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Developing a tapblock diagnostic system

L. GUNNEWIEK*, J. SUER*, R. MACROSTY*, T. GERRITSEN* and A. KARGES†
**Hatch Ltd, Ontario, Canada*
†Teck CominсoMetals Ltd, British Columbia, Canada

An advanced real-time monitoring system called the tapblock diagnostic system (TDS) has been developed. The purpose of the TDS is to help furnace operators manage the safe operation and economical maintenance of furnace tapblocks. This system is an evolution of the current practice of using historical records and operator interpretation to assess the 'health' of a tapblock. The main parameters affecting tapblock health are heat removal capacity and refractory wear, and these are currently difficult to assess *in situ* except in a global way. By using monitored and operating data together with predictive numerical modelling and multivariate statistical methods, real-time tapblock performance is assessed relative to expected performance. A state indicator in the form of a green, yellow, and red light is used by furnace operators to monitor the tapblock performance and health status during operation. Access to historical operating data and the provision of diagnostic functions allow for probable health degradation events to be deeply investigated. A recent opportunity to evaluate the actual performance of a first generation TDS installed in the KIVCET furnace at Teck Cominco's Trail Operations showed that a reasonable estimate of tapblock health was made. However, the evaluation also found that some areas of refractory wear were missed, and a new mechanism affecting refractory wear was discovered that was not previously known. This has reinforced the belief that there is a need to develop improved methods of monitoring so that data used to define the health of the tapblock is more comprehensive and accurate.

Introduction

The tapblock diagnostic system (TDS) described in this paper is an example of a condition-based maintenance (CBM) system. Jardine[1] provides an excellent summary of the developing field of CBM. Some examples of CBM systems that are under development are high performance machines like nuclear reactors and large combustion engines for helicopters, aircraft and ocean-faring vessels. The most advanced CBM systems to date are for rotating equipment where vibration sensors and oil analysis are used to detect deterioration in bearings, rotors and gearboxes, with the goal of avoiding failures that could be catastrophic to the system and human health.

Metallurgical smelting furnaces fall into the category of high performance machines. With metal prices at historical highs, there is economic pressure for operators to continually increase the throughput and campaign life of smelting furnaces. The increased demand on all aspects of the furnace leads to an increase in stress on the equipment, heightening concerns over vessel integrity and safety.

Tapblocks on a smelting furnace are used to remove the produced molten material in a batch-wise process called tapping, and are put under severe thermal and mechanical stresses during this operation. Proper design and maintenance of the tapblock is critical for achieving safe performance. The KIVCET furnace at Trail Operations is used to produce lead bullion from a variety of feedstocks. The lead bullion, because of its composition, must be tapped with a very high superheat and this translates into a very high thermal duty for the tapblocks. To accommodate these tapping conditions, the furnace is equipped with four water-cooled copper tapblocks designed by Hatch. These tapblocks are unique to Teck Cominco's KIVCET furnace.

Typical maintenance practice for the tapblocks is time-based with regularly scheduled repairs of the tapping channel refractory brick or replacement of the entire tapblock. Time-based maintenance means that the repair may be performed before it is required. Alternatively, waiting for a failure to occur is both a safety and productivity concern. The desire to avoid either of the two extremes provided the motivation for developing the condition-based TDS as previously described by Tracy *et al*.[2] As with any new technology development, there is continued learning once it is put into practice. In addition to describing the operation of the TDS, the work presented herein also describes what is being done to continue the development of the TDS so that its accuracy in predicting health is improved.

Background

Figure 1 is a section through an electric arc smelting furnace for primary metal production and is presented here in order to provide a basic picture of the principal components in such a furnace. The design and operation of such a furnace is described in more detail by Donaldson *et al*.[3] Raw feed material is charged into the furnace through feed ports located in the roof, and the feed is smelted to typically produce molten slag and metal. The molten material is tapped from the furnace through a set of copper tapblocks located in the sidewall of the furnace. The tapblocks are lined with refractory where contact with the molten material occurs, and an integral water-cooling system is used to remove sufficient heat in order to maintain the integrity of the refractory lining and copper block.

The tapblock is the most severe duty area in the furnace. The taphole is typically plugged with hard clay during the non-tapping period and is opened by drilling and oxygen lancing to allow the flow of molten material for tapping. During tapping, the tapblock is subjected to high heat loads and the resulting thermo-mechanical stress will deteriorate the tapblock over time. Furthermore, the refractory lining in the tapping channel can wear away due to a combination of mechanical wear from drilling and lancing, corrosion and erosion by the flowing molten material, and erosion due to the agitation caused by the gas bubbles that evolve during the curing of the clay plug.

