Blast furnace bosh design and repairs

The initial design of the blast furnace bosh is important as it will play an integral part in determining the condition of the bosh as the furnace campaign progresses. Early deterioration of the bosh can influence operations and potential future production levels. The bosh faces heavy process loadings such as high and fluctuating temperatures, and abrasion and erosion from the descending burden and ascending gas. Furthermore, the bosh forms the interface between the lining of the tuyere band and the belly, and so must provide a smooth process profile to help secure stable operations.

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The `Hoogovens` bosh design, comprising plate coolers and highly conductive graphite refractory, has proven to be very robust and able to cope with fierce process conditions, and has achieved lifetimes in excess of fifteen years. Stabilisation of wear is observed after five years, and an almost infinite campaign life can be obtained. The principles behind the design and the operational practices that are observed are explained in this paper.

Two successful `Hoogovens` bosh designs have recently been installed in furnaces of 6.5 and 14m hearth diameter. The original bosh designs of these furnaces included plate coolers and silicon carbide refractory, and cast iron stave coolers, respectively. Both systems experienced problems and were, therefore, influencing production output. Interim repairs have allowed upgrading of the bosh designs in both cases. Furthermore, the cooling systems have been modified to allow for continuous on-line heat flux monitoring, so enhancing the potential for improved process control. The project design features and repair methods are presented.

BLAST FURNACE SIZING AND PROFILING

Blast furnace productivity is influenced by an array of parameters, each of which has been the subject of much debate in their own right. The overall conclusions are that higher quality raw materials and higher quality operations allow for higher and more stable productivity. There is, however, another important pre-requisite to obtain high and stable productivity which is independent of any operating parameter or blast furnace input. The blast furnace internal lining sizing and profiling should support a high level of operation at the start, and remain unchanged during the entire campaign. This is particularly true for the throat armour and bosh as these directly influence solids, gases and liquid flow profiles.

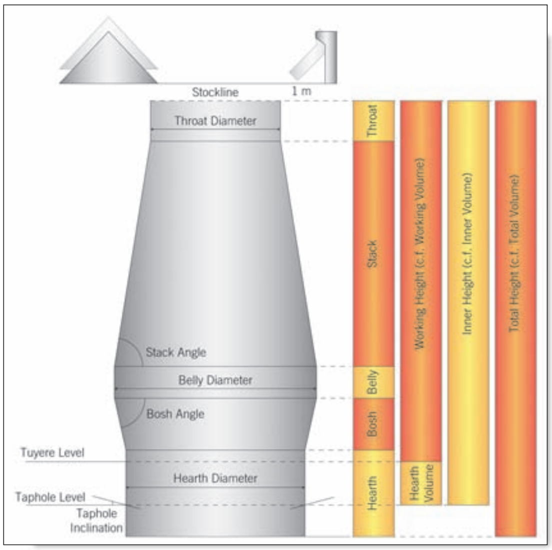

Fig.1 Key dimensions of a blast furnace

There exists a plethora of historical experience, empirical benchmarking and theoretical considerations that can be used to arrive at the sizing and profiling of a new blast furnace, but these can be further refined into a defined number of tried and proven relationships between certain key dimensions. The hearth diameter, working volume, belly diameter and hearth volume can be used to design the optimum sizing and profiling for a new blast furnace. Key dimensions are shown in *figure 1* and some examples of size relationships from our database collection of existing blast furnaces are shown in *figure 2*.

It is noticed that the bosh angle varies between 70° and 85°. This is partially explained by the fact that the lower bosh angle of many blast furnaces is steeper than the upper bosh angle since the hearth lining and belly lining thickness are different.

The profiling dimensions will have different effects on ▷

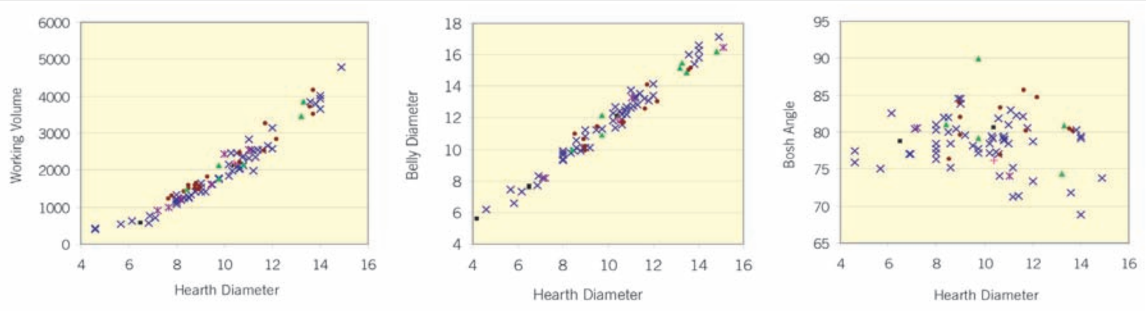

Fig.2 Relationships between blast furnace sizing parameters

the operations, so different considerations must be taken into account, as summarised in *Table 1*.

