The value and use of blast furnace operational auditing

Commissioning an audit of the operational and technical aspects of a blast furnace is a way to step outside the day to day routine of operations and gain an insight into how the current operating regime is influencing its future. Ultimately this will determine decisions that affect the entire site. The areas that are encompassed in such an audit cover the operations of the furnace itself, the condition of the component parts, and how these combine to form an outlook of campaign lifetime and extension capabilities. This paper sets out to describe which areas are covered in such an audit and how the results may be applied to best effect.

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Why would a BF manager want someone to tell him what is happening in his own blast furnace - surely no-one is in a better position to determine that but himself or his staff? Well, in the current environment of high productivity at low cost, the day to day operation of a blast furnace does not leave the operator with a lot of time for reflection. Manning levels are such that every individual is fully occupied with short and medium term perspectives. The longer term view is left to the senior manager, who is also charged with the same responsibility for all other departments and functions on the site or even the company as a whole. Within this atmosphere it is very difficult to step back and evaluate if all areas are operating together to maximise the potential of the end result.

A significant proportion of the cost of steelmaking is determined in the primary end: raw materials, coke and other energy sources. The greater the efficiency with which these materials are used in the BF, the greater the impact on the bottom line. There are major differences between blast furnaces in terms of efficiency and productivity and, by carrying out an independent audit these differences can be highlighted. Once identified, the first step toward overcoming any significant differences is made.

Lengthening the campaign of the furnace almost endlessly is another way to avoid spending a large amount of money or suffering production losses during reline. However the flip side to this is the increased risk of equipment failure or sudden unplanned end of the campaign. A BF audit can identify these risks and quantify the probability and associated consequences. In the case where insufficient information is available for a comprehensive risk assessment, dedicated inspection and testing programs can be implemented, for instance hearth assessment and monitoring, to increase the information source and so quantify the risks more accurately.

With this information at hand, informed decisions can be made with regard to productivity levels, intermediate repair plans, contingency plans, and long term reline planning, all with the aim of securing the profitable long term future of the BF.

AUDITOR REQUIREMENTS

In order to conduct a thorough and unbiased audit, and to formulate meaningful results, there are a number of preconditions that the auditor must meet. Because of the nature of these preconditions, it is often impossible to be able to conduct the audit with in-house personnel. In most cases an external industry consultant will be far better placed to conduct the audit effectively.

The first main criterion for the BF auditor is that they must have an independent, non-biased view. This can only come from someone who is not employed at the site, or even at the company. Even within large, multi-site companies, the presence of an outsider from within the same company can stifle the free exchange of information which is essential for an unbiased audit.

The second criteron is that the audit should be carried out over a short period of time, with the sole focus of the team on the audit itself. This can be achieved more easily by drafting in external assistance, which also facilitates the third criterion of guaranteed deadlines, as it will be known that the time period of the audit is fixed and firm. At the end of the audit period, the results should then be communicated to the entire BF team before the auditors leave the site. This maintains the relevance of the information and also the momentum of the exercise after the audit team has departed.

The BF auditor must also have knowledge of international BF practice so that the furnace being audited may be benchmarked. An in-depth knowledge ▷

