Blast furnace operation and maintenance in difficult times – are we prepared?

In the face of the increased risks that appear to be associated with operating and maintaining a blast furnace, we need to ask the question: "Are we prepared?" ie, are we prepared for more frequent process upsets, do we know how to respond, are we prepared for more frequent equipment failures, and do we know how to minimise these risks?

Industrial processes are always associated with risks, but these need to be assessed and monitored, so that risk mitigation can take place effectively. Equipment condition monitoring and campaign extension techniques need to be in place. Sufficient process monitoring tools should be available and, most importantly, Standard Operating Procedures (SOPs) should be developed to include measures to respond to abnormal process conditions, and staff should be trained to develop their knowledge of process irregularities that, until recently, most considered to be a thing of the past.

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Blast furnace ironmaking has gone through substantial changes in the 1980s and 1990s, with major advances in terms of productivity, process stability, campaign length and health, safety & environment (HS&E). The cast house, which is the most labour-intensive area around the blast furnace, has developed from a relatively cluttered place to an accessible, clean and safe working environment. Typical campaigns for major equipment have lengthened from just a few years to, in some cases, longer than 30 years. Operators have been able to focus on performance, achieving sustained high levels of productivity at the lowest possible cost, using, for example, high levels of pulverised coal injection.

Currently, the luxury of having a wide choice of raw material qualities available and keeping equipment in optimum shape appears to be something that belongs to the past. Our industry continues to be hit by slowdowns and crises and the operating envelopes for process as well as maintenance continue to tighten. While these conditions exert substantial pressure, they may also increase operating risk in many areas of operation. Most of these risks were common in earlier days, but many of us have become unfamiliar with them in the decades of development towards increased stability. These apply to the production process as well as equipment condition.

Increased risk will inevitably lead to more frequent occurrence of process mishaps and equipment failure. Recently, reports of major process upsets such as (near) furnace chills and failures such as furnace breakouts have already started to become more frequent in our (mature) global industry. The causes may vary in nature but, given the nature of our industry, the operating risks will probably only ease after a somewhat longer period of more favourable market conditions. In the face of the increased risks that appear to be associated with operating and maintaining a blast furnace, we need to ask the questions: "Are we prepared? Are we prepared for more frequent process upsets? Do we know how to respond? Are we prepared for more frequent equipment failure? Do we know how to minimise these risks?"

RISK ANALYSIS

A widely accepted approach towards risk analysis is that where the potential damage or impact of the incident is assessed against its likelihood. Incidents are plotted or quantified in a diagram or matrix and classified, eg:

- Acceptable risk – continue activity without adjustment
- Elevated risk – activity can be continued but calls for immediate attention and adjustment
- Unacceptable risk – stop the activity

Whereas the potential damage or impact for HS&E is usually quantified in terms of the gravity of the injury or environmental damage, failure of equipment requires to take into account not only the cost of repair, but also the liquidated damages in terms of lost production.

Something similar holds for process mishaps. Depending on the nature and perspective of the incident, it should be carefully assessed whether the associated risk should be analysed for the impact on the individual product unit (ie, blast furnace), on the production site or on the organisation/company.

Assessing the likelihood of occurrence may not be as straightforward in an industrial context as it may be elsewhere. Basing on statistics is not always evidently feasible given the relatively small universe of discourse for such an exercise. A practical approach is one whereby we review the frequency of occurrence within the perspective of a production unit, site, company, geographical area, etc. Did this type of incident occur at our furnace in the past six months? On our site? On the, for example, three sites within our group? In our country or region?

For some incidents, an approach based on condition monitoring of equipment may enable better risk analysis. For all of the equipment where this applies, it should be asserted that the correct monitoring procedures and tools are in place.

This approach requires, but also allows for, frequent re-assessment of risk. Based on industry reports, deteriorating equipment condition etc, it may become clear that a risk, given its higher likelihood or more substantial expected impact, is escalating from a risk towards a threat. How such shifts may take place is illustrated in *Figure 1*.