The taphole requires frequent maintenance that usually involves hot repairs during furnace idling conditions. Failure of the tapblock can involve steam explosions with considerable damage as a result. Careful monitoring, control, and maintenance of the tapblock are essential to prevent conditions that can lead to loss of control and catastrophic failures.

Good integrity of the tapblock is characterized by an adequate thickness of refractory lining in the tapping channel and good heat removal performance of the copper block. It was expected that a tapblock normally wears out at a steady rate with the erosion of tapblock refractory and deterioration of the bond between the water-cooling pipes and the copper occurring over an extended time period. However, a difficult-to-open taphole could require aggressive drilling and lancing that induces sufficient mechanical stress and physical damage and causes unacceptable deterioration of the tapblock integrity in a single tapping event.

Present monitoring practice involves measuring the temperature of the tapblock at several discrete locations in the copper block using thermocouples, and monitoring cooling-water temperature using resistive temperature devices (RTD). Generally, these temperature readings at each instant in time are compared to predefined alarm levels (Hi alarm and HiHi alarm). While the alarm levels provide a general assessment of the tapblock's thermal performance, the reason for a temperature excursion cannot normally be determined without some form of off-line analysis. In addition, as these temperature measurements are made at a limited number of discrete locations in the tapblock, it is possible that significant wear events may not be noticed.

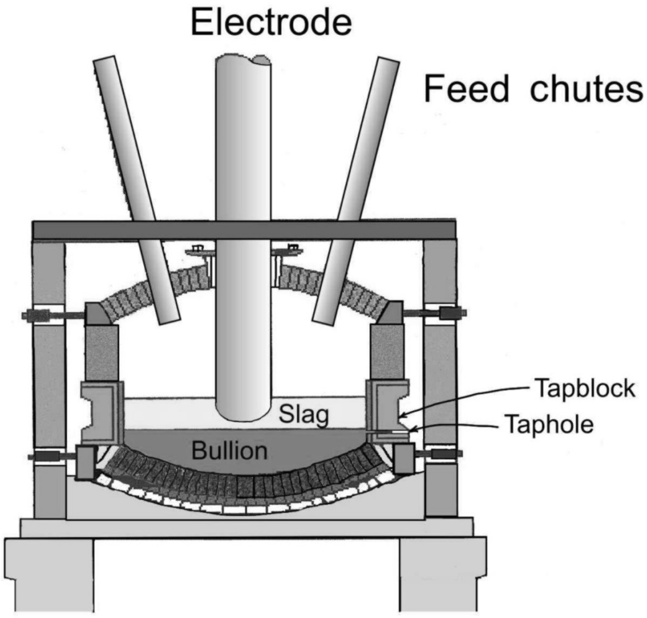


Figure 1. Section through an electric arc smelting furnace showing the principal components

Temperature excursions can be due to the following process variations and operating conditions: high metal tapping temperature; high metal levels in the furnace; bath agitation; worn/thin refractory lining; and poor contact between the cooling-water pipes and copper host block. Some of these conditions can be reasonably controlled through a change in the operating conditions of the furnace; however, the last two conditions reflect the health of the tapblock.

Description of the TDS

The TDS, like other CBM systems, includes three main parts: 1) data acquisition; 2) data processing; and 3) maintenance decision-making. The details of these three parts of the TDS are described below.

Data acquisition

Available measurements in a tapblock include water temperature, copper block temperature and water flow rates. The water temperature and copper block temperature are most often measured with RTD and thermocouples, respectively. The water flow in the cooling-water pipes is usually measured with a magnetic flow meter.

The copper block temperature is measured at about a dozen positions and each thermocouple can only detect temperature over a limited area of the tapblock. This provides some ability to detect wear areas, however, the entire surface of the hot face and tapping channel are not equally monitored. In addition, these measurements may be influenced by their proximity to the cooling water pipes that are cast into the copper block, and thus are less sensitive than desired. The resistive temperature devices are placed on the inlet and outlet of the cooling-water pipe(s) so that a heat load can be calculated using the temperature difference. The water temperature heat loads provide monitoring of the entire tapblock, but do not provide the ability to detect a localized hot spot. The cooling water system will also equilibrate the temperature distribution in the tapblock, thus making it impossible to be sensitive to local wear areas that are exposed to high heat loads.