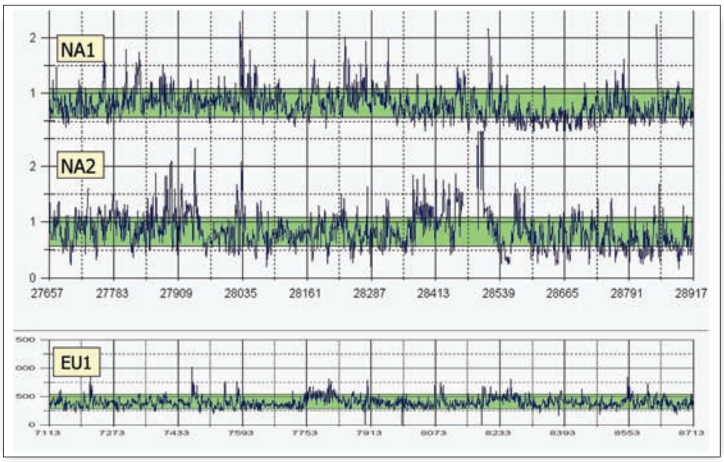

Fig.1 Hot metal silicon variation in three furnaces

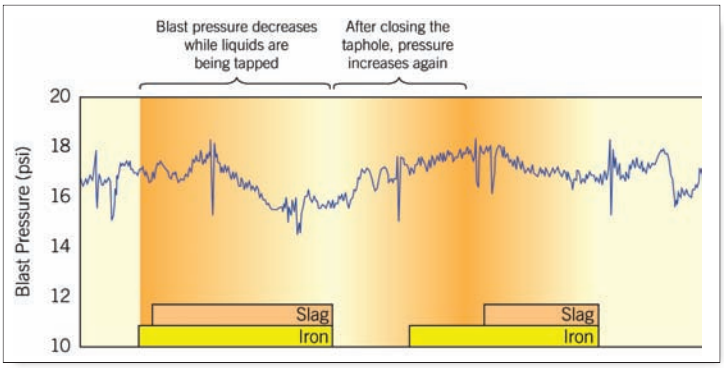

Fig.2 Effect of fluctuating liquid levels on the blast pressure

of inspection and condition monitoring techniques is essential, along with experience of how these have been applied and utilised at other BF units. The broad scope of the audit therefore requires a multi-disciplined team encompassing skills in process technology, operations, maintenance, repair and reline engineering options.

A typical audit for one BF will take anywhere between two and three weeks, depending on the scope, with the report delivered at the end of the audit period.

PROCESS TECHNOLOGY

The manner in which the BF is operated will have a significant impact on operating cost and productivity of that unit. In the long term, it will also have an impact on the potential for campaign extensions. The audit will identify where the BF is being operated to the best of its capability, and where it is not. The standard against which the results are compared is that of 100% consistency in operations, with stability being the key to profitable and sustainable operation

As a starting point, the main BF parameters are studied over the previous 12 to 24 months, and the last operating month will be compared with the best month in the study period. This gives an internal benchmark of current versus best achieved operation. The outcome can be further benchmarked with similar sized furnaces operating under comparable conditions.

The quality and consistency of raw materials have a major impact on stable operation. The importance of coke quality on BF performance is well known; less known but equally important are the low and mid-temperature degradation characteristics of the burden materials. For this reason, items such as raw materials are also included in such a benchmark study.

Whether this benchmark analysis is performed on current versus the best on the same furnace, or on representative data for two comparable furnaces, the result is the same. The larger differential factors are found, and from those a priority list of areas to be further investigated is made. One example shown here *(see Figure 1)* is the case of two North American blast furnaces (NA1,NA2) on one site where the silicon standard deviation was significantly larger than a similarly sized European blast furnace (EU1). The significant difference in values triggered further investigation, starting with the graphs for hot metal silicon over time. Such variability had a negative cost impact on the steel plant, leading to an investigation to the causes for the high variability. As a result an action plan for improvement was recommended, with specific goals for realistic improvement, based on local operating conditions.

The benchmark activities give a good overview of all the operational differences; however there are a few selected areas where more detailed investigations should be carried out due to the high impact they have on the process. The first of these is the casthouse practice and liquid management techniques. The problems caused by poor or irregular liquid removal from the hearth are more apparent in single taphole furnaces. However twin taphole furnaces are also vulnerable during periods of casthouse repair when only one taphole is available. The maintenance schedules for the casthouses are therefore scrutinised to identify where improvements are possible, always on the basis of zero to minimum investment with maximum returns. Opening and plugging practice of the taphole is observed and analysed, to identify potential problem or improvement areas.

This casting information makes a direct comparison with other process events on the furnace possible. Increases in blast pressure *(see Figure 2)*, stockline irregularities and drops in hot metal temperature can often be related to hearth drainage problems. By combining all this information, the influence of the

