Low-cost BF hot metal requires high productivity, high availability, long furnace life and a stable process. Modern BF designs include state-of-the-art refractories, a variety of internal and external water cooling systems, together with advanced instrumentation and control. Campaign lives in excess of 20 years, coupled with over 95% availability, are now obtained.

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Low-cost hot metal from a blast furnace (BF) can be achieved by:

- Low coke rate (<300kg/THM)
- High fuel injection rate (PCI >200kg/THM)
- High oxygen rate (>30%)  
- High productivity (>3.0 THM/m³WV/d)
- Stable operations and high availability (>95%)
- Ability to cope with a variety of sinter, pellets and lump ore

However, determining the sizing and profiling parameters of a new BF and maintaining these parameters during the campaign are also critical. Parameters include throat, belly and hearth diameter, bosh and stack angle, working height, sump depth and number of tuyeres (see Figure 1).

BF design has had many improvements in recent decades and campaigns of more than 20 years are now obtained. The bosh, stack and throat armour were critical design areas in the past, but today the application of copper plate coolers, graphite and SiC in the bosh, belly, lower and middle stack, in combination with cast iron stave coolers in the upper stack plus throat armour enables long campaign and high productivity operations, but now emphasising the importance of a robust bottom and hearth design.

**PROCESS AND OPERATIONS**

An advanced BF design requires high efficiency and high capacity cooling systems and advanced instrumentation and control. Such a system includes instrumentation and control systems for monitoring the process, operations and lining performance. Figure 2 is a schematic of typical instrumentation including gas, pressure and temperature measurements to maximise the quantity of performance data. These measurements have been useful in understanding the BF process, plant operations and lining performance for many years. Additionally, however, post-mortem analysis should be performed during (interim) relines and repairs, and the lining can also be monitored.
The hearth also faces demanding process and operating conditions, hence hearth lining performance is critical. We have been monitoring and assessing the performance of various hearth designs and operations worldwide including large block and hot pressed brick designs and including bottom air, water and oil cooling, as well as hearth shell spray, jacket and cast iron stave cooling. The operating range included all-coke as well as low-coke ultra-high PCI operations, dry-hearth and single taphole operations and low-grade to high-grade raw materials (pellets, sinter, lump ore, and combinations thereof).

**BOTTOM AND HEARTH**

The bottom and hearth performance is currently the limiting factor at many existing plants for low-cost hot metal and the condition of the bottom and hearth usually determines the timing of relines. This is partially due to the fact that the blast furnace working volume and production were increased during previous relines, whilst increases of the hearth were limited due to casthouse and foundation constraints. The hearth ‘productivity’ will then effectively increase, while the hearth volume is also reduced at low coke rate due to a reduction of the permeability of the hearth.
Advanced scientific CFD modelling and two-phase flow experiments were developed to simulate the hearth operations and process and demonstrate significant hot metal and slag flow and velocity differences depending on the geometry, tapping cycle and hearth voidage (see Figure 4). It is important to design a large hearth volume to support stable operations, and stable casthouse practice is required to minimise liquid level fluctuations. The hearth volume can be increased by adopting conical shell segments instead of a cylindrical shell, although the hearth diameter at the tuyere level will have to be in proportion to the intended production level.

The shell and bottom seal-plate must be protected, and water cooling has been shown to be the most effective method when considering the following:

- Cooling efficiency and capacity
- Design redundancy and maintenance
- Capital investment and operational costs

Advanced bottom and hearth designs include bottom water cooling and hearth shell jacket cooling as this provides more space within the shell. We have evaluated many hearth shell jacket cooling designs comprising angle bars, circular pipes, U-profiles or cassettes (see Figure 5). The optimum design includes shaped profiles, which results in minimum dry areas and enables installation of grouting and thermocouple nozzles.

High efficiency taphole jacket cooling systems have also been developed to cope with high heat load dynamic process conditions and to minimise shell deformations. Alternatively, copper stave coolers could be used in this area (see Figure 6). The bottom water cooling system includes two circuits with a series of parallel pipes embedded in high conductive SiC castable within grooves of graphite shapes. Conventional designs include carbon ramming, but this introduces the risk of evaporation of volatiles, which jeopardises the thermal conductivity of carbon ramming and the performance of the bottom cooling system.