The bosh acts as the interface between the hearth and belly/stack and is a critical zone in controlling descending liquid metal and slag and ascending gases. An incorrect bosh profile can result in unstable gases ascending and liquids descending.

Dimensions	Effect
Working volume	Production capacity
Throat height	Burden distribution
Throat diameter distribution	Gas velocity/burden
Stack height	Burden preparation
Belly diameter	Gas ascent/burden descent
Bosh and belly height	Slag fusion
Hearth volume	Liquid containment capacity
Sump depth	Hearth wear rate

Table 1 Relationship between furnace dimensions and operations

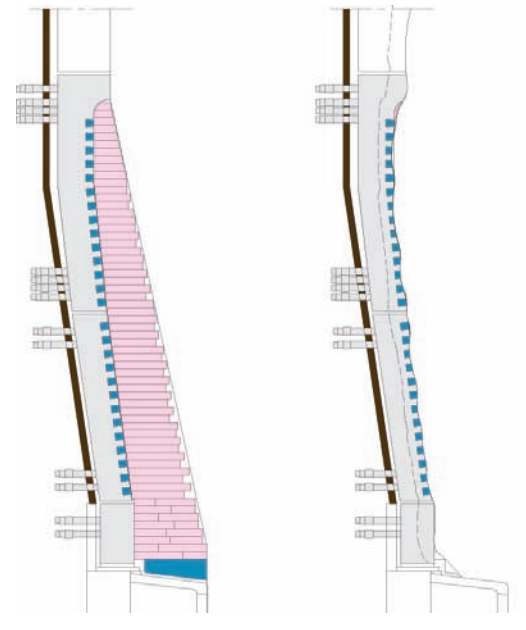

Fig.3 New and degraded bosh profiles

The sizing and profiling of new blast furnaces will generally be in accordance with theory and empirical relations. However, lining degradation as a result of a malfunctioning bosh lining, for example, will result in changes to the sizing and profiling and can have a negative impact on operations and productivity. The propensity towards lining degradation for a specific design should therefore be assessed along with the initial profile before finalising the design.

Unstable operations will impose higher loadings to the lining and may result in accelerated degradation of the bosh lining. The blast furnace lining design can be said to be failing once the shell is exposed to excessively high temperatures for prolonged periods of time, so initiating high stresses and physical deformation.

Typical examples of a new and degraded bosh profile are illustrated in *figure 3*. It is clear that the 'step' will have a negative impact on ascending gases from the tuyeres and descending liquids from above.

BOSH LOADINGS

It is necessary to define the loading conditions before developing and evaluating the bosh system design. This should be common practice in the industry, but we have noticed that this procedure is not always practised adequately, resulting in the selection of inadequate lining designs. The blast furnace (bosh) lining is exposed to physical, chemical and mechanical loadings.

Examples are summarised below:

- High heat flux, temperatures and fluctuations ...(Raceway gases and impinging metal and slag)
- Erosion and abrasion ...(Solids, gases and liquids)
- Oxidation ...(Water leakages, FeO)
- Alkalis, zinc and lead

It has already been noted that these loadings depend on the raw materials and blast furnace operations. The loadings should preferably be quantified. If not, it is recommended to qualify the loadings and investigate the (historical) performance and track records of other bosh designs.

It is our experience that the heat loads are not directly influenced by the lining and cooling system design, rather the heat loads are determined by the operations and raw materials. Furthermore, profile changes will have an impact on the operating stability. In other words, the lining is a reactive system instead of a proactive one. This means, for example, that intensive cooling and high conductivity refractory do not influence operations.

The loadings also depend on the temperature and may occur within a limited temperature range or above a certain threshold level. A simple rule states that the loadings converge to zero at lower temperatures and, conversely, 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 2*.

We believe that particularly the bosh heat loads, temperatures and fluctuations are critical in determining the lifetime of the bosh, therefore we will focus on these components. A basic understanding of blast furnace operations is required to ascertain that any hypotheses are correctly validated by empirical data and to explain observations.

