TOTAL COST OF OWNERSHIP OF CONVERTER REFRACTORIES AIDED BY LASER SCANNING TECHNOLOGY

Szymon Kubal[1], Stefan Kirchhoff[2], Guy Thomas[1]
[1]TATA Steel, Port Talbot, Wales; [2]MINTEQ International GmbH FERROTRON DIVISION, Duisburg, Germany

ABSTRACT
Total Cost of Ownership (TCO) of converter refractories is a complex subject that includes material selection, reline labour, fluxes mix, process control, maintenance and production planning. Analysis of the total cost of refractories per tonne of liquid steel, combined with material performance appraisal, provides a complete view of the TCO. This work enhances the monitoring of refractories by employing laser scanning technology for wear rate measurement and material performance assessment.
Laser scans provide information on refractory wear, and analysis of wear trends enables identification of outliers, projection of life of refractory products, and adjustment of maintenance practice. Comparison of the wear trends, complemented with relevant process parameters, helps to identify the best performing materials and to design a converter lining with uniform wear rate. Furthermore, laser scanning technology makes it possible to calculate the life of each converter repair, allowing appraisal of different material types and applications. As a result, fast wearing areas can be eliminated and application of refractory repairs optimised, leading to significant savings.
Campaign cost analysis combines information about refractory performance, and relevant process costs (e.g. reline labour, fluxes mix, availability, maintenance), and aids the optimisation of all refractory related costs. Short term, the analysis throws more light on the total cost of refractories per tonne of liquid steel, and indicates the optimum lining service life. Long term, the model can be used to identify the cheapest converter refractories strategy including lining life, use of slag splashing, selection of fluxes and application of repair materials.
Application of the refractories monitoring system resulted in a number of improvements at Tata Steel in Port Talbot. For example, heavy scrap was identified as the main cause of heavy wear in the impact pad area so its charge was reduced accordingly. Selection of repairs giving the highest value in use was possible thanks to direct comparison of self-flowing and gunning materials. Finally, the lining life expectation was aligned with appropriate costs leading to application of the refractory technology at the lowest cost possible.
The TCO approach linked the interdependent refractory costs – initial costs (reline labour, safety lining, working lining), process costs (scrap composition, fluxes, yield, reheating), maintenance costs (slag conditioning, slag splashing, refractory repairs) – and helped design an optimum converter lining strategy. This paper introduces the individual modules of the monitor and explains how they can be used to improve performance and maximise value in the use of refractories.
Key words: TCO, converter, refractories, laser, scanning.

INTRODUCTION
Laser scanning has been present in the steel plants since the early 1980s. Initially installed as a safety measure, the technology gradually developed into a powerful tool capable of assisting plant operators and managers in day-to-day and long-term decision making. As a result, refractory waste was reduced and value in use maximised without compromising process control and safety.

CONVERTER REFRACTORIES MONITOR
Information provided by laser scanning can not only be used for measuring the residual thickness of a refractory lining, but also for: (i) calculating bath height and corresponding vessel volume, (ii) controlling top cone condition in relation to slopping, (iii) predicting optimum tapping parameters including final tap angle, (iv) identifying correlations between varying process conditions and wear rate, (v) designing optimum slag maintenance practice from a process control point of view, (vi) predicting lining life and planning vessel maintenance and reline accordingly, (vii) reducing overall refractory cost, and more. The aforementioned functions were combined to form the converter refractories monitor; its utilisation in improving the refractory technology is explained in detail below.

Scan Results
Figure 1 demonstrates a 2D visualisation of results of a laser scan of a converter lining. The top two plots show the distribution of residual thicknesses in the converter wall and bottom respectively. The bottom two plots show the temperature of the lining hot face with six tuyères clearly marked on the plot of the bottom. The scan results can be used to identify heavy wear areas (residual thickness) and evaluate efficiency of the bottom mixing process (temperature).

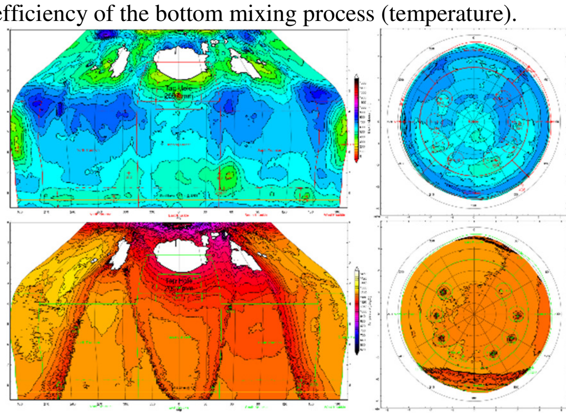


Figure 1 Typical scan results for converter lining thickness (top) and temperature (bottom).

