21st century lining design for blast furnaces

Modern blast furnaces need to focus on low cost production. This is aided by long campaign life and high productivity. The ‘Hoogovens’ lining design has a proven lifetime of more than 20 years at high productivity and high fuel injection rates. The design includes advanced bosh, belly and stack designs which combine (lower) bosh plate coolers and upper stack cast iron stave coolers. Bosh plate coolers are required to decouple process and equipment, as a robust bosh permits furnaces to achieve high productivity, low coke, high fuel injection and high oxygen rates.

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 Blast furnace design requirements in the 21st century should focus on low cost hot metal production. This requires the right balance between capital expenses (CAPEX) and operational expenses (OPEX). Low cost hot metal production can be achieved by:

- Low coke rate (<300kg/THM)
- High fuel injection rate (PCI >200kg/THM)
- High oxygen rate (>30%)
- High productivity (>3.0THM/m³WV/d)
- Stable operations and high availability (>95%).

The blast furnace must also be able to cope with various raw material compositions of sinter, pellets and lump ore and achieve a 20 year campaign life. It is of paramount importance that the profile of the bosh, belly and stack is maintained during the entire campaign as any degradation will immediately have a negative influence on low cost hot metal production requirements [1]. Hence, bosh, belly and stack designs must be robust and strong.

**PROCESS CONDITIONS**

The blast furnace is a high temperature, pressurised counter-current reactor. Abrasive raw materials are descending and gradually softening due to (s)melting, while high temperature gases are ascending through the burden but also along the lining. The tuyere level flame temperature is >2,000°C and the blast furnace operational pressure is 2-4 Bar(g). This can result in high thermal loadings to the lining.

The blast furnace process is semi-continuous since charging and tapping are batch operations and hot blast and fuel injection are continuous. This combination results in dynamic process conditions.

Average process conditions are well understood and reported in the industry. Designers, however, must also have a good understanding of the dynamic process condition fluctuations since these impose significantly higher thermal and mechanical loadings on the lining. Dynamic upsetting process conditions can also, for example, be a result of equipment failures, malfunctioning top sprays, unscheduled shutdowns, burden slips, casting deficiencies and ‘gas-jets’.

Local, incidental upsetting process conditions can result in loadings that are 10 times higher compared to average conditions. An example is illustrated in Figure 1: this dynamic temperature development has often been reported to reflect ‘loss of solidified protection layer’ and rapid solidification of a new protection layer due to a high efficiency cooling system. We believe, however, that it is more likely that this reflects the consequences of a high temperature gas-jet impinging on the lining.

Process conditions have been monitored at many plants and temperature fluctuations have often been observed exceeding >100°C/min. Table 1 summarises the actual maximum temperature fluctuation various lining materials can accommodate before they start spalling (A) and actual temperature fluctuations for three different raw material...
It is clear that only high conductive, ductile lining material such as copper and (semi-)graphite will survive (irregular) high productivity, particularly with high pellet operations.

Lining designs are often an ‘assembly’ of metal cooling members and refractory components. The design and engineering of the cooling system and refractory components may have been executed by different companies and consequentially may not match each other. For example, the application of low conductivity ceramics and high density plate coolers systems introduces opposing philosophies with regard to thermal fatigue.

It is our philosophy to evaluate the ‘integrated lining design’ as one system: this system includes mechanical (shell and cooling members), refractory and process engineering (cooling system) components. Customised systems can be developed to meet specific blast furnace requirements and loading conditions. Maximum peak heat load capabilities of typical bosh and stack lining designs are summarised in Table 2.

It is noticed that the blast furnace bosh and stack design impose conflicting requirements:

- Minimise fuel consumption /minimise heat loss
  - minimum cooling
- Minimise shell temperatures
  - maximum cooling

The heat load is a consequence of specific process conditions and lining design. History has shown that high efficiency designs using high conductivity materials are required to secure low shell temperatures and a long campaign life based on the premise that lining protection is achieved by a solidified layer in the bosh, belly and lower stack. However, copper stave cooler designs have a limited ‘anchoring’ functionality and this could result in exposure of the copper stave coolers to the abrasive and erosive descend burden and ascend of gases. Copper has a limited resistance against abrasion and erosion, and wear of the copper ribs will catalyse further loss of anchoring functionality.

The ‘Hoogovens’ bosh design comprises a dense pattern of machined copper plate coolers and (semi-)graphite; a 20+ year campaign was achieved in 2006[2]. The design is the optimum solution to secure a stable bosh profile and to allow high productivity levels. This first bosh design was installed at Hoogovens IJmuiden in the early 1970s and performed very well. Figure 2 shows the bosh of Hoogovens IJmuiden BF No. 4 after eight years of operation.

The bosh of Corus IJmuiden BF No. 6 was commissioned in 1986 and has been operating at very high productivity levels for many years. One of the principal advantages
of a high conductive plate cooler design relates to the ‘solidified layer adhesion’ capability – as seen in Figure 3.

**ADVANCED BOSH, BELLY AND STACK DESIGNS**

Two design philosophies have survived into the 21st century and share a similar engineering philosophy based on the ‘thermal solution’. Reference is made in Figure 4, which shows an advanced copper plate cooler and copper stave cooler design. Both include cast-iron stave coolers in the upper stack.