In this example, risks A, B and C could represent any possible risk, such as a chilled hearth, leaking coolers or structural corrosion – risks for which likelihood and/or impact may increase. An acceptable risk may develop into a risk calling for urgent attention or even an unacceptable risk and an immediate threat for health and safety or the company's or site's viability.

RISK MITIGATION

Under the current operating conditions, the obvious risk mitigation measures (maintenance, process adjustments, etc.) are likely to come at prohibitive Capex or Opex requirement. Risk mitigation is a matter of evaluating where the limited funds and resources are required most urgently based on risk assessment. If, after risk assessment has shown that risk is escalating, for example, a higher likelihood, risk mitigation which focuses on reducing the likelihood or reducing the potential impact is relatively irrelevant. Getting the correct tools for both risk assessment and risk mitigation in place is top priority. Once a healthy practice of risk assessment and monitoring is established, we need to define the next steps.

For blast furnace ironmaking, primary areas of focus are:

- Plant inspections, condition monitoring and campaign extension techniques
- Process monitoring and process measures

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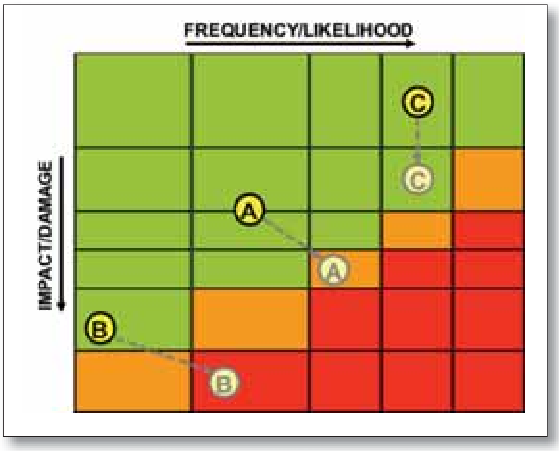