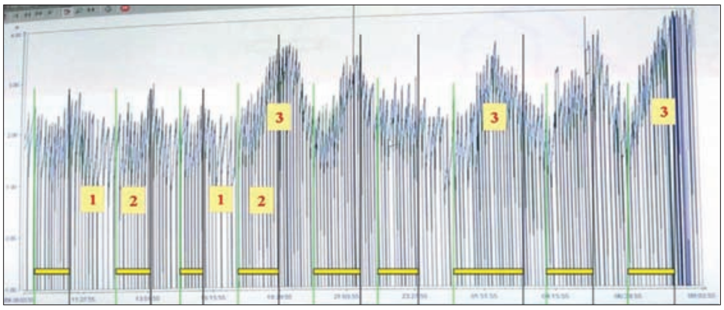

Fig.3 **Stockline chart and casting periods over time**

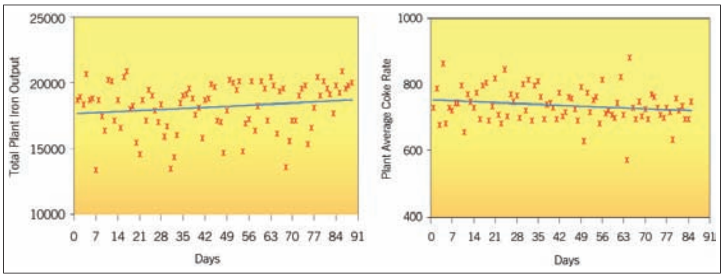

Fig.4 **Example of production and coke improvements following audit**

casting practice on any instances of irregular operation can be immediately assessed by the operator, and so appropriate actions can be taken. *Figure 3* shows a stockline chart with time with liquids casting superimposed with yellow bars. The frequency of charging, indicated by the line spacing, show that while the furnace is not casting (1) the charging rate slows down. After the taphole opens and the liquid level decreases the charging rate speeds up (2). In some cases this effect is so pronounced that the charging system is unable to keep up so stockline level is lost (3).

The gas flow pattern upwards from tuyeres to furnace top is also a key indicator for the operational performance of the furnace. The burdening philosophy of the plant is discussed in depth, with the desired aims compared with the actual results. The pressure difference between the tuyeres and the top gives a very quick overall impression of the gas flow, and this may be added to with information from the probes, stack thermocouples, top gas analysers, burden resistance and blast parameters to give a far more detailed insight. The regularity of the burden descent is assessed using the stockline indicators, such as mechanical stock rods or radar devices.

The interaction between all these parameters delivers a very good overview of the gas ascent, burden descent and areas were improvements can be made. The improvements in the gas flow pattern will bring improved efficiency to the process, which may also be seen in lower heat losses, and an improvement in total fuel rate. An example of such an improvement over a longer term operational auditing and advice project is shown in *Figure 4* where an improvement of production by 5.5% and coke rate by 3.33% at a blast furnace in North America over three months of operational improvements was identified through technical auditing.

REVIEW OF RAW MATERIALS

Along with the burden distribution, the raw materials themselves have a huge impact on the permeability of the descending burden, and so also on the ascending gas flow. The usual coke and ferrous burdens are assessed in terms of size, shape, chemistry and low temperature breakdown. Depending on the required output, the burden quality can be assessed in terms of its ability to meet these targets. *Figure 5* shows the variability of iron bearing materials used in one furnace over a period of 5 years. Each colour represents a different type of pellet and lump ore in quantity charged to the blast furnace per tonne of hot metal.

The selection of raw materials available at a specific site is usually rather limited and quality and consistency can be very variable. The purpose of an audit in this case is not merely to corroborate the variability, or lack thereof, but to quantify precisely where the variability counts in terms of its impact on blast furnace performance.

Where relevant, the on-site coke making, sintering and pelletising facilities are investigated for potential optimisation areas, with a view to realising through-cost benefits. Although many on-site coke or agglomeration plants are operated to achieve lowest cost product, it is often the case that running the plant with higher quality, albeit at higher cost, will produce a higher

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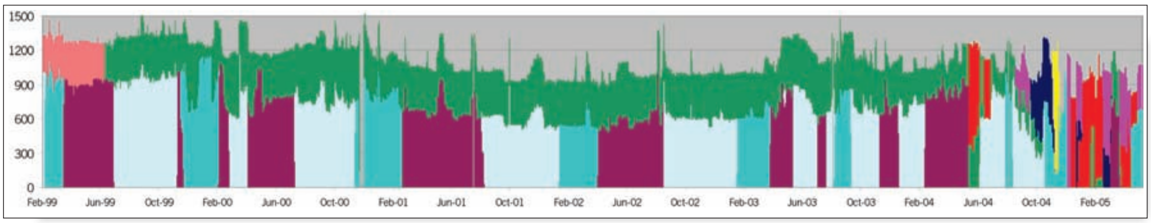