Figure 2 shows a 3D view generated from results of a laser scan measurement. The images provide an opportunity to analyse the profile of the refractory lining. A representation of the steel bath height obtained via a volumetric calculation is also included. The 3D view is particularly useful when planning refractory repairs as it helps localise the heavy wear areas and apply the repair material exactly where required.

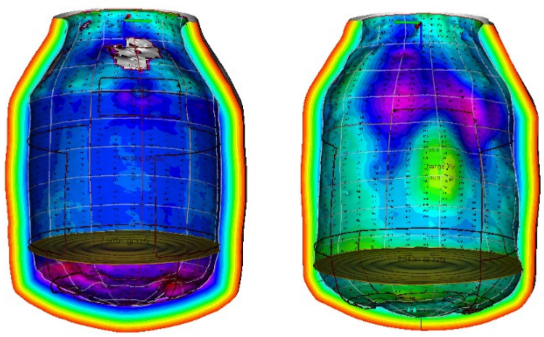


Figure 2 Bath height in vessel at ~500 lives (left) and ~2,000 lives (right).

The 3D view can also be used to visualise and optimise the tapping process (see Figure 3). Examples include:

1. Tapping angles – calculation of initial and final tapping angles for specific freeboard from lip ring or bottom tuyères.
2. Runout time – optimisation of tapping curve against ferrostatic head over the taphole for minimum tap time.
3. Yield – analysis of tapping breast profile and identification of localised indentations where steel can be retained at tap, volumetric calculation of weight of steel trapped in the vessel.
4. Wear – location of slag line at tap and its effect on localised wear of trunnions, knuckles and bottom.

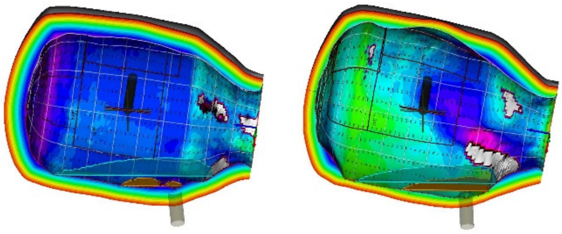


Figure 3 Tap Model: 3D view indicating metal retention at tap (left) and optimum final tap angle (right).

Minimum cross-sections of the top cone area are presented in Figure 4. The plot on the left shows a skulled vessel mouth while the plot on the right provides feedback on the effectiveness of a cleaning action. Furthermore, skulling of the top cone leads to a smaller cross-section and increased velocity of the gasses escaping the vessel and, consequently, results in an intensified slopping behaviour. It is therefore a common practice to apply a parting agent in this area to aid the process of removing skulls, and the scan results enable the performance of the agent to be monitored.

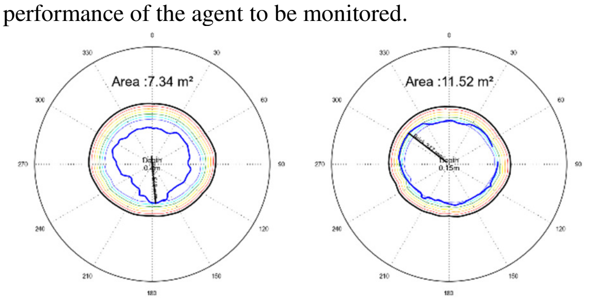


Figure 4 Lip ring cross-sectional area of 'dirty' and 'clean' vessel mouth.

Other information that can be extracted from the laser scans include (i) vessel internal volume (i.e. volume over bath and free volume), (ii) lining thickness change (i.e. comparison between the results of the latest scan and the previous one), and (iii) taphole length (calculated from the profile of the taphole vortex area). Furthermore, the technology can be used to scan the vessel shell to monitor its condition and identify any changes in shape that have occurred since the last reline. All details provided by the laser measurements enable close monitoring of the lining condition as well as a better understanding of the results of interactions between refractories and the production process.