The present level of instrumentation on a tapblock is adequate to provide a survey of the temperature throughout the tapblock and provide some ability to locate hot spots. The present level of instrumentation also provides a good basis for the development of the CBM algorithms. However, work has shown that more instrumentation is required for better spatial resolution of the temperature field. The use of a fibre-optic temperature probe as described in the paper by MacRosty *et al.*[4] is being developed. Another technique under development by Sadri *et al.*[5] is the use of acoustic signal pattern recognition and characterization using neural network principles. This technique is being developed to provide real time, continuous coverage of the tapblock performance during operation.

Part of the data acquisition task is to recognize faulty instrument readings as the quality of data is critical for accurate monitoring and diagnosis. Algorithms are provided in the TDS to check if instrument readings appear normal, e.g., open circuit readings are easily detected. In addition, some of the analysis provided by the TDS requires a complete set of instrument readings. Fortunately, if one of the instruments is detected as faulty, its data can be reconstructed using a soft-sensor as temperature readings from a tapblock are normally highly correlated. A linear combination of local readings provides the best estimate for reconstructing a missing temperature reading.

Data processing

The data processing portion of the TDS involves several main algorithms that extract information about the condition of the tapblock. The aim of these algorithms is to identify events and tapblock conditions that are beyond what was expected during the design phase of the tapblock and as a result, may represent damaged or damaging conditions. When a damaging condition or event is detected, the data processing module also provides a first-pass evaluation of the cause of the event. The events and first-pass analyses are keyed to a particular tap for easy reference, for example, tap number 518. A historian and event log are used to store relevant information for later evaluation by experts.

Thermal modelling—calibration of the diagnostic system

To calibrate the TDS, a fully three-dimensional computational fluid dynamic (CFD) model was developed. The model simulates the transient thermal response of the tapblock to tapping events for various operating conditions and predefined wear conditions. Figure 2 shows an example of a simulated tapping event compared to actual plant data for a typical 45-minute tapping event. The model very closely replicates the temperature profile as a function of time, thus verifying that the model is able to accurately predict the thermal performance of the tapblock during tapping.

The CFD model provides the opportunity to examine the effects of a change in a single process or operating parameter on the temperature response while holding all other parameters constant. In this way, the design engineer can determine the relationship between different parameters and tapblock behavior. Examples of some of the parameters evaluated include metal bath temperature and level, refractory wear, bath agitation, and pipe/casting bond integrity. The information provided from this analysis forms the base of information that the TDS uses for its condition-based monitoring and diagnostic functions.

Individual instrument evaluation

The temperature signal of each thermocouple in the copper tapblock is evaluated to extract metrics such as the duration of the tapping event, the rate of change of temperature at the start and end of the tap, the maximum temperature achieved during the tap, and at what time during the tap the maximum temperature occurred. These metrics are used for real-time diagnosis and are also stored in a database for later use by process experts.

The temperature readings of individual thermocouples are compared in real-time to known predefined temperature thresholds that reflect the limits of performance of the tapblock, e.g., boiling of the cooling water. The thresholds are not steady, but are correlated to the cooling water inlet temperature. This avoids false interpretation of measured data due simply to a temporarily high cooling-water temperature, for example.

Tapping indicator

The automated detection of tapping is an important algorithm that allows the number of tapping events to be counted and provides an important index for future evaluation of the database. All temperature events logged by the TDS can be referenced by the tap count.

Multi-instrument evaluation

A powerful real-time diagnostic tool has been developed as part of the TDS using principal component analysis (PCA) together with the CFD modelling data to identify normal and abnormal operation of the tapblock. A multivariate technique such as PCA correlates a large number of measured data into a few principal components that can explain the most significant sources of variation in the data. The PCA evaluation for a new tapblock indicated that the data from 14 instruments could be represented by only two principal components which capture 97% of the variance in the data. A detailed description of the PCA method is given in Erikson *et al.*[6]

