irregularities, the melt then has to be reheated and this requires a considerable amount of energy.[46]

The develoment provides a tapping pipe of the type described above that will exhibit a tapping period as identical as possible. For this reason, the following considerations have been made:

According to the patent, the object is fullfilled by the profession of a tapping pipe in a vessel (BOF) with a maximum bath level x_m (fig. 21). The pipe defines a flow-passage therethrough. The flow-passage at the discharge zone has flow cross-sections approximately the same as the cross-sections of the flow profile of a free falling melt stream. But – that´s the relevant fact – from a melt bath level x_0 between 30 % and 70 % of the maximum bath level x_m. Preferably the melt bath level x_0 is situated between 40 % and 50 % of the maximum melt bath level. A future feature is, that the tapping pipe is provided with a feed zone having flow cross-sections which are approximately flow-shaped based on the melt from a minimum bath level x_u.

The flow cross-section of the profile of a free flowing melt stream is determined by the equation[47]:

$$A_{(x)} = \frac{\dot{m}}{\rho\sqrt{2gx}} \tag{1}$$

$A_{(x)}$ flow cross-section at level x
$\dot{m}$ mass flow of the melt per unit time
ρ density of the melt

---

[46] Cf.: United States Patent 5,310,164 and European Patent 0561181 A2: Tapping pipe and system for a converter (1993), pp. 2-4

[47] Cf.: United States Patent 5,310,164 and European Patent 0561181 A2: Tapping pipe and system for a converter (1993), p. 2

g force of gravity
x level for a respective flow cross-section

A part of this equation - Torricellis Law - pays respect to the ferrostatic height and hence the pouring velocity in dependence on the bath level[48]:

$$v = \sqrt{2gh} \tag{2}$$

The pouring velocity v defines the velocity of a liquid or gas flowing out of a vessel. It is dependent on the bath height h but not on the liquid itself. For example: Water and Mercury at same pressure height have got the same pouring velocity. $g = 9{,}81\ m/s^2$ is the force of gravity. In our case, the bath level x_i changes from the maximum level x_m to the minimum level x_u and velocity chages.

Back to the flow-cross-sections: For example, a flow profile S_0, as seen in fig. 21 (prouced at the average bath level x_0 without the tapping pipe) can be calculated from the formula above for different levels between the feed level x_1 and the discharge level x_2. According to the calculation, the flow cross-sections A_1, A_3 and A_2 at levels x_1, x_3 and x_2 respectively, and also at intermediate levels, can be dimensioned to be as identical as possible to the respective cross-sections of the flow profile S_0 of the melt at that point. Due to the fact that the tapping pipe is then adapted to the flow profile S_0, the outer contours of the flow profile always rest against the tapping channel. In this manner, the tapping channel should always be filled with the metal melt.[49]

Summarized, this development defines a tapping pipe, which shape is defined by a flow-passage similar to the optimized flow. Therethrough the tapping period of a melt should be substancially constant over a taphole lifetime. This flow-passage is adjusted to the profile of a free flowing stream of a melt bath level between 30 % and 70 % of the maximum bath level x_m.

As to these new developments, first analysis and comparisons concerning tapping time and taphole lifetime between the different pipe types were established (fig. 23). The cylindrical tapping pipe shows a huge wear within the first few tappings and a short lifetime based on the straight cylindrical anti-optimized-flow-shape. Stepped pipes are adjusted to the flow and therefore the wear at the beginning of tapping campaign is less and ifetime is longer. Optimized pipes show a low wear during the first few heats and a relevant longer lifetime according to the flow shape. Further more, by adjusting the flow cross-section to the hot metal flow from the average bath level x_0 during tapping, the tapping periods are in resulting narrow ranges, becoming as identical as possible. The maximum and minimum tapping periods (T_o and T_u) are prefered, be-

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[48] Cf.: Fluid dynamics; lecture script, Institute of mechanics, University of Leoben (2000)

[49] Cf.: United States Patent 5,310,164 and European Patent 0561181 A2: Tapping pipe and system for a converter (1993), p. 3

cause tapping periods between these two points do not cause problems from the metallurgical point of view.

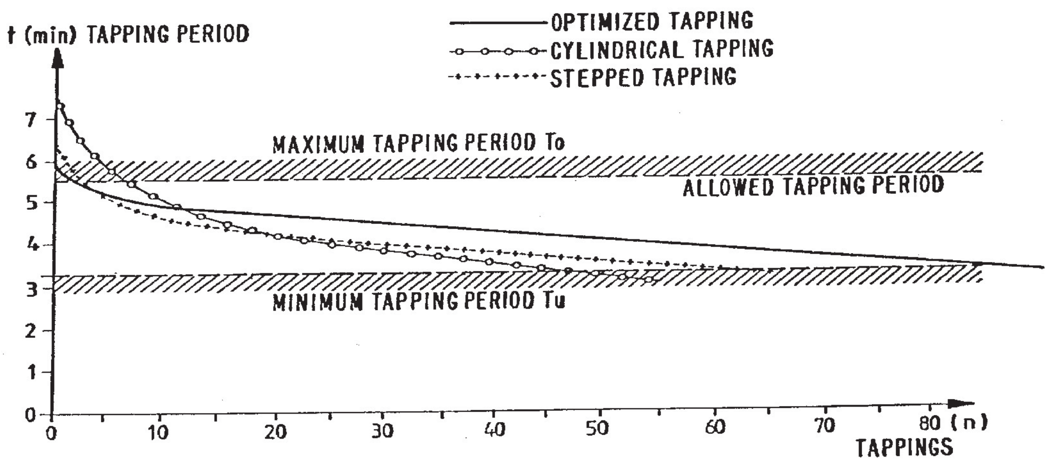

fig. 23: tapping time vs. tappings [50]

The next and latest enhancement of tapping pipes is demonstrated in the RHI patent DE 102004027440 B3[51], that relates to the discussed patent (DE 4208520C2-1993 respectively US-patent 5310164-1994) above.

Within this patent it is stated, that the height of metal bath is nearly constant during tapping, because the converter is constantly tilted while tapping. But at the end of tapping, the height of the bath decreases inevitabely. Based on this fact, the risk of carrying over slag through the tapping pipe increases. Consequences are the formation of turbulences, underpressure in the pipe, reoxidation and nitrogenization of the melt.

It is tried to optimize the taping pipe, so that the mass flow therethrough is constant and doesn´t tear off during the whole tapping period. That means, it has to be constant during pouring the whole bath height and not at least 30 % to 70 % like mentioned in the former patent.

According to the former patent, the flow profile of a melt can be calculated with equation (1). A decesive point of view for the calculation is the flow profile for the respective bath level, especially < 30 % of the maximum bath height. When the bath level reaches less than 30 %, the required cross-section at the pipe end increases and deviates form the cross-section calculated with equation (1).[52]

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[50] Cf.: United States Patent 5,310,164 and European Patent 0561181 A2: Tapping pipe and system for a converter (1993), p.7

[51] Cf.: Patent WO 2005/118889 A2 and Patent DE 102004027440 B3: Tapping tube (2004)

[52] Cf.: Patent WO 2005/118889 A2 and Patent DE 102004027440 B3: Tapping tube (2004), p.4

The new development will secure a constant mass flow and pipe-filling pouring stream also in these areas. Here the flow cross-section of the profile of a free flowing melt stream is calculated as followed[53]:

$$A_{(y)} = A\sqrt{\frac{\left(h_l + h_k\right)}{\left(h_l + h_k - y\right)}} \tag{3}$$

$A_{(y)}$	flow cross-section at level y
A	flow cross-section at pipe end
h_l	effective height of bath above entry of tapping pipe
h_k	length of tapping pipe between pipe entry and discharge
y	level for a respective flow cross-section, (discharge → y=0 and $A_{(y)}$=A)

h_l should be lower or equal than 0,3 times of the maximum height (h_{max}) of the bath. The variable factor (h_l/h_{max}) takes the different flow behaviour of the fluid into account, especially within low bath levels.

h_k reflects the actual length of tapping pipe between entry and discharge. While discharge remains the same, the position of the entry changes due to wear and erosion. It adapts the position of the converter lining.

As a special case of a circular cross-section (like a tapping pipe), the diameter between pipe entry and discharge $d_{(y)}$ is[54]:

$$d_{(y)} = d \cdot \sqrt[4]{\frac{\left(h_l + h_k\right)}{\left(h_l + h_k - y\right)}} \tag{4}$$

d	diameter at discharge
$d_{(y)}$	diameter at level y
h_l	0,3*h_{max} or less than maximum height
h_k	length of tapping pipe between pipe entry and discharge
y	level for a respective flow cross-section, (discharge → y=0 and $d_{(y)}$=d)

d is the diameter at discharge. If a certain discharge-diameter is chosen, the diameters of the cross section in the whole tapping pipe can be calculated. The higher the decided mass flow through the pipe, the higher is diameter d. As seen, different cases can be calculated, for example a decided diameter of 0,13 m at level y=1 m and y=1,35 m above discharge with an actual bath level of 0,25 m above entry and an actual pipe length of 1,35 m[55]:

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[53] Cf.: Patent WO 2005/118889 A2 and Patent DE 102004027440 B3: Tapping tube (2004), p. 4

[54] Cf.: Patent WO 2005/118889 A2 and Patent DE 102004027440 B3: Tapping tube (2004), p. 4

[55] Cf.: Patent WO 2005/118889 A2 and Patent DE 102004027440 B3: Tapping tube (2004), p. 5

$$d_{(y=1)} = 0{,}13 \cdot \sqrt[4]{\frac{(0{,}25 + 1{,}35)}{(0{,}25 + 1{,}35 - 1{,}00)}} = 0{,}17m \qquad (5)$$

$$d_{(y=1{,}35)} = 0{,}13 \cdot \sqrt[4]{\frac{(0{,}25 + 1{,}35)}{(0{,}25 + 1{,}35 - 1{,}35)}} = 0{,}17m \qquad (6)$$

So the diameter of a 1,35 m tapping pipe one meter above discharge and with an actual melt level of 0,25 m is 0,17 m. 1,35 m above discharge – at the entry of pipe – the diameter is 0,21 m. Within these equations it is also obvious, that diameter at level y increases with increasing pipe length, while the desired diameter at discharge remains unchanged.

As said before, the factor (h_l/h_{max}) should be less than 0,3 for the calculation of the stream within a low baht level of less than 30 % of maximum bath level. Dependent on the calculations, the execution form of the factor ranges between 0,05 and 0,3 respectively between 0,1 and 0,2. First of all it depends on the dimension at the entrance area of pipe due to relation of the low bath level < 30 %. The dimensioning especially of the pipe entrance gets into focus. The cross-section at the discharge is calculated by the *nominal value* of flowthrough (flow rate at maximum bath level).

Concerning slope of the tapping channel, the calculation is made as followed[56]:

$$S = \frac{r}{4}\sqrt[4]{\frac{(h_l + h_k)}{(h_l + h_k - y)^5}} \qquad (7)$$

S	slope of tapping channel
r	radius of pipe cross-section at discharge

The slope S describes in this case the radius $r_{(y)}$ of a circular cross-section in dependence on the distance to discharge of the tapping pipe. Calculations showed, that the slope within the first third of the entry should be > 0,02. In case of very low bath levels and shorter pipes this area expands to half the pipe and the value can be increased up to > 0,25.

As an addition, also variety of the diameter ($S_{A(y)}/A$) dependent on length of the pipe can be calculated[57]:

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[56] Cf.: Patent WO 2005/118889 A2 and Patent DE 102004027440 B3: Tapping tube (2004), p. 6

[57] Cf.: Patent WO 2005/118889 A2 and Patent DE 102004027440 B3: Tapping tube (2004), p. 7

$$S_{A(y)}\Big/A = \frac{1}{2 \cdot \sqrt{\frac{(h_l + h_k)}{(h_l + h_k - y)^3}}} \qquad (8)$$

That means – for example – that the cross-section at the entrance has to decrease for a certain percentage ($S_{A(y)}/A*100$), to secure advantageous liquid flow.

Assumed, this new and latest design of the tapping pipe enables to perform the tapping process with less turbulences and constant mass flow also at low bath levels. Due to these facts, the wear, temperature losses and slag-carry-over during tapping can be reduced and lifetime of the tapping pipe increased.

According to this patent, RHI has created a new series of tapping pipes – “ISOJET B-Type” and “ISOJET C-Type”, which are specified in the following paragraphs.

ISOJET B – pipe in pipe

The ISOJET B-Type is a taphole system which accords to the developments of patent DE 102004027440 B3. The stream section is adjusted to the optimized flow and it also pays attention to the influence of the actual bath level to the taphole shape. This pipe in pipe system consists of a quadratical surround block assembled of rectangled bricks, and a tapping pipe assembled with annual bricks (fig. 24). These bricks are connected on base of a conical joint design, that means joint-free surfaces, which reduces the risk of steel infiltrations and significantly simplifies taphole repair.[58]

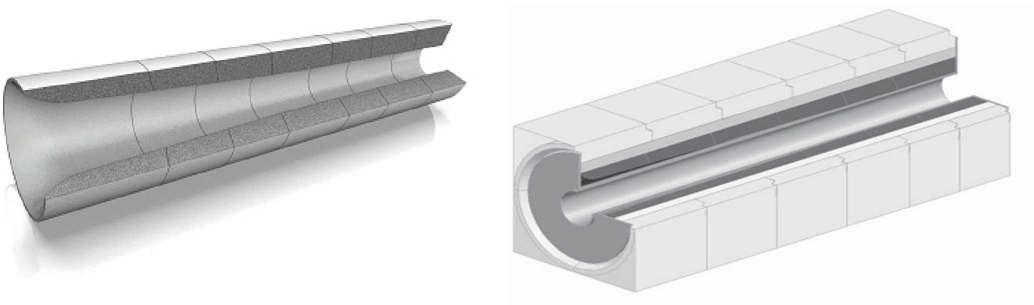

fig. 24: RHI, ISOJET B-Type with mother block [59]

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[58] Cf.: Jeitler, Pungersek, Sauer (2007), pp. 20-23

[59] Cf.: Zettl (2008)

Characteristics:

- Highest lifetimes
- Shorter tapping times
- High sophisticated refractory grades
- Pre-assembled repair sets => fast & easy application
- Lengths according to customers requirements
- Compact tapping stream
- Almost joint-free inner surfaces.
- Less slag suction
- Huge durability through an even wear of the taphole material. The compact tapping stream reduces reoxidation and saves alloying material
- Shorter tapping times (the fluidicly optimised taphole-channel leads to more consistent decrease of the tapping time, starting with lower tapping times)
- The conical joint design means smooth, virtually joint-free surfaces, which reduces the risk of steel infiltrations and significantly simplifies taphole repair.
- Later slag suction → higher steel output

ISOJET C – self centring

The ISOJET C-Type taphole system is a development of the B-Type concerning its handling and maintenance advantages. The flow optimized shape remains the same. The brick-shape has been changed and a conical fitting mechanism was adapted, so that this tapping pipe is self centering and makes quicker repair times and easier handling possible.

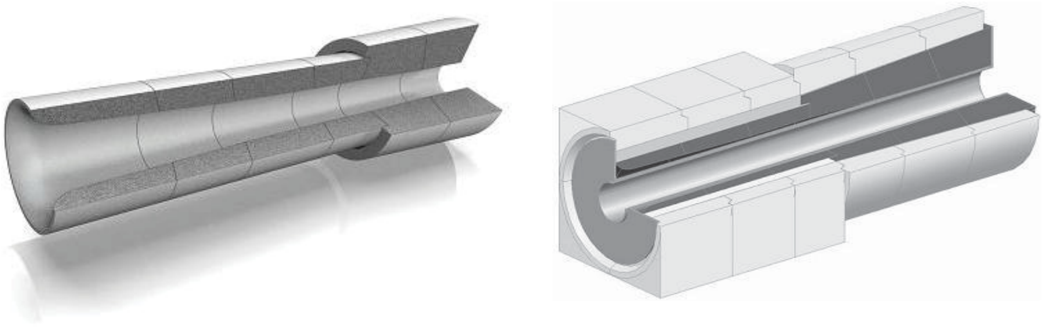

fig. 25: RHI, ISOJET C-Type with mother block [60]

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[60] Cf.: Jeitler, Pungersek, Sauer (2007), pp. 20-23

Advanages (further to B-Type):

- Self centering taphole repair set (the conical construction adapts to the frame design → ensures quick repair times and consistent wear mechanisms)
- Shorter gunning gap → less ring-gap mix (less time necessary for hardening)
- Fastest possible taphole repair
- Optimum precondition for slag detection / prevention systems
- Optimum basis for clean steel production

According to these new tapping systems RHI started to examine the flow conditions of the pipes in order to make computer aided simulations based on the program Computational Fluid Dynamics – (CFD-FLUENT), and gained a further optimization of the design of taphole channel. These CFD-designed tapping pipes are called “HYFLO”.

3.1.4 Comparison between the developed tapping systems

In fig. 26 the latest developments of tapping systems are presented. It shows how the shape changes from the linear inner layout of the stream channel up to the latest, form and functional optimized model.

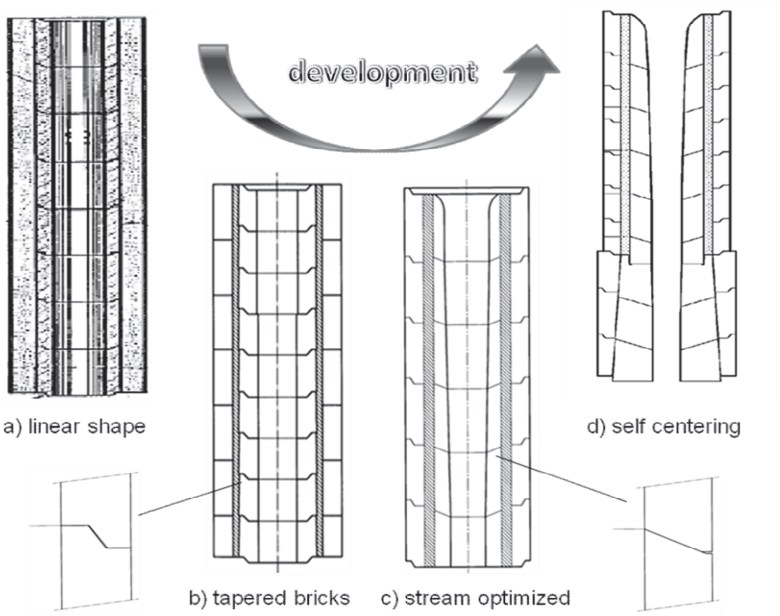

fig. 26: development of tapping pipes [61]

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[61] Cf.: RHI AG (2008)

The step from linear shape (a) to tapered sleeve design (b) brought a better stream quality, but both had the classical tongue and groove construction between the annual bricks. The disadvantage is the risk of steel infiltration during tapping due to the imprecise fitting. This fact and the analysis of the liquid flow developed the stream optimized pipe (c). The self centering taphole (c) facilitates the handling during taphole changeout and guarantees a proper fit.

3.2 Tapping flow dynamics based on simulations

Computational Fluid Dynamics (CFD) researches were developed and several simulations realised to get a better understanding of the main factors influencing the performance of the tapping system during tapping. Its big advantage is the fact, that the taphole shape could be adjusted to the various conditions of the customer. The CFD-research was carried out by RHI. In discussion with the responsible people the characteristics, parameters and influences on tapping and flow dynamics were gathered and are discussed in this chapter.

The output of this kind of simulations are the following influencing factors, which can then be analyzed very detailed:

- pressure distribution, dynamic as well as total
- turbulence intensity
- velocity; distribution and vector plot showing the direction of the flow

The CFD simulations are based on the Navier Stokes Eqations, which combine the conservation of mass, momentum and energy.[62] With these equations the theoretical dynamic flow of fluids can be calculated by computational simulations.

All those factors depend on the mass flow and the geometries, which are the hot face inlet geometry and diameter, the cold face outlet, the length of taphole and the steel bath above the taphole.[63] Examples what can be the output of such simulations are shown in fig. 27 and fig. 28 - velocity and pressure distribution during a tapping simulation.

In fig. 27 the velocity distribution is shown. In the bath the velocity is around zero. At the pipe entry the velocity increases and reaches its maximum at the discharge. Proportional to velocity the pressure increases too (fig. 28).

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[62] Cf.: Schröder (2004), pp. 37-48

[63] Cf.: Berger, Cormier; (2006), p. 2

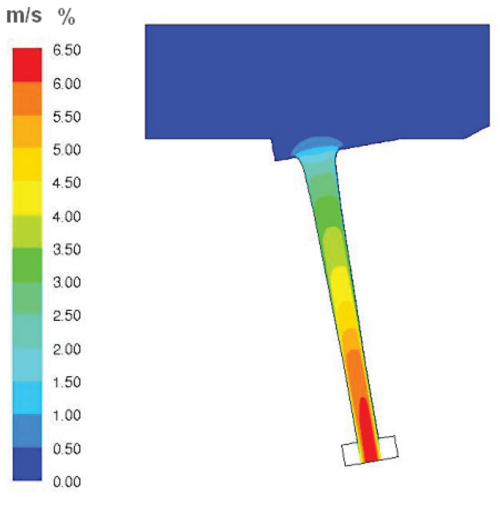

fig. 27: velocity distribution [64]

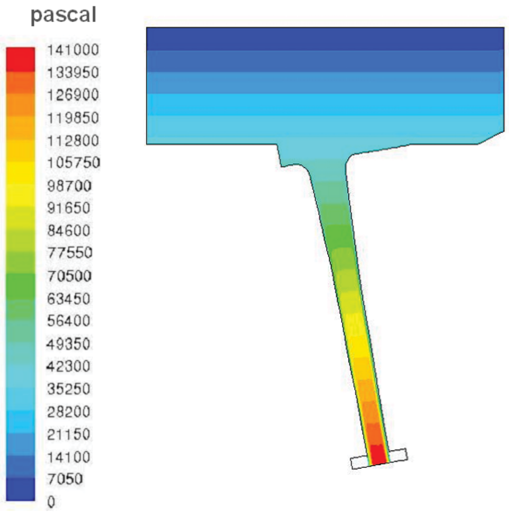

fig. 28: pressure distribution [65]

The optimum design of the channel depends on the particular conditions of a steel plant and therefore has to be calculated individually. The most important factors are:

- Tapping weight
- Tapping time window
- Ferrostatic height

The tapping time itself is known to be dependent on the inner geometry of the taphole channel, the steel bath level and the amount of steel running through the taphole.

The simulations show factors to be the predominant ones effecting the situation regarding turbulences, internal velocities and the distribution as well as maximum values of pressure[66]:

- Geometry and diameter at the hot face inlet
- Design of the taphole channel
- Diameter at the cold face outlet
- Concerning ferrostatic height, length of the taphole and the steel level above entry, it was found, that the design of the channel has to be adapted as the ferrostatic height is changing during a BOF vessel campaign. Once the converter

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[64] Cf.: RHI AG (2008)

[65] Cf.: RHI AG (2008)

[66] Cf.: Berger, Cormier; (2006), p. 2

refractory lining is wearing, the taphole sets are getting shorter and the steel bath level above the hot face inlet is decreasing as the free volume of the vessel is increasing.

In respect to the flow pattern the negligible factors are:

- Steel temperature and
- The chemical analysis

The following advantages consequently result from these findings:

- Minimised and more constant wear rate
- Better separation of steel and slag

  the adaptation of the inner geometry results in a flattening of the velocity gradient at the hot side inlet area. This consequently leads to a postponed formation of the “vortex-effect”. Thus, pulling of slag starts later, minimizing the total amount of slag carry-over into the steel ladle. That does not only improve the steel quality but also increases the overall steel output.
- Less temperature loss during tapping: The loss of temperature expected during tapping is around 12 – 15 °C per minute.
- Two different approaches for optimisation: lifetime increase and tapping time reduction
- Lower wear of the upper-cone taphole area because of shorter contact times between slag and refractory

CFD simulation is a very good tool to get an understanding of what happens inside the taphole during tapping operations. The results of the CFD simulations show that the most important parameters influencing the performance of the taphole and its wear rate are the turbulences and the pressure, especially areas of negative pressure. Important in taphole channel design is, that the smallest, limiting diameter is at the cold face outlet. This guarantees, that the channel is totally filled with steel and the turbulence intensities are minimized during the entire tapping period.[67]

fig. 29 draft the differences of the flow characteristics of the inner sleeves of a usual line shaped pipe compared to the flow optimized ISOJET C shown by means of a CFD-simulation. In this figure the turbulence caused by the shape difference is obvious and the wear of refractory material and pressure contitions are optimized.