Fig 1 **Simplified risk matrix**

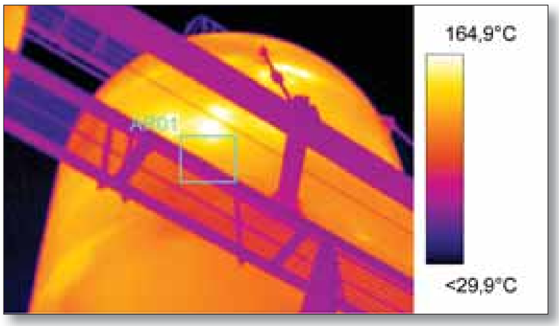

Fig 2 **Infrared (IR) thermographic inspection**

Fig 3 **Non-destructive testing of a steel shell**

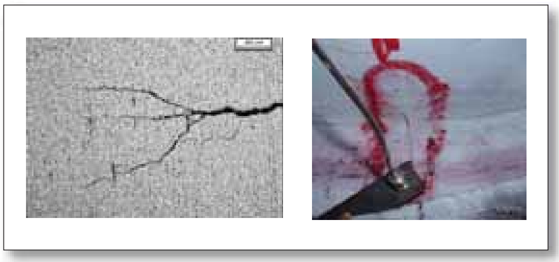

Fig 4 **Microscopic detection of ISC in hot blast system components**

Fig 5 **Endoscopic condition monitoring**

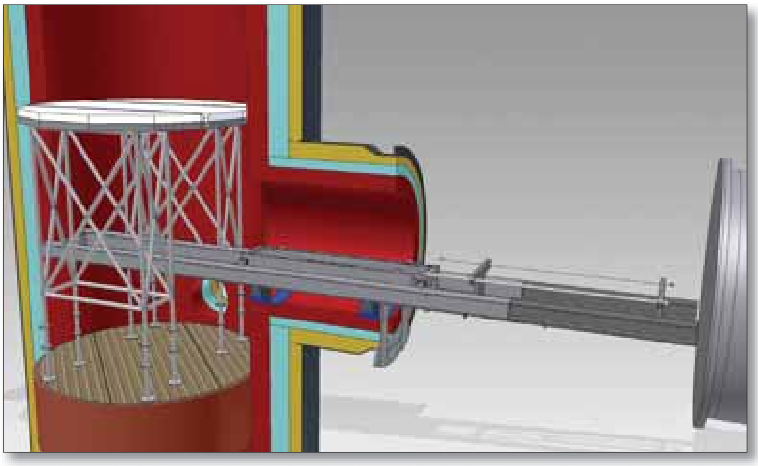

Fig 6 **Hot repair method for hot blast stove**

- Development of Standard Operating Procedures (SOPs) and training the organisation for out of normal process conditions

Plant inspections, condition monitoring and campaign extension techniques Inspection and condition monitoring have moved on from the early days of holding a screwdriver on a gearbox and listening to the rumbling noises. The sophistication of sensors has improved dramatically and areas where critical failures can occur can receive continuous and particular attention during condition monitoring processes. A few of the available techniques are described below.

A technique that has become very popular in our industry and that can be applied for condition and hence risk monitoring purposes for much of the equipment at a blast furnace installation is thermographic inspection. An example is shown in *Figure 2*. In many cases, it is the quickest method for defect detection and more targeted scheduling of inspection procedures for steel and refractories. It should be applied at regular intervals and with emphasis on critical areas.

The condition of structural steel and steel shells and vessels can usually be monitored successfully with non-destructive testing (NDT) testing, often using ultrasonic devices as illustrated in *Figure 3*. There is one exception to this rule, this being inter-crystalline stress corrosion (ISC) in hot blast systems. This type of corrosion is caused by NOx formation and condensation of acids against the steel shell in hot blast systems. The process accelerates above 1,380°C and appears as a fine divided network of microscopic cracks that are very hard to detect by conventional ultrasonic NDT methods (see *Figure 4*). It is usually first found around and across welds or highly stressed parts, hence where detailed inspection should take place. Once it becomes evident as through-blowing cracks, it is usually too late to repair it in a simple way. The final solution is generally either to replace all or part of the shell, or to encapsulate the entire hot blast system by a double shell.

The condition of the hot blast system refractory in ducts and particularly the stoves, which are critical given the dynamic process conditions, can be monitored and assessed using an endoscope (see *Figure 5*). Intermediate repairs can be done based on a traditional approach, but hot repair methods whereby the majority of the stove refractory is kept at levels close to operating temperature to limit contraction, have been developed to full maturity for a number of areas of the hot blast system. *Figure 6* shows a heat shield to enable hot repair of a hot blast stove burner. Temperatures above it are kept at >1000°C, the area below it, where repairs are required, is a <40°C working environment

Monitoring the condition of the blast furnace proper's refractory lining requires a different approach. The hearth and taphole refractory conditions are usually considered the most critical for campaign safety. 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 as illustrated in *Figures 7 and 8*. In reality, the situation for older furnaces is that the thermocouple grid is not always fully functional or reliable. An insufficient number of thermocouples may have been installed in the first place, tag numbers and physical positions get mixed up, electrical connections become unreliable or completely lost. After 10-15 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. For risk monitoring purposes, getting the hearth monitoring systems up-to-date should be considered.

Even with a solid hearth monitoring system in place, elevated risk may be left unnoticed when a brittle zone in the hearth refractory causes misleading temperature readings. 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 can be done safely under controlled conditions. Gas leakage through the shell, even in small quantities, can cause major CO attack on carbon hearths and should be eliminated.