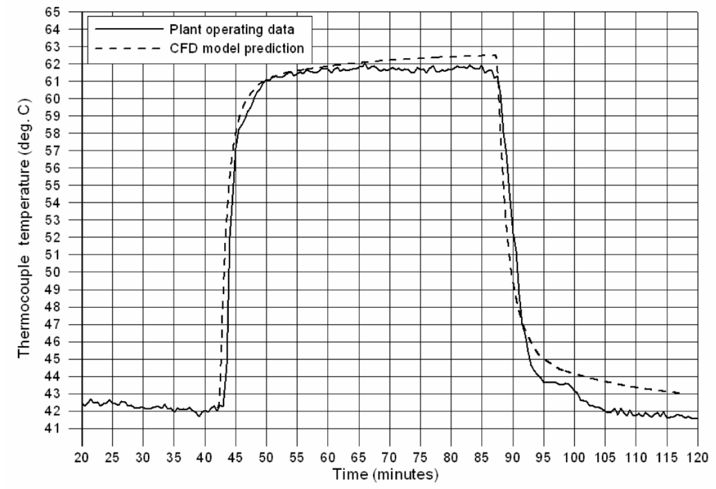


Figure 2. Sample plant and computer modelled temperature profile

Figure 3 illustrates the behavior of the two principal components during an idealized tapping event. The entire tapping event from start to finish is a heating and cooling cycle which appears as an ellipse in the principal component plot. Process and tapblock conditions affect the size, shape and location of the ellipse on this plot. By examining an actual heating and cooling cycle and comparing it to predefined ellipses for various process conditions and degrees of tapblock wear, regions of normal and abnormal operation can be determined from the principal component plot. More details of the PCA method used in the TDS can be found in the paper by Plikas *et al*.[7]

Maintenance decision-making

The literature on CBM calls the step of estimating health or remaining life 'prognostics'. In the case of the TDS, this step involves converting the measurements into a health index from 0% to 100%. The aim is to have a tapblock start at 100% health and then monitor the health as it deteriorates over the life of the tapblock down to 0%, at the lowest acceptable conditions for operation. The TDS includes both condition- and event-based prognostics and a health indicator for each.

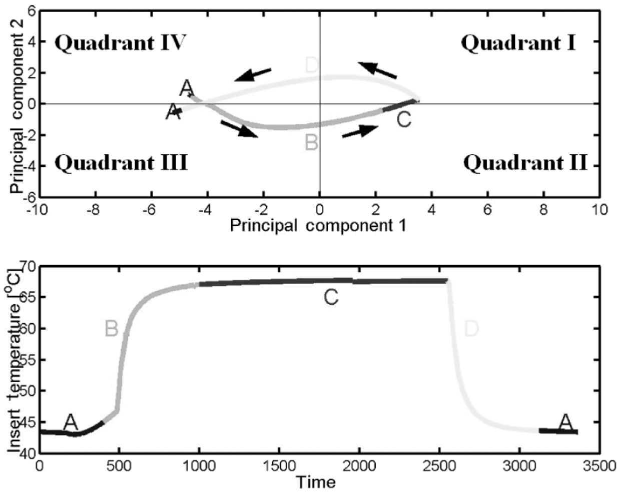


Figure 3. The top plot shows a tapping event on principal component plot. The bottom plot shows an idealized tapping temperature profile where A = non-tapping condition, B = open taphole and start of metal flow, C = tapping, and D = end of tapping and closure of taphole.

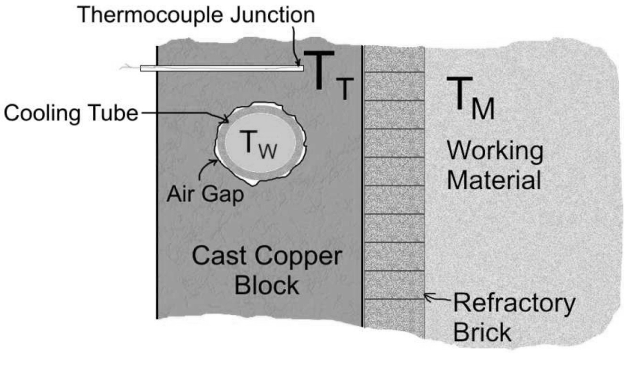


Figure 4. Illustration of the different temperature readings in a tapblock

Condition-based health index

The major modes of tapblock health reduction are: 1) loss of the bond between the cooling-water pipes and the copper casting, which acts as a barrier to heat removal; 2) wearing of the refractory, which allows more heat to reach the copper castings; and 3) high copper temperatures, which degrade the material properties of the tapblocks with time. All three of these modes are accounted for in the condition-based health index. Some key features of the algorithm are described below.