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[67] Cf.: Jeitler, Pungersek, Sauer (2007), pp. 20-23

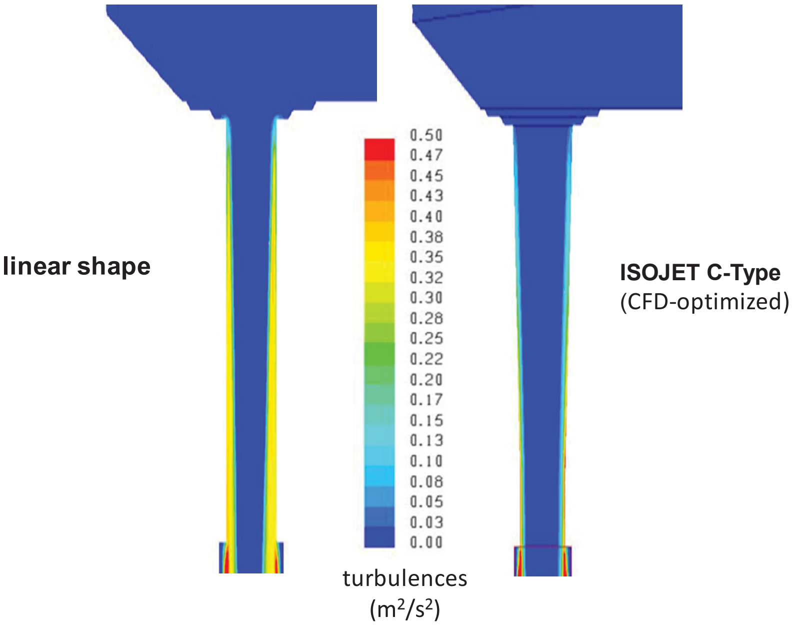

fig. 29: shaped pipe compared to the flow optimized ISOJET C [68]

Concluding a special attention has to be paid to the shape of tapping pipe and the way the installation is done as an unadaptable and incorrect assembly has a major impact on the flow pattern within the taphole and consequently a negative effect on tapping time and lifetime.[69]

3.3 Taphole changeout process and equipment

During a converter campaign, it is essential to keep the maintenance activities on the vessel as small as possible, due to reasons of efficiency. The converter tap spout requires regular maintenance, to ensure a dense compact jet during the tapping. And also to avoid slag carry-over due to refractory irregularities round the entrance area. The taphole set has also to be resistent to the harsh conditions during operation. In fig. 30 the influences on lifetime are shown. This requires a tap spout which must be renewed within the life of the converter many times as part of a hot repair.[70] The target is, to develop a fast taphole changing technique with implementation of the latest stream optimized tapping pipe sets.

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[68] Cf.: RHI AG (2008)

[69] Cf.: Berger, Cormier; (2006), p. 7

[70] Cf.: United States Patent 4,984,769: Tap spout for metallurgical vessels (1991), pp. 3-4

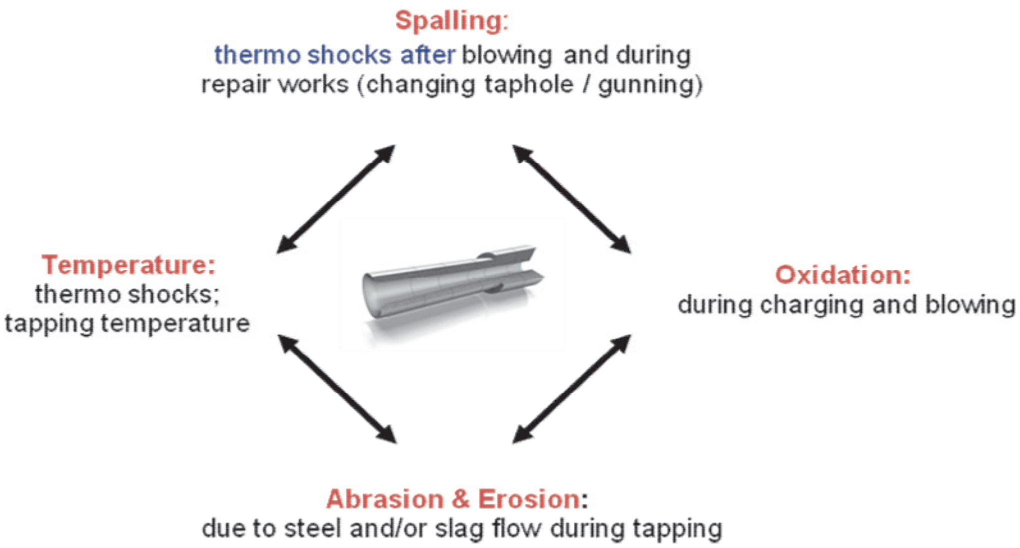

fig. 30: influences on taphole lifetime [71]

Due to erosioin, oxidation, spalling and temperature changes, the taphole has to be changed after a certain number of heats. Therefore a couple of changing procedures and machines are used worldwide. The common (chapter 3.3.1) and an innovative taphole change/repair procedure (3.3.2) are described.

3.3.1 Standard practice

The common way of changing the taphole is shown on the example of ASI. This common pracitce is performed in steelplants all over the world.

Mode of operation

When the melt is finished and the BOF is deslagged, the converter is tilted, so that the taphole is on the charging side (depending on the space in the steelplant, it may also be the tapside). A drilling out-device with a proper drilling head is placed in front of the taphole, which drills out the annular bricks of the tapping pipe and cleans the inner surface of the surround block (fig. 31 and fig. 32).

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[71] Cf.: Jeitler, Pungersek, Sauer (2007), pp. 20-23

fig. 31: drilling device

fig. 32: drilling head

fig. 33: common taphole

After the removal of the worn taphole, the new taphole is carried on (fig. 33). The taphole is inserted into the surround block by a forklift, till the positioning iron cross is positioned on the doghouse flange, and should be held in the correct place (fig. 34).

Because this assembly is very heavy, it is difficult to position and maintain the annular bricks at the location of the taphole. The position has to be executed in a very accurate way, that pipe and doghouse flange implicate an angle of 90°. If the angle differs, a lot of disadvantages, like shorter lifetime due to unlaterally wear during tapping and skull formation on the doghouse flange may result.

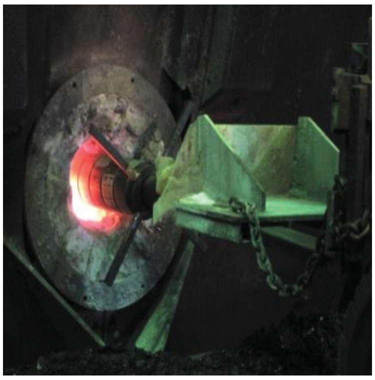

fig. 34: positioning taphole

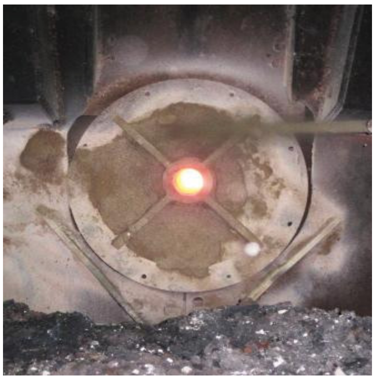

fig. 35: gunning

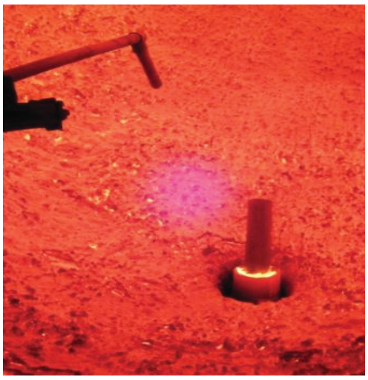

fig. 36: gunning hot face

After the pipe has been introduced and located at the tap hole position, the outer repair is finished by gunning a refractory mix to fill the joint between the surround block and the change set (fig. 35). Then the forklift is driven away and – after an idle time of about 20 minutes for sintering of the gunning mix - the vessel is tilted to the other side to repeat the procedure to fill the joint on the hot face (fig. 36). Therefore a long gunning lance (about 10 m) is used to reach this area. After a second idle time of 20 minutes the repair is finished. This whole process takes in average 120 to 130 minutes.

new head

used head after one taphole change

fig. 37: wear of a classic drilling head [72]

Another important fact is the need of expensive drilling equipment. As seen in fig. 37, the wear of a classic drilling head is enourmous after one single taphole change.

Common Taphole changing devices

fig. 38 to fig. 40 show some common older and newer devices for taphole drilling.

fig. 38: Allied [73]

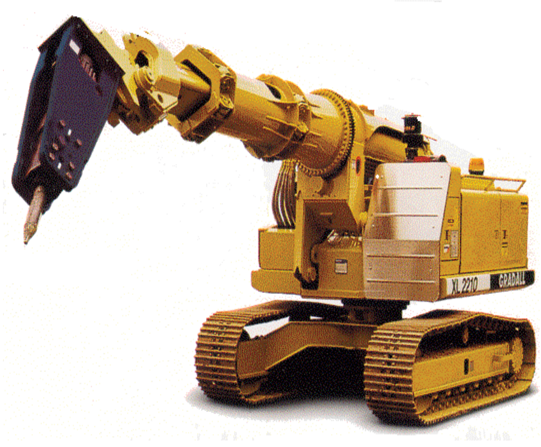

fig. 39: Gradall [74]

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[72] Cf.: RHI AG (2008)
[73] Cf.: RHI AG (2008)
[74] Cf.: Kia Jamaica (2009)

fig. 40: TML Unidachs [75]

fig. 41: taphole changing device [76]

The machine in fig. 41 is already a development of the taphole changing process. With its two arms, it is able to drill and clean the taphole with one side and to put in the new tapping pipe with the other side. It shows the new way of taphole changing and process improvement. Therefore RHI has made process to invent a new Taphole repair device together with Böhler Baugeräte GmbH (BBG). This device and the application of the latest tapping pipes represent the new way of taphole changing, named iTap and TBD.

3.3.2 iTap and TBD practice

i-TAP is a complete system solution and stands for “innovative tapping”. The taphole-system consists of two components. One is the taphole-set with the developed refractory material and stream optimized design (IsoJet B, IsoJet C), as seen in chapter 3.1. The second is the TBD-machine (Taphole Changing Device), which guarantees a quick and simple operation. Compared to the common systems, these components together promise a much more efficient way of taphole changing.

The TBD 407 machine is built for a rapid change of the worn tapholes. This method of operation is based on RHI’s and BBG’s (Böhler Baugeräte GmbH) patented counter-percussion technique.[77] The unit ows its ability to a catapillar traction system fitted with a device with two special designed tools. It is equipped with a breakout tool for remov-

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[75] Cf.: People Freenet (2009)

[76] Cf.: RHI AG (2008)

[77] Cf.: European Patent EP 0926458 A1 and EP 0926458 B1 (2004)

ing the worn taphole sleeves and cleaning the channel, and a repair tool for the precise insertion of the new taphole set (fig. 44).

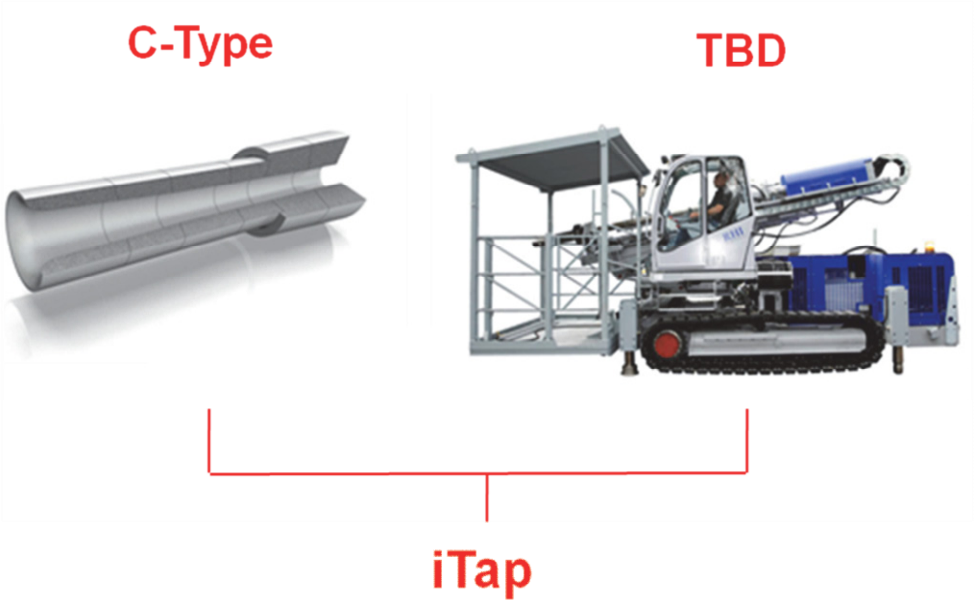

fig. 42: iTap-System [78]

Depending on the specific converter platform, which varies from steelplant to steelplant, the TBD offers a service platform in front of the device, to make manual repair operations safer and easier.

Mode of operation

After finishing the heat and deslagging, the vessel is tilted, so that the taphole is on the charging side (optional other side, depends on the space) (fig. 62). Then the TBD is positioned precisely in front of the converter by means of two positioning cylinders (fig. 43). This guarantees the proper position in front of the vessel and reduces the risk of operational errors. The TBD can be manoeuvred similar to a caterpillar. For operation, compressed air and cooling water connections are required. After finishing the positioning and connecting the air and water hoses, the operation sequence begins.

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[78] Cf.: RHI AG (2008)

fig. 43: positioning cylinders

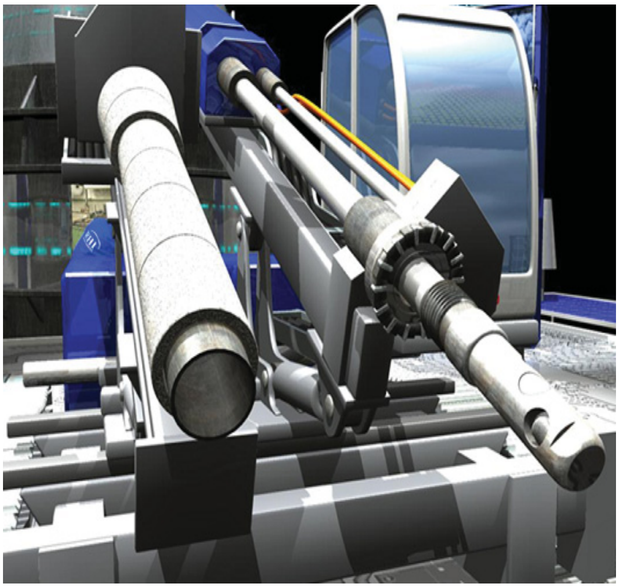

fig. 44: breakout- and repair tool [79]

The worn taphole sleeve now is broken out by means of the counter percussion technique. Herefore the breakout-hammer with its water-cooled head (including three extendable claws) is pushed into the taphole (fig. 45). The claws are extended and the taphole sleeves are knocked out in direction of the cold face which avoids damages of the taphole surrounding block in the hot face area of the tapping system. The backwracking sequence has finished.

In the reaming sequence, the drilling head, a tool with individually adjustable drill units with tungsten-carbide bits – is put on to the breakout tool. The residual brick and mixes are removed by means of the drilling had and the taphole-channel is cleaned and calibrated for the next taphole set.

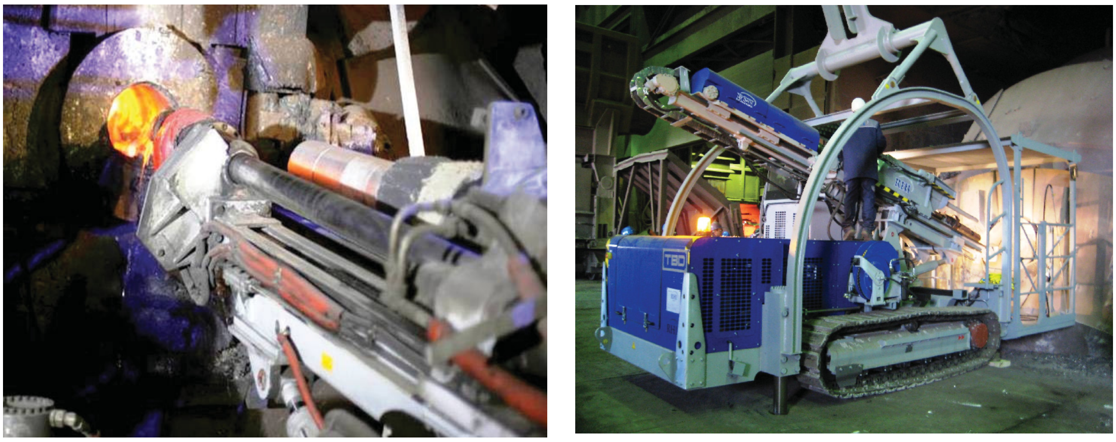

fig. 45: backwrecking of the worn taphole and cleaning of taphole channel

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[79] Cf.: BBG and RHI AG (2007)

The last step in process is the insertion of the new taphole set (fig. 46). The repair unit directs it towards the converter, centers it precisely into the surround block, inserts it and fixes it. After fixing the new taphole, the converter is tilted for gunning the taphole joint at the hot face of the converter (fig. 48). Within a short period of time, the vessel is available again.

fig. 46: inserting new taphole

fig. 47: gunning hot face

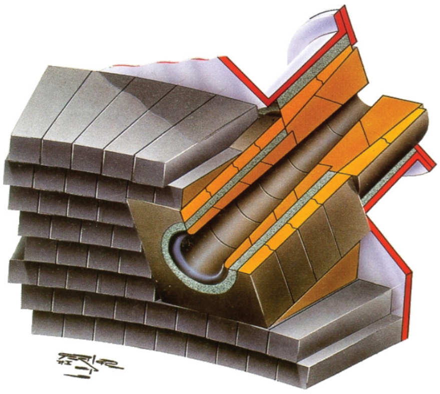

fig. 48: installed C-Type with mother block [80]

3.3.3 Comparison between the systems

The advantages of iTap compared to common taphole changing systems are[81]: quicker and more precise removal of worn taphole sleeves, reduced taphole repair costs, increased productivity due to higher converter availability, shorter tapping time caused by the stream optimized tapping channel and the maximum exploitation of the pipe diameter, higher lifetime of the taphole, compact tapping stream, consistant wear mechanism due to the centered insertion, minimised slag carryover, reduced re-oxidation during

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[80] Cf.: Veitscher and BPI (2006), p. 3

[81] Cf.: Jeitler, Pungersek, Sauer (2007), pp. 20-23

tapping, lower [N]-pick-up, reduction of alloying materials, one-man operation, individual customisation of the machine and advantages due to the small machine dimensions.

The big problem and disadvantage of the common changing system is the availability and production downtime caused by the allocation of the machines, ramming and cleaning of taphole, gunning and drying the gunning mass. Repairing the taphole with the common procedure is on one hand very hard, on the other hand it suffers from the defect of poor positioning of the new tap hole in the vessel wall. This results in the fact, that the maximum number of melts to be processed with a common repaired taphole – about 90 in average - is not as high as possible in an optimally repaired vessel with up to 140 heats. This leads to higher operating costs because of the earlier repair need. Compared to the common way, with iTap (C-Type) no refractory mix is necessary on the cold face of the vessel due to the conical fitting system.

description of work	***TBD*** *time [min]*	***common device*** *time [min]*
positioning device in front of vessel	3	1
removal of retaining plate	5	5
backwrecking	5	-
reaming	2	5-60
cleaning wellblock	3	
inserting taphole and fixing	1	5-60
ramming retaining-mechanism	4	5
blow out remaining water and tbd off vessel	1	-
turning vessel into gunning-position	5	5
preparing for gunning	5	5
gunning cold face	-	5-20
gunning hot face	5	5-20
drying time	10	20
total time taphole change	**49**	**60-200**

tab. 4: taphole changing time with TBD vs. common system

The taphole changing time of the common system at ASI ranges between 60 and more than 200 minutes, depending on the easyness of drilling out the old taphole, positioning and gunning activities. The operating time for every repair step could differ a in a wide range. tab. 4 shows taphole changing procedures with TBD and the common system.

4 Productivity requirements at Essar Algoma

In this chapter the productivity requirements at ASI are discussed. Chapter 4.1 includes the theory of productivity, efficiency, effectivity (chapter 4.1.1) and goes into detail of partial productivity and time as a productivity pressing characteristic (chapter 4.1.2).

Additional an example of the Overall Equipment Effectiveness (OEE) – a way to measure productivity and efficiency of a manufactoring process – of a representative steelplant was established to mention the importance of availability and the big losses in BOF process (chapter 4.1.3). Refering to the results, the big losses in BOF process are described.

On the research into productivity - with a detailed inspection and analysis of cycle time and performing a delay study (chapter 4.2) - it is demonstrated, that the tapping procedure and its maintenance-chain is a significant weak point in the BOF-steelplant, especially concerning process-time and turndown performance.

In order to employ the so called iTap-system, preliminary taphole performance field trials, carried out by RHI were used for studies (chapter 4.3.1). A mathematical model is created to figure out the optimum taphole start diameter based on a decided tapping time window and start tapping time in dependence on vessel refractory thickness and ferrostatic bath height over a vessel lifetime. This model is a tool, which enables a simple calculation of the optimum taphole layout within a converter lifetime. Summarizing the results of the productivity elevations and preliminary taphole trials, a justification study for the implementation is carried out (chapter 4.3.2).

4.1 Productivity

Productivity is defined as a concept in close relation to such concepts as profitability, economic growth, efficiency, surplus value, quality, performance, partial productivity, need, etc.[82] For the needs of this thesis, the basics of productivity are described at the beginning and then the focus goes into partial productivity measurement.

Productivity in the 19th century was defined having regard to the agriculture and describes the productiveness of the production factors work, land and capital. In modern business economics productivity is the relation between produced goods and services and the deployed production factors (work, capital, material).[83] Gutenberg for example defines the production factors as follows: work, resources (facilities and machines), materials (raw-, auxillary- and operating materials) and anticipated factors (manage-

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[82] Cf.: Saari (2006), p. 1

[83] Cf.: Dellmann, Pedell (1994), p. 16

ment, planning, organisation).[84] Productivity can be described as ratio between output- and input-quantities.[85]

$$productivity = \frac{output}{Input} \tag{9}$$

Output and input could be measured by different technical dimensions, for example pieces, weight or time.[86] The primary purpose underlying any economic activity is the satisfaction of human needs. Welfare can be understood as an adequate degree of needs satisfaction. Need is either a physical or a mental state in which the lack of something necessary, desired or hoped for is experienced consciously or unconsciously. A need initiates a target-oriented activity towards meeting the need.[87] Regarding *Schierenbeck,* welfare factors generated by needs are[88]:

- Potential on natural and human resources
- Use of productivity supporting division of labour
- Standardization of automation
- Standardization of materials and products
- Technical and economical improvement
- Efficiency of the economic system

Needs are met by means of tools. Tools provide some value for their user. Man creates various material and immaterial tools for his use, and tools provide him with some value, need satisfaction. The purpose of use is an idea derived from the qualities of the need and from the characteristics of the tool or it is a more specified plan for the use of the tool and for the value it will produce (fig. 49). Need satisfaction is a result of the value the tool provides, and the degree of need satisfaction varies all according to the success of the tool in its purpose of use.[89]

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[84] Cf.: Gutenberg (1976), vol. 1
[85] Cf.: Dellmann, Pedell (1994), p. 16
[86] Cf.: Dellmann, Pedell (1994), p. 16
[87] Cf.: Saari (2006), p. 1
[88] Cf.: Schierenbeck (2008), p. 3
[89] Cf.: Saari (2006), p. 1

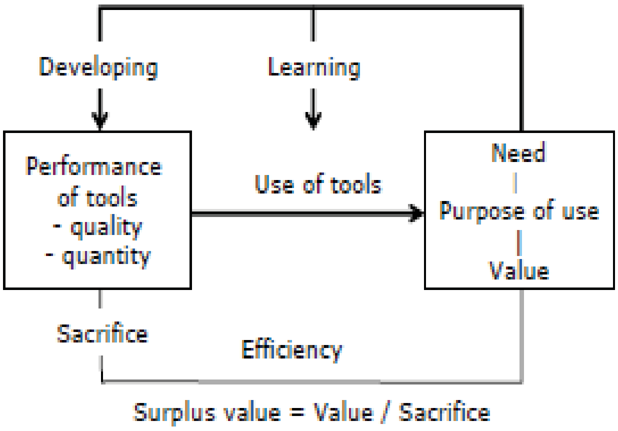

fig. 49: model of economic activity [90]

The ability of a tool to perform its task is its performance. The tools' performance depends on their quality and quantity. Improving the performance takes place by developing their quality and increasing their quantity as well as by evolving the use process. The tools' quality means their characteristics. Both quality and quantity are usually developed on the basis of the latest know how and experience, and the work is carried out by means of investment and development projects. The use process of tools evolves over the time through learning.[91]

Output and input factors can be measured with different technical dimensions, for example pieces, weight and time. Productive relationships could range from single processes to the whole added value of a company, inasmuch as a certain output and the causal input could be defined and differenciated.[92]

4.1.1 Efficiency and effectivity

A basic feature of economic behaviour is the interest to satisfy the needs to the maximum at minimal sacrifice. Here we speak about striving for efficiency which is typical of economic activity.[93] Productivity is a measure of the efficiency of manufacturing. The real success-sources, which is associated with the capacity- and product side, are called effectiveness, while the improvement of productivity is characterized as efficiency[94]:

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[90] Cf.: Saari (2006), p. 1
[91] Cf.: Saari (2006), p. 2
[92] Cf.: Dellmann, Pedell (1994), p. 17
[93] Cf.: Saari (2006), p. 1
[94] Cf.: Dellmann, Pedell (1994), p. 25

- Efficiency [latin: efficere (to accomplish something)] is a measure value of process performance, in other words “to do things right to achieve defined targets” or “practice the lowest effort to achieve defined targets”.