A closed-loop cooling system will be required to minimise contamination. ‘Chillers’ could be considered to reduce and stabilise the average cooling water temperature, however, a more robust and economic water temperature control system can be implemented to eliminate the effects of seasonal and daily temperature fluctuations.

Despite all the scientific experiments and models available, actual performance of the hearth is difficult to forecast due to the large variety of influencing factors, and many plants run the hearth in campaign extension mode, requiring modifications to the process and operations and sometimes interim repairs.

An example of an advanced bottom and hearth design is illustrated in Figure 7. This design includes bottom water cooling pipes above the seal-plate and a graphite, semi-
Graphite and micropore carbon bottom course protected by a high alumina and chamotte ‘arrestor’ course. The hearth lower sidewall includes graphite against the shell and high conductive micropore semi-graphite (ultra-micropore carbon) and the upper sidewall comprises micropore carbon as this is exposed to low heat load levels. This design also allows for a ceramic cup, which provides better resistance against hot metal erosion, but also reduces the effective hearth volume and could cause higher stresses and strains in the hearth sidewall.

Large blocks are used for the bottom and ‘thin’ hearth sidewall lining comprises small blocks as this enables to minimise the ramming thickness to 50mm.

The authors recommend ‘thin’ hearth sidewall lining blocks <1,000mm to reduce thermal stresses and strains. These cause (micro-)cracks and joint openings, which catalyse lining erosion and reduce the campaign lifetime. The hot face temperature will also be reduced if the sidewall lining is thin and this will reduce chemical degradation and the chance of dissolution of carbon refractory in hot metal.

The performance of the hearth also depends on the (carbonaceous) refractory grades. We have executed an extensive benchmark test program and evaluated 14 carbonaceous grades from US, European and Asian manufacturers. The test program includes conventional ISO measurements and also customised experiments to compare the performance of the refractory upon exposure to more realistic process conditions. The test program is summarised in Table 2.

Some typical results are illustrated in Figures 8 and 9. It is clear that the performance depends on the material selection. The advanced bottom and hearth design is based on the results of this test program and our ‘thermal’ design philosophy for reducing hot face temperatures.
and temperature gradients. The design also accounts for minimum stresses and strains: high stresses cause (micro-) cracks, brittle layer, shell deformation and sometimes shell cracks. Dynamic thermo-mechanical stress-strain analysis computer models have been developed to simulate the bottom and hearth and the results are compared to actual field measurements at several different designs using strain gauges, acoustic emission sensors, circumferential length measurements and radial bars. The models and measurements are in good agreement and confirm that shell stresses and strains are highest at the interface of the bottom and hearth.

Our analysis confirms this is mainly the result of radial expansion of bottom mullite courses and insufficient expansion allowance. The strong mullite courses result in high radial forces contributing to creation of (micro-) cracks in the refractory and deformation of the shell and also catalyse preferential flow as mullite has a strong erosion resistance. The advanced design incorporates chamotte, which can erode until process equilibrium is achieved, which results in a reduction of preferential ring flow. Radial forces are reduced since the Young’s modulus of chamotte is lower than mullite and the advanced design includes expansion provisions. These effects are illustrated in Figure 10.

The taphole is the one of the most challenging of BF components as it is exposed to an extremely violent environment: operations and process conditions are discontinuous at high temperature and pressure (difference), and it contains chemical, corrosive and erosive mechanisms. Low-cost hot metal operations will increase the loading conditions as the productivity will increase. This means that the taphole performance design must always be monitored and evaluated, and ‘lessons learned’ must be identified and implemented in the design. An advanced taphole design incorporates double densified graphite against the shell, external jacket cooling and large block micropore semi-graphite (ultra-micropore carbon). A centre-castable core provides maximum redundancy and minimises operational flaws such as gas leakage, and provides better resistance against oxygen lancing or oxidation due to leaking cooling elements. Alternatively, copper stave coolers could be considered at the taphole.