An important factor for long hearth life is the ability to establish effective cooling of refractory linings. This can be achieved by having good thermal contact between the refractory, the shell and the cooling system. If there are doubts about the cooling efficiency, the thermal contact can be restored by injecting carbon paste, however, if this is not done carefully, uncontrolled injection can destroy more that it will solve, since the carbon hearth wall bricks can easily be dislocated. If the data collected and observations made over time are incomplete or contradictory, further in-depth analysis of the hearth condition is required.

Campaign extension repairs to the taphole can usually be done within limited shutdown times. Successful external repairs to the hearth side wall as illustrated in *Figure 9* require substantial expertise and experience to be successful. The risk of running into new hearth problems after the repair can only be prevented with sufficient attention to detail (design, materials, installation).

In the case of plate-cooled furnaces, the most significant refractory wear mechanism in bosh and stack is cracking, or spalling, of the bricks caused by temperature fluctuations. Bosh and stack monitoring is usually more straightforward compared to the hearth, since thickness can be measured ▷

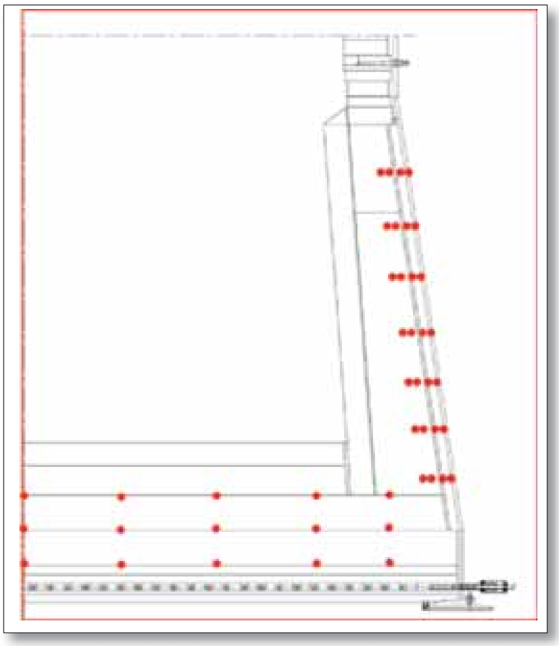

Fig 7 Hearth thermocouple grid

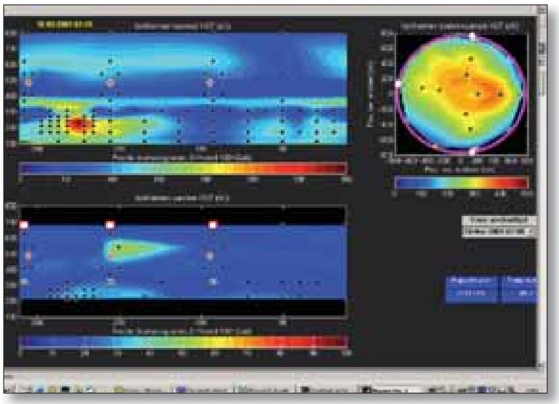

Fig 8 Visual representation of thermocouple readings

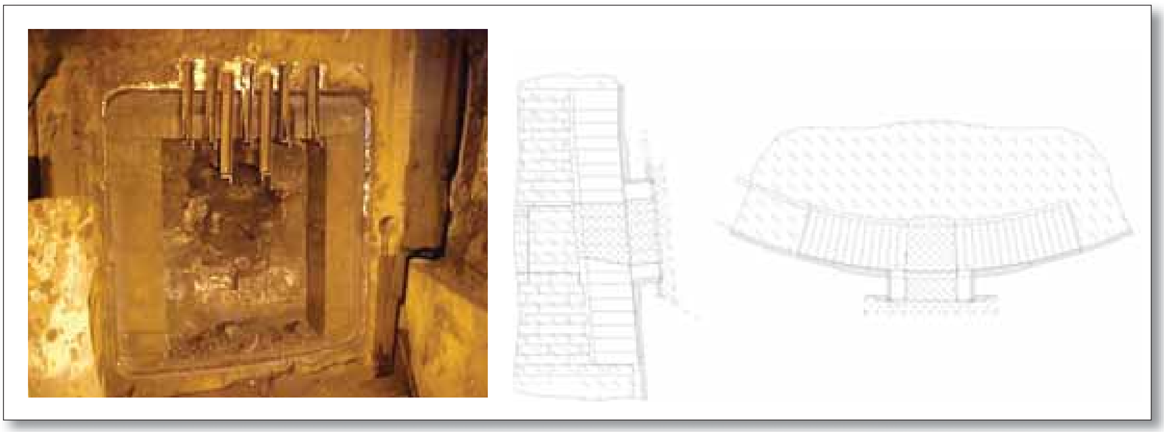

Fig 9 Campaign extension repairs to the taphole

Fig 10 **Installation of additional cooling capacity from outside the furnace**

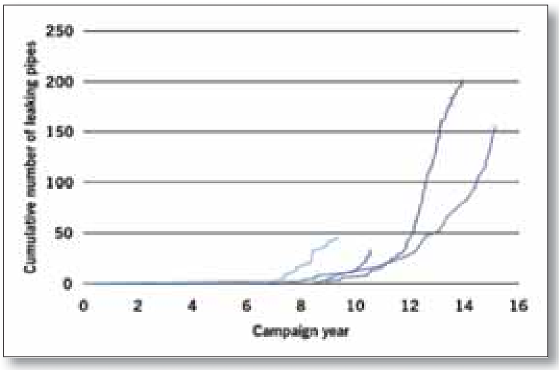

Fig 11 **Leaking cooling water pipes in stave coolers for four blast furnaces**

Fig 12 **Severely damaged throat armour**

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 be repaired by gunning or shot-creting of pumpable refractory material, though in the bosh area this is not always an easy task. This solution, however, has a limited effect in terms of protection and only works for a limited time and the procedure has to be repeated regularly. When the cooling capacity in a specific area turns out to be insufficient, the installation of additional cooling members from outside the furnace may be considered (see *Figure 10*).