- Effectiveness [latin: effectivus (causing)] is the ratio between achieved and defined targets, in other words “to do the right things”

Effectivity describes the effort independent activity while effectiveness could be indicated as effort specific activity. Regarding *Saari*, efficiency, in general terms, speaks about the relation between producing a value and sacrifices made in doing so. Hence, efficiency is at issue when the required sacrifices are being balanced against the value produced. Efficiency is a general concept related to economic activity, and it needs to be given a precise name and a formula case by case. Productivity and profitability are typically such specified concepts of efficiency. The basic idea of efficiency is, that the produced value is larger than the sacrifices made to provide and use them.[95]

Generally efficiency and effectiveness could be indicated as “potency or impact of an action”. Efficiency postulates effectiveness and goes beyond it.[96] Another interesting definition: “Productively efficient is, when you cannot produce more of one good without producing less of another”.[97] All in all productivity depends on “practising the lowest effort to achieve a defined target with a defined quality”.[98]

4.1.2 Productivity measurement

The success of economic opterations can be measured in different ways. The main principle is the so called economic principle, which says, that a target should be reached with the lowest possible effort.[99] This principle has already been discussed by means of efficiency and effectivity in chapter 4.1.1.

Business operations can be divided into sub-processes in different ways; yet, the following five are identified as main processes, each with a logic, objectives, theory and key figures of its own. It is important to examine each of them individually, yet, as a part of the whole, in order to be able to measure and understand them. The main processes of a company are as follows[100]:

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[95] Cf.: Saari (2006), p. 1

[96] Cf.: Dellmann, Pedell (1994), p. 25

[97] Cf.: Mackintosh (1996), p. 244

[98] Cf.: Schneider (1997), p. 66

[99] Cf.: Schierenbeck (2008), p. 3

[100] Cf.: Saari (2006), p. 3

- real process
- income distribution process
- business process
- monetary process
- market value process

Market value process Productivity is created in the real process, productivity gains are distributed in the income distribution process, and these two processes constitute the business process. The business process and its sub-processes, the real process and income distribution process occur simultaneously, and only the business process is identifiable and measurable by the traditional accounting practices. The real process and income distribution process can be identified and measured by extra calculation, and this is why they need to be analysed separately in order to understand the logic of income formation in business.[101]

The ratio between output quantities and the total input quanitites deployed therefore is called “total productivity”.[102]

$$productivity_{total} = \frac{output}{Input_{(work+capital+material)}} \tag{10}$$

The productivity based on a value (monetary) basis is called profitability.[103] If output quantities are opposed to the input quantity of a single factor, the partial productivity is defined.

Partial Productivity

Productivity figures can be built out of quantity and value based output and input data. The most common partial productivities are labour productivity, capital productivity and material productivity.

Labour productivity relates output in different ways to work with average number of employees, working hours and working costs[104]:

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[101] Cf.: Saari (2006), p. 3
[102] Cf.: Dellmann, Pedell (1994), p. 21
[103] Cf.: Schneider (1997), p. 66
[104] Cf.: Dellmann, Pedell (1994), p. 22

$$labour\ productivity = \frac{output}{work\ input} \tag{11}$$

$$= \frac{output}{average\ number\ of\ employees} \tag{12}$$

$$= \frac{output}{working\ hours} \tag{13}$$

$$= \frac{output}{real\ working\ \cos ts} \tag{14}$$

Capital productivity (which is also known as equipment productivity) relates to the investment (machines, buildings, patents, licences). Output is opposed to the employment of capital and in a narrower correlation to quantity per machine or machine hours[105]:

$$capital\ productivity = \frac{output}{employment\ of\ capital} \tag{15}$$

$$= \frac{output}{quantity\ per\ machine} \tag{16}$$

$$= \frac{output}{machine\ hours} \tag{17}$$

With these definitions the figures of identical aggregates and machines can be compared.

Material productivity can be calculated with the input of resources, like raw-, auxilliary- and operating material.[106] In other words, the input of materials:

$$material\ productivity = \frac{output}{material\ usage} \tag{18}$$

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[105] Cf.: Dellmann, Pedell (1994), p. 23

[106] Cf.: Dellmann, Pedell (1994), p. 24

Time as a producitvity pressing characteristic

The understanding of the adding value as a process-chain includes a series of actions over a specific period of time. Therefore different time aspects in the operative function areas are relevant:

- process time
- down time
- cycle time
- production time
- idle time
- delivery time
- storage time
- transport time
- information time

These times should be kept as small as possible. On one hand to minimize the binding of ressources, on the other hand to guarantee a high availability of the processes. The process time is a conflict between minimum cycle time and maximum availability of the machines.[107] This requires a high degree of coordination. A qualified way to measure productivity and effectiveness of a manufacturing process is the Overall Equipment Effectiveness.

4.1.3 Overall Equipment Effiectiveness (OEE)

OEE is a way to show and improve the effectiveness of manufacturing processes (for example machines, production lines or even whole plants).[108] The OEE was invented by the Japanese Seiichi Nakajiama and the Japanese Institute for Plant Maintenance (JIPM) more than 25 years ago.[109]

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[107] Cf.: Dellmann, Pedell (1994), p. 26

[108] Cf.: Vorne Industries (2002-2008), p. 3

[109] Cf.: May, Koch (2008), p. 245

It takes the most common sources of manufacturing productivity losses and places them into three categories: availability, performance and quality. In doing so, it distills complex production data into simple understandable metrics that provide a gauge for measuring true maufacturing efficiency. It also forms the foundation for tools that help to improve productivity.[110] Further more it is an important tool for improvement processes, like Total Productive Maintenance (TPM), Lean Production and Six Sigma.[111]

Definition of the three factors[112]:

- Availability measures productivity losses from downtimes. It is the ratio of operating time (planned production time minus downtime) to planned production time, and accounts for down time loss:

$$Availability = \frac{operating\ time}{planned\ production\ time} \tag{19}$$

- Performance measures losses from slow cycles (process operates at less than the maximum possible speed). It is the ratio of net operating time to operating time and is calculated as:

$$Performance = \frac{ideal\ cycle\ time * total\ \ pieces}{operating\ time} \tag{20}$$

- Quality measures losses from manufactured parts that do not meet quality requirements. It is the ratio of fully productive time (time for good pieces) to net operating time (time for total pieces) and is caldulated as:

$$Quality = \frac{good\ \ pieces}{total\ \ pieces} \tag{21}$$

Together these three factors combine into one OEE score – a single number that provides a complete measure of manufactoring efficiency and effectiveness. It provides a

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[110] Cf.: Vorne Industries (2002-2008), p. 3

[111] Cf.: May, Koch (2008), p. 245

[112] Cf.: Vorne Industries (2002-2008), p. 11

consistant, proven way to measure the effectiveness of lean manufactoring initiatives, TPM programs and other productivity initiatives. OEE is the ratio of fully productive time to planned production time. In other words, it represents the percentage of production time spent making good pieces (no quality losses), as fast as possible (no speed loss), without interruption (no downtime loss).[113] The ideal effective machine should work without interruption at maximum velocity without producing defective products.[114] In practice it is calculated as:

$$OEE = Availability * Performance * Quality \tag{22}$$

A top OEE for manufacturing plants is considered to be 85 % or better.[115] For this OEE-score the amount of the three single categories could be calculated for example as:

$$OEE = 90\% \; * \; 95\% \; * \; 99{,}5\% = 85\% \tag{23}$$

Studies indicated, that the average OEE score for discrete manufacturing plants is approximately 60 %.[116] Clearly, there is significant room for improvement in most manufactoring plants.

According to this thesis, an OEE of a converter is described. Due to the need of huge data bases to perform this model, the OEE of ASI couldn´t be calculated at this point. Therfore data of a representative steelplant was used to demonstrate the evaluation method.

As seen in fig. 50, the total production (calendar) time is 17520 hours. After availability losses (due to planned maintenance, preparation, breakdown and waiting periods), the net production time amounts to 14692 hours or 6,494 mio tons or 84 % of total production time. Net production time diminished by capacity losses of the BOF in process, results in the real output quantity (88 % of net production time). Comprising 2 % quality losses (relating to output quantity) caused by rejection and rework, the OEE amounts to 74 %, which is a moderate value compared to the average OEE of manufactoring plants of 60 %.

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[113] Cf.: Vorne Industries (2002-2008), p. 7

[114] Cf.: May, Koch (2008), p. 248

[115] Cf.: Vorne Industries (2002-2008), p. 10

[116] Cf.: Vorne Industries (2002-2008), p. 10

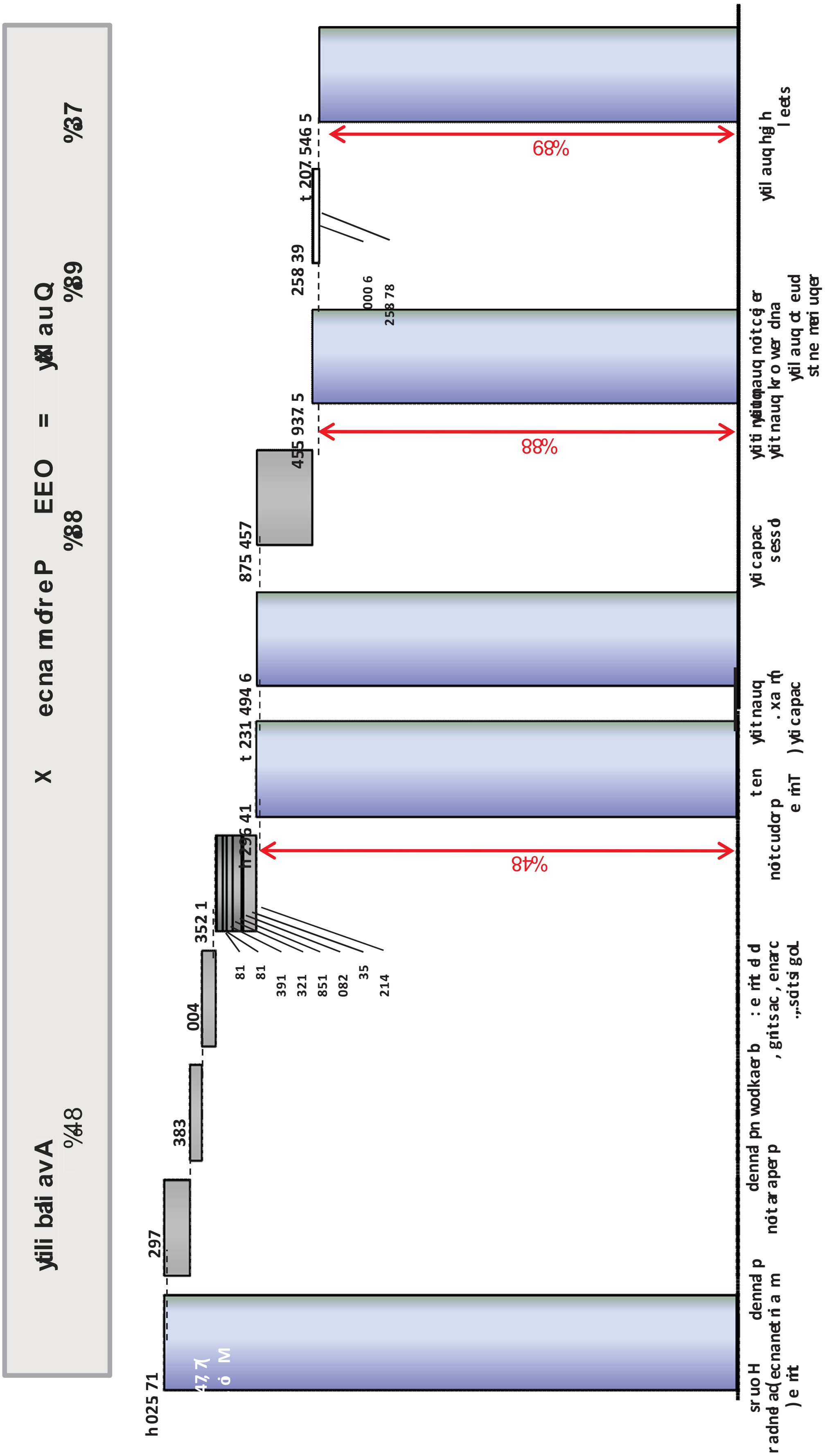

fig. 50: representative OEE of a BOF

The big losses in BOF process

Refering to the OEE model (fig. 50) the big losses in BOF process are discussed[117]:

- *Planned maintenance and planned preparation*

  Planned downtimes can be calculated and integrated very easy. In the BOF process planned downtimes are for example lining of the vessel, lining repair activities, taphole change and other planned maintenance and preparation activities.
- *Breakdown and Idle time*

  Unplanned down time (breakdown) and idle time are critical inputs for the OEE. If process is down, other losses cannot be adressed. It is necessary to know the average experienced downtime as well as the reasons of breakdowns and how to avoid them. Breakdown and idle times are for example technical problems, wait on metal, crane problems and other delays.
- *Capacity losses*

  Capacity losses during cycle time due to reduced speed and small stops are the most difficult factors to monitor. Therefore cycle time analysis should be performed to point out the weak points. Cycle times of a lot of cycles can be compared to figure out the ideal cycle time.
- *Rejection and rework*

  To fulfill the quality requirements, rejection and reworking activities have to be performed. In BOF process for example metal-rejection and steel-reworking.

OEE is a good tool to show up the weaknesses in a process. It defines very clearly the time and efficiency losses in every process step.[118] The key goal is a fast data collection and demonstration of time losses throughout the day in real time.

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[117] Cf.: May, Koch (2008) p. 246; The fast Guide to OEE (2002-2008)

[118] Cf.: May, Koch (2008), p. 245

4.2 BOF cycle time and idle time

The process of productivity enhancement by employing the new tapping system can be described by a BOF-sequence diagram. In fig. 51 the time consumption for every sequence step of the one melting cycle is shown on the basis of ASI. This so called pacing screen shows the way of every single heat from BOF over LMF to caster in real time.

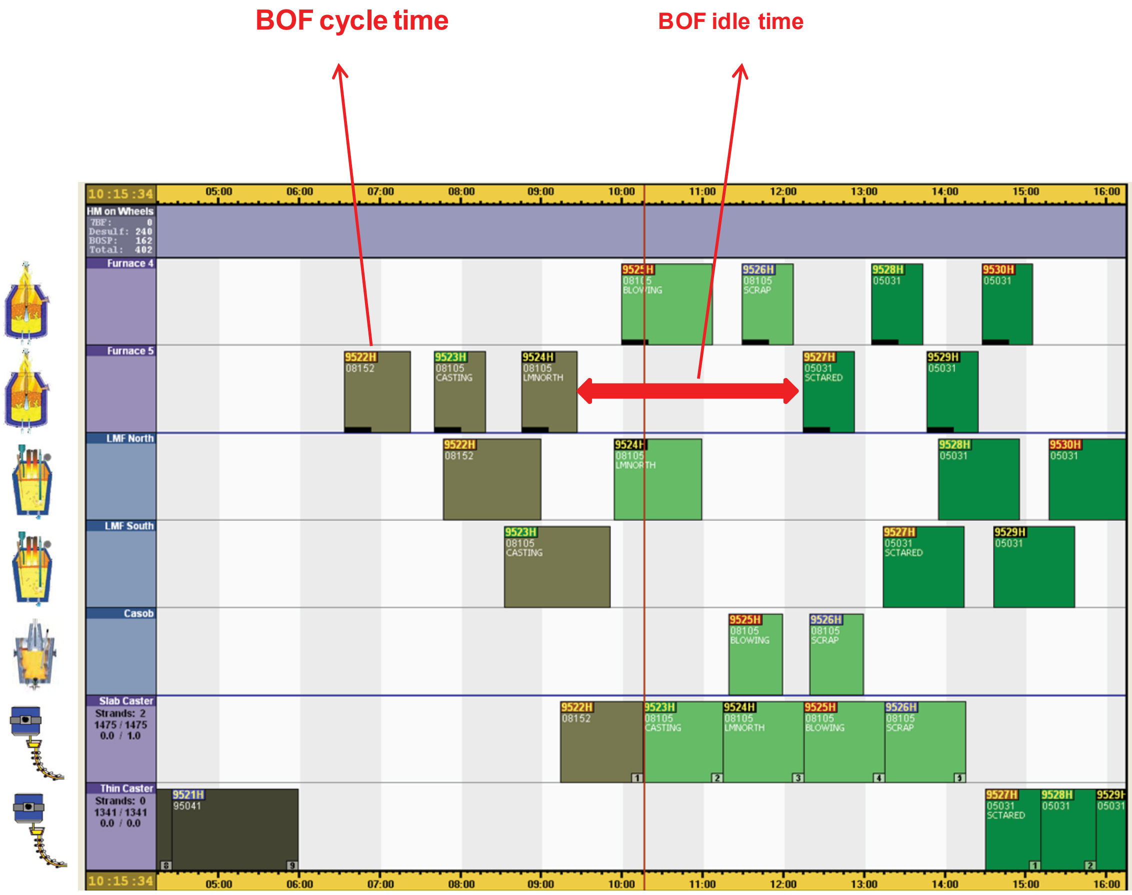

fig. 51: pacing screen [119]

The first two horizontal categories represent the two converters in operation. The next three ones stand for aggregates of secondary metallurgy, like the ladle metal furnaces (LMF) or vacuum treatment. The two aggregates on the bottom are representing the casters. The vertical thin red line shows the actual time. The dark fields on the left hand side of the line are already operated charges, the green fields on the right side are

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[119] Cf.: ASI (2008); Krieger (2003), Foseco Steel (2009)

planned sequences or sequences in operation. The gaps between the operating sequences between are demonstrating the idle time. The identification of the heats are mentioned in the fields and so it is easy to follow up the melt from BOF to caster.

In this juncture it is important, that the casters are well supplied with metal to operate continously without break. Converter maintenance and preparation should be coordinated in a way, that the caster process doesn´t suffer from vessel downtimes. So the utilization of caster preparation breaks for vessel maintenance becomes an important issue. Depending on the number of casters to be supplied, the vessels should be scheduled due to the casters capacities.

This fact is not only valid for the efficiency enhancement of the operation sequences, but also for maintenance activities to be executed in the idle time. If the BOF is the bottleneck (caster capacities are huge enough), the vessel operation efficiency and reduction of idle time become the most important issues anyway.

BOF cycle time

fig. 53 shows the breakup of an operating sequence, containing the characteristical steps of a complete heat of a BOF.

The tap to tap process time ranges between 30 and 50 minutes from plant to plant. The tapping time is about 15 % of the BOF sequence.

Concerning tapping practice there are two ways of improvement: On one hand improvement of tapping efficiency due to reducing tapping time, on the other hand enhancement of taphole lifetime, which reduces the idle time. These two parameters can be described and confronted in one diagram: Tapping time vs. taphole lifetime (fig. 52).

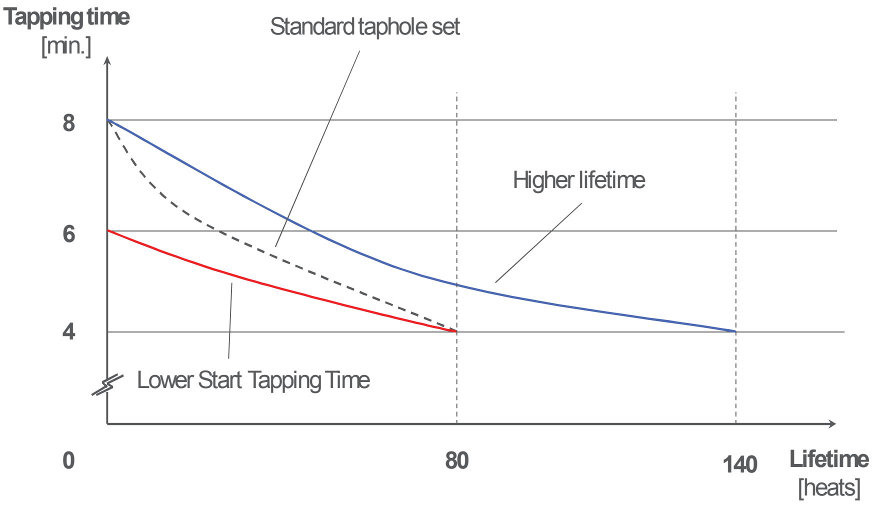

fig. 52: graph tapping time vs. lifetime [120]

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[120] RHI AG (2008)

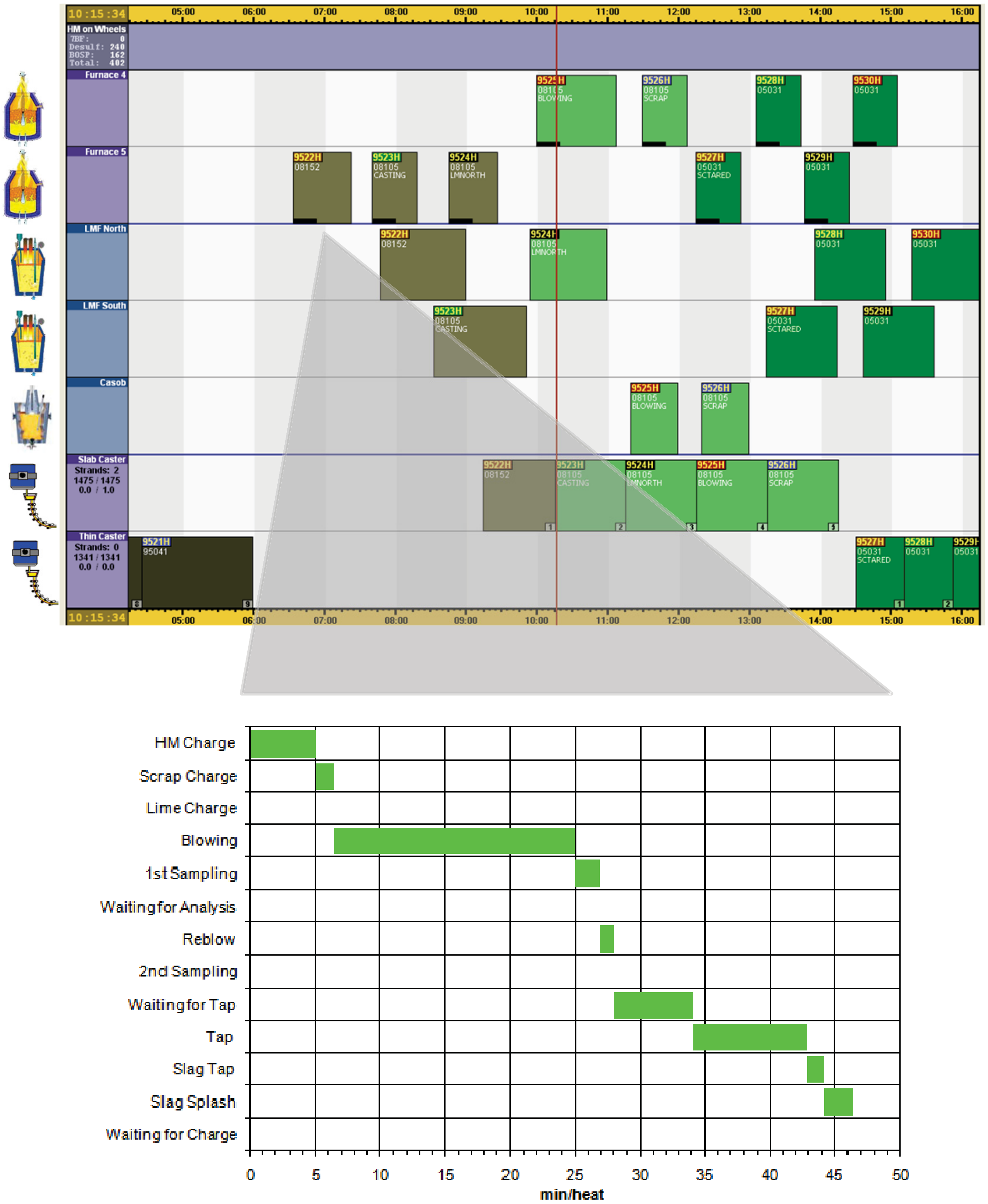

fig. 53: BOF sequence and sequence detail [121]

The figure represents the tapping time in dependence on taphole lifetime. At the beginning – when the new taphole-set is installed – the tapping time is rather high. In process the taphole wears, the start diameter extends and the tapping time decreases due to the higher liquid mass flow.

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[121] Cf.: ASI (2008); Krieger (2003), Foseco Steel (2009)

The target is to decrease tapping time while increasing taphole lifetime. For increasing lifetime and flow dynamics for a fast and constant flow, the durability and shape of the taphole set has to be optimized. The taphole layout has already been discussed in chapter 3. The two parameters range in a certain window. Tapping times below a specific value are not useful, as well as too high taphole lifetimes.

The minimum tapping time is limited due to the duration of adding alloying elements and slag forming additions. This period depends on the capacity of the conveyor system and the fact, that the elements mustn´t be added before a certain level of liquid steel (30-50 %) is tapped into the ladle. Cold additions in the ladle would scorch on refractory immediately when they get in contact with the hot tapping stream. Also there is a risk of blow up.

Maximum start-tapping-time after installing a new taphole is limited by the choice of tapping pipe length and its cold face diameter. The size of the diameter depends on the reachable taphole lifetime and on the desired minimum tapping time (limited by alloying time) due to wear in course of taphole lifetime. Additionally it has to be pointed out, that flow dynamic calculations play an important role concerning turbulences, steel quality (O and N-pick up) and slag carryover.[122] In dependence on vessel bath height during tapping and thickness of vessel refractory lining the shape and diameter of the taphole should be chosen in respect to a constant mass flow.