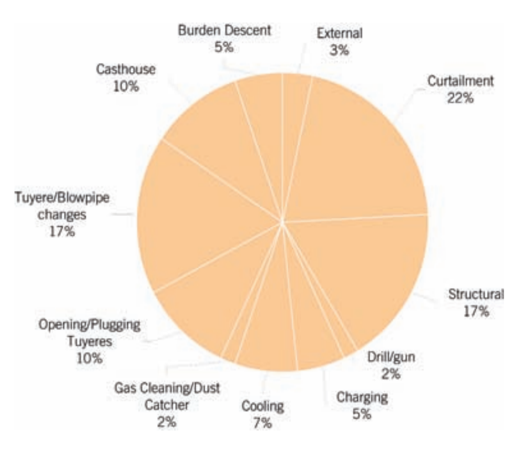
Fig.5 **Variability of iron bearing materials used in one furnace**

quality raw material that realises a higher cost benefit in the blast furnace. This benefit will then outweigh the additional costs, achieving lower end product costs, and so greater profitability for the company. Each of the blast furnace raw material inputs can be scrutinised independently, and then in their interaction with one another. Using this information, an improved raw material use scenario can be formulated. This encompasses the original source, the handling method and practice, bulk storage and a recommendation as to the combination of raw materials that may be used to best effect.

The handling, screening and stockhouse facilities do not escape the scrutiny of the BF audit procedure. The value of the raw materials that have been carefully produced or procured can be dramatically reduced by excessive handling, poor stockhouse logistics or insufficient screening. Each of the handling and processing stages are assessed in terms of necessity against penalty, with the overall material handling logistics subject to review.

Certain constituents of the burden, such as scrap, steelmaking slag, fines and briquettes are often attractive additives in terms of their price per carbon and iron units. There is, however, an associated cost in using a large proportion of these additives in the burden. The furnace will normally show a higher and irregular resistance, lower productivity and a higher fuel rate. Return streams and plant revert usage are reviewed in terms of the entire through-cost, taking into account additional handling and preparation steps, balanced against the realised benefits.

Once the optimal burden is determined, the objective is to maintain this on a regular basis, and to eliminate areas where variability is a problem. Items such as coke moisture variability, fines segregation, and chemistry variations are all relatively hidden effects, which may not be identified until after the material has been charged to the furnace. In these instances the importance of regular sampling and rapid availability of these results to the blast furnace operators is of prime concern. Further to this, the appropriate actions to take in the case of known variability in the input materials should be determined and incorporated into Standard Operating Procedures (SOPs). These actions are aimed at preserving the stable operation of the furnace under any circumstance, so that problems in one area, such as raw materials, is localised only to the raw materials and not magnified by disruption to the process itself.



Ⓐ **Fig.6 Stoppage analysis**

OPERATING PRACTICE

The operating practice of a plant can be a difficult area to benchmark, as many of the operating practices will be sensitive to cultural differences and also management styles. Is the focus on tonnage, on cost or on quality? An audit of operating practices does not have the goal of erasing these local differences, but to assess the practice in terms of success in achieving its purpose.

Regular checks on the installation that are carried out by the operator, such as preventative water leak detection, should be done in a comparable, controlled manner. Whatever the method that is employed, it should be representative and repeatable and for that to be the case, each operator must be familiar with the correct method. Controls should be in place to ensure that each sector of the cooling system is regularly checked, confirmed by both those carrying out the checks and the supervisor responsible. Developing preventative water leak detection practice as part of the daily tasks of the operators can go a long way to minimising the damage to the carbon hearth refractory caused by undetected water leakages.

Many of the items above will be represented in the SOPs. These documents are designed to standardise the operations from one shift to another, so that the same, correct, actions will be carried out regardless of who is on duty. It is therefore important that the SOPs accurately reflect the required actions, and are accepted by all concerned, with no ambiguity or contradictory statements contained therein. SOPs often cover a wide range of subject matter; however those that relate to the stable operation of the furnace can be reduced to fifteen to twenty key documents. These few will categorise the actions to be taken under any operational difficulties, with the aim to return to stable process, at aim production rate as quickly as possible.