With reference to Figure 4, the temperature read by a copper block thermocouple (T_T) is a combination of: 1) the temperature of the molten material in the furnace (T_M) as seen on the other side of the refractory material; and 2) the water temperature (T_W) as seen through a portion of the copper block.

In addition to the metal temperature and refractory condition, the thermocouple reading T_T is strongly affected by the condition of the bond between the cooling-water pipe and copper block. This bond is described by a proxy heat transfer parameter of an 'air gap'. This air gap can be only microns in thickness, but it has a large negative influence on the heat transfer because it restricts the flow of heat from the copper casting into the cooling water. In a new tapblock, the air gap should be negligible, but due to thermal cycling it is thought that it may increase. A 'bump test', which involves temporarily lowering the cooling water temperature, is performed to accumulate the data necessary to estimate the air gap using data from the numerical model. An example of the temperature response to a bump test for different air gaps is shown in Figure 5.

The relationship between air gap and the thermocouple temperature can be characterized by a first-order response during the cooling portion of a bump test. While other factors affect the magnitude of measured temperatures, the shape of the bump test response is, for all intents and purposes, solely dependent on the air gap. During a bump test, the actual thermocouple responses are compared to the simulated cases and the air gap is reported as the simulated case that best fits the actual data.

Apart from the air gap, the temperatures within the tapblock during a tap are also dependent on tapping channel refractory thickness. The numerical model was used to derive a relationship between the air gap, thermocouple temperature, and refractory thickness for each thermocouple location. Figure 6 shows a calibration curve used to calculate the refractory thickness from the average thermocouple temperature and the air gap. For example, an average thermocouple temperature of 75°C and an air gap of 14 microns would correspond to a refractory thickness of 25 mm.

The condition-based health index is calculated using the estimated air gap and remaining refractory thickness. For Teck Cominco's TDS, a part of the health index calculation involves setting the area health index to 100% when the refractory thickness is 50 mm and setting the area health index to 0% when the refractory thickness is 10 mm. The overall condition-based health index for the tapblock is taken as the minimum area health index for the tapblock.

Event-based health index

The event-based health index is meant to replicate closely the method a process engineer might use to evaluate the tapblock condition or health without the aid of the algorithms described above. The event-based health index involves identifying the frequency, duration and magnitude

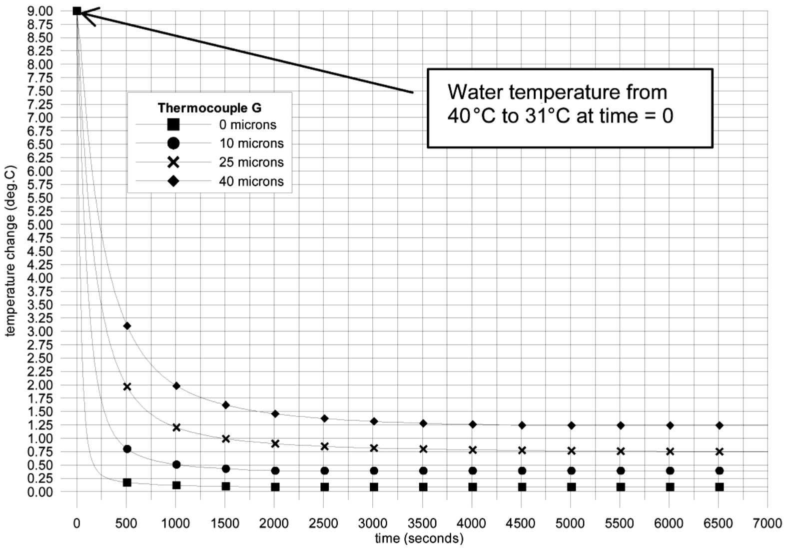


Figure 5. Time-temperature response of a thermocouple to a step change (i.e. bump test) in cooling water inlet temperature from 40°C to 31°C for various air gaps