Concerning steel quality, the mix of the liquid steel with alloying materials and the bath movement has to be mentioned in this juncture. After end of tapping, no further alloying elements should be added.

The taphole lifetime is limited because of the wear of the taphole. When wear reaches a certain value, the dart-plug may slip through the taphole or isn´t able to prevent slag-flow. Also the danger of damaging the surrounding block and refractory lining of the vessel is a big issue in case of destruction of the taphole. With common tapholes, the early change was a problem. The taphole refractory was still too hard and so the breakout operation was very difficult to perform. With the iTap system this fact doesn´t matter.

BOF idle time

When the steelplant runs a higher capacity, the time gaps between the operation sequences have to be decreased and maintenance activities have to be coordinated very strict and efficient. The main target is to supply the casters continuously with metal to guarantee uninterrupted production and to avoid cost-intensive intermissions.

So, BOF maintenance operations should be adjusted to the time gaps of caster preparation. If the average set-up time between two caster sequences is about 40 minutes,

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[122] Cf.: Jeitler, Pungersek, Sauer (2007), pp. 20-23

the maintenance operations at the BOF (Mouth cleaning, Taphole block change, gunning etc.) have to be adapted to this period.

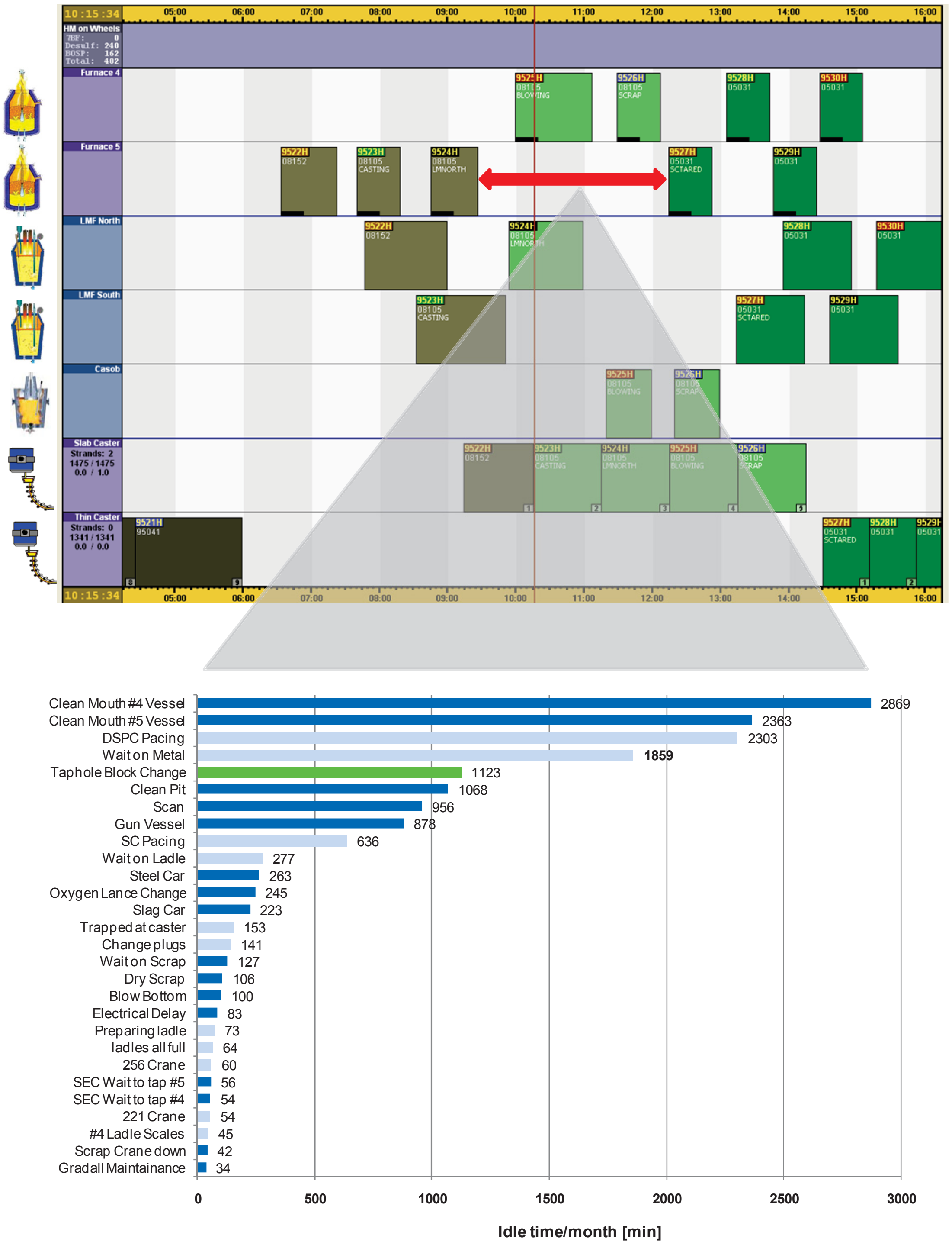

fig. 54: BOF sequence and average idle times/month (jan – sept 2008) [123]

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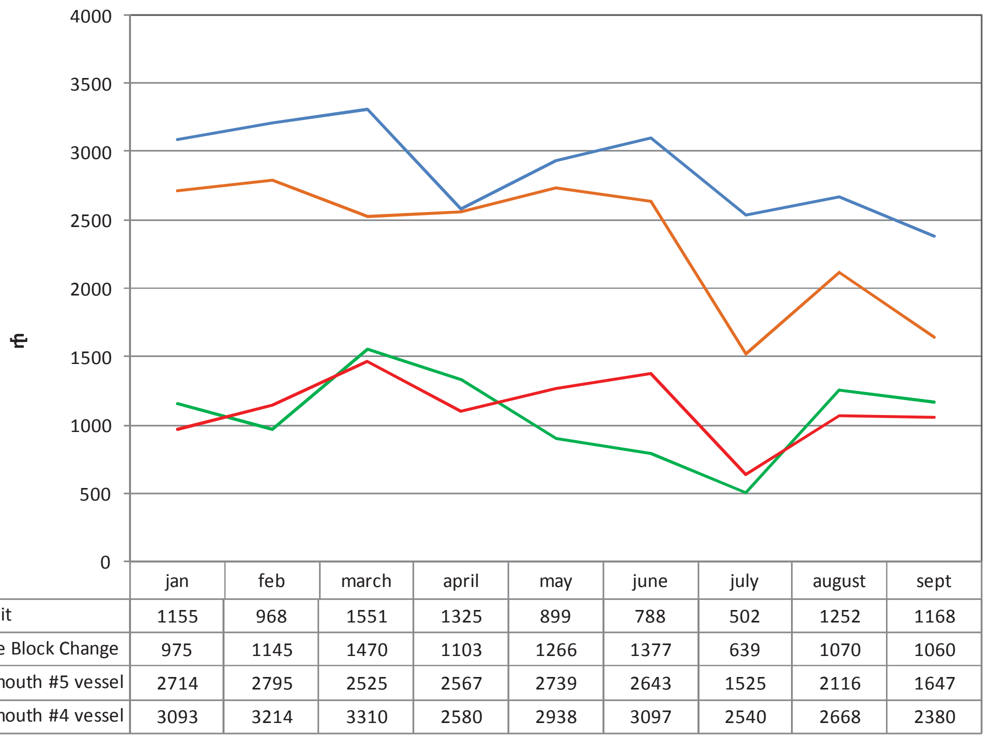
[123] Cf.: ASI (2008); Krieger (2003), Foseco Steel (2009)

To demonstrate the idle times, a delay study is performed representing data from January to September 2008 (fig. 54) to figure out the biggest losses. Regarding BOF-process, mouth cleaning, pit cleaning and taphole block change are the most time consuming factors. The dark blue colored idle times can be influenced by the BOF-process, the light blue idle times not, but they are necessary due to logistic reasons. The green bar shows the monthly time consume of taphole block change.

As seen in fig. 55 the monthly average idle times of the most important BOF maintenance activities decreased during 2008 because of better coordination due to productivity enhancement. Many activities have been set to save time. Most of them are based on more efficient exploitation of workforce (gunning, clean pit..), but also on coordinating activities (better coordination of metal supply, ladle and slag car availability etc.). The TBD wasn´t commisioned at that time and the monthly average taphole changing time was 1123 minutes. After comissioning of the TBD, the expected monthly changing time is about 400 minutes.



	jan	feb	march	april	may	june	july	august	sept
Clean Pit	1155	968	1551	1325	899	788	502	1252	1168
Taphole Block Change	975	1145	1470	1103	1266	1377	639	1070	1060
Clean mouth #5 vessel	2714	2795	2525	2567	2739	2643	1525	2116	1647
Clean mouth #4 vessel	3093	3214	3310	2580	2938	3097	2540	2668	2380

fig. 55: monthly average idle times before comissioning TBD

The tapping practice influences the idle times in two ways. One is the frequency of taphole changes due to the durability of the taphole set. The second is the taphole block change itself.

- Taphole lifetime (campaign life): With a higher lifetime of a taphole set, the frequency of block changes decreases over a converter lifetime. Increasing availability and more stability in process due to a better load factor are the consequences.

- Taphole replacement time: A taphole set has to be changed in certain periods of time because of the wear of the tapholes. The time consumption with a common taphole repair system is huge and an enormous time reduction is possible.

In respect to increase taphole lifetime and to decrease taphole replacement time (and adjust this maintenance sequence to the caster preparation activities), the iTap system (TBD + C-Type) could bring the desired efforts.

4.3 iTap and TBD project

In order to employ the so called iTap-system, preliminary taphole performance field trials, carried out by RHI were used for studies (chapter 4.3.1). A mathematical model is created to figure out the optimum taphole start diameter based on a decided tapping time window and start tapping time in dependence on vessel refractory thickness and ferrostatic bath height over a vessel lifetime. This model is a tool, which enables a simple calculation of the optimum taphole layout within a converter lifetime. Summarizing the results of the productivity elevations and preliminary taphole trials, a justification study for the implementation is carried out (chapter 4.3.2).

4.3.1 Preliminary studies

In early 2008 six trials were carried out by RHI at ASI. For these trials a series of RHI B-Type tapholes were installed (fig. 24). The diameter of the trial sets were selected with 140 and 130 mm. The results after analysis of the data is shown in fig. 56.

The red lines show the regression of average tapping time of common tapholes installed at ASI. On one hand with, on the other hand without repair operations by piping a mortar mass (“piping”). The start tapping time is about 9,8 minutes. The end tapping time after 60 heats is 6 minutes. So the tapping time window ranges 3,3 minutes. With the B-Type taphole (green line, 140 mm diameter), the start and end tapping time is 6,8 and 5,0 minutes after about 60 heats and tapping time window is 1,8 minutes.

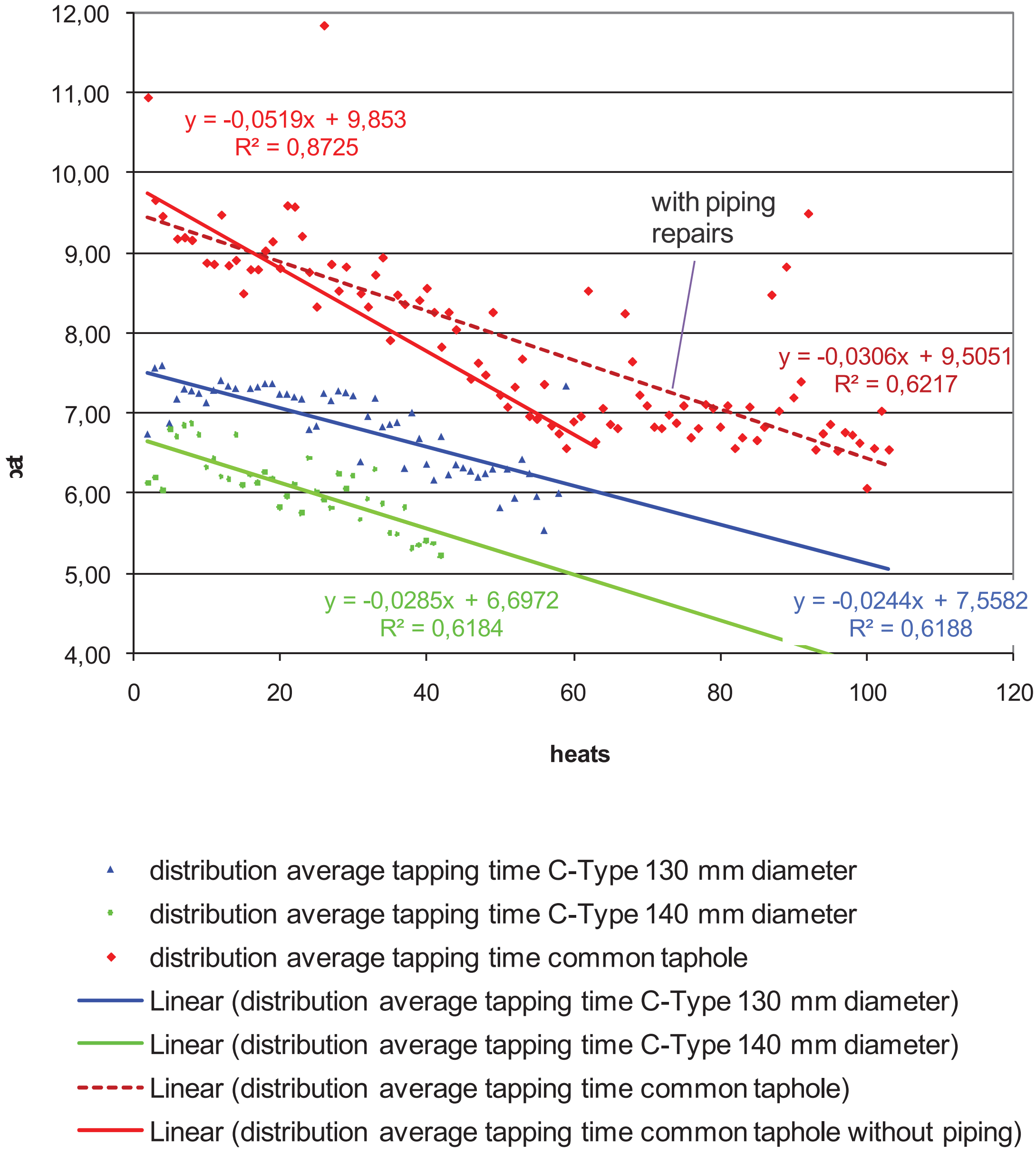


fig. 56: common taphole (red, dark red) and trial sets (blue, green)

The inclination is less steep, but the minimum tapping time at Algoma is limited at about 5 minutes. So the start diameter was decreased to 130 mm. With this new diameter the start tapping time is 7,5 minutes with an end tapping time of 6 minutes after 60 heats (blue line). Also this diameter is too large. If the taphole lifetime increases over 100 heats, the minimum tapping time of 5 minutes would be undershoot very soon. So tapping time window is too narrow and tapping time too short. With four minutes tapping window, lifetime over 100 heats should be possible. Increase of tapping velocity shows significant better wear patterns compared to common used tapholes. The trial tapholes showed already the potential in time savings.

Decision: due to the elongation of the taphole lifetime to over 100 heats and not to fall below the minimum tapping time of 5 minutes, an optimum start diameter of the taphole sets has to be clarified.

Creating a model for optimum start diameter in dependence on taphole length

In respect to flow dynamics (chapter 3.1) and requirements discussed in chapter 4.2 and 4.3.1, a model has to be created to figure out the best start diameter based on a decided tapping time window and start tapping time in dependence on vessel refractory thickness and ferrostatic bath height over a vessel lifetime.

Due to refractory wear, the taphole length has to be adjusted continuously. Also the vessel volume is increasing and hence the bath height and ferrostatic pressure changes continuously.

The aim is, to figure out a method to estimate the lining wear within a vessel lifetime. Therefore the BOF-Scans (attachment 1 to attachment 8) and the corresponding data were analyzed. It was tried to forecast the lining wear by estimation of the volume increase of the vessel.

It was figured out, that the calculation based on the scans is not possible. The converter volume of the analyzed scans range between 164,3 m^3 (attachment 2) and 189,1 m^3 (attachment 8). The calculated volume of a new lined BOF of ASI is 227,6 m^3.[124] So the volume of the scans is unrealistic and not valid for calculations. Also the slag splashing procedure falsifies the results due to coating the lining with slag.

Thus, a theoretical model is established to describe the best start diameter in dependence on vessel wear.

Therefore the wear of a common converter is adducted. A new vessel has got a lining thickness of about 700 mm. At the end of the vessel campaign at about 3000 heats, the lining is about 200 mm, hence the wear during a converter campaign is about 500 mm. The refractory wears constant during a converter campaign. Graph and slope are calculated in (fig. 57).

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[124] Cf.: RHI AG (2008)

heat no.	lining thick-ness
0	700
3000	200

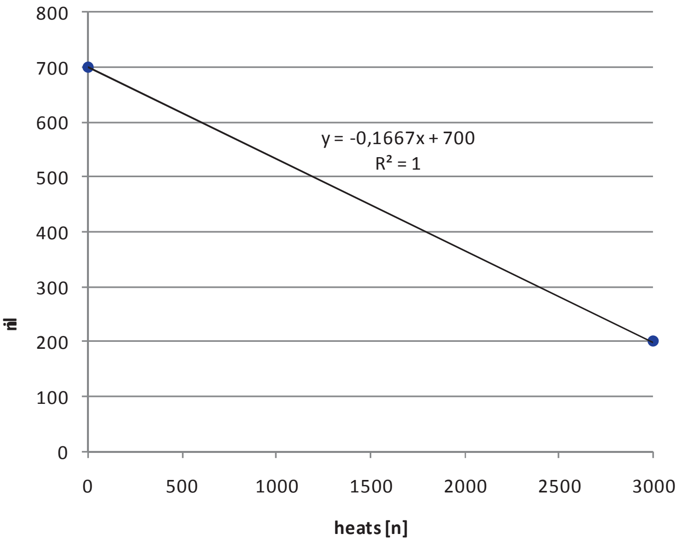

fig. 57: lining wear over a converter lifetime

Now the volume growth of the converter with constant wear over its lifetime has to be estimated. Therefore a preference model of the ASI-converter is created – a sphere with radius from the entrance of the taphole to the vertical center axis of the vessel. The radius is about 3,22 m.

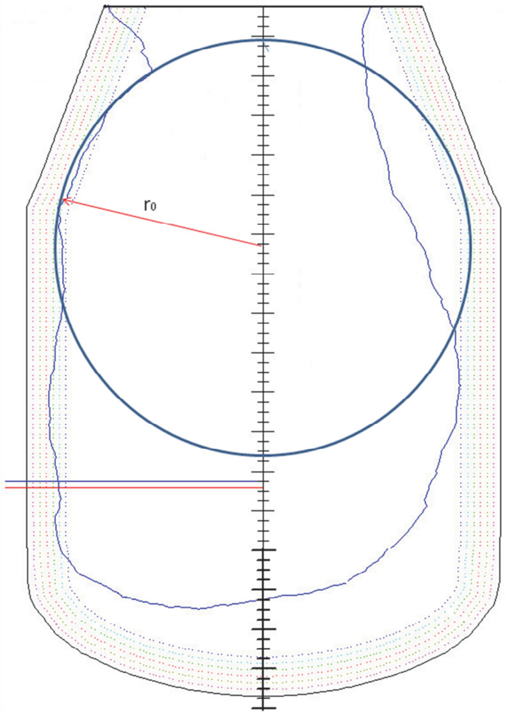

fig. 58: preference model of the ASI vessel [125]

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[125] Cf.: BOF scans by Ferrotron (2008)

This radius and hence the volume of the vessel increases continuously due to wear. With given increasing radius, the volume growth of the sphere can be calculated with equation 24.[126]

$$V_{vessel} = \frac{4r^3\pi}{3} \tag{24}$$

The results show an almost constant increase of the sphere within a wear range of 500 mm over a converter lifetime (fig. 59). Hence the real volume increase can be hypothesized as linear constant.

Volume sphere	
radius [m]	**volume [m³]**
3,22	139,848
3,32	153,2861
3,42	167,5587
3,52	182,6908
3,62	198,7075
3,72	215,6341

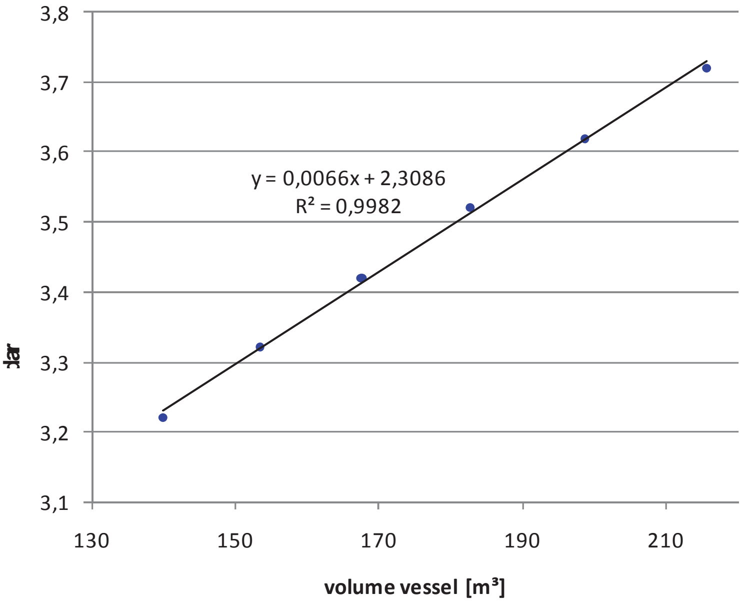

fig. 59: hypothetical volume increase over a converter lifetime

The real volume of the ASI converter is 227,6 m^3.[127] Now the real volume increase of the vessel can be calculated with the slope of the hypothetical volume increase (fig. 59). The (constant) steel volume in the converter at tapping begin can be calculated with equation 25.[128] The steel mass of the ASI converter is 265 short tons, which is 240,404 metric tons and the dense of steel is 7200 kg/m^3.

$$V_{steel} = \frac{m}{\rho} = \frac{m_{steel}}{\rho_{steel}} = \frac{240404\ kg}{7200\ {}^{kg}/_{m^3}} = 33{,}4\ m^3 \tag{25}$$

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[126] Cf.: Papula (2006), p. 37

[127] Cf.: RHI AG (2008)

[128] Cf.: Tipler (1998), p. 339

Hence the steel volume is 33,4 m^3. With the percentage of steel volume related to the vessel volume, the effective bath height above taphole entrance can be calculated.

Usually the maximum bath height above the entry of the taphole at the beginning of tapping is about 1,2 – 1,3 m. Relating to the flow dynamic calculations (chapter 3.1), the effective bath height is lower or equal than 0,3 times of the maximum height (h_{max}) of the bath. With a common h_{max} of 1,3 m, the effective height is about 0,4 m. Due to wear, the steel bath broadens and h_{max} decreases.

heats	lining thickness [mm]	radius vessel at taphole [m]	volume vessel [m^3]	steel bath (% of volume)	effective bath height [m^3]	pipe length [m]	start diameter [m]			
							for 6 min	for 8 min	for 10 min	for 12 min
0	700	3,221	**227,6**	14,7	**0,4**	**1,500**	0,139	0,120	0,108	0,098
100	683	3,238	229,1	14,6	0,397	1,483	0,139	0,121	0,108	0,099
200	667	3,254	230,6	14,5	0,395	1,467	0,140	0,121	0,108	0,099
300	650	3,271	232,1	14,4	0,392	1,450	0,140	0,121	0,109	0,099
400	633	3,288	233,7	14,3	0,390	1,433	0,141	0,122	0,109	0,099
500	617	3,304	235,2	14,2	0,387	1,417	0,141	0,122	0,109	0,100
600	600	3,321	236,8	14,1	0,385	1,400	0,141	0,122	0,109	0,100
700	583	3,338	238,3	14,0	0,382	1,383	0,142	0,123	0,110	0,100
800	567	3,354	239,9	13,9	0,379	1,367	0,142	0,123	0,110	0,100
900	550	3,371	241,5	13,8	0,377	1,350	0,142	0,123	0,110	0,101
1000	533	3,388	243,1	13,7	0,375	1,333	0,143	0,124	0,111	0,101
1100	517	3,404	244,7	13,6	0,372	1,317	0,143	0,124	0,111	0,101
1200	500	3,421	246,3	13,6	0,370	1,300	0,144	0,124	0,111	0,102
1300	483	3,438	247,9	13,5	0,367	1,283	0,144	0,125	0,112	0,102
1400	467	3,454	249,6	13,4	0,365	1,267	0,144	0,125	0,112	0,102
1500	450	3,471	251,2	13,3	0,362	1,250	0,145	0,125	0,112	0,102
1600	433	3,488	252,9	13,2	0,360	1,233	0,145	0,126	0,113	0,103
1700	417	3,504	254,5	13,1	0,358	1,217	0,146	0,126	0,113	0,103
1800	400	3,521	256,2	13,0	0,355	1,200	0,146	0,127	0,113	0,103
1900	383	3,538	257,9	12,9	0,353	1,183	0,147	0,127	0,114	0,104
2000	367	3,554	259,6	12,9	0,351	1,167	0,147	0,127	0,114	0,104
2100	350	3,571	261,3	12,8	0,348	1,150	0,148	0,128	0,114	0,104
2200	333	3,588	263,0	12,7	0,346	1,133	0,148	0,128	0,115	0,105
2300	317	3,604	264,8	12,6	0,344	1,117	0,149	0,129	0,115	0,105
2400	300	3,621	266,5	12,5	0,342	1,100	0,149	0,129	0,115	0,105
2500	283	3,638	268,3	12,4	0,339	1,083	0,150	0,129	0,116	0,106
2600	267	3,654	270,1	12,4	0,337	1,067	0,150	0,130	0,116	0,106
2700	250	3,671	271,8	12,3	0,335	1,050	0,151	0,130	0,117	0,106
2800	233	3,688	273,6	12,2	0,333	1,033	0,151	0,131	0,117	0,107
2900	217	3,704	275,4	12,1	0,331	1,017	0,152	0,131	0,117	0,107
3000	200	3,721	277,3	12,0	0,328	1,000	0,152	0,132	0,118	0,108

tab. 5: mathematical model for start tapping diameter

Due to the increasing converter volume, the percentage of the (constant) steel volume decreases, as well as the steel bath height, which is dependent on this. With this knowledge the bath height in dependence on lining wear can be estimated (tab. 5).