Data format and exchange
Besides the graphical output, the laser scanning system automatically computes detailed numerical data. This includes minimum and average lining thickness values for selected areas, temperature data and various volumetric calculations. All information is saved in XML format files, which provide the necessary hierarchical structure. When the measurement is finished, the data files are copied to the plant network.
The image files and the data files, which contain data tailored to the requirements of the steel plant, are detected by a constantly running piece of software that uploads them. The image files are stored in a folder hierarchy to be available for viewing access via an intranet page. The data in the XML data files is extracted and stored in a database, from where it is used by the wear trend analysis and refractory repairs reports. In this way, the information is available instantaneously and converter refractory performance can be reported live.

Wear Trends
Wear of refractories is a complex process influenced by installation, process conditions, slag maintenance and refractory repairs. Precise measurement of wear rate is essential to improving understanding of refractory behaviour in different stages of a converter campaign. Frequent use of laser scanning equipment makes possible the generation of wear trends, analysis of which allows accurate tracking of the wearing behaviour of refractories. Benefits of wear trend analysis include:
1. Identification of outliers – easy finding and removing of incorrect data points.
2. Projection of lining life – drawing a trend (best fit) line through collected data points.
3. Calculation of wear rate in mm/heat – using the slope of the trend line to represent the wear rate over time.
4. Identification of heavy wear areas – easy comparison of selected areas based on calculated wear rate in mm/heat.

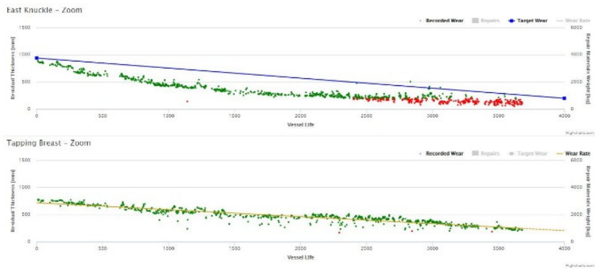


Figure 5 Converter wear trends including target wear line (blue) and life projection line (gold) for knuckle and tapping breast respectively.

Table 1 Process parameters showing correlation with performance of converter refractories.

BOS process parameters	Bottom	Charge Pad	Cone	Knuckles	Taphole	Trunnions	Tuyeres
Bath Height				X			
CO Product							X
Cycle Time		X					
Heavy Scrap		X					
EB to Tap Time				X			X
Idle Time	X						
Lip Ring Area			X				
Pre-charging	X						
Slag Splashing	X	X		X	X	X	X
Vessel Volume	X						
Slag Washing	X			X			X

Figure 5 shows typical wear trends, drawn from the data extracted from laser scans. The top wear trend includes a line representing target life planned for the selected converter area. Initially, the data points do not follow the line, meaning the applied maintenance strategy is not sufficient to achieve the planned target life. The bottom wear trend is complemented by

the best fit line, the gradient of which gives the wear rate in mm/heat, while its extension throws more light on the predicted life of the selected area. Comparison between the target line and the wear trend gives very good feedback on how the material in the selected area is performing against its target life.
Appraisal of the performance of refractories using wear trends is incomplete without analysing the process conditions. Various process parameters can affect refractory wear rates in certain converter areas. A careful statistical analysis of different process conditions and their correlation to the wear rate of refractories was carried out by the authors of the paper. A summary of results of the study can be found in Table 1. It is important to remember that the presented set of parameters and the relationships between them are characteristic to one particular converter process and cannot simply be applied to other steelmaking processes without using a correcting factor.

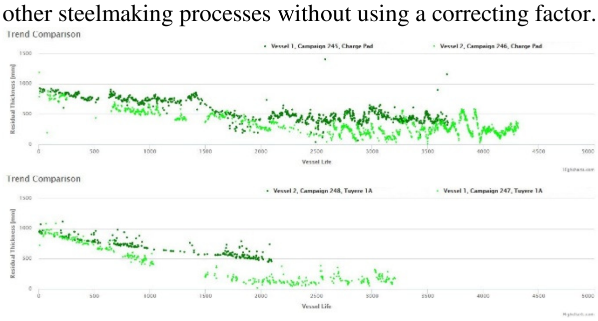


Figure 6 Wear trends comparison: charge pad (top) and tuyeres (bottom).