When a furnace is stave-cooled, a different approach is required. Water leaks are the main concern with cooling staves so a programme of intensified leakage detection and wear measurement activities should be initiated. The consequences of minor leaks may be reduced by adjusting the cooling water pressure, but for more substantial leaks, the insertion of a 'double sleeve' cooling channel and grouting may be considered, or even blocking the cooling channel altogether. When multiple leaks are found, the installation of additional cooling elements is an option.

Whereas with plate cooling, replacing a leaking cooling member can be performed from outside the furnace within a short, scheduled maintenance stop, replacing stave coolers can only be done from inside the furnace after it has been blown down and the burden sealed. Stave leakage should in any case be monitored closely since it can escalate quickly, in turn leading to escalating risk for both process and equipment. *Figure 11*, which was compiled from several maintenance records published in our industry, illustrates the effect of increasing numbers of leaking cooling pipes over time to apparently exponential levels.

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 a cooling and lining system, better suited to the prevailing operating conditions.

The condition of the throat armour is very 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, as illustrated in *Figure 12*. 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.

Given the substantial interaction between process and equipment condition in this respect, the throat armour condition is related to risks that could escalate severely when not monitored carefully. Short-term repair procedures are available, but should be developed based on the throat armour design present.

Process monitoring and process measures The importance of process monitoring with respect to risk mitigation is twofold. In addition to enabling more sophisticated levels of process engineering and measures in the case of destabilisation, process conditions also give a firm indication of equipment condition in many cases. As an example, escalating cooling losses or temperature peaks in the hearth are not only an indication of process irregularities, but also of potential imminent degradation, eg of refractories. Examples of under-hearth thermocouple temperatures showing progressively higher temperatures, indicating a reduction in remaining refractory thickness are shown in *Figure 13*.