It is important to distinguish blast furnace heat losses and heat loads. A blast furnace heat loss is an average value and it is often expressed in MJ/thm or GJ/hr. It must be identified to ascertain correct sizing of the cooling system heat exchangers and/or cooling towers. We relate the heat loss to the hearth diameter, productivity and ore (pellets) composition. An example of theoretical curves is shown in *figure 4* which relates to the tuyere zone, bosh, belly, stack and throat armour lining heat losses. We have observed that higher pellet percentages generally result in higher heat losses.

The heat load is generated by the internal operations and process conditions which vary irregularly in time and space and is a stochastic variable. A heat load diagram (HLD) is useful to visualise the distribution of the heat load for each zone. A typical profile is illustrated in f*igure 5*. Incidental, local heat loads may be 10 times higher, and bosh heat loads > 500,000 W/m^2 have been recorded in the past. Furthermore, we have noticed that the lower bosh heat loads can also exceed peak belly and lower stack values. This has often been related to the fact that the lower bosh profile had been changed due to lining corrosion and spalling.

	Critical threshold temperatures °C	Critical threshold temperatures °F
CO disintegration	480 - 850	900 -1560
Alkali and zinc attack	800 - 950	1470 -1740
Oxidation by O_2	> 400	>750
Oxidation by CO_2 and H_2O	> 700	>1300

Table 2 Critical threshold temperatures for chemical attack / corrosion

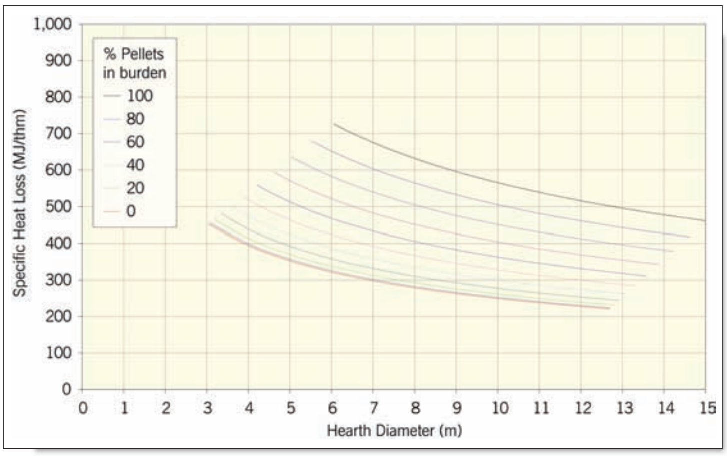

Fig.4 Heat loss compared to hearth diameter at different percentages of pellets in the burden

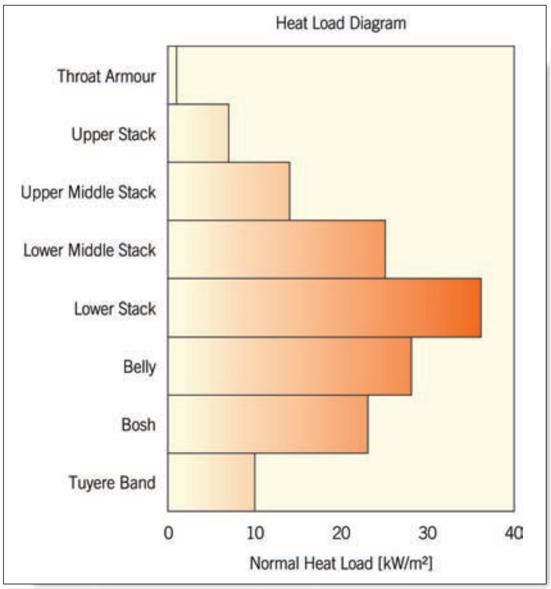

Fig.5 Heat load diagram

High heat load and temperatures can result in high lining temperatures which will endanger the lining condition as other loadings such as oxidation, will ▷