The lining thickness of a relatively new vessel is about 0,7 m (taphole length at this point is about 1,5 m depending on taphole doghouse geometry) and the minimum lining thickness at the end of converter lifetime is about 0,2 m (with a taphole length of about 1 m).

Based on the bath height decression, the adapted tapping pipe length over a converter lifetime can be calculated. With this data it is tried to create the taphole start diameter for a certain start tapping time in dependence on refractory thickness and bath height.

Due to the change of bath height, also massflow and torricellis law has to be integrated. As seen in equation (1), the flow cross section of a free flowing melt stream is:

$$A_{(x)} = \frac{\dot{m}}{\rho\sqrt{2gx}} \tag{26}$$

The area of a circle is defined with:

$$A = \frac{d^2\pi}{4} \tag{27}$$

Introducing equation 27 into 26, the diameter can be expressed:

$$d = \sqrt{\frac{\dot{\mathrm{m}} \cdot 4}{\rho \cdot \pi \cdot \sqrt{2\mathrm{gx}}}} = \sqrt{\frac{\frac{m}{t} \cdot 4}{\rho \cdot g \cdot \sqrt{2 \cdot g \cdot (h_l + h_k)}}} \tag{28}$$

h_l	effective height of bath above entry of tapping pipe
h_k	length of tapping pipe between pipe entry and discharge

This diameter now can be calculated for every situation (tab. 5), for example:

m = 240.404 kg	mass of liquid steel
t = 8 min	decided start tapping time
h_l= 0,40 m	effective height of the bath
h_k= 1,50 m	length of tapping pipe between pipe entry and discharge
ρ = 7.200 kg/m^3	dense of steel

$$d = \sqrt{\frac{\frac{240404}{8 \cdot 60} \cdot 4}{7200 \cdot \pi \cdot \sqrt{2 \cdot 9{,}81 \cdot (0{,}4 + 1{,}50)}}} = 0{,}120\ m \qquad (29)$$

In fig. 60, the optimum start diameter for a chosen tapping time in dependence on tapping pipe length, bath height and vessel wear is demonstrated.

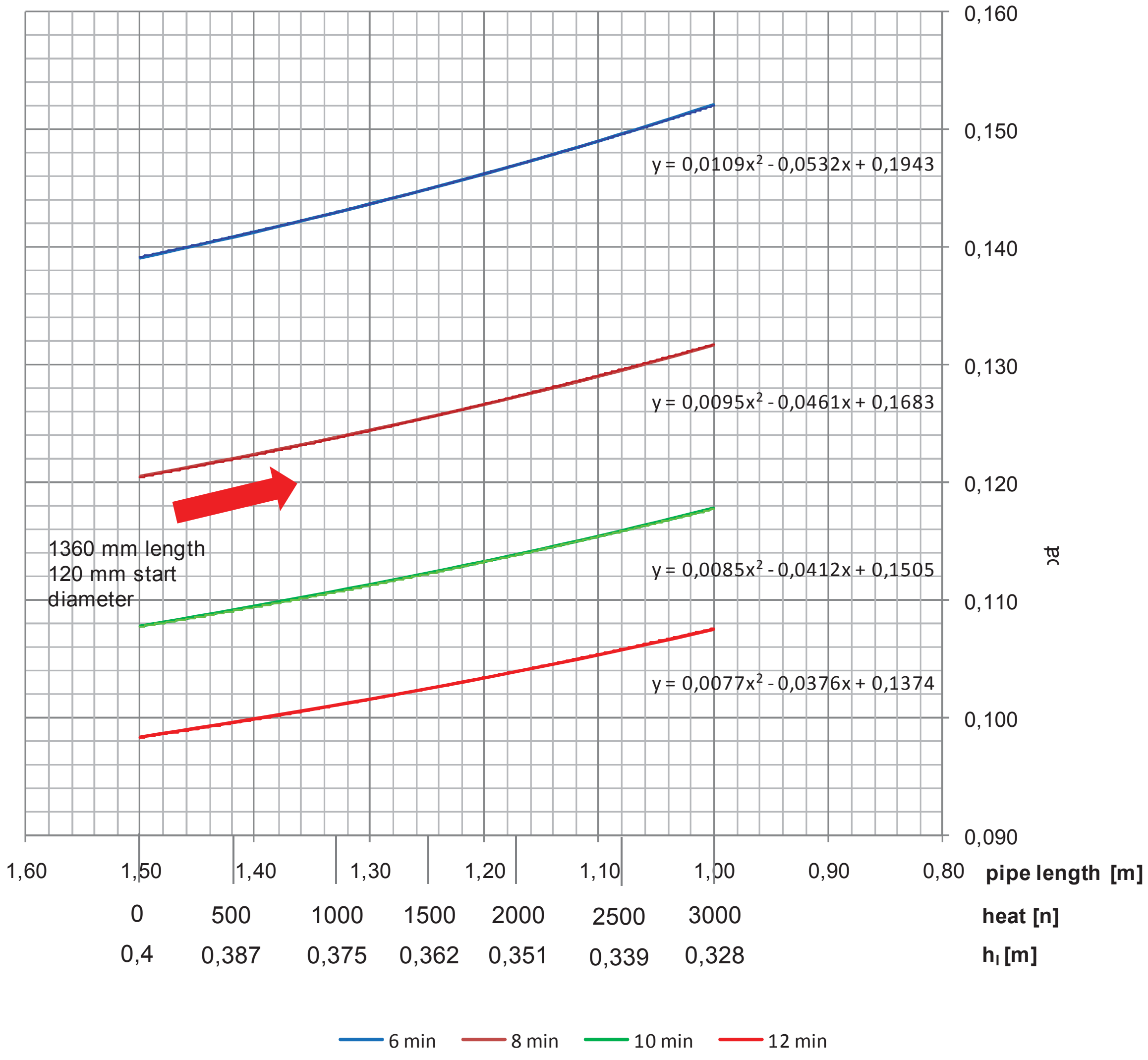

fig. 60: taphole radius in dependence on pipe length

For example: with a new converter lining (0 heats), the tapping pipe length is 1,50 m with an effective bath height of 0,4 m. If the decided start taping time is 8 min, the taphole diameter is 0,120 m. Due to wear and changes in ferrostatic height, the pipe length after 1000 heats is 1,333 m with an effective bath height of 0,375 m. Now the tapping pipe diameter for 8 minutes start tapping time increases to 0,124 m.

So the tapping pipe length and its diameter has to be adjusted over a converter lifetime. The model delivers the mathematical background. But it is not valid for every BOF in general. Due to the characteristics of every single BOF (volume, steel mass), it has to be calculated in respect to their specific data and operation mode.

For the situation at ASI, the decided start tapping time is 9 minutes with a pipe length of 1,36 m at the beginning. In respect to flow dynamics and requirements discussed in chapter 4.2 and 4.3.1, and based on the mathematical model (fig. 60), the start tapping pipe diameter is about 0,116 m. Including mass flow losses due to friction the start tapping diameter is chosen with 0,120 m or 120 mm.

4.3.2 Justification

Calculation annual turnover taphole changing device				
	common device		**TBD**	
Price Machine		150.000 €		640.000 €
Depreciation		6 y		6 y
Taphole changes		192		125
heat size		240,4 t		240,4 t
Depreciation		25.000 €		106.667 €
Tapholes	pieces: 192 price/pc: 800 €	153.600 €	pieces: 125 price/pc: 1600 €	200.000 €
Mixes	(500 kg/taphole) price/kg: 1 € total	96.000 €	(150 kg/taphole) price/kg: 1 € total	18.750 €
Spareparts		35.000 €		11.000 €
Maintenance		3.750 €		32.000 €
Service	1 h/change 45 €/h	8.640 €	2 h/change 45 €/h	11.250 €
Grand total		**321.990 €**		**379.667 €**
additional costs				**57.677 €**

tab. 6: justification, annual turnover TBD

To justify a new installation, a justification study has to be executed. Within this, the results of the trials concerning productivity enhancement and costs of installation of the new tapping system are summed up. The results have to be compared with the current productivity situation. This pre-profitability calculation enables a company to decide, whether an installation is profitable and efficient or not.

In the first step, the new device has to be calculated in respect to the new productivity demands. The price of the common changing system is 150.000 € and the price of the TBD-machine is 640.000 €. Depreciation is given with 6 years. Due to preliminary studies and field trials in other steelplants, the taphole lifetime should be at least 100 heats in a normal process. The taphole lifetime of the common system is about 65 heats.

The C-Type taphole costs 1.600 € and a common taphole 800 €. Gunning mix costs about 1.000 € per ton. An empirical estimation results in 32.000 € maintenance- and 11.000 € sparepart-costs per year for the TBD. The maintenance costs for the common system are about 3.750 € and spareparts are about 35.000 €. Service for every taphole change can be calculated with 1 hour for the common system and 2 hours for the TBD with 45 €/hour personell costs. As seen in tab. 6 the grand total for the annual turnover of the TBD is 379.667 € and of the common system 321.990 €. Hence the additional costs of the TBD are 57.667 € per year.

In the next step, the productivity enhancement by means of the new system has to be discussed. Therefore the current situation must be confronted with the situation after installing the new system (tab. 7).

Starting point is an annual steel production of 3 million tons with a converter size of 240,4 tons, which results in 12.479 heats per year. With a current taphole lifetime of 65 heats and an average changeout time of 137 minutes, the idle time for taphole changes is 26.302 minutes/year. Regarding to the trial analyzis in fig. 56, the tapping time is calculated with an average tapping time of 8,25 minutes/tap, which means 102.953 minutes/year. Hence total tapping time of the old system is 129.256 minutes/year.

With the new TBD system an average taphole lifetime of at least 100 heats should be reached and average changing time can be estimated with 50 minutes/change. The aspired tapping time of the new tapholes should range between 10 and 5 minutes/tap with an average of 7,5. The calculation of the new situation results in 6.240 minutes/year for taphole changes, 93.594 min/year tapping time and 99.834 min/year for total tapping procedures.

After comparison of the two situations, the gained time of tapping improvement procedures is 29.422 minutes/year and the possible utilization of gained time (50 %, empirical value) is 14.711 min/year. This means an additional steel output of 48.013 tons produced steel per year. Including the additional costs of the TBD, the margin per additional produced ton of steel is 68,8 €, which means a total of 3.303.205 € margin per year.

Position	**Situation old 2008**	**Situation new 2009**	**Difference**
Steelproduction	3.000.000 t	3.000.000 t	
Heatsice	240,4 t	240,4 t	
Heats/year	12.479 heats	12.479 heats	
Taphole lifetime average	65 heats	100 heats	
Taphole changes/year	192	125	
Average changing Time	137 min	50 min	
Minutes for changes/year	26.302 min/y	6.240 min/y	**20.063 min**
Tapping time max.	10 min	10 min	
Tappin time min.	6,5 min	5 min	
Average tapping time	8,25 min	7,5 min	
Tapping time/year	102.953 min/y	93.594 min/y	**9.359 min**
Total Time "TAPPING"	129.256 min/y	99.834 min/y	**29.422 min**
possible utilization of gained time		50%	14.711 min
tap-to-tap time (including average idle time)			76,6 min
additional steel produced			**48.013 t/y**
additional costs TBD per additional produced ton of steel			1,20 €
Margin per additional ton produced steel		(70 €/t steel)	68,80 €
margin for additional produced steel			**3.303.205 €**

tab. 7: calculation of tapping benefit

Trials and justification delivered good and auspicious results and showed up the advantages of iTap. So ASI decided to order and install the system.

5 Implementation and results

In this chapter the implementation (chapter 5.2) and results are discussed and compared to the situation before (chapter 5.3.1). With these results a description of the process- and productivity optimization is carried out concluding in a profitability calculation (chapter 5.3.2).

5.1 Project schedule

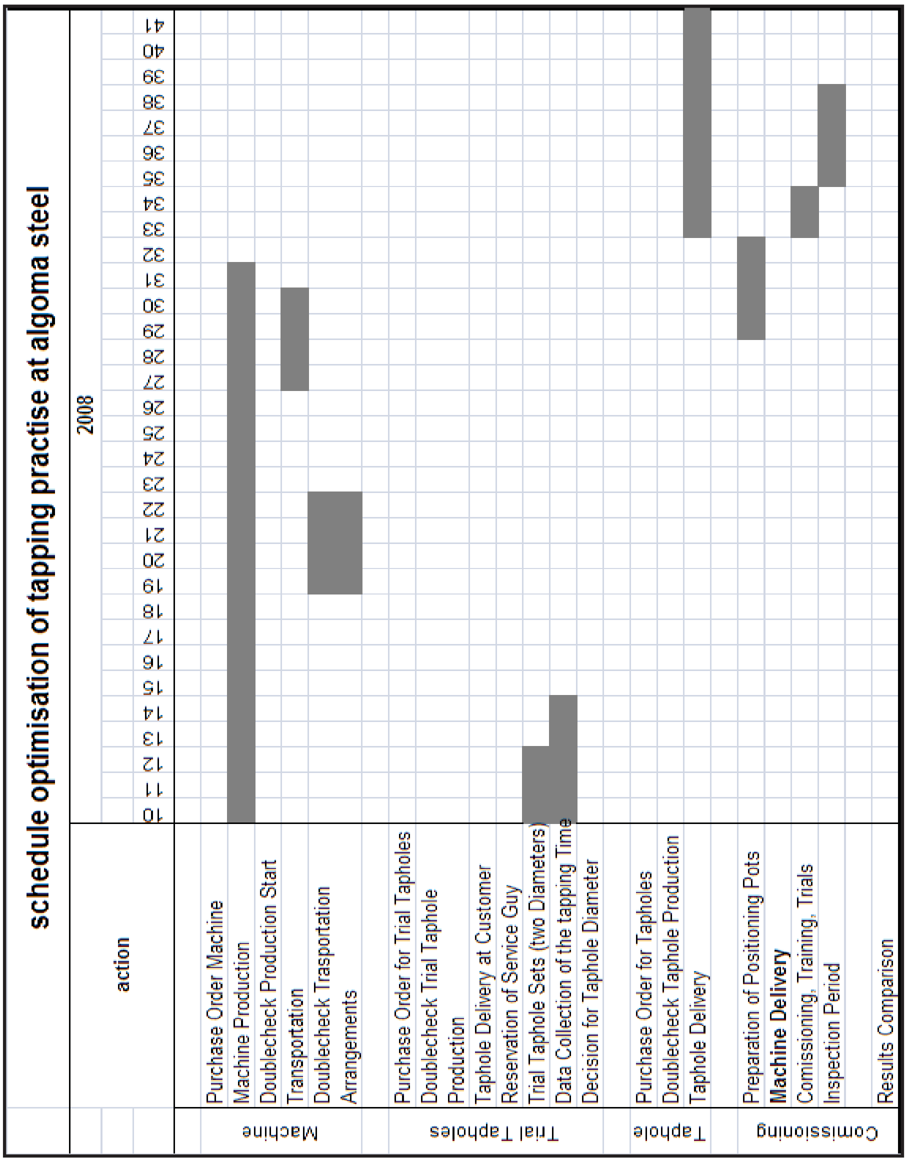

fig. 61: project schedule

5.2 Installations

TBD Layout

After ordering the system, the layout and installation was discussed. fig. 62 demonstrates the drawing of the TBD-layout at the charging floor in front of the BOF.

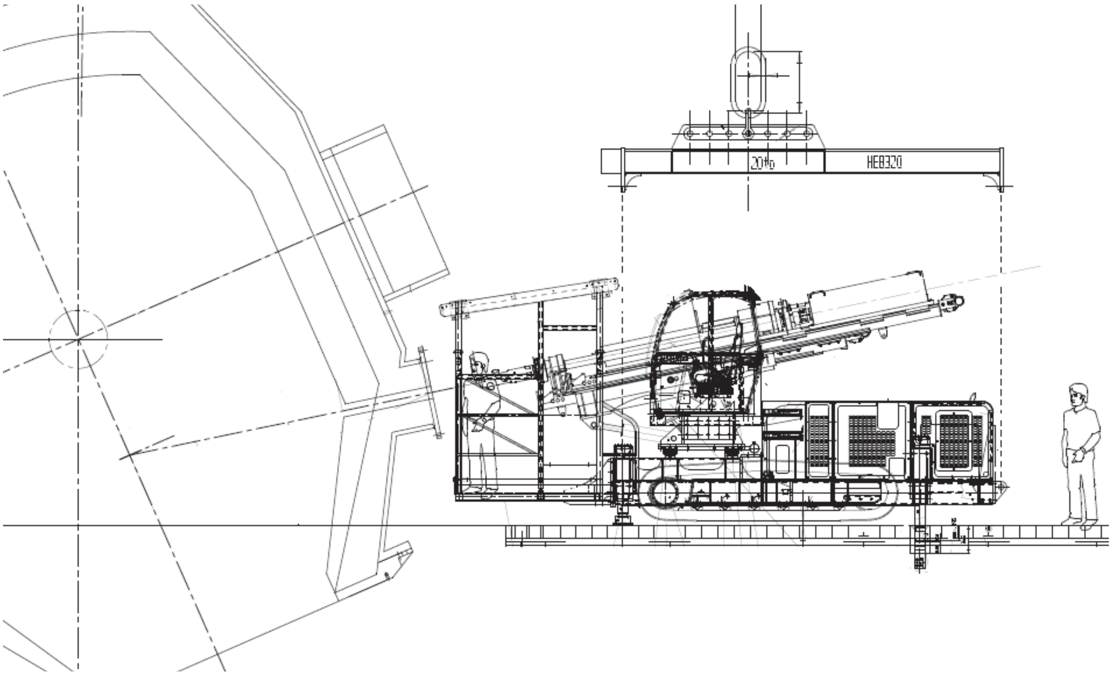

fig. 62: layout of TBD [129]

Installation of TBD and tapping system

The installation of the tapping system at ASI was a challenge for the engineers. Usually the new tapping system is installed during a complete relining of the BOF vessel. In this case, the change should take place within just a few hours and in hot condition of the converter.

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[129] Cf.: RHI AG (2008)

Algoma didn´t want to establish the complete taphole set within the first system change, due not to damage the inner lining and because of the short vessel downtime. So the hot face anels of the surround block were left out. It was decided to assemble the whole tapping set (surround block and pipe) completely before installation to safe time. The diameter of the new taphole is 120 mm according to the trial results discussed in chapter 4.3.1.

fig. 63: lifting up surround block

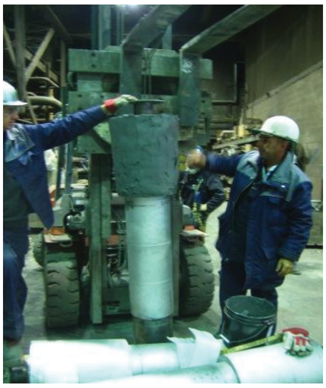

fig. 64: covering of the conical part of C-Type

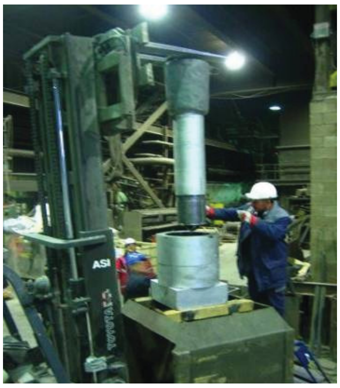

fig. 65: insertion of taphole to surround block

At the beginning of the preparations the surround block was turned upside down on a stand (fig. 63). After that, the tapping pipe was fixed by a sling, lifted up by a forklift and the conical part was covered with a parting agent (fig. 64). This should be done very carefully to ensure proper seal between surround block and tapping pipe. The inner face of the surround block was cleaned (from glue) to have a planed surface that tapping pipe fits 100 % into the cone. Then the C-Type was inserted (fig. 65).

Angle irons were welded on the pipe flange in order to maintain proper spacing on the cold face and the tapping set is positioned 100 % rectangular to the converter (fig. 66). The set was fixed with iron straps. Two angle irons were welded at 9 to 3 o´clock, one angle iron was welded from center of the taphole to 12 o´clock. Spacers were welded on to each piece of angle iron in order to ensure correct fit of turret plate (0-Gap tolerance) (fig. 67).

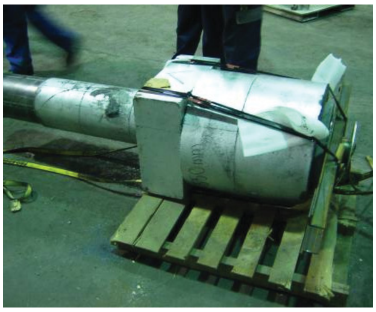

fig. 66: prepared taphole set

fig. 67: sight on the spacers

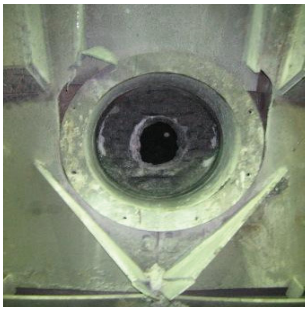

fig. 68: breakout of old surround block

Begin of breakout of old surround block and gunning mix inside the turret to a depth of approx. 800 mm (taphole surround = 700mm) to have enough clearance for gunning the new block properly (fig. 68). The surround block was brougt to the BOF with a forklift and inserted to the doghouse. The centering of the set was very complicated because of its weight and the positioning with the forklift.

fig. 69: gunning of cold face

fig. 70: installation of retaining mechanism

fig. 71: positioning of TBD and calibration of the floor pots

After centering the set, the cold face and the hot face was gunned (fig. 69). The angle irons were burned off and the gunning material was chipped off to have a plane surface. Turret-plate and taphole-retaining-mechanism were prepared and installed (fig. 70). A crane lifted up the TBD on the converter floor for positioning of the floor pots and calibration of the operation position (fig. 71).

Then the first heat was blown, the taphole worked (tapping time about 9 min, T about 1600°C). In fig. 72 the tapping stream of the new taphole is demonstrated, compared to the bad tapping stream of the common one (fig. 73). For the first taphole change with the TBD the floor-pots were installed on the converter floor one day later.

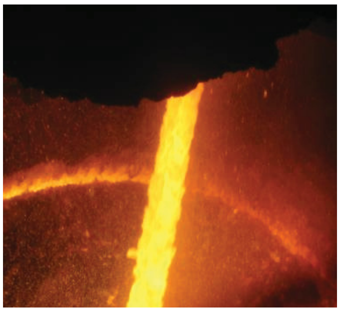

fig. 72: tapping stream of first C-Type taphole

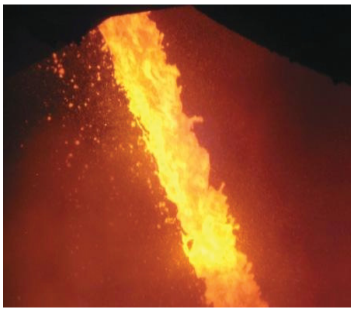

fig. 73: tapping stream common taphole

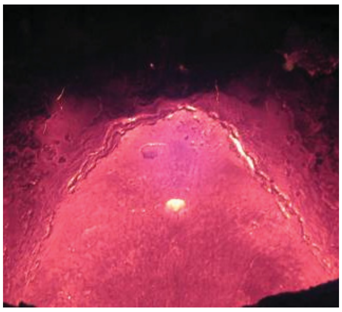

fig. 74: hot face after first tap

5.3 Results

5.3.1 Field trials

In fig. 75 the tapping time courses of a number of taphole campaigns are demonstrated. As discussed in chapter 4.2 the tapping time should range within a certain tapping time window. The tapping time begins at a higher level at maximum tapping time and decreases constantly to the minimum tapping time. Then taphole is changed and the new campaign starts. In order to fulfill the demands on efficiency, the taphole campaigns should be enlarged and the tapping time window should be reduced.