**TUYERE AREA**

The tuyere (cooler) area is an important interface between the hearth and bosh and stack and is exposed to high temperatures and temperature fluctuations and erosion plus high oxygen enrichment and PCI which could increase loadings to the tuyere area. Many installations include tuyere area ceramics such as SiC or corundum to prevent oxidation and provide erosion resistance, but they do require expansion provision to prevent stress cracking.
and ceramic refractory materials cannot cope with large temperature gradients or temperature fluctuations. Two examples of tuyere area and lower bosh failures are illustrated in Figure 11.

An alternative design includes double densified, low iron and low ash content graphite in close contact to the tuyere coolers. Additional copper plate coolers can be considered if the spacing between the tuyere coolers is large. This design is illustrated in Figure 12.

This design has proven campaign life over 25 years at high productivity and ultra-high PCI and oxygen enrichment rates. Figure 13 illustrates the excellent performance of this design.

Long campaigns are achieved at high productivity, high PCI and high oxygen enrichment rates since double densified, low iron and low ash content graphite has a very high oxidation threshold temperature compared to other carbonaceous and graphite grades. Furthermore, combining high conductive graphite and high efficiency tuyere coolers and copper plate coolers will result in low hot face temperatures thus preventing risk of oxidation. The low hot face temperature will also promote protective accretion eliminating erosion.

**BOSH AND STACK**

Two different lining designs have been developed since the 1960s:

- Cast iron and copper stave cooling
- Copper plate cooling and refractory

The performance of the designs depends on the application and local process conditions and operations.

Cast iron stave coolers cannot cope with high temperatures and high temperature fluctuations as this will cause material degradation and cracking despite many improvements in coatings, cast iron grade and refractory inserts. The application of cast iron stave coolers in the upper stack and throat armour, however, has proven to be very successful as this area is usually not exposed to high temperatures or temperature fluctuations. These areas face erosion due mainly to the descending burden and impact as a result of (incorrect) charging practice. Cast iron stave coolers and SiC refractory inserts have a good resistance against erosion and impact and are thus preferred in the upper stack and throat armour.

Copper stave coolers have been developed since the 1980s and are currently installed in many plants in high-thermal load zones such as the bosh, belly and lower stack. Recently various plants have reported failure of copper stave coolers in these areas. We have surveyed the literature and performed experiments, and developed FEA and CFD computer models to evaluate and compare the
performance of copper stave coolers and other designs and materials such as cast iron, SiC, high alumina and graphite. This included:

- Friction abrasion experiments
- Impact erosion experiments
- Impact erosion CFD modelling
- Burden descent modelling
- Diffusion of Fe in Cu
- Transient FEA thermo-mechanical modelling
- Corrosion by sulphur and halogens

The resistance of copper and cast iron against mechanical, thermal and chemical attack reduces with increasing temperature. It is expected that the root cause of copper stave cooler failures is erosion by the descending burden and ascending gas. This could be enhanced by changes to the cohesive zone location and implies that the copper stave coolers are not adequately protected by an accretion. Burden descent models also suggest that copper stave coolers have a lower ability to stabilise an accretion compared to copper plate cooler designs.

Advanced bosh, belly and stack designs include machined copper plate coolers, high conductive graphite and SiC (see Figure 14).

This design provides optimum synergies between cooling and refractory and also between high conductive graphite and erosion-resistant SiC refractory. Alternative designs are vulnerable to stress cracking and fatigue due to thermal cycling. Crushing temperatures of different refractories are shown in Table 3.

It is clear that graphite is required to cope with the high temperature fluctuations that could occur in the bosh, belly and stack. SiC is required to provide protection against erosion of descending burden and ascending gas. Graphite surrounding refractory in close contact with machined copper plate coolers secures low SiC temperatures. This results in low stresses and strain. In addition, special shaped SiC bricks and expansion provisions are used to further reduce stresses at the hot face and eliminate the risk of spalling. This design is illustrated in Figure 15.