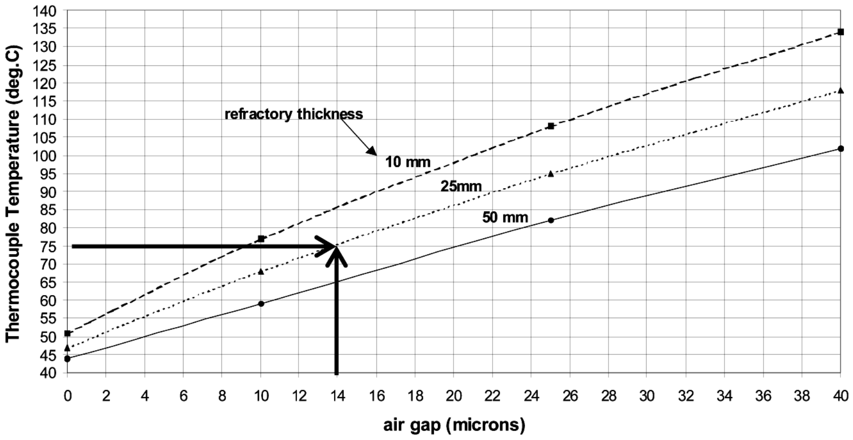


Figure 6. Sample curve for calculating refractory thickness from the air gap and thermocouple temperature during tapping

of temperature spikes above a predefined threshold. This information is used to account for loss of health. The precise interpretation and tuning of this algorithm is difficult because the exchange rate between these events and tapblock health is not well understood. However, this algorithm, when tuned using well-understood experiential data, does provide insight into tapblock health, consistency of interpretation, and consistent knowledge transfer.

Human machine interface

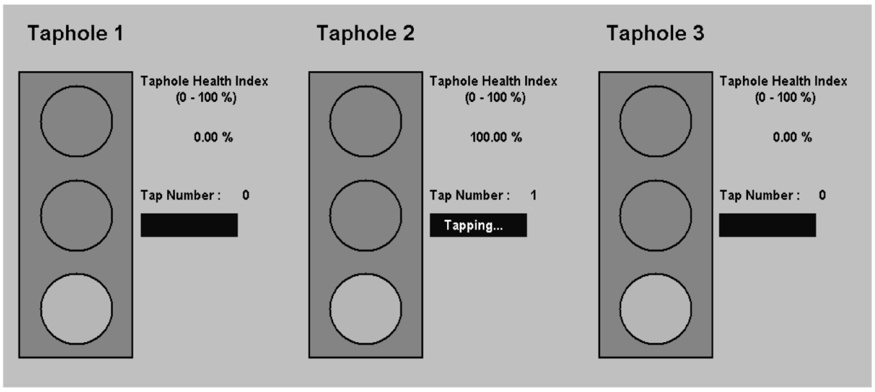
A diagnostic system must present the results in a meaningful way to highlight significant events. For example, one hundred time-varying data points can come from the tapblocks in a single furnace and the human machine interface (HMI) must quickly point out key conditions that require operator attention and provide a process engineer with insight into particular events of interest with a first-pass analysis.

Figure 7 shows a sample operator display for the TDS HMI with an easy-to-interpret state indicator using a Red/Yellow/Green traffic light for each tapblock. The light alerts operators to warnings ranging from instrument failure to tapblock degradation to strict instructions not to tap. The HMI also permits further investigation into warnings as required. Two major warnings parlayed through the state indicator are the results of the PCA and the value of the health indices. To complement this, a rule-based diagnostic was developed to summarize the findings of the TDS in an easy-to-understand fashion. Figure 8 shows the rule page display that highlights the conditions causing a red or yellow warning.

Discussion and current status

Computer architecture

The first generation of the TDS is built on a server running the Windows operating system. This approach permitted the coding of complicated algorithms and the necessary data storage capacity in the gigabyte range. However, the software had to be organized so that the computer could literally be unplugged in mid-operation and returned to operation without loss of data except, of course, for the time period while it was unplugged. Computer stability and the integration of the TDS into existing control system



Taphole Health Index (0 - 100 %) 0.00 %
Tap Number : 0

Taphole Health Index (0 - 100 %) 100.00 %
Tap Number : 1
Tapping...