Trending wear rates together with process conditions can be used to improve the material selection process in every steel plant. Figure 6 shows wear trends comparisons between two different refractory materials in two selected converter areas. The top figure compares two different charge pad materials with the dark green showing lower wear rate as well as a requirement for less maintenance including refractory repairs, throughout the whole length of campaign. The bottom figure presents comparison of two different bottom materials with the dark green wearing at a significantly lower rate in the first 2,000 heats. The trend analysis can not only be used to understand the wear mechanism in different converter areas but also to identify strengths and weaknesses of different refractory materials and to challenge suppliers to improve their products.

Vessel 2, Campaign 248

Start Date	04/12/2016	End Date		Lining Supplier	Vesuvius
Target Life	3500	Actual Life	2098	Projected Life	2719

Lining details

	Initial Thickness	Thickness Limit	Target W/R	Scan Life	Residual Thickness	Actual W/R	Projected Life	Total Repair Weight (kg)	Total Repair Cost (£)	Comment
Cone	650	100	0.16	2013	247	0.16	2982	2,500	1,031.48	
Tapping Breast	900	100	0.23	2098	375	0.16	3799	400	206.90	
Taphole Vortex	750	100	0.19	2098	233	0.16	3185	6,700	4,018.80	Taphole Block snapped during the 1st 10 heats
Charge Pad	900	100	0.23	2098	379	0.22	3001	0	0.00	
North Trunnion	850	100	0.21	2098	380	0.16	4180	0	0.00	
South Trunnion	850	100	0.21	2098	300	0.20	3140	3,200	2,017.55	
East Knuckle	900	200	0.20	2098	368	0.18	3023	300	154.20	
West Knuckle	900	200	0.20	2098	358	0.19	2924	0	0.00	
North Knuckle	900	200	0.20	2098	362	0.18	3167	300	154.20	
South Knuckle	900	200	0.20	2098	320	0.21	2719	650	334.10	~100 mm spall during burn-in
Bottom	900	100	0.23	2098	448	0.23	3284	0	0.00	
Tuyere 1A	900	100	0.23	2098	514	0.20	4070	0	0.00	
Tuyere 1B	900	100	0.23	2098	734	0.09	8920	0	0.00	
Tuyere 2	900	100	0.23	2098	597	0.18	4286	0	0.00	
Tuyere 3	900	100	0.23	2098	620	0.22	3808	0	0.00	Installed when Vessel Life 889
Tuyere 4A	900	100	0.23	2098	920	0.23	3367	0	0.00	
Tuyere 4B	900	100	0.23	2098	621	0.18	4617	0	0.00	
Tuyere 5	900	100	0.23	2098	493	0.21	3832	0	0.00	
Tuyere 6	900	100	0.23	2098	500	0.23	3710	0	0.00	Installed when Vessel Life 889

Figure 7 Lining condition and life projection summary report.

Life Projection

In order to summarise lining condition information from the wear trends, a life projection page was created for each converter campaign. The summary page includes the following data displayed per converter area: thickness limit in mm, target wear rate in mm/heat, residual thickness in mm, actual wear rate in mm/heat, projected life in heats, repair weight in kg and repair cost in £.
The lining condition page is used to support reline planning by optimising utilisation of a converter refractory, designing slag maintenance activities that lead to more uniform wear rates across the lining and, should slag maintenance be insufficient, planning refractory repair requirements. In addition, the page can be used to compare the results of different converter campaigns, helping to identify materials that optimise value in use while extending refractories life and increasing vessel availability.

Slag Splashing

Slag splashing and washing is a well-established maintenance technique that helps to extend the service life of a converter refractory by creating a sacrificial layer of slag on the lining. On the lining condition page, predicted life is compared to the target life, and the traffic light system is used to help identify areas requiring attention. In this way, slag splashing and washing can be designed to protect specific areas in the vessel without compromising metallurgical benefits of the process.

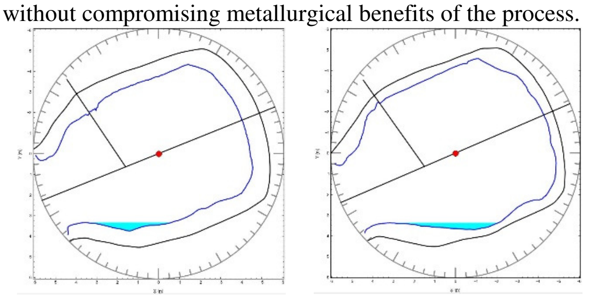


Figure 8 Slag decanting model: retention of 2 t of slag for slag sintering purposes in a new and old lining (left and right respectively).