The application of copper plate coolers, graphite and SiC has been demonstrated at more than 50 plants worldwide and many records have been achieved:

- Campaign Life: >25 years
- Productivity: >3.5THM/m3WV/24
- Oxygen Enrichment: 18%
- Coal Injection: 260kg/THM
- Coke Rate: 250kg/THM

Table 3 Refractory crushing temperatures

<table>
<thead>
<tr>
<th>Material</th>
<th>Compressibility %</th>
<th>Expansion at 1,000°C %</th>
<th>Crushing temperature °C</th>
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<tr>
<td>Silicon carbide</td>
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<td>0.3</td>
<td>160</td>
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<tr>
<td>High alumina</td>
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<td>0.4</td>
<td>200</td>
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<tr>
<td>Carbon</td>
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<td>0.5</td>
<td>800</td>
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<tr>
<td>Graphite</td>
<td>1.00</td>
<td>0.3</td>
<td>3,300</td>
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</tbody>
</table>

Fig 14 Advanced bosh, belly and stack design

Fig 15 Copper plate coolers, refractory and SiC

Typical thickness measurements of Tata Steel Ijmuiden BF6 are illustrated in Figure 16.
COOLING SYSTEM

Advanced BF designs require high pressure closed-loop cooling systems which increases the cooling capacity and efficiency. The cooling system design should be able to cope with normal process and operating conditions as well as incidental, local peak heat load conditions. An example of a typical heat load diagram is illustrated in figure 17. This reflects normal process and operations conditions.

This heat load diagram is independent of the BF design: the values are determined by historical records and measurements and computer modelling and depend on parameters such as productivity, pellet % and size of BF. Incidental, local peak heat load levels could be 10 times higher. Also, the average heat loss could be higher if raw materials or burdening practices are changed. The primary ‘on-furnace’ cooling system design should enable adequate leak detection and leak searching functionality.

The cooling system could also be used for ‘heat flux monitoring’ process control. This has been demonstrated to be an effective tool to control and stabilise operations, which is a pre-requisite for low-cost hot metal.

The bosh, belly and stack copper plate coolers are usually coupled in series of 4-5 plate coolers and an array of these series are combined in a ‘panel’. The bosh, belly and stack are divided in 20-48 panels depending on the size of BF.

The upper stack cast iron stave coolers and hearth shell jacket cooling include a re-circulating cooling system with water temperature control (see Figure 18). This eliminates temperature fluctuations of the hearth shell jacket cooling and minimises the chance of condensation of the burden moisture in the upper stack. This will prolong the campaign life and contribute to stable process and operations.

INSTRUMENTATION AND CONTROL

21st century low-cost stable operations can only be accomplished by improved instrumentation and measurement control. This allows the process to be monitored and studied online. The increased predictability and repeatability of the process allows the process to be further optimised and stabilised, with productivity rates reaching new highs and campaign lifetimes ever increasing. This improvement is a necessity to remain competitive in the iron and steel industry. Modern BF instrumentation includes:

- Hearth monitoring (thermocouples)
- Heat flux monitoring
- Above burden probes (ABP)
- Short in-burden probes (IBP)
- Top gas analysis for ABP and IBP
- Refractory (ceramic) wear rods
- Bosh and stack monitoring (thermocouples)
- Profile meter
- Topscan camera
The data are processed in a Level 2 control system. It is advised to implement a modular approach with dedicated modules individually designed to be of optimum benefit to the operations of that specific area. Each module should be designed specifically for the operator in mind, using the experience of current and previous operators.

Although the modules are area-specific, there is of course an overlap between areas, and where this occurs the information is shared as much as possible to give the relevant and timely information to the operator. A modern configuration is illustrated in Figure 19.

The Operator Advisory and Control System (OACS) for the BF is continuously improved. The OACS is an integrated part of a modern Level 2 system and is capable of identifying process deviations at a very early stage. It is also designed to compare historical and calculated data in order to avoid major and costly incidents. The system advises and gives guidance to operators and process operators to help in taking the correct actions to keep the furnace operating in the most optimum and economic way.

CONCLUSIONS
Low-cost BF hot metal requires high productivity, and a stable process and operations, low coke consumption and high oxygen enrichment and fuel injection rates, a stable BF profile and 20-year stable lining performance. Modern BF designs include state-of-the-art bottom and hearth refractories including high conductive micropore semi-graphite (ultra micropore carbon), external hearth shell jacket cooling and bottom water cooling. Bosh, belly and stack designs, including machined copper plate coolers, graphite and SiC refractory, have demonstrated their ability to enable low-cost hot metal. Upper stack and throat armour cast iron stave coolers enable long campaigns and advanced instrumentation and control secure appropriate process and operations control and monitoring of the lining performance.

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