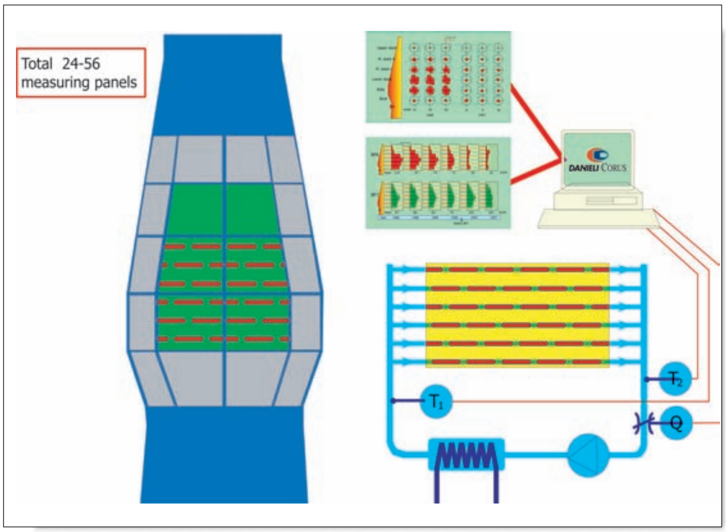

Fig.6 **Cooling system with heat flux monitoring**

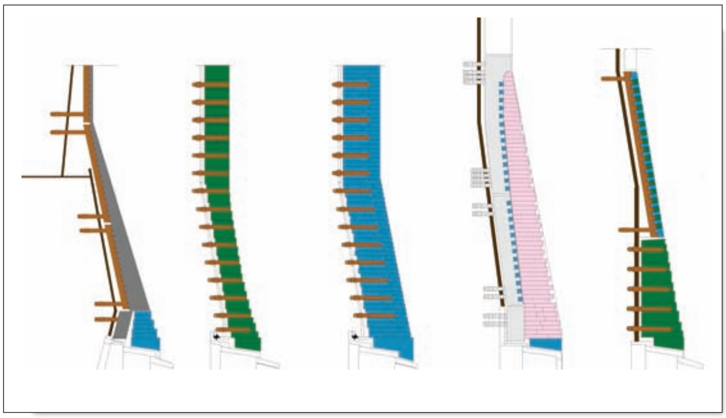

Fig.7 **Bosh designs**

increase accordingly. Large temperature fluctuations can result in rapid and instantaneous degradation due to spalling of the lining components.

We have been monitoring many blast furnaces since the 1980s and an adequate heat flux monitoring system allows us to measure local (panel) heat load levels in the bosh, belly and lower stack. A basic cooling system layout and heat flux monitoring system is illustrated in *figure 6*. The blast furnace cooling system is divided into 24 to 56 panels and the inlet and outlet temperatures and water flows of each panel are measured, allowing for an estimate of the local heat losses. Lining thermocouples allow for spot measurements.

Material	**Temperature fluctuations °C/ min**	**Temperature fluctuations °F/ min**
Graphite	500	900
Semi graphite	250	450
Silicon carbide	50	90
Cast iron (staves)	50	90
85% Al_2O_3	5	9
45% Al_2O_3	5	9
Chrome corundum	4	7
Measurements		
Sinter burden > 90%	50	90
Mixed burden 50/50%	150	270
Pellet burden > 70%	180	320

Table 3 **Temperature fluctuations**

`HOOGOVENS` BOSH DESIGN

A stable and smooth bosh profile is required to achieve and maintain high and stable productivity levels. A variety of lining designs have been developed over time which encompasses cooling systems such as plate coolers, cast iron and copper stave coolers, external spray or double shell / jacket cooling. *Figure 7* illustrates some typical bosh designs.

Various refractories, ranging from ceramics such as chamotte and high alumina, to silicon carbide to carbonaceous materials such as carbon and (semi-) graphite have been applied. We believe that only carbonaceous refractory (particularly semi-graphite and graphite) will survive bosh heat loads and temperature fluctuations, since the high thermal conductivity will result in lower lining temperatures and the materials have a large flexibility/elasticity *(see Table 3)*. Characteristic crushing temperatures for fully constrained refractory are summarised in *table 4*. It can be seen that ceramics such as silicon carbide and high alumina exceed the critical maximum crushing temperatures once exposed to rough bosh operations.

	Compressibility %	**Thermal expansion at 1000°C, %**	**Crushing temperature, °C**
Silicon carbide	0.05	0.3	160
High alumina	0.10	0.6	130
Amorphous carbon	0.40	0.5	800
Graphite	1.00	0.3	3300