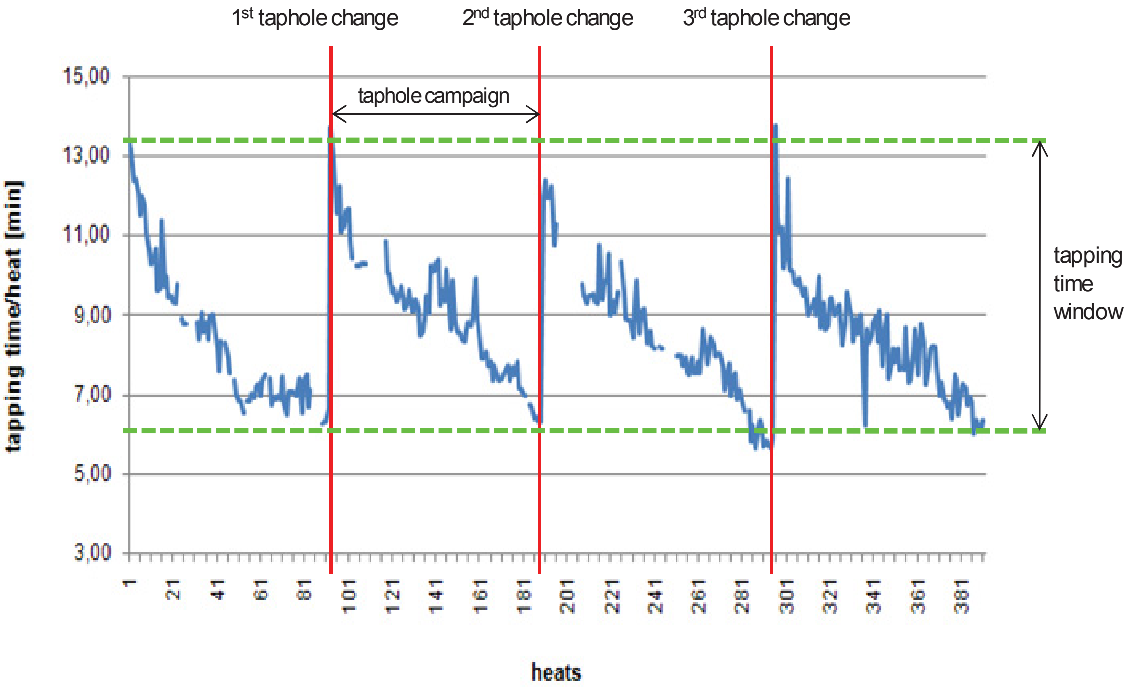

fig. 75: tapping time course, control chart

When the individual courses of every single taphole campaign are overlapped, statements of regularity can be given. In fig. 76 and fig. 77 the tapping time courses of a huge number of common taphole sets and C-Types before and after the installation of the iTap system are compared.

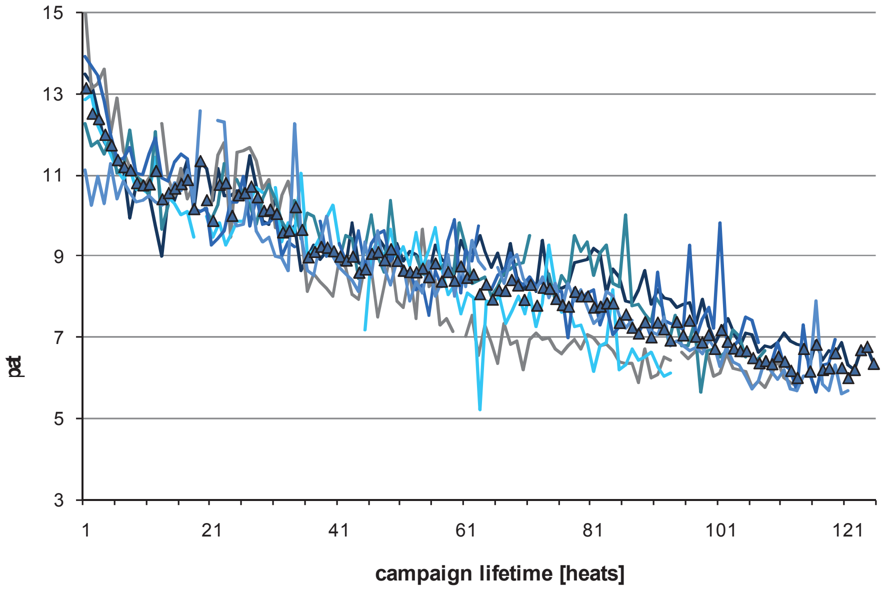

fig. 76: tapping time/heat vs. Taphole campaign life common taphole

Length and cold face diameter of the new tapohle sets (1360 mm and 120 mm) were chosen in respect to the tapping time window of about 10 to 5 minutes and to the flow dynamic demands mentioned before.

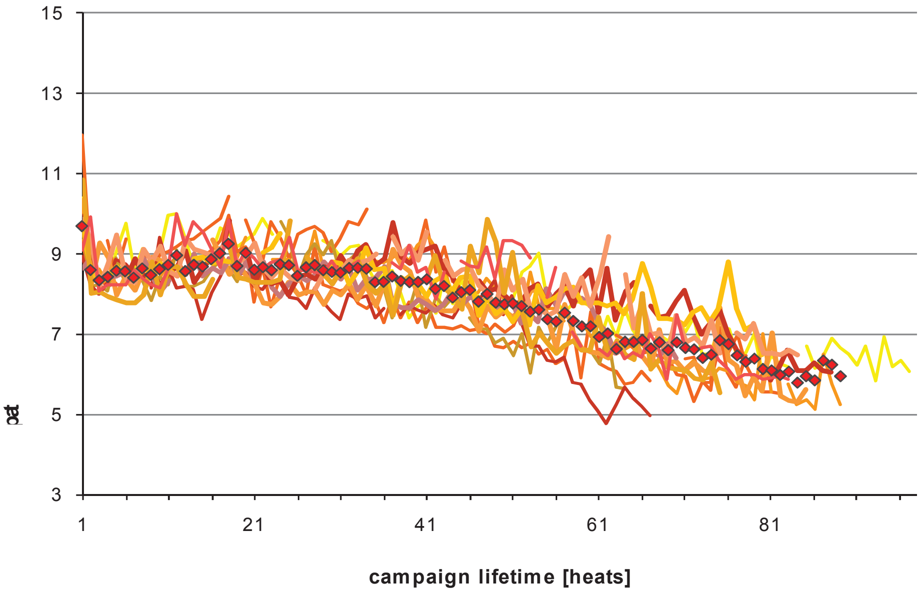

fig. 77: tapping time/heat vs. taphole campaign life C-Type

For a better interpretation, the mean values and their correlations are opposited (fig. 78). The first few C-Type heats were neglected because of non reliable proces parameters due to the setting-in period and adjustment activities. The courses in the diagram are corrected. Exaggerated and understated values due to timekeeping mechanisms (when exceeding a certain vessel tilting angle) or other incidents were excluded.

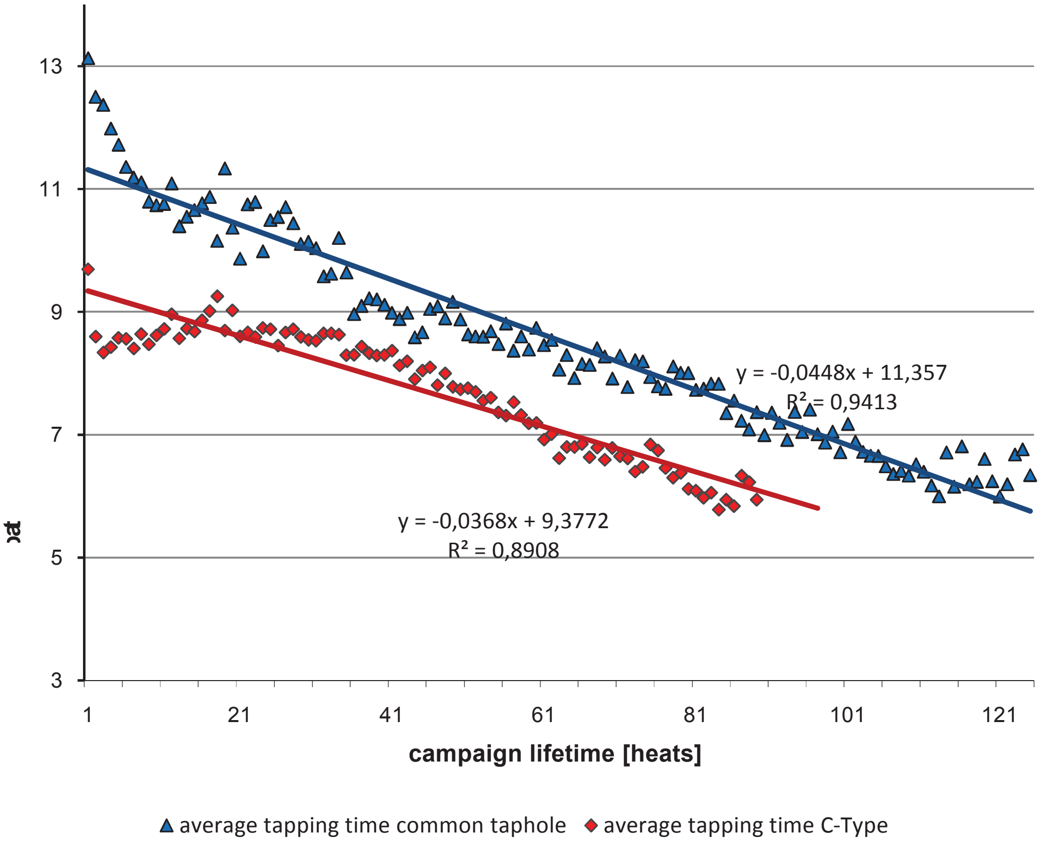

fig. 78: average tapping time/heat vs. taphole campaign lifetime
(C-Type vs. common taphole)

Running time could be reduced about 2 minutes. In relation to the common taphole set the wear rate of the C-Type is less at the beginning. This fact is based on the non stream optimized shape of the standard taphole - the diameter at the hot face is too weak. After the first few heats the shape of the taphole aligns to the optimized flow conditions due to wear mechanisms.

The regression line of the C-Type shows a more even slope than the common taphole. The advantage of this finding is, that the tapping time window reduces and – for a certain start tapping time - longer lifetime without going below the minimum alloying time is possible.

A huge number of runout times are confronted with a similar number of runout times after the iTap installation. The comparison of the distribution of the runout times (common taphole vs. new taphole) (fig. 79) shows, that the new system gains time. Further more - compared to the common system - the sum frequency demonstrates a slightly more constant distribution of the tapping times.

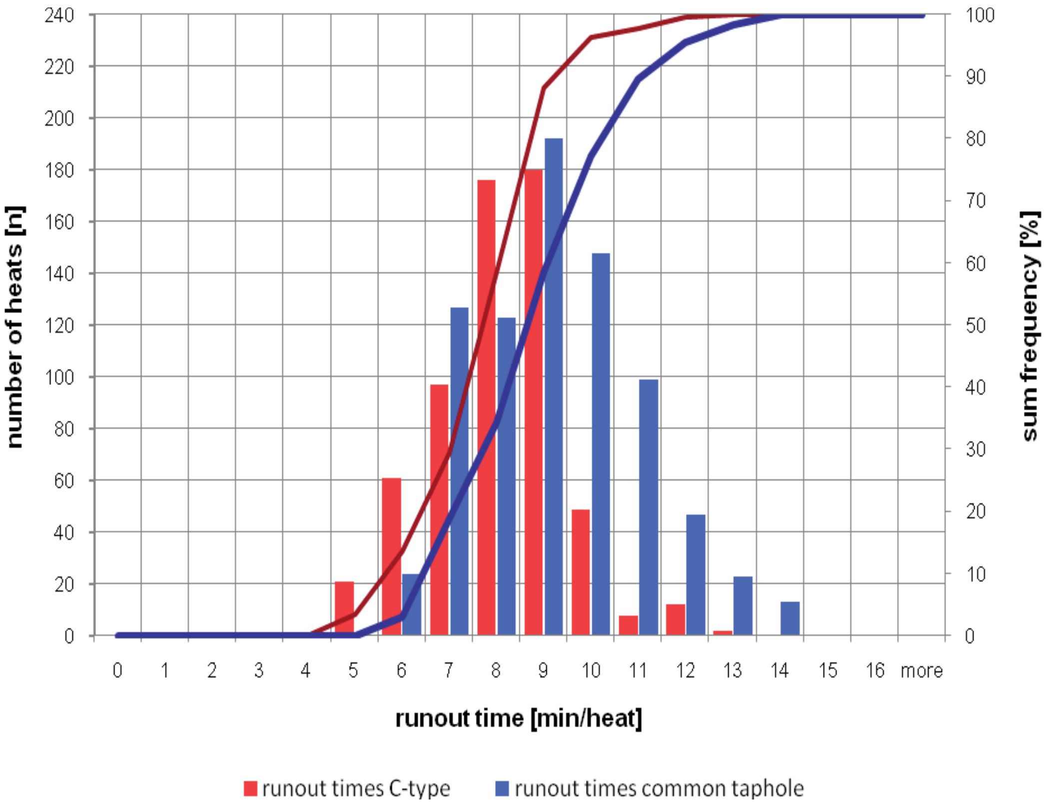

fig. 79: runout time # 5 furnace (common taphole vs. C-Type)

Regarding taphole lifetime, the control chart of the lifetime course is demonstrated in fig. 80. The blue bars show the lifetime before, the red bars the lifetime after taphole system change. The green bars present taphole changes without piping.

It is obvious, that taphole lifetime of the common system waves very unstable, while the new taphole shows a more constant range. Also the taphole lifetime increases slightly due to the improving adjustment to process.

The common taphole reaches 102 heats in average from January to October 2008, while the C-Type averaging 77 heats reclines beneath this value (October 2008 to April 2009). In fig. 81 the distributions are confronted.

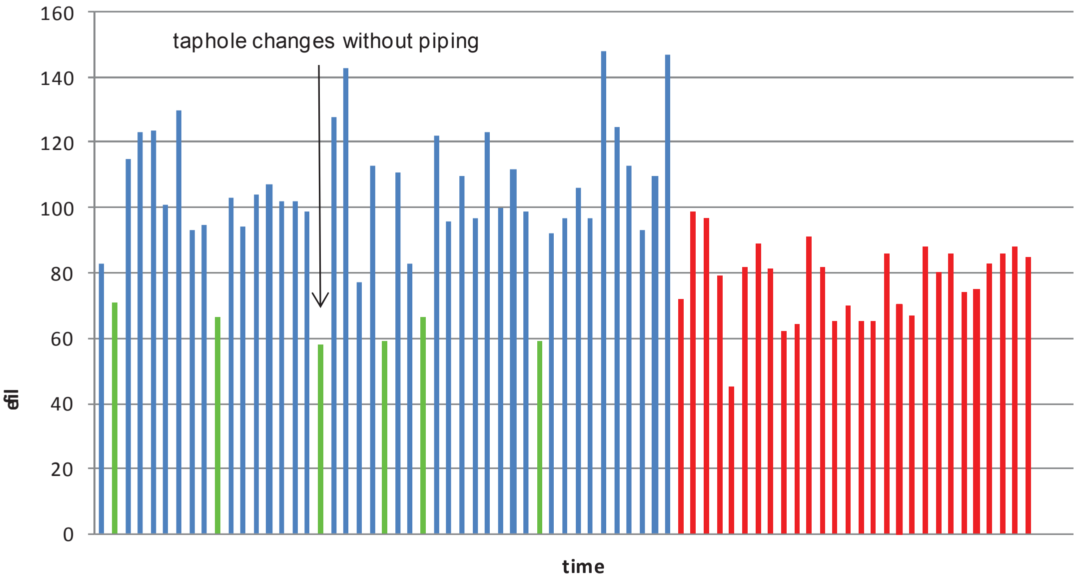

fig. 80: control chart taphole lifetime

The reason is the production decrease due to the beginning of Recession in October 2008. Demand broke in and production slashed from about 20 heats/day to max. 10 heats/day on one vessel. As a consequence the time gaps between the heats increased and hence huge temperature fluctuations occurred. Thermo-shock caused material stress and less durability. Under regular circumstances lifetime of C-Type reaches 110 heats minimum, as seen in trials at Port Talbot Steelworks.[130] Also for training purposes tapholes were changed.

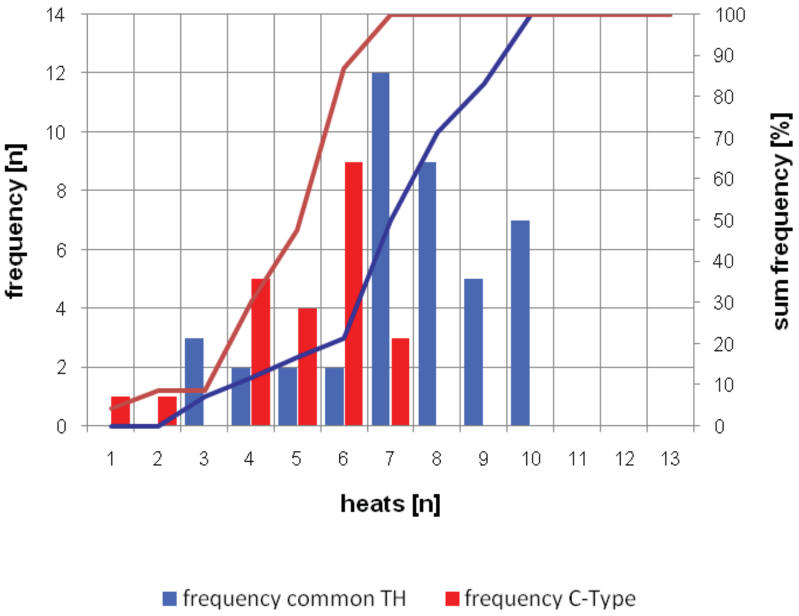

fig. 81: taphole lifetime C-Type vs. common taphole furnace # 5

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[130] Cf.: Berger, Cormier; (2006), pp. 1-7

The comparison of the taphole replacement time brought a huge time gain due to the faster repair sequence. fig. 82 shows the control chart of the replacement time before (blue bars) and after the taphole system change (red bars).

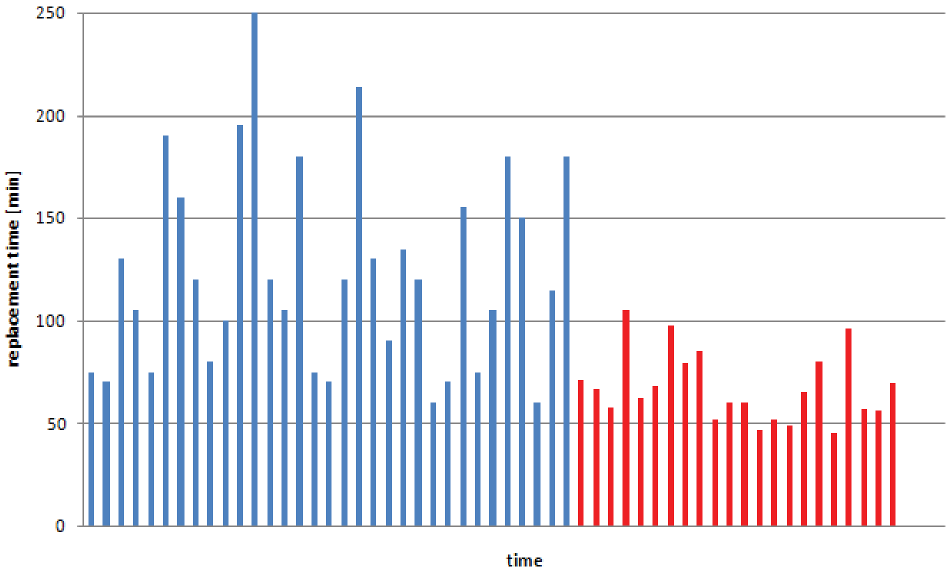

fig. 82: control chart taphole replacement time

In fig. 83 the old and new system are compared and the difference is huge. The replacement time of the common system (blue bars) had a very bad distribution between 60 and more than 200 minutes, with an average value of 120 minutes.

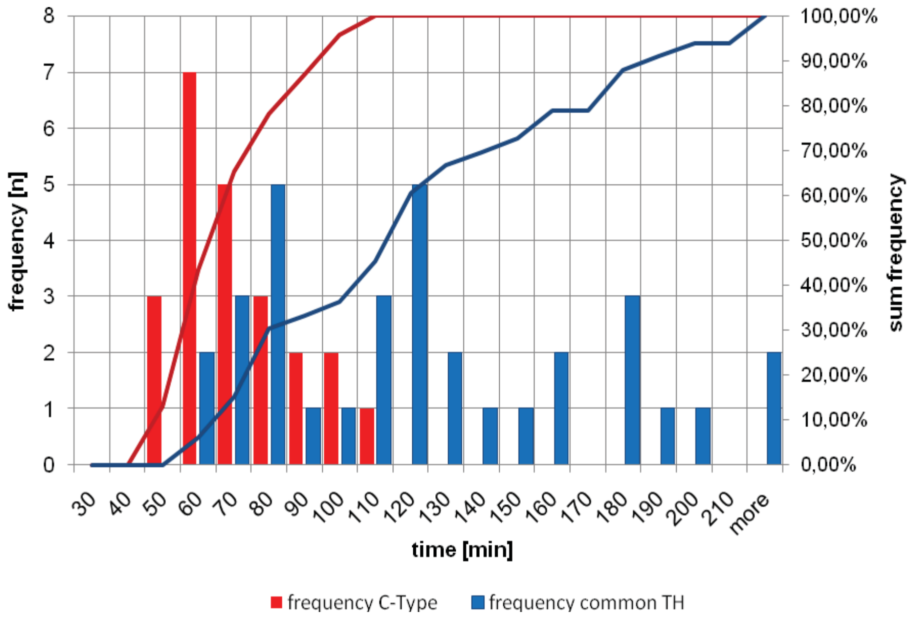

fig. 83: taphole replacement time common taphole vs. C-Type

After installation of the iTap system the replacement time ranges between 50 and 100 minutes (red bars) with a very steady course and an average of 65 minutes at the moment. A further decression of repair time below 50 minutes in the near future is expected.

5.3.2 Profitability calculation

Relating to the justification discussed in chapter 4.3.2, the profitability calculation can now be executed with the field trial results after installation of the TBD. The results of productivity enhancement (tab. 8) and operation costs of the new tapping system (tab. 9) are summed up (tab. 10) and compared to the situation before.

Further more this calculation is executed for four different cases to figure out the profitability of different operation modes. Case 1 shows the common taphole changing operation without piping the tapholes. In Case 2 the taphole is piped with a gunning mass when taphole lifetime exceeds 63 heats (to increase lifetime). These operation modes were executed at ASI. Case 3 represents the new iTap system at current situation due to the economic difficulties.

The results of case 3 are only valid, when the BOF’s work at full capacity. In the actual situation the efficiency doesn´t play a big role because of the production decrease due to recession. Case 3 is an indication of the actual working point and a good originator to estimate the situation at full capacity, which is demonstrated in case 4.

	Position	**Case 1** common taphole without piping	**Case 2** common taphole with piping	**Case 3** C-Type & TBD without piping (current)	**Case 4** C-Type & TBD without piping (optimized)
production	Production [t/year]	3.000.000	3.000.000	3.000.000	3.000.000
	Capacity BOF [t]	240,4	240,4	240,4	240,4
	Production [heats/year]	12.479	12.479	12.479	12.479
tapping time	Taphole life:				
	- without piping [heats]	63	-	77	110
	- with piping [heats]	-	102	-	-
	Tapping time:				
	- maximum [min]	11,00	11,00	9,30	9,00
	- minimum [min]	6,50	6,00	6,00	5,00
	- average [min]	8,75	8,50	7,65	7,00
	- total [min/year]	109.193	106.073	95.466	87.354
changeout	Taphole changes [n]	*198*	*122*	*162*	*113*
	Changeout time [min/change]	137	137	65	50
	- year [min/year]	27.137	16.761	10.534	5.672
	- month [min/month]	2.261	1.397	878	473
	Mix consumpthin [kg]	500	500	150	150
piping	Start of piping [heat #]	-	63	-	-
	Number of pipings	-	3	-	-
	Time consumption/piping [min]	-	10	-	-
	Mix consumtion/piping [kg]	-	1.000	-	-
	Total piping time [min]	-	3.670	-	-
results	Tapping time [min/year]	109.193	106.073	95.466	87.354
	Changeout time [min/year]	27.137	16.761	10.534	5.672
	Changeout time [hours/year]	452	279	176	95
	Piping time [min/year]	0	3.670	0	0
	Time consumption	136.783	126.784	106.176	93.121
	Taphole consumption [pcs]	**198**	**122**	**162**	**113**
	Mix consumption [kg]	**99.041**	**428.208**	**24.310**	**17.017**
	Time gain [min. savings]	**-**	**9.998**	**30.607**	**43.661**

tab. 8: additional profit due to tapping time gain

Position	**Case 1** Gradall	**Case 2** Gradall	**Case 3** TBD	**Case 4** TBD
Acquisition	150.000 €	150.000 €	640.000 €	640.000 €
Depreciation (6 years)	6 years	6 years	6 years	6 years
	25.000 €	25.000 €	106.667 €	106.667 €
Maintenance	2,5 %	2,5 %		
	3.750 €	3.750 €	40.000 €	40.000 €
Operating resources	10 l/h * 0,8 CAD * 352 h	10 l/h * 0,8 CAD * 224 h	10 l/h * 0,8 CAD * 130 h	10 l/h * 0,8 CAD * 130 h
	1.760 €	1.120 €	650 €	650 €
Driver (45 CAD/hour))	848 h	891 h	500 h	321 h
	23.863 €	25.062 €	14.054 €	9.040 €
Drill	5 changes/piece 1500 CAD/piece	5 changes/piece 1500 CAD/piece	maintenance drilling head	maintenance drilling head
	37.140 €	22.940 €	11.000 €	11.000 €
Machine incl. maintenance & service	**91.513 €**	**77.871 €**	**172.371 €**	**167.357 €**
Tapholes	800 €/piece	800 €/piece	1600€/piece	1600€/piece
	158.466 €	97.876 €	259.308 €	181.516 €
Mixes	49.521 €	214.104 €	12.155 €	8.509 €
Grand total (€/year)	**299.500 €**	**389.851 €**	**443.834 €**	**357.381 €**
costs/ton produced steel	**0,100 €**	**0,130 €**	**0,148 €**	**0,119 €**
Δ costs (€ additional)	**- €**	**90.351 €**	**144.334 €**	**57.881 €**
Δ costs/ton (€/ton additional)	**- €/t**	**0,030 €/t**	**0,048 €/t**	**0,019 €/t**

tab. 9: additional machine and maintenance costs

Position	**Case 1** common taphole without piping	**Case 2** common taphole with piping	**Case 3** C-Type & TBD without piping (current)	**Case 4** C-Type & TBD without piping (optimized)
time gain [min. savings]	-	9.998 min	30.607 min	43.661 min
possible utilization of gained time		50 %	50 %	50 %
netto time gain [min. savings]		4.999 min	15.303 min	21.831 min
additional melts	76,6 min tap-to-tap	76,6 min tap-to-tap	76,6 min tap-to-tap	76,6 min tap-to-tap
	-	65	200	285
additional production (tons/year)	-	15.689 t/y	48.028 t/y	68.513 t/y
additional costs (machine and maintenance)	-	90.351 €	144.334 €	57.881 €
additional costs (machine and maintenance) per additional produced ton of steel		5,76 €/t	3,01 €/t	0,84 €/t
Margin per additional ton produced steel	(70 €/ton steel)	64,24 €/t	66,99 €/t	69,16 €/t
Grand total cost savings (€/year)	-	1.007.907 €	3.217.614 €	4.738.022 €
Grand total cost savings (CAD/year)	-	1.612.652 CAD	5.148.183 CAD	7.580.835 CAD
Savings/ton produced steel (€)	-	0,34 €	1,07 €	1,58 €
Savings/ton produced steel (CAD)	-	0,54 CAD	1,72 CAD	2,53 CAD

tab. 10: grand total cost savings

6 Discussion

After successful taphole trials in March 2008 and additional benefits on productivity caused by the implementation of a new tapping system, ASI decided the acquisition of iTap. To define a correct taphole length and shape, the trials showed the necessarity of a calculation model.