The Hoogovens copper plate cooler design includes high conductive graphite refractory in the bosh, belly, lower and middle stack. This graphite provides thermal protection to the embedded SiC refractory courses. The SiC provides protection against abrasion and erosion and this design gives a synthesis of thermal and mechanical components.

Copper stave coolers also have a high cooling efficiency but cannot survive all process conditions. Exposing conventional copper stave coolers to fluctuating high temperature process conditions can result in leaking cooling channels due to expansion issues (cracking of pipes) and abrasion/erosion. This has been observed at various plants on different continents and prohibits low cost hot metal production.

Additional refractory protection is required such as graphite and SiC inserts, vis à vis the plate cooler design. However, this offsets typical copper stave cooler advantages such as reduced CAPEX and increased working volume. Furthermore, stave cooler designs require long shutdowns during repairs.

In addition, copper plate coolers are always required in the (lower) bosh to permit high coal injection rates and to protect tuyere-coolers. This area is exposed to a variety of loadings (see Figure 5):

- Heat (raceway gases and impinging metal and slag)
- Erosion and abrasion (solids, gases and liquids)
- Oxidation (water leakages, FeO)
- Alkalis, zinc and lead

<table>
<thead>
<tr>
<th>Cooling</th>
<th>Refractories</th>
<th>Maximum peak heat load capability (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dense pattern plate coolers</td>
<td>Graphite</td>
<td>500,000</td>
</tr>
<tr>
<td>Copper stave coolers</td>
<td>SiC/gunnite</td>
<td>500,000</td>
</tr>
<tr>
<td>Medium to low density pattern plate coolers</td>
<td>Graphite</td>
<td>320,000</td>
</tr>
<tr>
<td>Dense pattern plate coolers</td>
<td>SiC bricks</td>
<td>180,000</td>
</tr>
<tr>
<td>Third-generation cast iron stave coolers</td>
<td>SiC/castable</td>
<td>170,000</td>
</tr>
<tr>
<td>Dense pattern plate coolers</td>
<td>Alumina/chamotte</td>
<td>110,000</td>
</tr>
<tr>
<td>First-generation cast iron stave coolers</td>
<td>Alumina/chamotte</td>
<td>110,000</td>
</tr>
<tr>
<td>Wide pattern plate coolers</td>
<td>Alumina/chamotte</td>
<td>35,000</td>
</tr>
</tbody>
</table>

Table 2 Maximum peak heat load capabilities
These loadings depend on the raw materials and blast furnace operations and should preferably be quantified. Alternatively it is recommended to qualify the loadings and investigate the (historical) performance and track records of other bosh designs.

The loadings depend on the temperature and may occur within a limited temperature range or above a certain threshold. A simple rule states that the loadings converge to zero at lower temperatures. Vice versa, loadings are increased when temperatures are increased.

Stable and moderate process temperatures at the interface between the burden and gas and lining will thus minimise lining corrosion and degradation. Some critical threshold temperatures for lining corrosion mechanisms are summarised in Table 3.

PERFORMANCE MONITORING
Advanced instrumentation permits continuous and accurate process and equipment control. We have also attended many postmortem analyses and provided FMEA consulting and engineering services.

The Hoogovens bosh, belly and stack design has proved robust and stable, and it permits multi-campaign low cost hot metal production\cite{3,4}. Many myths have developed around copper stave cooler designs, and specific operational precautions are often required to prevent premature failures.

These observations are supported by extensive RD&T analysis and multi-physics models. Our models also indicate that copper stave cooler designs are more sensitive to dynamic process conditions and that providing ultra-efficient copper stave cooling systems could de-stabilise operations.

In this respect, it can be said that the dense plate cooler design de-couples the process from the limitations of equipment. This then provides a sound equipment base from which a long-term improvement in process stability and fuel rate can be realised.

**SUMMARY**
- The Hoogovens lining design has a proven (multi-campaign) lifetime of more than 20 years at high productivity and high fuel injection rates, contributing to low cost hot metal production
- Advanced bosh, belly and stack designs combine (lower) bosh plate coolers and upper stack cast iron stave coolers
- Bosh plate coolers are required to decouple process and equipment – a robust bosh permits operators to achieve high productivity, low coke, high fuel injection and high oxygen rates

**REFERENCES**
\[2\] P den Exter, R Molenaar, G Tijhuis and H Toxopeus, “Corus IJmuiden BF No. 6 ends successful 16-year campaign”, ISSTech 2003.

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**Table 3 Critical threshold temperatures for chemical attack/corrosion**

<table>
<thead>
<tr>
<th>Attack type</th>
<th>°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO disintegration</td>
<td>480-850</td>
</tr>
<tr>
<td>Alkali and zinc attack</td>
<td>800-950</td>
</tr>
<tr>
<td>Oxidation by O(_2)</td>
<td>&gt;400</td>
</tr>
<tr>
<td>Oxidation by CO(_2) and H(_2)O</td>
<td>&gt;700</td>
</tr>
</tbody>
</table>

*Fig 5 Bosh loadings*