Table 4 **Refractory properties**

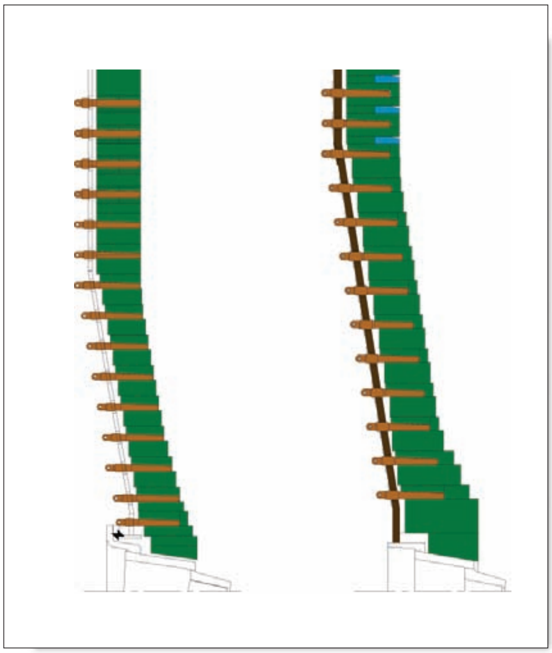

Fig.8 `Hoogovens` bosh designs

Cooling	Refractory	Maximum peak heat load capability (W/ m^2)
Dense pattern plate coolers	Graphite	500,000
Copper stave coolers	SiC/Gunnite	500,000
Medium to low dense pattern plate coolers	Graphite	320,000
Dense pattern plate coolers	SiC bricks	180,000
Third generation cast iron stave coolers	SiC/Castable	170,000
Dense pattern plate coolers	Alumina/Chamotte	110,000
First generation cast iron stave coolers	Alumina/Chamotte	110,000
Wide pattern plate coolers	Alumina/Chamotte	35,000

Table 5 Maximum peak heat load capabilities

Lining designs are often an 'assembly' of steel components and refractory. The design and engineering of the cooling system and refractory may have been executed by different companies and consequentially may not be compatible with each other. For example, the application of low conductivity ceramics and high density plate cooler systems introduces opposing philosophies with regard to spalling.

Fig.9 `Hoogovens` IJmuiden No. 4 after 8 years

It is our philosophy to evaluate the 'integrated lining design' as one system. This system includes mechanical (shell and cooling members), refractory and process (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) lining designs are summarised in *table 5*.

The `Hoogovens` bosh design (see Fig. 8) comprises a dense pattern of Cu plate coolers and (semi-) graphite, and a 20 plus year campaign will be achieved in 2006. We believe that this design is the optimum solution to secure a stable bosh profile and to allow high productivity. The first `Hoogovens` bosh design was installed at `Hoogovens` IJmuiden in the early 1970s and performed very well.

Figure 9 illustrates the bosh in blast furnace No. 4 after 8 years of operation. The bosh of blast furnace 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 'skull adhesion' capability which this is also clearly observed in *figure 10*.

BOSH MODERNISATION PROJECTS

Two bosh modernisation projects will be discussed in this section which will provide further insights into the functioning of other bosh designs and reasons for selecting `Hoogovens` bosh designs. The projects were executed in 2004 and operations are stable and at higher productivity levels since installation. The blast furnaces ▷

	Blast furnace `A`	Blast furnace `B`
Hearth diameter, m	6.5	14.0
Working volume, m^3	561	3680
Inner volume, m^3	652	4364
Number of tapholes	1	4
Number of tuyeres	16	36
Commissioning	2001	1994
Bosh design	Plate coolers and SiC	Cast iron stave coolers

Table 6 Blast furnace dimensions

Fig.10 Skull formation

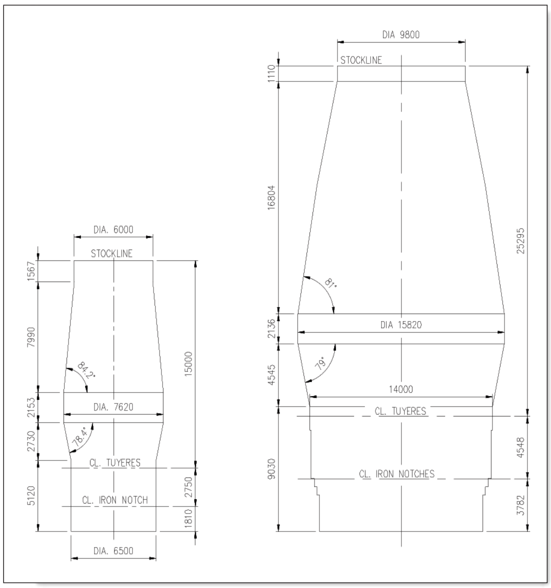

Fig.11 Blast furnace sizing and profiling, main dimensions

will be referred to as 'A' of < 1 Mthm/y and 'B' with an annual output > 3 Mthm/y, and are the principal hot metal production facilities within both plants.

The basic blast furnace dimensions are summarised in *table 6* and *figure 11.*

History of blast furnace 'A' Blast furnace 'A' was relined in 2001 and includes a typical (dense) plate cooler bosh design with SiC refractory and a SiC tuyere zone. The heat losses could only be identified per zone. Typical bosh heat losses are illustrated in *figure 12* and which, on occasion, exceeded 50,000 W/m^2. Since local and incidental peak heat loads can be 10 times higher, it is expected that heat loads > 500,000 W/m^2 have also occurred.