Taphole Health Index (0 - 100 %) 0.00 %
Tap Number : 0

Figure 7. Main TDS HMI operator screen showing the traffic lights and health index for each tapblock

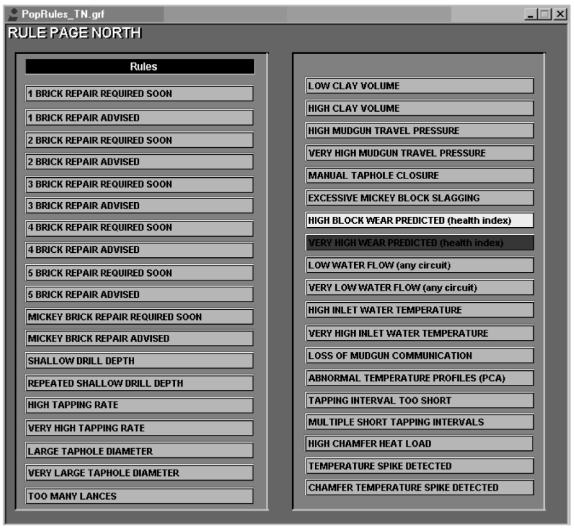


Figure 8. Rule page display showing active rules triggering a yellow or red warning

architecture had been an early hurdle to deployment, but this issue appears to have been resolved.

Taking this learning, the next version of the TDS will use computer architecture with a very reliable processor combined with a local historian and HMI for long-term data storage and visualization. This architecture is familiar to process control engineers as the programmable logic controller (PLC), HMI and historian architecture. Current generation programmable logic controllers are very reliable but do not have the advanced algorithms required for the TDS although this is improving every year. The latest generation of process automation controllers (PAC) may be a better choice and is being assessed.

Interpretation of results

Despite the inclusion of faulty instrument detection, events not directly related to tapblock operation can cause false readings, especially with the reduction in tapblock health. For example, there is no account of heat applied at the 'cold face' of the tapblock. Heat applied to the cold face by a lance or torch to clean the launder, for example, is interpreted as coming from a change in conditions at the 'hot face', tapping channel or cooling-water circuit. Usually the external source is reported as a temperature spike that can reduce the event-based health index. As a workaround, a health index rebuild function has been included so that process engineers can rebuild the health if a false event is identified. Future versions of the TDS will consider incorporating the necessary instrumentation and algorithms to capture such events so as to minimize the occurrence of faulty and misleading readings.

The most controversial algorithms in the diagnostic system are the health index calculations because a health index by nature is subjective and experiential. Providing a numeric value for health ranging from 100% down to 0% provides a veneer of precision that is really not there and it must be cautioned that an expert opinion is still required. However, if the same temperature data is given to two experts it is unlikely that they will precisely agree on the meaning of the readings in terms of remaining health. There is still a lot to be learned about how a tapblock deteriorates over time and how this is reflected by the temperature readings. At a minimum, the TDS allows the background process information to be collected and that will lead to more accurate health assessments. In addition, the TDS provides a common interpretation of the measured data, and this provides for a consistent basis on which to make a decision. The TDS is also an effective technique to store and transfer knowledge, and in so doing, makes the learning process for young operators and engineers more efficient.

Evaluation of TDS performance

The performance of the TDS installed at Teck Cominco was recently evaluated. The TDS had operated over the last four months of the tapblock's 30-month life. The focus of the evaluation was on how well the TDS predicted the refractory condition. This work showed that the TDS predicted the wear and health reasonably accurately, but individual location readings varied greatly. There were areas of the tapblock that were not monitored where refractory wear was observed but this was not picked up by the TDS.

Figure 9 shows a new tapblock on the left and a used tapblock that was removed after 30 months of service. The TDS predicted the health of this tapblock to be at 50%, based on the indicators employed. The photograph of the worn tapblock shows that all of the refractory is remaining on the lower left hot face of the tapblock (green colour). To the right and above the taphole the refractory was worn to about 50% of its original thickness and it is covered by a black accretion. At the bottom right of the taphole, the refractory was found to be worn to about 20% of the original refractory thickness. This was at the borderline of