MAINTENANCE

Reviewing maintenance plans and budgets can be helpful in assessing the maintenance level of a plant. However a far more representative test is to analyse the stoppage frequency and causes and relate this to the known or logged wind rate data.

Usually the analysis can separate the causes into a few main areas, such as;

- Planned stops
- BOF/caster down
- Hot metal logistics
- Raw material supply
- Tuyere or cooling elements change
- Charging system or raw material problems
- Unplanned stops caused by breakdown of mechanical, electrical or control systems

An example is given in *figure 6* as to how the results of this analysis can be displayed. As this type of analysis is usually carried out in terms of `time off-wind` rather than number of occurrences, a clear view is given as to the magnitude of the delays attributable to each area. Although a frequently recurring problem should be given attention, it may not warrant as much attention as a less regular problem which nonetheless results in more down-time. The balance between planned and unplanned stops can also be benchmarked to determine whether sufficient planned maintenance is being done in the correct areas to reduce the number of unplanned breakdowns in those areas. The total number of maintenance hours spent can similarly be compared, as well as the quantity of maintenance that is carried out during stops for other reasons, such as steel shop problems.

CONDITION MONITORING AND EVALUATION

Condition monitoring systems have improved substantially over recent years, with much more sensitive sensors than have ever been available before, together with phenomenal calculation power at low cost. With these developments, the analysis and filtering of raw data takes much less time, as does the reworking of this into highly meaningful and presentable results. This then provides the information for condition monitoring of equipment and subsequent repair planning. Repairs to essential items such as bell-less top rotating distributor bearings or skip winch motors can be scheduled with far more accuracy than has previously been the case**[1]**.

Certain items that are subject to critical failure are given particular attention in the audit, as these are the items that will often dictate the remaining

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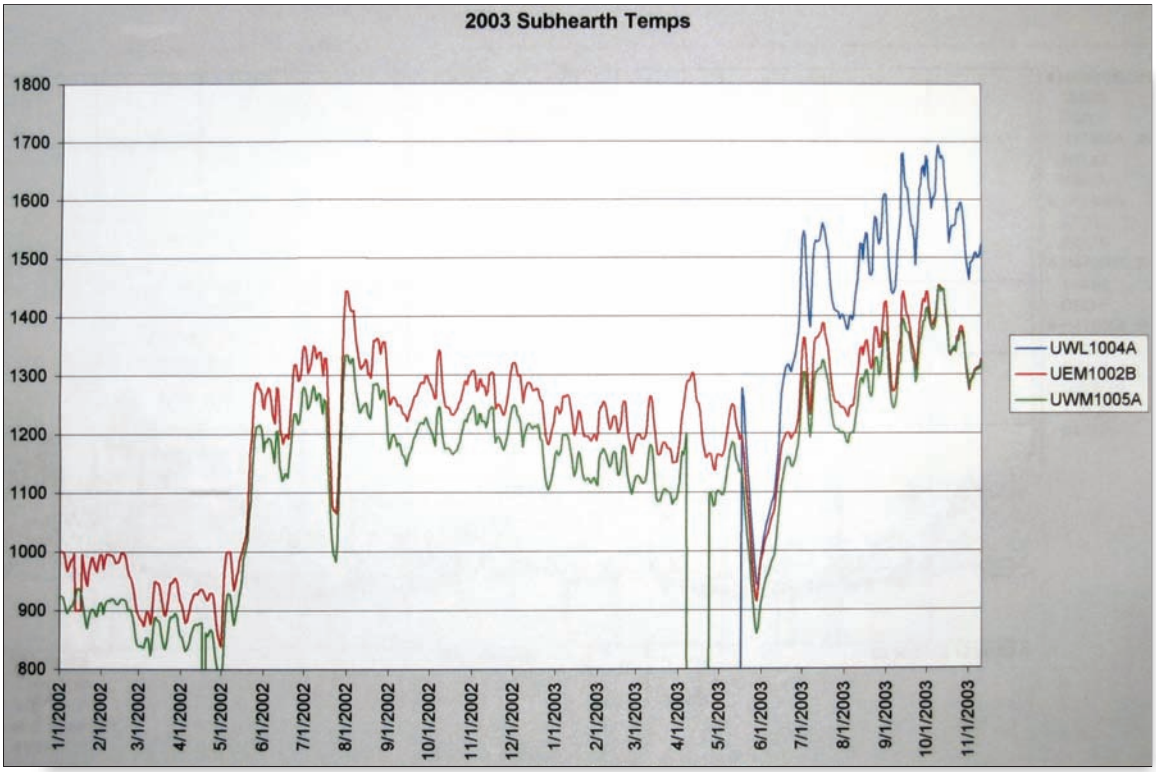