By means of this created mathematical basis and after the successful implementation of the new iTap taphole changing system in October 2008, the field trials provided good results. Relating to the calculation model in chapter 4.3.1, the field trials were performed with C-Type tapholes with a length of 1360 mm and a start diameter of 120 mm. To compare the situation before and after installation, huge process data sets were evaluated.

In fig. 76 and fig. 77 the tapping time courses of the old and new system are compared. Exaggerated and understated values due to timekeeping mechanisms or other incidents were excluded. The comparison of the mean values and their correlation lines show a tapping time reduction of about 2 minutes (fig. 78). Further more it shows a more even slope. This is an important finding, because this fact reduces the tapping time window and longer lifetime within a certain tapping time range is possible. The wear at the beginning is less, due to the stream optimized shape of the new taphole.

A curious effect is the slight increase of tapping time within the first 20 heats of the new taphole. This effect is probably based on the wear inside the taphole over the first few heats, with the consequence, that the stream optimized shape suffers. After a number of heats the shape might be growded in – due to converter characteristics – and wear is constant. Also the interplay between metal and slag could be conductive to this effect.

Also the comparison of the frequency of tapping times (fig. 79) confirmed the time gain. The sum frequency of the new system shows a more constant distribution, which means a more constant tapping time.

The shorter taphole lifetime of the new tapholes (fig. 81) is based on thermo-shock due to discontinuous operation mode and idle times caused by the production decrease. In case of a normal operation mode, the taphole lifetime would be at least as high as the common system (as seen in trials at Port Talbot[131] and refered to the increasing lifetimes during the field trials (fig. 80)).

Taphole replacement time – which is one of the most important issues in respect to capacity adjustment and also concerning time gain – slashed down from 120 minutes average with the common system to 65 minutes average with iTap (fig. 82 and fig. 83).

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[131] Cf.: Berger, Cormier; (2006), pp. 1-7

50 minutes or less can be expected. Further more the replacement time of the iTap system shows a more constant time range.

With these calculations and findings, the productivity and profitability calculations can be realized. Initial point is to demonstrate the common changing system with its two different operation modes: case 1 with and case 2 without piping repairs (tab. 8). These cases have to be compared to the actual TBD operation mode and the TBD operation mode under efficient production (case 3 and 4).

The first case works at a high average tapping time of 8,75 minutes. The taphole lifetime is 63 heats in average and hence 198 taphole changes have to be performed with a changing time of 137 minutes each.

The second case operates with piping repairs, so lifetime increases up to 102 heats. Although piping time is huge, this case gains time because of the decreasing number of taphole changes. The big disadvantages are additional costs due to massive mix consumption.

In comparison, the iTap system is more efficient. With a defined tapping time window between about 9,5 and 5 minutes and an average tapping time 2 minutes below the old system, the time gain is enourmous. Also taphole replacement time is lower. Time gain ranges between 30.607 to 43.661 minutes per year (case 3 and 4) in dependence on the taphole lifetime. The gunning mix consumption is low (no piping repair and self-centering conical surround block).

Machine and maintenance costs declare high annual costs of iTap in comparison to the common system (tab. 9). The acquisition of the taphole changing device in case 1 and 2 (Gradall) is 150.000 € and for the TBD machine (case 3 and 4) 640.000 €. Calculating and summing up the depreciation, maintenance-, and driver costs, the annual costs of the TBD are higher compared to the common changing system.

Including the taphole costs and gunning mixes, the situation is changing. Now the additional costs of the TBD are more than 30.000 € lower (case 2 and 4) than the additional costs of the common system with piping. At the actual TBD operation mode (case 3) the additional costs of the TBD are more than 50.000 € higher (compared to case 2).

Summing up the additional savings by production increase and additional costs of installation of the new system, the grand total shows a gain in profitability (tab. 10).

The additional margin of the current situation (case 3) compared to case 1 would be 3,2 million € per year with 1,07 € savings per ton produced steel. Compared to case two the savings are about 2,2 million €. When the steelplant runs efficient and the capacity utilization is good (case 4), the annual margin would be over 4,7 million € per year with 1,58 € savings per ton produced steel (case 4).

7 Summary

The topic of this thesis deals with the productivity enhacement of an integrated steel plant in Ontario/Canada by employing an innovative tapping system calls iTap. For development of capacity, a series of structural changes and improvements of process is essential. The challenge is to find, optimize or remove the weaknesses in process.

A customer wants devices which work, decrease of steel production costs and enhancing profitability – quality of process and products. Based on availability and performance studies, and defining the BOF shop with its BOF´s as key production stage for bottlenecking-activities, ASI decided to implement the system.

Within this thesis the whole system installation beginning with analyzing taphole trials in March 2008 performed by RHI is accompagnied. The new system called iTap is a complete package consisting of stream optimized tapholes (C-Types) and the Taphole Changeout Device (TBD).

Regarding to patents and performance studies made within this thesis, the optimum layout of the tapping pipes concerning flow dynamics was calculated and resulted in a mathematical model. Based on this model, the tapping pipes can be adjusted to process.

The implementation of the system implicated extensive preparatory work resulting in a complete system change within one day at the beginning of October 2008, which was successful. After this, the field trials began and huge quantities of process data before and after installation had to be worked off. The target was to emblaze the process concerning productivity and profitability and to show customers the advantage of the system. The results are demonstrated in chapter 6.

Due to recession beginning in autumn 2008 and decreasing production, the trials had to be performed over a longer period of time, to provide correct results. Comprising process data of more than 9 months, the analysis brought out reliable facts of productivity and profitability enhancement caused by the implementation of iTap.

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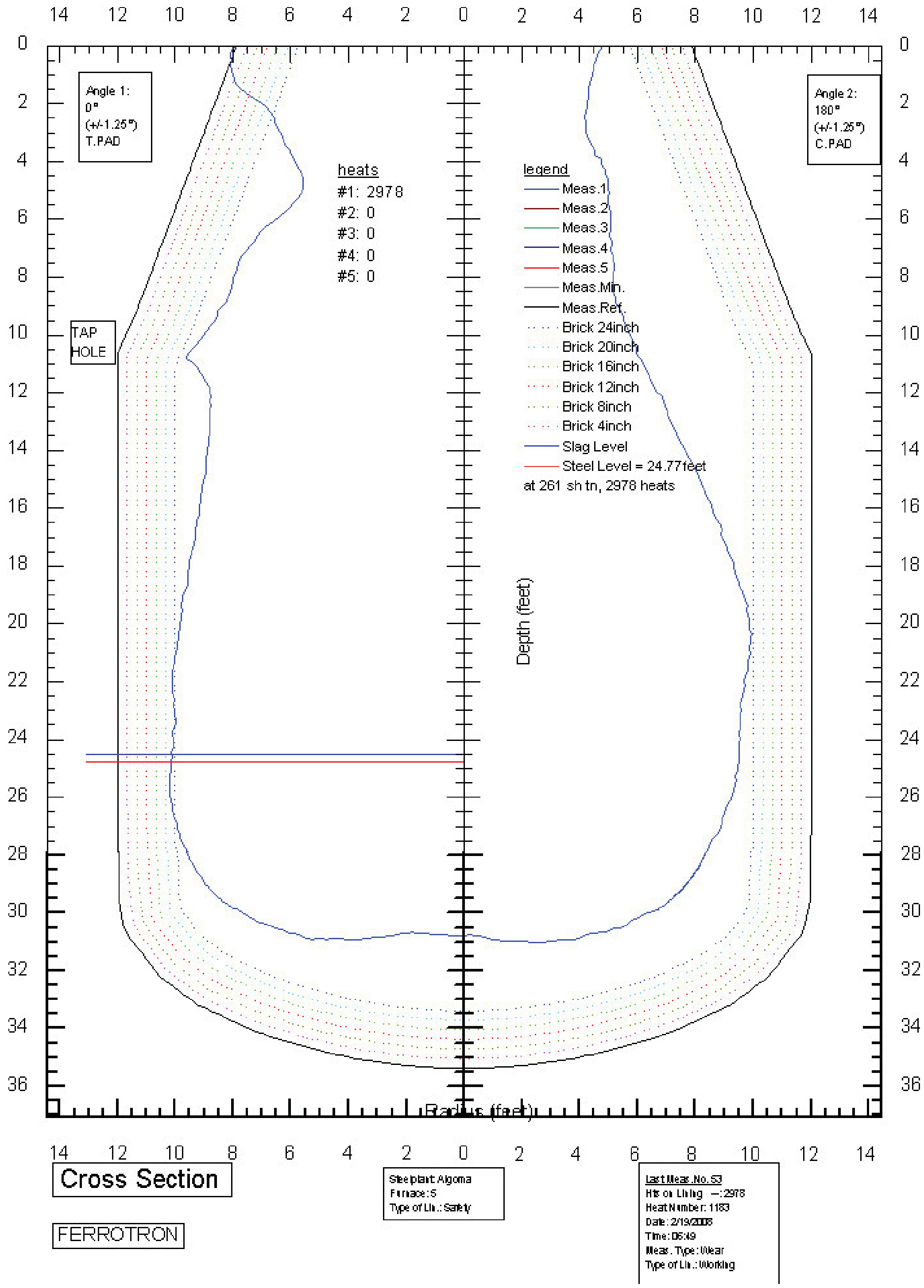
Attachments



attachment 1: BOF scan, 2978 heats on lining [132]

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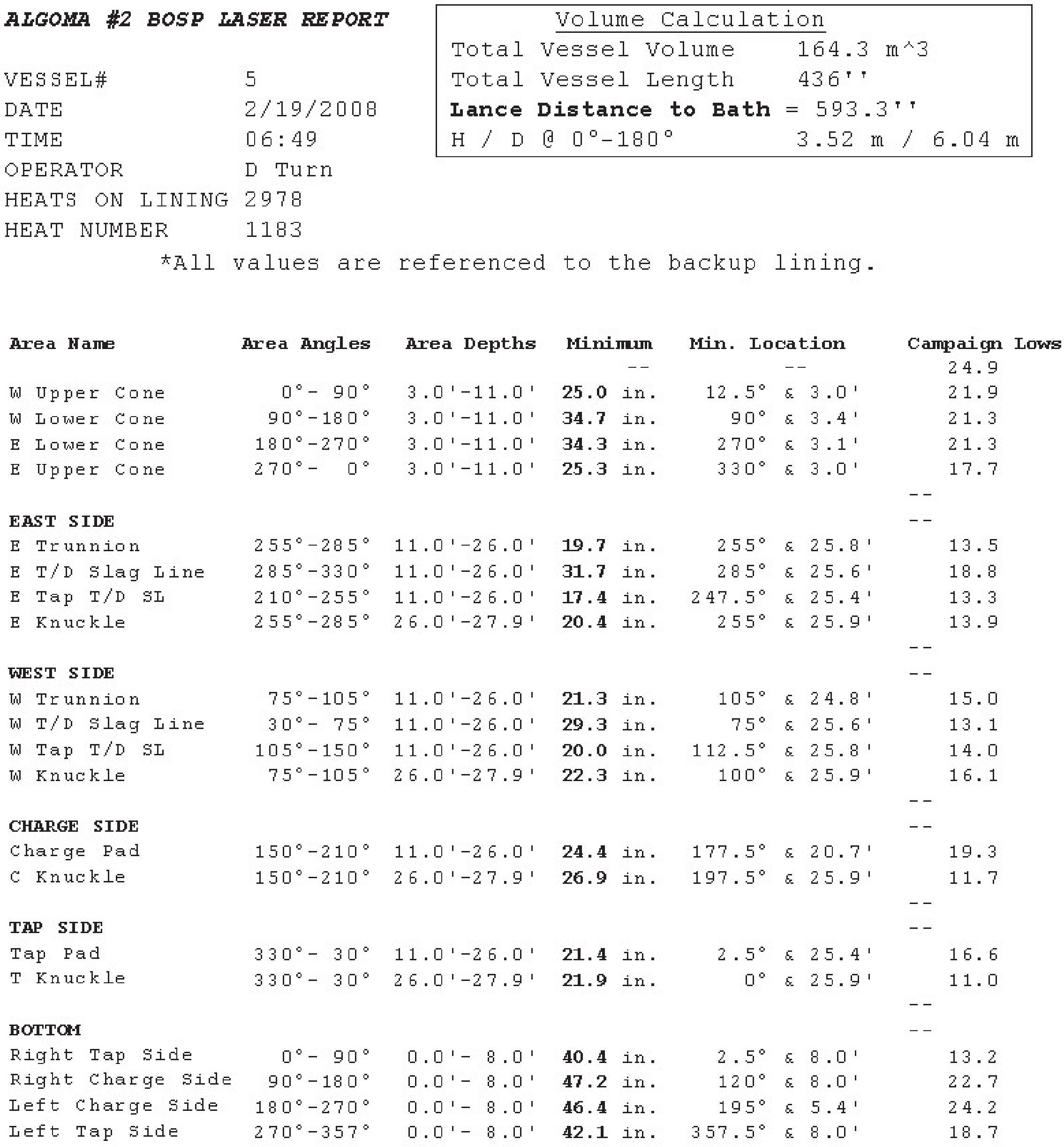
[132] Cf.: Ferrotron (2008)



```
ALGOMA #2 BOSP LASER REPORT        Volume Calculation
                                   Total Vessel Volume    164.3 m^3
VESSEL#          5                 Total Vessel Length    436''
DATE             2/19/2008         Lance Distance to Bath = 593.3''
TIME             06:49             H / D @ 0°-180°        3.52 m / 6.04 m
OPERATOR         D Turn
HEATS ON LINING 2978
HEAT NUMBER      1183
          *All values are referenced to the backup lining.

Area Name           Area Angles  Area Depths  Minimum   Min. Location    Campaign Lows
                                                 --          --              24.9
W Upper Cone          0°- 90°    3.0'-11.0'  25.0 in.   12.5° & 3.0'        21.9
W Lower Cone         90°-180°    3.0'-11.0'  34.7 in.     90° & 3.4'        21.3
E Lower Cone        180°-270°    3.0'-11.0'  34.3 in.    270° & 3.1'        21.3
E Upper Cone        270°-  0°    3.0'-11.0'  25.3 in.    330° & 3.0'        17.7
                                                                         --
EAST SIDE                                                                --
E Trunnion          255°-285°   11.0'-26.0'  19.7 in.    255° & 25.8'       13.5
E T/D Slag Line     285°-330°   11.0'-26.0'  31.7 in.    285° & 25.6'       18.8
E Tap T/D SL        210°-255°   11.0'-26.0'  17.4 in.  247.5° & 25.4'       13.3
E Knuckle           255°-285°   26.0'-27.9'  20.4 in.    255° & 25.9'       13.9
                                                                         --
WEST SIDE                                                                --
W Trunnion           75°-105°   11.0'-26.0'  21.3 in.    105° & 24.8'       15.0
W T/D Slag Line      30°- 75°   11.0'-26.0'  29.3 in.     75° & 25.6'       13.1
W Tap T/D SL        105°-150°   11.0'-26.0'  20.0 in.  112.5° & 25.8'       14.0
W Knuckle            75°-105°   26.0'-27.9'  22.3 in.    100° & 25.9'       16.1
                                                                         --
CHARGE SIDE                                                              --
Charge Pad          150°-210°   11.0'-26.0'  24.4 in.  177.5° & 20.7'       19.3
C Knuckle           150°-210°   26.0'-27.9'  26.9 in.  197.5° & 25.9'       11.7
                                                                         --
TAP SIDE                                                                 --
Tap Pad             330°- 30°   11.0'-26.0'  21.4 in.    2.5° & 25.4'       16.6
T Knuckle           330°- 30°   26.0'-27.9'  21.9 in.      0° & 25.9'       11.0
                                                                         --
BOTTOM                                                                   --
Right Tap Side        0°- 90°    0.0'- 8.0'  40.4 in.    2.5° & 8.0'        13.2
Right Charge Side    90°-180°    0.0'- 8.0'  47.2 in.    120° & 8.0'        22.7
Left Charge Side    180°-270°    0.0'- 8.0'  46.4 in.    195° & 5.4'        24.2
Left Tap Side       270°-357°    0.0'- 8.0'  42.1 in.  357.5° & 8.0'        18.7
```

attachment 2: data of scan 2978 [133]

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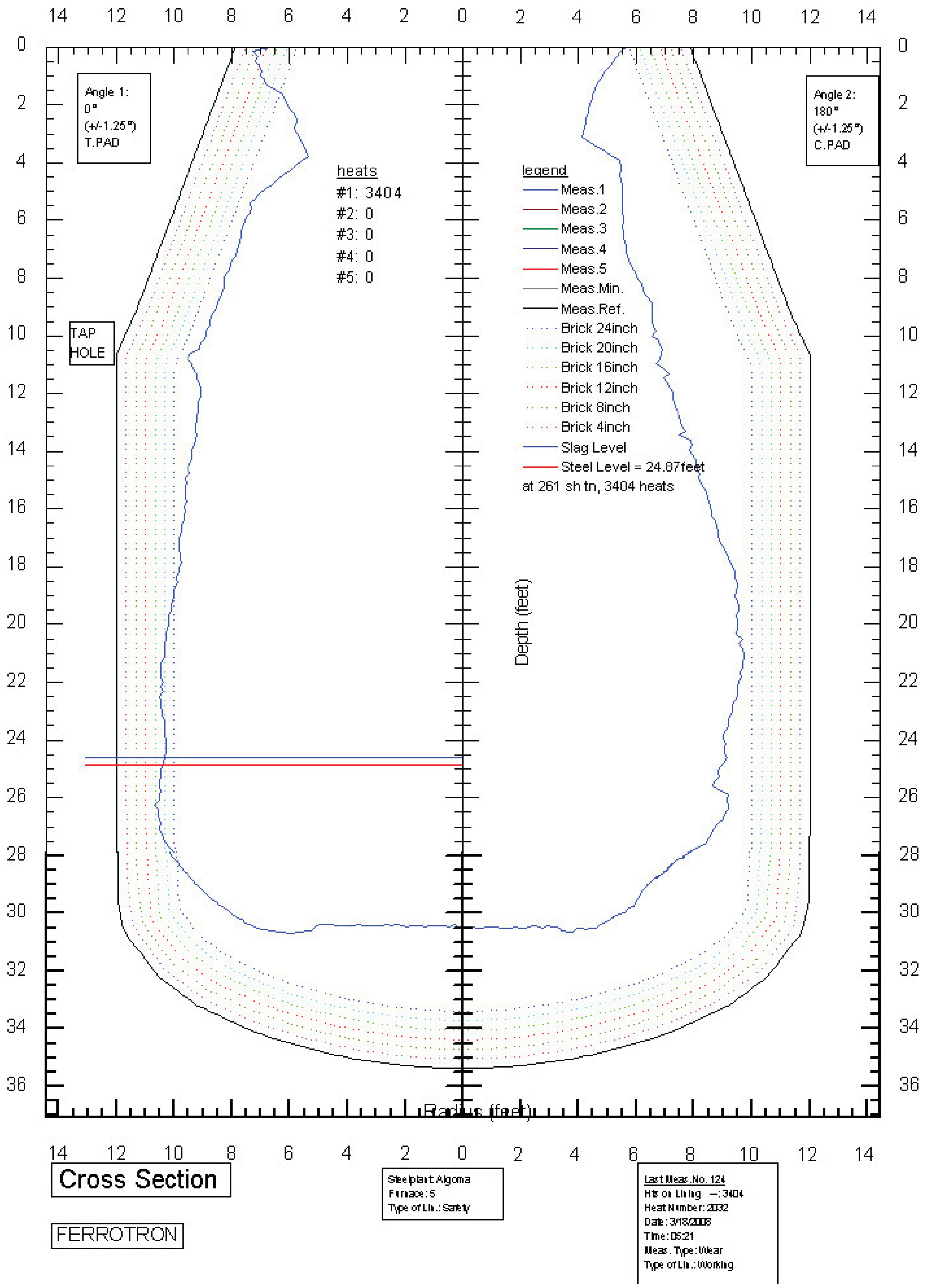
[133] Cf.: Ferrotron (2008)



attachment 3: BOF scan, 3404 heats on lining [134]

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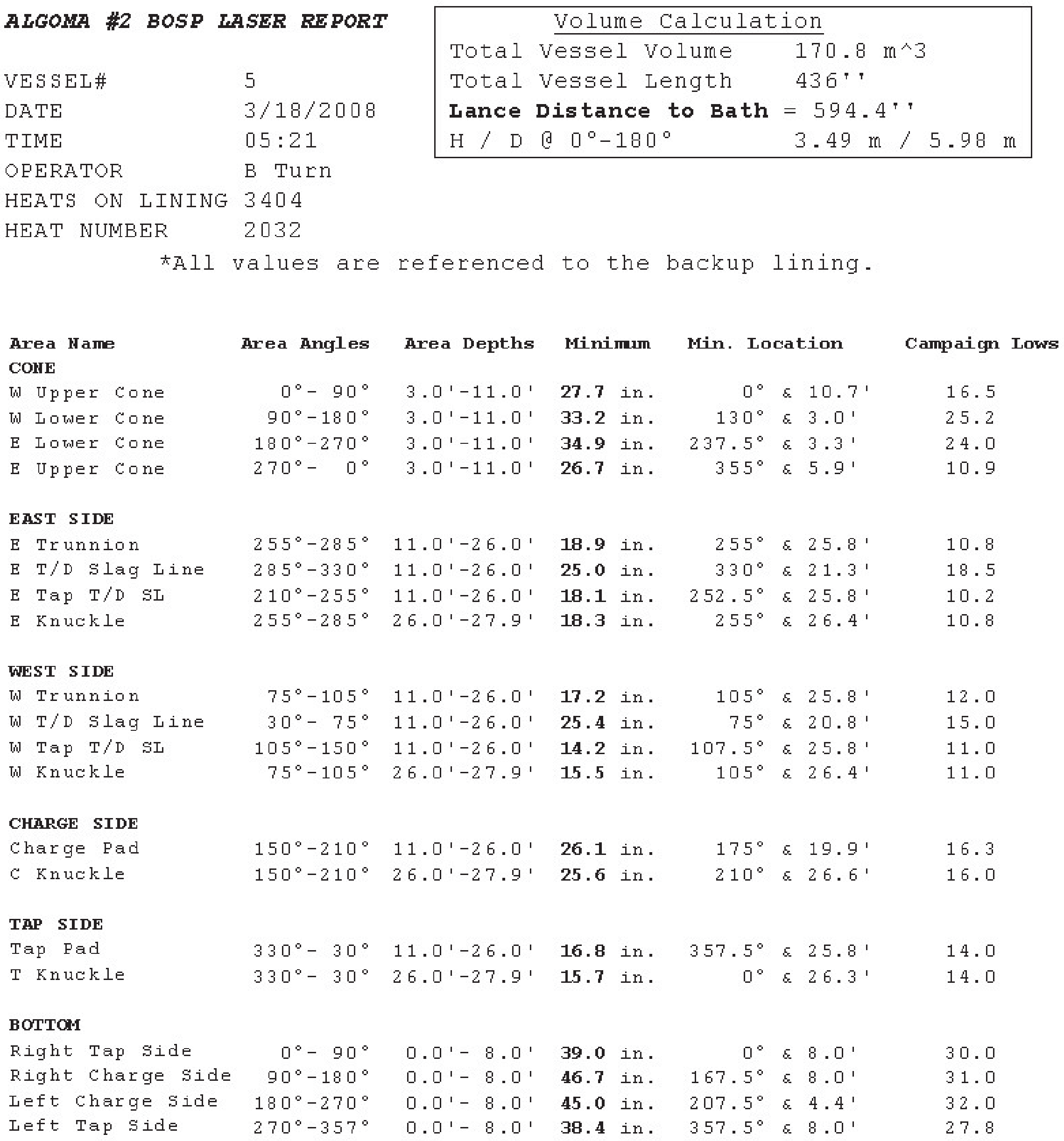
[134] Cf.: Ferrotron (2008)



ALGOMA #2 BOSP LASER REPORT

VESSEL# 5
DATE 3/18/2008
TIME 05:21
OPERATOR B Turn
HEATS ON LINING 3404
HEAT NUMBER 2032

Volume Calculation
Total Vessel Volume 170.8 m^3
Total Vessel Length 436''
Lance Distance to Bath = 594.4''
H / D @ 0°-180° 3.49 m / 5.98 m

*All values are referenced to the backup lining.