The 2001 bosh design is schematically illustrated in *figure 13*. This figure also includes the bosh profile after one year of operations and the new 2004 bosh design. The blast furnace raw materials included charcoal and sinter before the reline, but this was changed to pellets at the end of the last campaign.

High bosh heat losses were observed after commissioning and blow-in in 2001, and the shell temperatures exceeded critical levels within several months. Furthermore, irregular operations were observed and several fixed throat armour plates had been damaged. An audit was performed, which resulted in several conclusions:

- The raw materials modifications - sinter to pellets - resulted in new process conditions and thus required new operational methods
- Pellet burden operations are generally more unstable and result in higher heat losses, heat loads and temperature fluctuations
- Malfunctioning fixed throat armour - the lower part of many plates had cracked and disappeared - resulting in irregular burden descent and contributing to process instabilities
- The original bosh design had a limited capability to cope with the high heat load levels and temperature fluctuations
- Bosh profile changes had a negative effect on ascending gases contributing to irregular operations
- A negative spiral was activated where unstable operations catalysed further degradation of the (lower) bosh lining and vice versa.

The (lower) bosh refractory had collapsed at various places and this resulted in changes to the profile. An irregular profile can result in localised ultra high incidental peak heat loads, which could be enhanced on single taphole operations and irregular hearth liquid levels. The shell temperatures continued to increase,