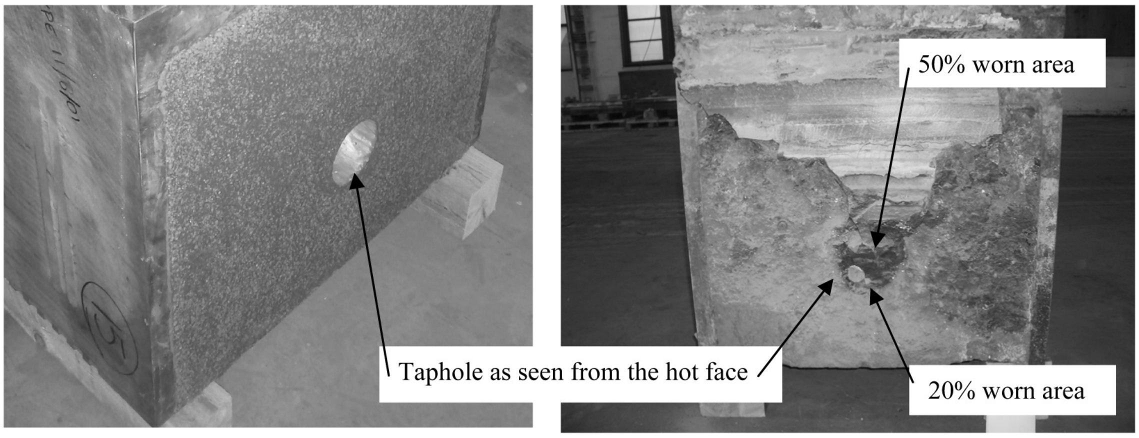


Figure 9. Photograph showing a new and used tapblock, left and right, respectively. The tapblock is a cast copper block with internal cooling water channels, and uses refractory to provide the interface between the molten metal stream and the copper block. The bottom of the tapblock sits on the furnace hearth.

acceptable thickness, and disconcertingly, the TDS did not pick this up because there is no temperature measurement in this area. This highlights the need for methods of temperature measurement that provide increased spatial resolution[4,5].

Figure 10 shows a piece of accretion that spalled off one of the tapblocks during removal from the furnace. This shows layers of refractory, metal and accretion that have developed over time. The reason for the layering is not fully understood, but is of course related to changing process and operating conditions in the furnace. None the less, this was an interesting discovery and it provides new insight into the self-healing capability of water-cooled tapblocks.

This cyclic change in refractory thickness was picked up by the TDS as shown in Figure 11. The blue dashed line shows how the refractory thickness was thinner at some periods of time, i.e., first at the end of June and then three more times in the last half of August and the first part of September. The TDS makes these predictions of refractory thickness based on tapblock temperature measurements, and would interpret the decrease in refractory thickness as a loss of health. As the inferred refractory thickness is increased, the health will be restored. This refractory behavior provides a significant challenge for the designers of the TDS. The interpretation of this behavior in terms of tapblock health has not been fully realized. More work is required and this highlights the value in continuing to study the interaction between furnace cooling systems and the molten material that must be contained.

Conclusion

This paper has presented a summary on the continuing development of a TDS. The system was designed to provide operator guidance during the tapping process and to pinpoint events that are outside of the design envelope of the tapblock. Experience with the system so far indicates it can achieve this, as the work to evaluate the performance of the TDS has demonstrated. However, the evaluation work has also shown that there are behaviors and aspects that are not well understood, e.g., the layering materials, and this represents a new aspect of the process that the designers of the TDS must capture to improve the accuracy of health estimates. The work has also highlighted the need to improve the resolution of the measurements that are used to evaluate and interpret the health of the tapblock and work is underway to do this. The efforts are in line with other efforts being made in the area of CBM, and to bring

Figure 10. Spalled piece showing the layers of refractory, metal and accretion

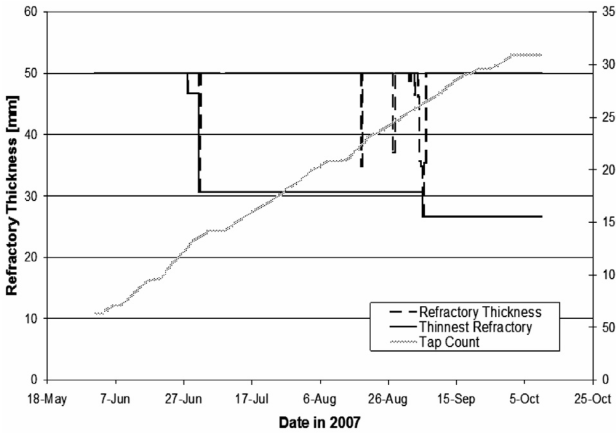


Figure 11. Refractory thickness measurements made by the TDS at a specific thermocouple location

maturity and value to this effort it is necessary to continue to explore methods to unlock the value of advanced diagnostic systems.

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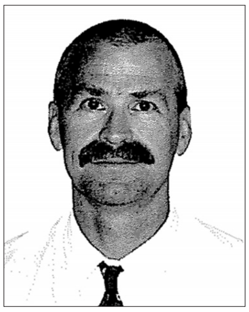

Lowy Gunnewiek

Global Practice Director, Specialized Engineering Analysis and Design, Hatch Ltd.

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