Fig.7 **Under hearth thermocouple temperatures**

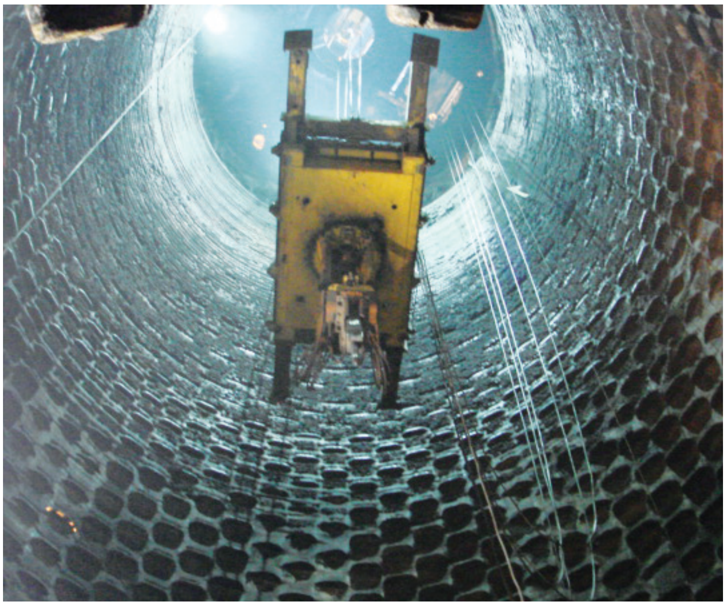

Fig.8 **Example of a plate cooled bosh**

Fig.9 **Severe distortion to throat armour**

lifetime of the furnace. Some of these items are now described.

Structural steel condition and inter-crystalline stress corrosion Wear and tear of structural sections can usually be monitored effectively by non-destructive testing (NDT) techniques, such as ultrasonics. One significant exception to this is the mechanism of inter-crystalline stress corrosion (ISC) in hot blast systems. This corrosion mechanism is triggered by NOx formation and condensation of acids against the steel shell in hot blast systems above a temperature of 1380°C (2500°F).

ISC appears as a finely dispersed network of microscopic cracks that are very difficult to detect in the early stages by conventional ultrasonic NDT methods. The phenomenon usually first appears around and across welds or highly stressed parts. Once it becomes obvious as through-blowing cracks, it is usually too late to repair it in a straightforward manner. The final solution is generally to replace the shell completely, or to encase the entire hot blast system with a double shell.

BF hearth The hearth and tapholes refractory condition is usually considered as most critical for campaign extension. It has been found that refractory wear is usually attributable to unusual or exceptional conditions such as water or gas leakage, than to normal operational wear and tear.

An in depth analysis of the hearth condition can be made using thermocouple data, combined with thermal models. *Figure 7* shows under hearth thermocouple temperatures showing progressively higher temperatures, indicating a reduction in remaining refractory thickness

In reality the situation for older furnaces is that the thermocouple (TC) grid is not always fully functional or reliable. Tag numbers and physical positions get mixed up; electrical connections become unreliable or completely lost. After ten to fifteen years, data may have been lost in irretrievable archives. Last but not least thermocouples themselves show drift or `aging` over time through exposure to high temperatures for a long period of time.

The brittle zones that can form over time in carbon hearths can cause major conductivity anomalies leading to false interpretations of the measurements. A more direct way of determining the hearth refractory condition is to perform core drilling which nowadays can be done safely under controlled conditions.

Bosh and stack The most significant refractory wear mechanism in bosh and stack is cracking, or spalling, of the bricks caused by temperature fluctuations. *Figure 8* is an example of a plate cooled bosh, demonstrating very limited wear after ten years in operation. Bosh and stack monitoring is usually more straightforward compared to the hearth, since thickness can be measured with mechanical rods during short stops. It can also be measured ultrasonically by installing ceramic rods in the refractory lining. Wear in the bosh and stack regions can easily be repaired by regular gunning or shot-creting of pumpable refractory material.