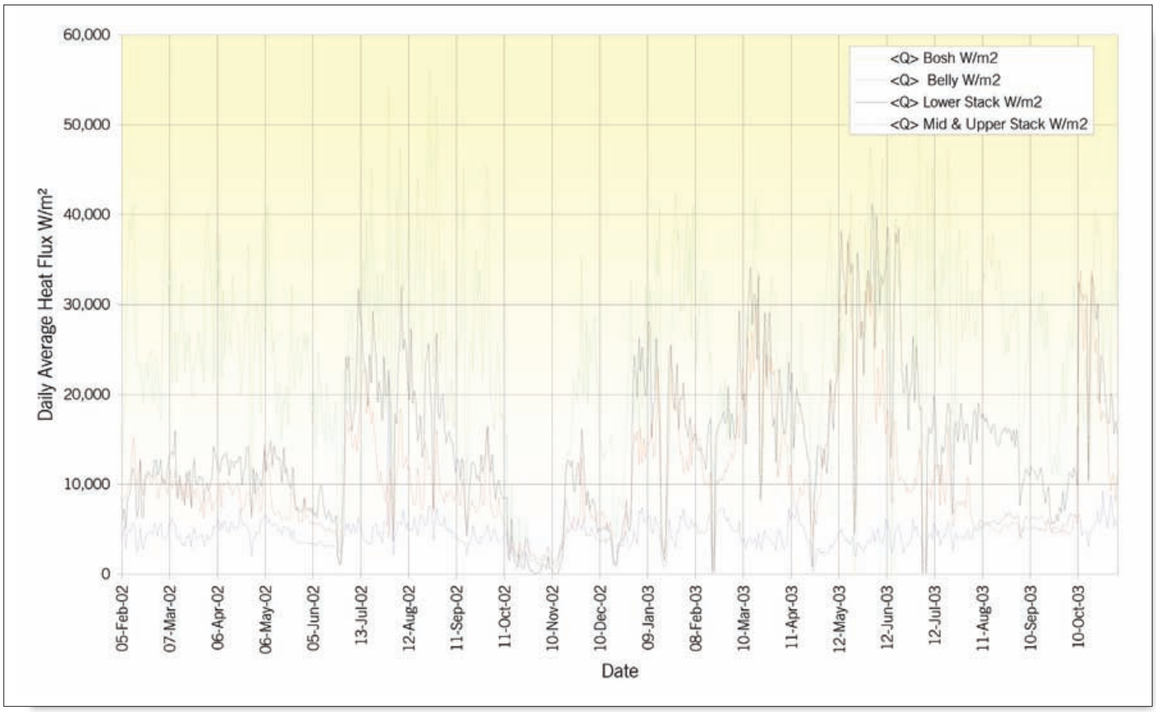

Fig.12 **Heat flux history**

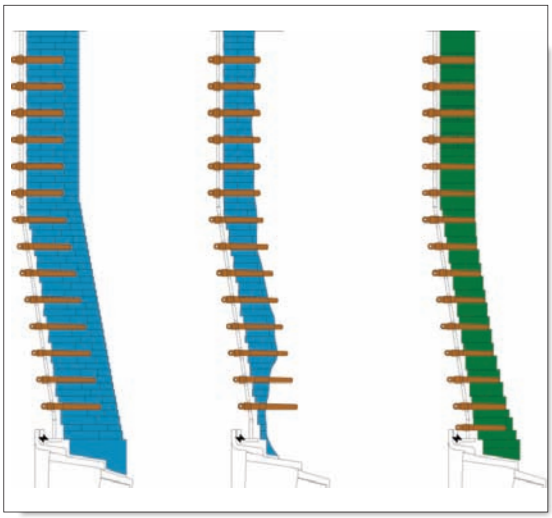

Fig.13 **2001 and 2004 bosh designs**

resulting in distortion, the shell showed a crack and a small breakout was observed. External spray cooling was applied to prevent further irreversible damage of the shell and shortened plate coolers were installed at several locations.

It was decided to restore the bosh profile and optimise operations and raw materials simultaneously. Various bosh repair scenarios were evaluated and the `Hoogovens` bosh design was eventually selected to obtain a stable bosh profile and bosh condition.

History of blast furnace 'B' Blast furnace 'B' was completely relined in 1993/94 and recommissioned in 1994. This design included cast iron stave coolers with refractory inserts in the bosh, belly and stack. Operations were stable and the production was high (> 10,000t/d) in the early years of the campaign. However, irregular operations had been experienced since 2001 and the ore/coke ratio and the blast volume were reduced in order to stabilise operations. Consequently the production level decreased and coke consumption increased.

We were invited to support an operational audit to find possible explanations for the decline in furnace performance and indicate solutions. The audit focused primarily on charging theories and practices and raw materials. Furthermore, 'central' versus 'wall' working practices were evaluated, as well as the consequences of constant or variable ore or coke layer practices.

The bosh cast iron stave coolers and refractory had also degraded. The 1994 design included an 'unstable' refractory construction and cast iron stave coolers have a limited capability to cope with high heat loads and temperature fluctuations. The refractory had disappeared completely exposing the cast iron stave coolers to the process and resulting in a significant change to the (lower) bosh profile. This stepped profile can result in localised ultra-high incidental peak heat loads - which can be catalysed by a wall-working operating practice. ▷

	Blast furnace `A`	**Blast furnace `B`**
Shell	Re-use existing shell, minor local repairs and new cooler openings above and at the tuyere zone	New bosh shell
Cooling system	New interconnecting piping, new supply- and return small bore piping, new layout allowing for heat flux monitoring system	New pumps, new mains, new ring lines, new supply and return small bore piping, new interconnecting piping
Refractory	New tuyere zone design; graphite	Repair tuyere zone: graphite
	New bosh design; graphite	New bosh design; graphite
	New belly design; graphite	New belly design; graphite
Cooling elements	New machined Cu plate coolers	New machined Cu plate coolers
		Replacement of several belly and lower stack cast iron stave coolers
Throat armour	Excluded	Included
Instrumentation	Heat flux monitoring system	Heat flux monitoring system
	Lining instrumentation	Lining instrumentation
	Leak detection	Leak detection
Commissioning	Cold commissioning	Cold commissioning
	Hot commissioning	Hot commissioning
	Ramp-up	Ramp-up
Taphole	Patch repairs	Excluded

Table 7 **Main scope items**

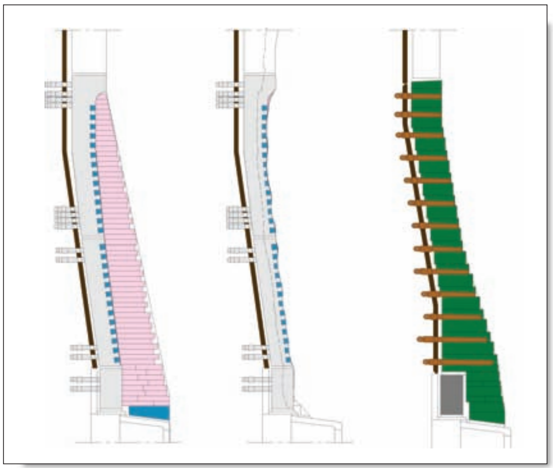

Fig.14 **1994 and 2004 bosh designs**

It was decided to restore the bosh profile and optimise operations and raw materials simultaneously. Various bosh repair scenarios were evaluated and the `Hoogovens` bosh design was eventually selected to obtain a stable bosh profile and condition. The 1994 design, degraded and new bosh designs are illustrated *in figure 14.*

Failure analyses Both blast furnace bosh designs had a limited capability to cope with (ultra)high heat loads and temperature fluctuations, which were occurring as a result of changes in operations and raw materials. These high heat loads were catalysed by single taphole operation of furnace 'A' and wall-going operating practice of furnace 'B'.