Instrumentation and process control systems in our industry have developed a long way towards the level of operator advisory, and automation systems have relieved the operator of many of the laborious tasks of day-to-day process control. These systems are well-equipped with respect to predicting, preventing and, more importantly, responding to process irregularities, but the trained eye and skilled judgment of the operator remain indispensable. Process monitoring tools that help the operator pick up early warning of irregularities include, but are not limited to, the following:

- Top gas analyser
  - temperature
  - pressure
  - gas analyser
- Radar
  - burden profile and level
  - burden descent speed
- Above burden probe
  - temperature
  - pressure
  - gas analyser
- In-burden probe
  - temperature
  - pressure
  - gas analyser
- Stack pressure probes

Another very useful tool is the advent of tuyere cameras. These allow the operator to monitor tuyere and raceway conditions at a glance from the control room (see *Figure 14*). New generations of these devices are starting to operate even better despite the harsh conditions at the blast furnace tuyere. Combining them with existing process monitoring and control tools mounted on the tuyere is usually possible.

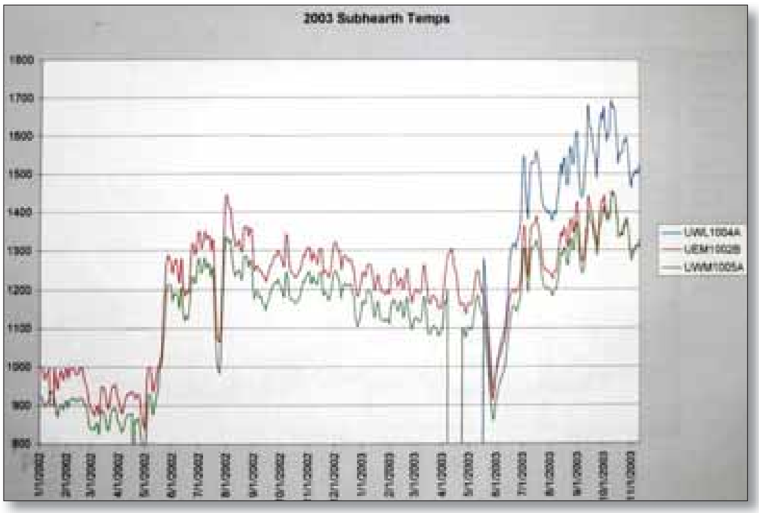

Fig 13 Under hearth thermocouple temperatures over time

Whenever process conditions indicate process irregularities or suspected failure of equipment, it is of the utmost importance that the operator adjusts the process in order to return to stable operations. Some process measures also reduce the risk of failure of equipment through, for instance, reducing the load on the equipment or buying time to perform maintenance or campaign extension jobs. Typical measures in this respect are the reduction of furnace productivity, reduction of the hot blast temperature, charging an improved coke quality and charging or injecting ilmenite for the protection of refractories.

Process conditions that could lead to serious irregularities if not recognised and addressed properly included heat shortages caused by interrupted coal injection, slag chemistry or escalating direct reduction, but also process asymmetry, bridge formation and increased amounts of fines in the burden. In many cases, the fitting response includes adjusting the ore burden or increasing the coke rate. In all cases, it is important that the correct response is implemented quickly and conscientiously.

DEVELOPING SOPS AND TRAINING THE ORGANISATION FOR ABNORMAL PROCESS CONDITIONS

Operating practices should be synchronised and standardised between shifts, furnaces and sites so that the same, correct actions will be carried out regardless of who is on duty. This is especially important in case of process irregularities given their relatively infrequent occurrence.

As mentioned earlier, blast furnace ironmaking operations have gone through fundamental development during recent decades. This has brought sophisticated high productivity and low cost operations in good times, ▷

but process mishaps that used to be everyday practice in earlier times have become an absent or, at best, a rare experience for the operators of today. Through retirement of older casthouse staff and operators and the development of the modern blast furnace process, knowledge and skills that are required for a quick and fitting response to process irregularities have made way for knowledge and skills that fit scenarios based on high productivity and stability.