When excessive wear is present and the steel shell is directly exposed to the burden, embrittlement and cracking of the shell will occur six to twelve months after initial exposure. In this case the only remedy is to replace the shell. When shell replacement is required, it may be combined with a replacement of the cooling and lining system, better suited to the prevailing operating conditions.

During the BF audit procedure, a detailed relining and refractory maintenance program can be defined, along with longer term strategies for either complete or partial replacement of worn areas.

Throat armour The condition of the throat armour is most important, not only to achieve stable operation and a low fuel rate, but also to prevent excessive wear on the lining caused by uncontrolled gas flows that are caused by uncontrolled burdening. The irregular process behaviour itself can cause high temperature gas flows leading to further damage to the throat armour. In many cases uncontrolled behaviour of the cohesive zone or even high heat loads in the bosh can be traced back to a bad or distorted throat profile.

Figure 9 shows severe distortion to throat armour, which would render any efforts to control burden distribution useless

The hot blast system (HBS), including stoves This is another area that can determine the economic viability for a worthwhile campaign extension program. A well designed and operated HBS can have a lifetime of over twenty years, but this of course can be considerably reduced if not operated correctly.

There are many tools and techniques that may be used to establish the actual condition of the stoves while still in operation. Thermographic pictures with high temperature cameras of critical areas can be made at regular intervals to monitor known problem areas for signs of deterioration. Efficiency calculations of the stoves may be done by analysing the operating data and composition of gas, air and flue gas during normal cycles. Analysis of the timing of the cycles at regular intervals also gives a monitor for the efficiency of the stoves to detect any problems before they develop too far. Other measurements that should be done frequently are pressure drop measurements over the checker column during firing, calibration check of all instruments and a detailed inspection for the presence of ISC cracking in the shell and around all welds in the system.

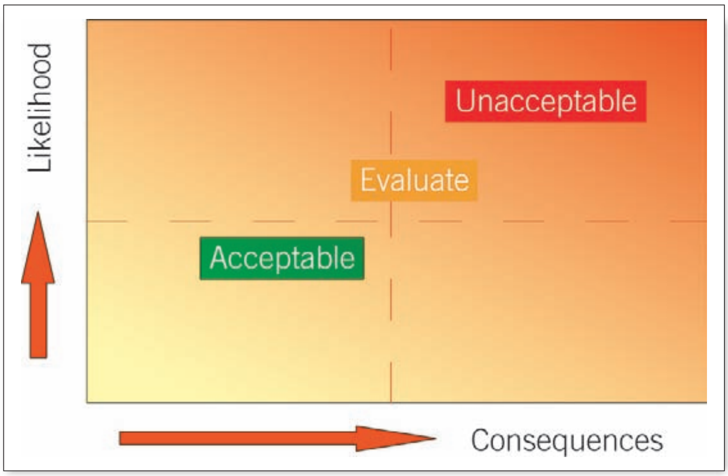

Fig.10 Risk analysis matrix

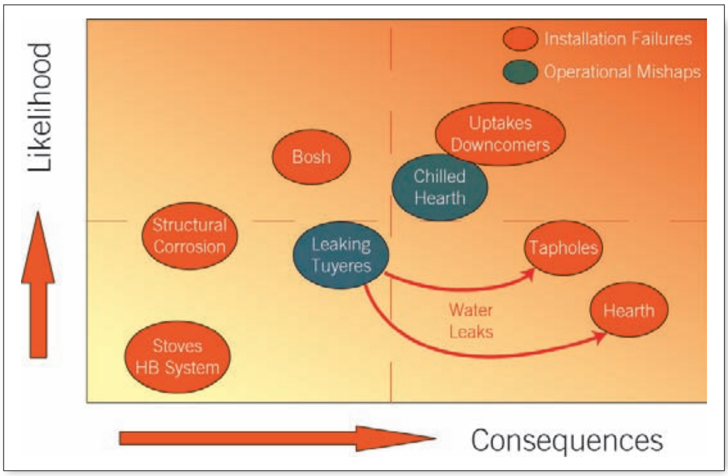

Fig.11 Example of a completed presentation of risk analysis

Risk analysis The risk analysis of the blast furnace and auxiliary equipment centers on those items of equipment that are the most essential to continue operations. Of course this is not to say that there are many non-essentials, but in many cases it will still be possible to charge a blast furnace with raw materials if a screening station fails. Operations may suffer slightly with unscreened materials, but the decision may be taken that that is not acceptable so the furnace will be stopped until it is repaired, and that presents a choice to the operator. With items such as the charging system, the bosh, or the hearth, this choice does not exist. Without those items, the furnace cannot be operated, and can even enter into a danger zone, so it is for these items the risk analysis is performed.