We believe that the system integrity is a result of the right selection and design of the cooling system, cooling elements, shell and refractory. The performance of the bosh lining will then be determined by the 'weakest' component, assuming that the materials and installation meet the minimum quality requirements.

Local and incidental (lower) bosh heat loads often exceed 300,000W/m^2 and levels of 500,000W/m^2 have also been recorded. The water cooling system basic minimum requirements can be directly determined by identifying 'failure' limits of the cooling system: (nucleate) boiling should always be prevented for obvious reasons, and it is recommended to consider a safety margin. Furthermore, cooling system velocities should be sufficiently high to prevent fouling and scaling. Higher pressures will increase the capacity of the cooling system, but are not always required. The abovementioned heat load levels require a minimum water quantity of approximately 5m^3/m^2/hr - we recommend higher values for the lower bosh. The cooling systems of both 'A' and 'B' were adequate.

Furnace 'A' had been using Cu plate coolers and furnace 'B' cast iron stave coolers. The Cu plate cooler design included 'rough' unmachined surfaces which hinders heat transfer and will result in higher refractory temperatures. The joint between the refractory and plate coolers is a critical component in determining this heat transfer. Cu plate coolers have a high capability to survive rough operations, but (micro) cracks and casting defects may eventually propagate and result in leakages. The plate coolers can also fail once exposed to impinging hot metal, which could happen in the (lower) bosh and often this also damages tuyeres.

Cast iron stave coolers have a limited heat transfer capability as the inner pipe and outer casting are separated. This will result in exposing the hot face to higher temperatures. This can result in malfunctioning cast iron stave coolers once (repeatedly) exposed to higher heat loads, and will eventually result in cracking and rupturing and ultimately leaking pipes. The bosh cast iron stave coolers are considered the weakest component in the original design of furnace 'B'.

The refractory of blast furnace 'B' was originally installed to provide the right bosh profile and provide protection to the cast iron stave coolers, however, this specific design and construction does not enable a stable performance. Furthermore, expansion provisions were absent, increasing lining stresses and premature failure. This refractory construction is, in effect, a temporary 'system component'.

The SiC refractory of blast furnace 'A' was produced by a reputable manufacturer and high quality materials have been used. Nevertheless, we believe that SiC is not the right material for high productivity bosh applications as it has a limited spalling resistance and also a limited resistance to withstand thermal stress cracking.

Scope of projects The main focus of the repair related to the bosh, but included several other components. *Table 7* summarises the main scope items.

The bosh designs for both blast furnaces are very similar and include typical `Hoogovens` features such as a dense pattern of plate coolers, machined Cu plate coolers with small tolerances and high quality (low iron, low ash) graphite. Provisions have been made for a tuyere zone and upper hearth repair of both furnaces as their condition was uncertain. The tuyere zone comprises double-densified, high quality graphite, and similar designs have been performing extremely well in many applications.

The belly design of blast furnace 'A' includes unmachined plate coolers, and carbon ramming is required between the refractory and plate coolers. This will limit the 'cooling capability' and result in higher refractory temperatures. However, this zone - and the stack - will be more easily repaired in the future. This decision was only based on economic merits. Cast iron stave coolers have been replaced in the belly and (lower) stack of blast furnace 'B'.

Blast furnace 'A' outage was limited to 29 days and a successful salamander tapping contributed to safe and efficient working conditions and allowed rapid entry into the furnace. The outage of furnace 'B' was limited to 69 days as a result of the fact that the entire bosh shell was replaced and new cooling systems and piping installed. This outage also included salamander tapping.

CONCLUSIONS

The bosh is a critical component in obtaining high and stable productivity. Inadequate bosh designs have a limited capability to withstand rough operations, high heat loads and temperature fluctuations. These can occur as a result of changes in raw materials and operations. Both effects catalyse each other as changes to the bosh profile can result in uneven gases ascending and liquids descending. This can enhance degradation of the bosh Lining.

Two malfunctioning bosh designs have been replaced by a new system with a high density plate cooler pattern and highly conductive graphite refractory. The cooling systems have been changed to allow for future heat flux monitoring and improved process control. The new bosh designs allow for high and stable productivity levels and long campaign lives.

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