Area Name	**Area Angles**	**Area Depths**	**Minimum**	**Min. Location**	**Campaign Lows**
CONE					
W Upper Cone	0°- 90°	3.0'-11.0'	**27.7** in.	0° & 10.7'	16.5
W Lower Cone	90°-180°	3.0'-11.0'	**33.2** in.	130° & 3.0'	25.2
E Lower Cone	180°-270°	3.0'-11.0'	**34.9** in.	237.5° & 3.3'	24.0
E Upper Cone	270°- 0°	3.0'-11.0'	**26.7** in.	355° & 5.9'	10.9
EAST SIDE					
E Trunnion	255°-285°	11.0'-26.0'	**18.9** in.	255° & 25.8'	10.8
E T/D Slag Line	285°-330°	11.0'-26.0'	**25.0** in.	330° & 21.3'	18.5
E Tap T/D SL	210°-255°	11.0'-26.0'	**18.1** in.	252.5° & 25.8'	10.2
E Knuckle	255°-285°	26.0'-27.9'	**18.3** in.	255° & 26.4'	10.8
WEST SIDE					
W Trunnion	75°-105°	11.0'-26.0'	**17.2** in.	105° & 25.8'	12.0
W T/D Slag Line	30°- 75°	11.0'-26.0'	**25.4** in.	75° & 20.8'	15.0
W Tap T/D SL	105°-150°	11.0'-26.0'	**14.2** in.	107.5° & 25.8'	11.0
W Knuckle	75°-105°	26.0'-27.9'	**15.5** in.	105° & 26.4'	11.0
CHARGE SIDE					
Charge Pad	150°-210°	11.0'-26.0'	**26.1** in.	175° & 19.9'	16.3
C Knuckle	150°-210°	26.0'-27.9'	**25.6** in.	210° & 26.6'	16.0
TAP SIDE					
Tap Pad	330°- 30°	11.0'-26.0'	**16.8** in.	357.5° & 25.8'	14.0
T Knuckle	330°- 30°	26.0'-27.9'	**15.7** in.	0° & 26.3'	14.0
BOTTOM					
Right Tap Side	0°- 90°	0.0'- 8.0'	**39.0** in.	0° & 8.0'	30.0
Right Charge Side	90°-180°	0.0'- 8.0'	**46.7** in.	167.5° & 8.0'	31.0
Left Charge Side	180°-270°	0.0'- 8.0'	**45.0** in.	207.5° & 4.4'	32.0
Left Tap Side	270°-357°	0.0'- 8.0'	**38.4** in.	357.5° & 8.0'	27.8

attachment 4: data of scan 3404 [135]

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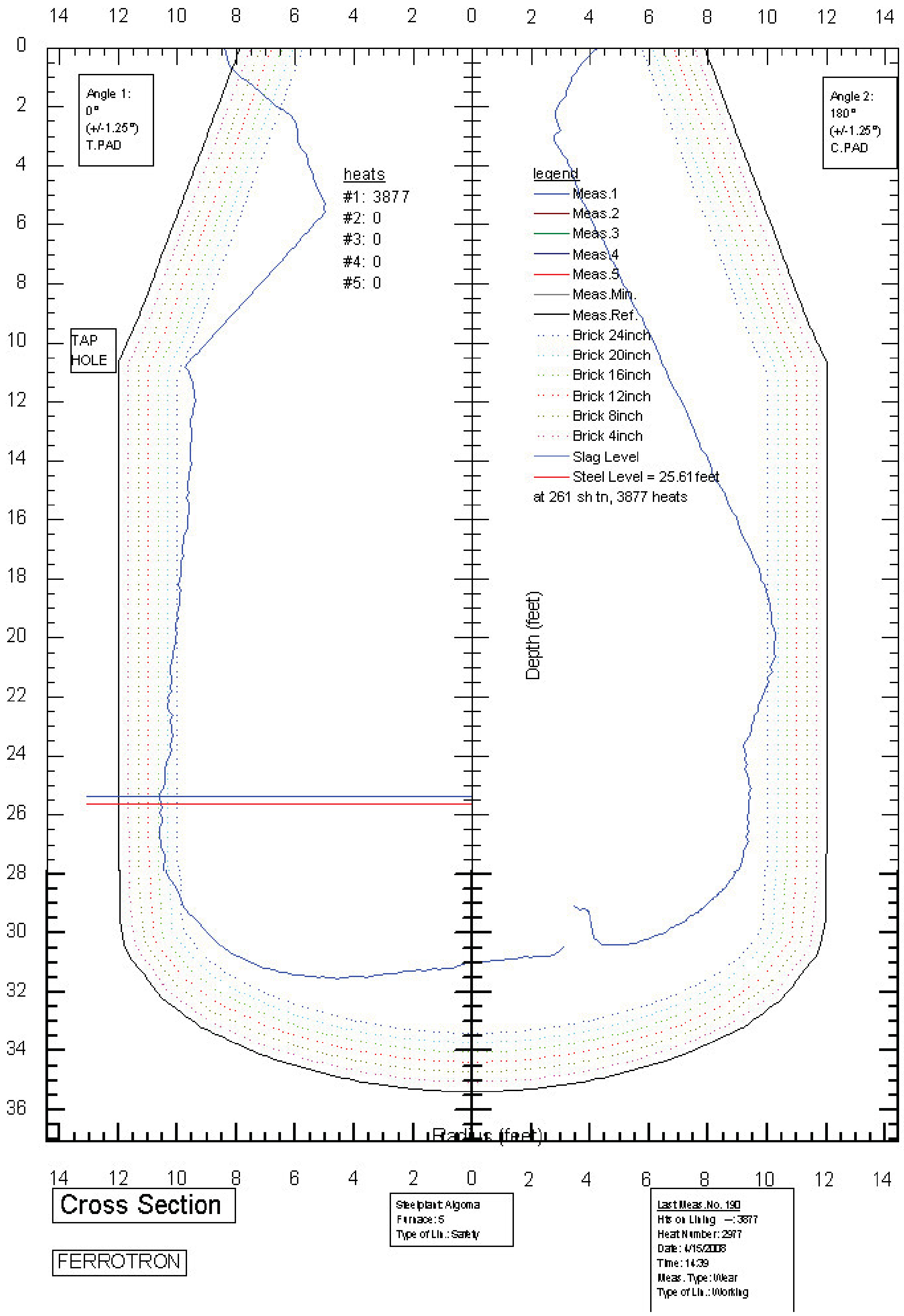
[135] Cf.: Ferrotron (2008)



attachment 5: BOF scan, 3877 heats on lining [136]

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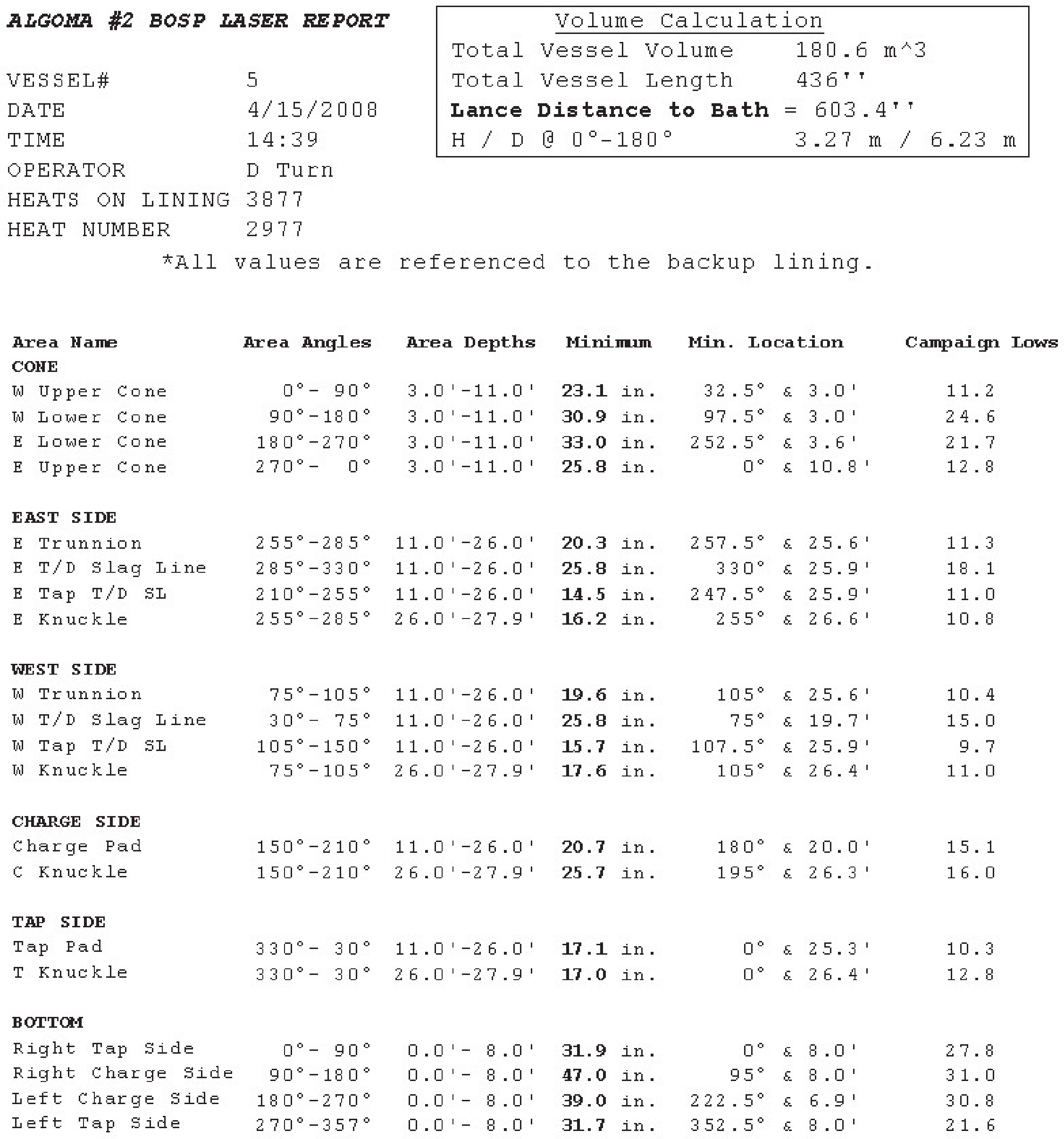
[136] Cf.: Ferrotron (2008)



ALGOMA #2 BOSP LASER REPORT

VESSEL# 5
DATE 4/15/2008
TIME 14:39
OPERATOR D Turn
HEATS ON LINING 3877
HEAT NUMBER 2977

Volume Calculation
Total Vessel Volume 180.6 m^3
Total Vessel Length 436''
Lance Distance to Bath = 603.4''
H / D @ 0°-180° 3.27 m / 6.23 m

*All values are referenced to the backup lining.

Area Name	**Area Angles**	**Area Depths**	**Minimum**	**Min. Location**	**Campaign Lows**
CONE					
W Upper Cone	0°- 90°	3.0'-11.0'	**23.1** in.	32.5° & 3.0'	11.2
W Lower Cone	90°-180°	3.0'-11.0'	**30.9** in.	97.5° & 3.0'	24.6
E Lower Cone	180°-270°	3.0'-11.0'	**33.0** in.	252.5° & 3.6'	21.7
E Upper Cone	270°- 0°	3.0'-11.0'	**25.8** in.	0° & 10.8'	12.8
EAST SIDE					
E Trunnion	255°-285°	11.0'-26.0'	**20.3** in.	257.5° & 25.6'	11.3
E T/D Slag Line	285°-330°	11.0'-26.0'	**25.8** in.	330° & 25.9'	18.1
E Tap T/D SL	210°-255°	11.0'-26.0'	**14.5** in.	247.5° & 25.9'	11.0
E Knuckle	255°-285°	26.0'-27.9'	**16.2** in.	255° & 26.6'	10.8
WEST SIDE					
W Trunnion	75°-105°	11.0'-26.0'	**19.6** in.	105° & 25.6'	10.4
W T/D Slag Line	30°- 75°	11.0'-26.0'	**25.8** in.	75° & 19.7'	15.0
W Tap T/D SL	105°-150°	11.0'-26.0'	**15.7** in.	107.5° & 25.9'	9.7
W Knuckle	75°-105°	26.0'-27.9'	**17.6** in.	105° & 26.4'	11.0
CHARGE SIDE					
Charge Pad	150°-210°	11.0'-26.0'	**20.7** in.	180° & 20.0'	15.1
C Knuckle	150°-210°	26.0'-27.9'	**25.7** in.	195° & 26.3'	16.0
TAP SIDE					
Tap Pad	330°- 30°	11.0'-26.0'	**17.1** in.	0° & 25.3'	10.3
T Knuckle	330°- 30°	26.0'-27.9'	**17.0** in.	0° & 26.4'	12.8
BOTTOM					
Right Tap Side	0°- 90°	0.0'- 8.0'	**31.9** in.	0° & 8.0'	27.8
Right Charge Side	90°-180°	0.0'- 8.0'	**47.0** in.	95° & 8.0'	31.0
Left Charge Side	180°-270°	0.0'- 8.0'	**39.0** in.	222.5° & 6.9'	30.8
Left Tap Side	270°-357°	0.0'- 8.0'	**31.7** in.	352.5° & 8.0'	21.6

attachment 6: data of scan 3877 [137]

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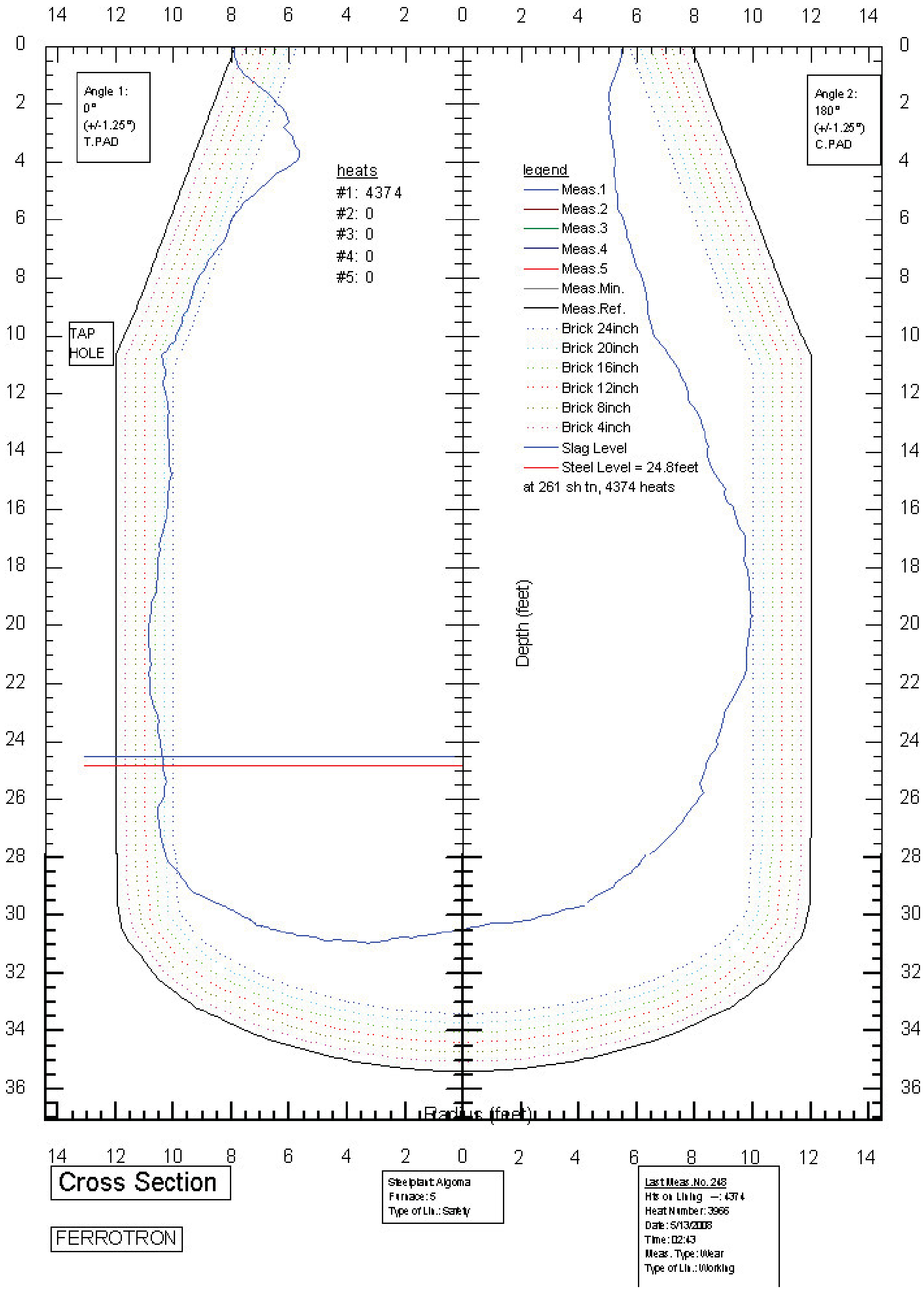
[137] Cf.: Ferrotron (2008)



attachment 7: BOF scan, 4374 heats on lining [138]

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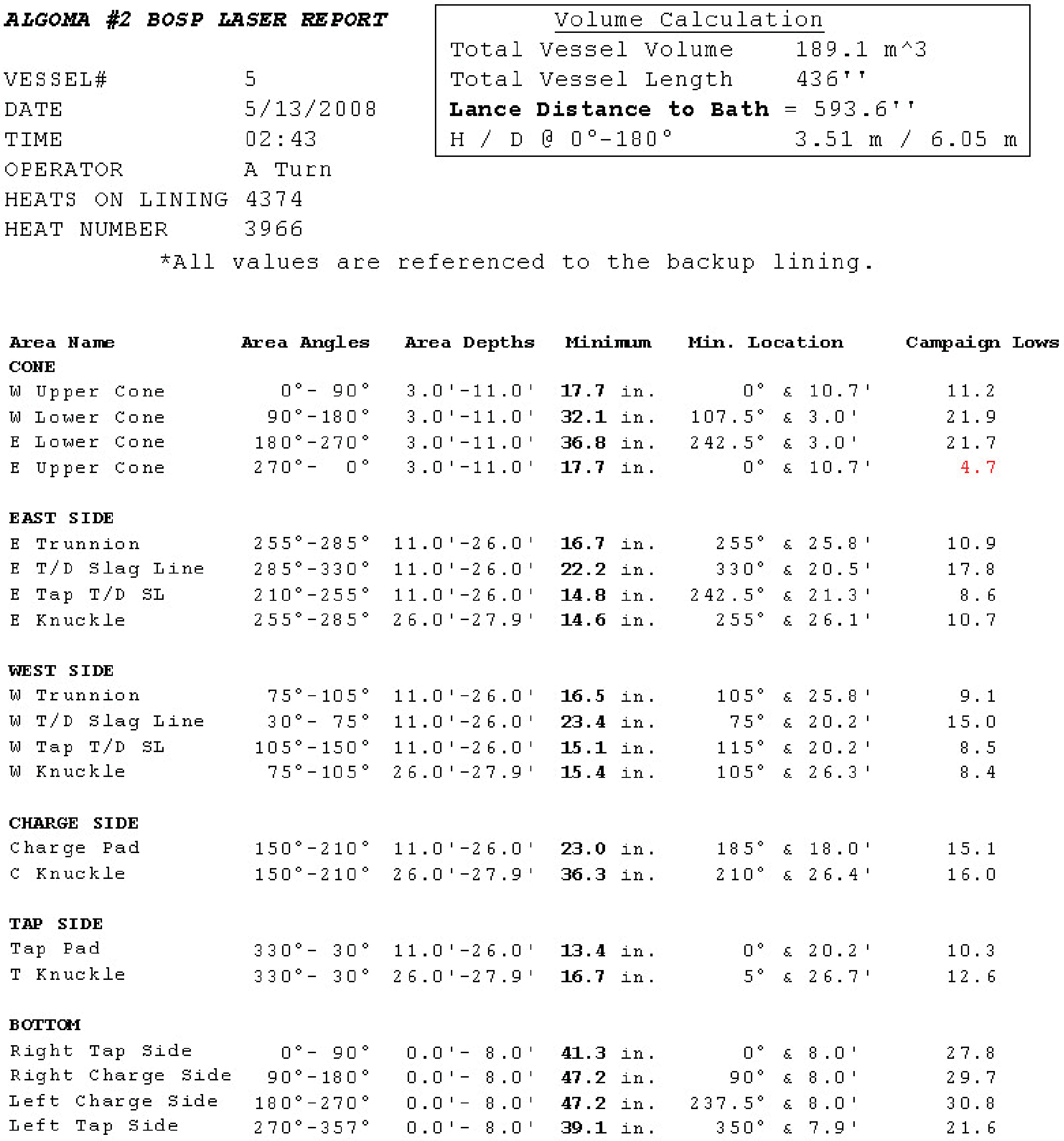
[138] Cf.: Ferrotron (2008)



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ALGOMA #2 BOSP LASER REPORT          Volume Calculation
                                     Total Vessel Volume     189.1 m^3
VESSEL#          5                   Total Vessel Length     436''
DATE             5/13/2008           Lance Distance to Bath = 593.6''
TIME             02:43               H / D @ 0°-180°         3.51 m / 6.05 m
OPERATOR         A Turn
HEATS ON LINING  4374
HEAT NUMBER      3966
          *All values are referenced to the backup lining.

Area Name            Area Angles  Area Depths  Minimum    Min. Location   Campaign Lows
CONE
W Upper Cone           0°- 90°    3.0'-11.0'  17.7 in.       0° & 10.7'       11.2
W Lower Cone          90°-180°    3.0'-11.0'  32.1 in.   107.5° & 3.0'        21.9
E Lower Cone         180°-270°    3.0'-11.0'  36.8 in.   242.5° & 3.0'        21.7
E Upper Cone         270°-  0°    3.0'-11.0'  17.7 in.       0° & 10.7'        4.7

EAST SIDE
E Trunnion           255°-285°   11.0'-26.0'  16.7 in.     255° & 25.8'       10.9
E T/D Slag Line      285°-330°   11.0'-26.0'  22.2 in.     330° & 20.5'       17.8
E Tap T/D SL         210°-255°   11.0'-26.0'  14.8 in.   242.5° & 21.3'        8.6
E Knuckle            255°-285°   26.0'-27.9'  14.6 in.     255° & 26.1'       10.7

WEST SIDE
W Trunnion            75°-105°   11.0'-26.0'  16.5 in.     105° & 25.8'        9.1
W T/D Slag Line       30°- 75°   11.0'-26.0'  23.4 in.      75° & 20.2'       15.0
W Tap T/D SL         105°-150°   11.0'-26.0'  15.1 in.     115° & 20.2'        8.5
W Knuckle             75°-105°   26.0'-27.9'  15.4 in.     105° & 26.3'        8.4

CHARGE SIDE
Charge Pad           150°-210°   11.0'-26.0'  23.0 in.     185° & 18.0'       15.1
C Knuckle            150°-210°   26.0'-27.9'  36.3 in.     210° & 26.4'       16.0

TAP SIDE
Tap Pad              330°- 30°   11.0'-26.0'  13.4 in.       0° & 20.2'       10.3
T Knuckle            330°- 30°   26.0'-27.9'  16.7 in.       5° & 26.7'       12.6

BOTTOM
Right Tap Side         0°- 90°    0.0'- 8.0'  41.3 in.       0° & 8.0'        27.8
Right Charge Side     90°-180°    0.0'- 8.0'  47.2 in.      90° & 8.0'        29.7
Left Charge Side     180°-270°    0.0'- 8.0'  47.2 in.   237.5° & 8.0'        30.8
Left Tap Side        270°-357°    0.0'- 8.0'  39.1 in.     350° & 7.9'        21.6
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attachment 8: data of scan 4374 [139]

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[139] Cf.: Ferrotron (2008)