The risk analysis involves an identification stage whereby all the major components are quickly assessed in terms of their operating life, design life and current ▷

condition. From there the risks may be identified and quantified in terms of the cost of failure, and likelihood of such a failure occurring. This appraisal, presented in a schematic graph shown in *figure 10*, gives a very clear overview of where the priorities for attention should lie. Once the analysis is complete *(see Figure 11)*, the costs of repair or replacement of the essential items in need of attention can be estimated. These can vary depending on whether a 'quick-fix' can be carried out, to make the item last until the next major repair, or indeed if the item requires a major repair in itself.

RELINE PLANNING

Once the current state of the BF and associated kit are known, with the risks and consequences evaluated, and the operating level determined, future scenario planning is then possible.

The number of scenarios, if not infinite, are certainly numerous, and so certain criteria should be set for assessing the possible alternatives.

The key questions of each reline or repair scenario are:

- How soon will repairs be necessary to eliminate or reduce the risk?
- How much will it cost?
- How long will it take?
- What will be the expected life after the repair?

To answer these questions effectively, the forecast for future demand and prices should be estimated, and from that the necessary investment to meet these demands can be identified. It is in this latter part that the many possibilities may be discussed. Depending on the current plant configuration it may be appropriate to discuss reline plans over a number of years for a succession of furnaces. Alternatively the challenge may be to maintain output while planning and even beginning a rebuild project.

By addressing these points in a systematic way, all repair scenarios form 'emergency patch repairs' to 'full scale relines' can be reviewed on their business aspects. An independent auditor can help in making the most realistic risk assessment.

Where demand exists for small, but regular boosts to the iron output, it could be covered by improving productivity on existing installations, or by building a supplementary small iron producing unit.

The obvious solution to this dilemma may at first appear to be the avoidance of capital expenditure by increasing productivity of existing units. However, this may in itself require an ongoing increase in operating costs by investment in improved raw materials, or even capital investment into upgrading raw material handling systems. The effect on the fabric of the furnace should also be considered, as increasing productivity on an already worn furnace can bring an earlier end to the campaign that would otherwise be the case. Given these considerations, the overall investment in a supplementary alternative ironmaking unit, for example, may well be the most financially attractive option.

Depending on the local conditions, it may also be possible to aim for the 'endless campaign' strategy. This philosophy aims to delay indefinitely, a long stoppage to completely rebuild the furnace. This can be achieved by identifying the wearing parts in enough time to allow repair strategies to be implemented in shorter stops, with or without tapping the salamander. Areas such as tapholes and throat armour can be replaced in 8 to 10 days, with hearth repairs possible in 30 to 40 days. If wear has stabilised in the bosh and stack, with consistent operation and ancillary plant kept in reasonable condition, this approach to furnace campaigns is quite attainable.

Whatever strategy is decided upon and followed, it is always the case that future situations may cause it to be changed. Market conditions fluctuate, as well as the financial state of the controlling company, and so opportunities can arise for extra investment, or, unfortunately as is more often the case, the curtailment of already planned investment. When this happens, the review of risks and consequences may then be revisited and, if necessary, updated, to determine where the money that can be spent should be spent, to best secure the future of the plant.

CONCLUSION

The results of an audit in itself may bring up as many questions as it answers, but the nature of the answers it gives allows more knowledgeable questions to be formed. Rather than "where are we?" the question becomes "where do we go from here?" The future can never be predicted, but it can be prepared for, and the information that an audit provides can be used for operational improvements, campaign extension management, reline planning, all of which are future determining steps.

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[1] A statistically based approach to developing a condition monitoring program, O. Aspoy, Iron and steel Technology, December 2005