The pressure that is currently exerted on our industry and the increasing risks make clear that we need to prepare for when threats become reality. When better times return to the industry, the current circumstances will have still left their traces in the form of delayed maintenance and suboptimal equipment conditions. When operations have to return to high productivity to accommodate demand, processes and equipment will be driven to their limits once again – limits, that may have shifted substantially during the current stages of the development of the industry, meaning that when we return to high productivity, increased risk is just as present as today, and maybe even more so. To secure quick and fitting response in these situations, the organisation needs to be fit for purpose both in the formal (procedures) and informal sense (people).

Knowledgeable staff may no longer be present on the casthouse floor due to retirement, but sufficient sources remain in the control room and in the blast furnace management offices to prepare the organisation to enable quick responses. An essential step is to develop the existing SOPs for the abnormal process conditions that may occur. These documents should include the measures that need to be taken in case of irregularities that are considered by many to be a thing of the past, ensuring that these are taken correctly at any time, and under all circumstances. It is important that the SOPs accurately reflect the required actions, and are accepted by all concerned, with no ambiguity or contradictory statements contained therein. Those that relate to operating the furnace can usually be limited to around 20 key documents. These will categorise the actions to be taken under any operational difficulties, with the aim to return to stable operations at acceptable risks as quickly as possible.

Critical for the successful implementation of these SOPs is not only that all concerned accept and acknowledge the stipulated content, but also that they familiarise themselves with it thoroughly. The people in the trained organisation should, however, not simply be confronted with the content of procedures and documents. All of them should be empowered by a solid base knowledge of the blast furnace process and its particularities. An essential element of the trained organisation is to be prepared for uncertain times characterised by less stable operations and more frequent process irregularities and that the knowledge and skills are not only based on know-how but also on know-why. This contributes greatly to quick, fitting and accurate responses.

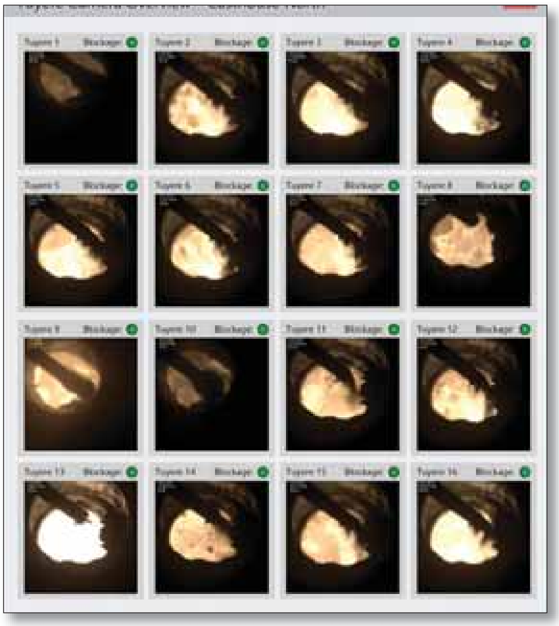

Fig 14 **Tuyere camera overview for half of the tuyeres of a 32-tuyere furnace**

CONCLUSIONS

Industrial processes are always associated with risk. In times of pressure, postponed capital expenditure and maintenance as well as a less stable process within a tightening operating envelope increase risk. These need to be assessed and monitored, so that risk mitigation can take place effectively.

With respect to equipment, this means asserting that condition monitoring and campaign extension techniques are in place. With respect to the process, sufficient process monitoring tools should be available to the operator. Finally, and most importantly, SOPs should be developed to include measures to respond to abnormal process conditions and staff should be trained to develop their knowledge of process irregularities that, until recently, most considered to be a thing of the past. With these issues covered, our industry can state that it is prepared for what is still to come. **MS**

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