Slag Sintering

Another well-established maintenance technique is slag sintering. In this method, a small quantity of conditioned slag (depending on converter size usually between 2 and 4 t) is left in the vessel, and then rocked into an area of concern i.e. knuckle, charge pad, or tapping breast, where it is left to solidify. The challenge related to this maintenance activity is in precise decanting of the excess of slag and retaining in the vessel the right quantity for the sintering purposes. Too much slag will not solidify to form a patch while too little slag will not provide sufficient protection. However, information from laser scans helps to solve this problem. Figure 8 shows screen shots from the slag decanting model where the profile of the slagging off side of the vessel is taken into account in defining the relationship between the slagging off angle and the quantity of slag retained in the vessel. A volumetric calculation is used to determine the slagging off angle needed to retain the right quantity of slag for the size of the area of concern. Another functionality of the model allows detailed planning of the repair – by rotating the profile of the vessel in 2D and 3D it is possible to visually predict where the slag will flow and select the optimum vessel angle for successful sintering action. Thanks to the application of virtual reality, the slag sintering practice can be optimised and its benefits maximised.

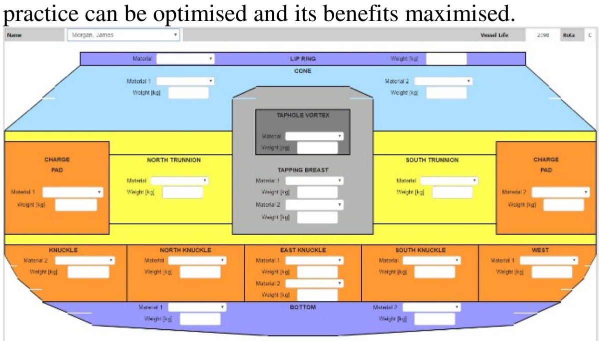
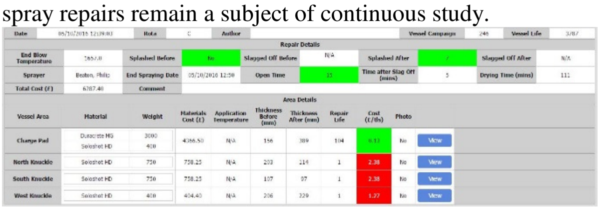


Figure 9 Screen for logging details of refractory repair actions.

Refractory Repairs

Refractory repairs are applied to balance wear in heavy wear areas when slag splashing and slag sintering do not deliver the desired effects. There are two types of refractory repairs used in converters: spraying repairs and self-flowing repairs. The latter can be further categorised into dry and wet mixes. Frequent laser scanning allows the identification not only of areas requiring repair action but also of the life and performance of applied materials. Figure 9 shows an easy way of logging refractory repairs where a system of drop down menus distributed on a schematic of a converter lining assists operators at recording details of material applications.

Whenever possible, a repair is preceded and followed by a laser scan to confirm that material was applied in the right place and quantity as well as to verify its immediate effect. This approach provides operators with feedback that is essential to improve their manual skills or the settings on the machine. Details from laser scans and the repair logging page are combined into a repair summary report that includes a traffic light checklist of application conditions (i.e. process parameters). These parameters were discussed and agreed with material suppliers and include details of slag maintenance prior to and after the repair (i.e. slag washing or slagging off direction), time after slagging off in minutes, drying time in minutes, application temperature in °C, thickness before and after in mm, repair life in heats and cost in £/tls. Figure 10 shows a repair summary report from an application of a wet mix material in the charge pad area followed by a spraying repair applied to north, south and west knuckles. The lining thicknesses recorded before and after the wet mix repair report a gain of over 200 mm while application of the spray material results in a lining thickness gain of around 10 mm. The effectiveness and the value in use factor of self-flowing and spray repairs remain a subject of continuous study.



Date	05/10/2016 12:39:03	Rota	C	Author		Vessel Campaign	246	Vessel Life	3/87

Repair Details							
End Blow Temperature	1657.0	Splashed Before	No	Slagged Off Before	N/A	Splashed After	?
Slagged Off After	N/A						
Sprayer	Beaton, Philip	End Spraying Date	05/10/2016 12:50	Open Time	15	Time after Slag Off (mins)	5
Drying Time (mins)	111						
Total Cost (£)	6287.40	Comment					

Vessel Area	Material	Weight	Materials Cost (£)	Application Temperature	Thickness Before (mm)	Thickness After (mm)	Repair Life	Cost (£/tls)	Photo	
Charge Pad	Duracrete MG Soloshot HD	3000 400	4366.50	N/A	156	389	104	0.10	No	View
North Knuckle	Soloshot HD	750	758.25	N/A	203	114	1	2.38	No	View
South Knuckle	Soloshot HD	750	758.25	N/A	107	97	1	2.38	No	View
West Knuckle	Soloshot HD	400	404.40	N/A	206	229	1	1.27	No	View

Figure 10 Refractory repair application and performance summary.

Figure 11 Slag splashing and washing shift log.

Shift Log

Information from the refractories consumption monitor are summarised in the shift log presented in Figure 11**.** The page displays facts essential for designing refractory maintenance in line with the process control requirements as well as providing an overview of maintenance actions already undertaken. The log includes the following sections:

1. Bath height – recorded by sublance and from scans.
2. Pre-charging – addition of CaO or MgO source prior to scrap charge.
3. Bath agitation – monitors of effectiveness of the process, include CO product and phosphorus partition.
4. Tapping – information on up on metal grades and vessel drainage.
5. Slag chemistry – slag bulk, temperature and chemical composition.
6. Slag decanting – slag decanting angles from scans.
7. Slag conditioning – addition of coolant agents.
8. Slag maintenance – splashing, washing, sintering.
9. Refractory repairs – spray and self-flowing repairs, taphole changes.
10. Adherence – place for operators to comment on issues with following the currently employed maintenance strategy and to provide feedback on adherence to the practice.

The shift log not only summarises all converter refractory related information but also provides shift personnel with an opportunity to comment on effectiveness of the employed strategy and to suggest appropriate changes.

TOTAL COST OF OWNERSHIP

Figure 12 shows an output graph from the total cost of ownership model – an attempt to present all interdependent refractory costs for a single campaign. The graph below includes only three curves compared to the target line, but the model can also take into account other refractory related costs like reline labour, process fluxes, slag conditioners and taphole changes. Based on the information provided by the individual modules of the converter refractories monitor, the model helps identify the optimum lining life from the cost perspective as well as to realise the magnitude of other interdependent refractory costs. The analysis can be used to review the currently applied lining life strategy in terms of number of relines per year, scrap menu, flux menu, yield, slag chemistry, slag splashing, refractory repairs, and to choose the most optimal approach from the cost perspective. The model remains a subject of continuous study with the focus on quantifying and adding other costs related to lining life strategy i.e. the cost of lost production time, the cost of quality downgrade and the cost of engineering maintenance.

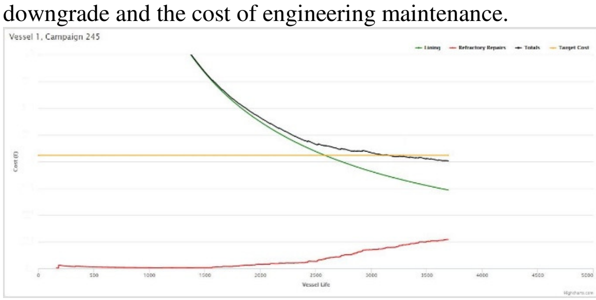


Figure 12 Lining campaign cost curves including safety lining and working lining (green), refractory repairs (red) and total cost (black).

CONCLUSIONS

Modern laser scanning technology offers much more than just information on residual thicknesses of converter lining recorded for safety purposes. Scan results can (i) provide information on lining hot face temperature, (ii) help stabilise the process by reducing slopping, (iii) optimise runout time and yield by assisting tapping, (iv) aid material selection to eliminate heavy wear zones and equalise wear across all converter areas, (v) optimise maintenance practices and maximise value in use.

A new converter refractories monitor is described, based on cost information, aided by performance data collected by the laser scanning system, that offers detailed analysis of the value in use of different types of refractories and interdependent process and maintenance costs. In addition, a link between selected process control parameters and refractories performance is made explaining why different converter areas at different stages of campaign can become a bottleneck that limits the service life of a converter lining. Finally, a total cost of ownership of converter refractories model is proposed which combines process, performance and cost data and thereby assists plant management to design and implement a cost effective refractory strategy.

Continuing study will focus on maximising the value in use of refractory repair materials and adding production availability and quality control to the TCO analysis.