Intelligent BOF steelmaking

Tenova's *i* BOF® platform is a comprehensive array of BOF automation and process control modules designed to increase productivity and yield, reduce fugitive and particulate emissions and lower operating costs for all phases of the BOF process from charge management through to secondary metallurgy and degassing. By **Dr. DJ Zuliani***

Tenova's *i* BOF® platform provides control and optimization across all BOF steelmaking process steps **(Fig 1)**.

The *i* BOF® process modules include slop control, endpoint control, auto tapping and slag carryover control as well as charge management and level 2 automation **(Fig 2)**. Each can operate independently and can be added individually or as a complete *i* BOF® solution. Tenova also offers a BOF post combustion control module for increased scrap melting, and secondary metallurgy modules for degassing endpoint control using *insitu* laser off-gas analysis and for alloy cost optimization, which are beyond the scope of this article.

i BOF® Digitalized Systems enable standalone *i*BOF® modules to communicate and thereby work together as part of an 'intelligent' network.

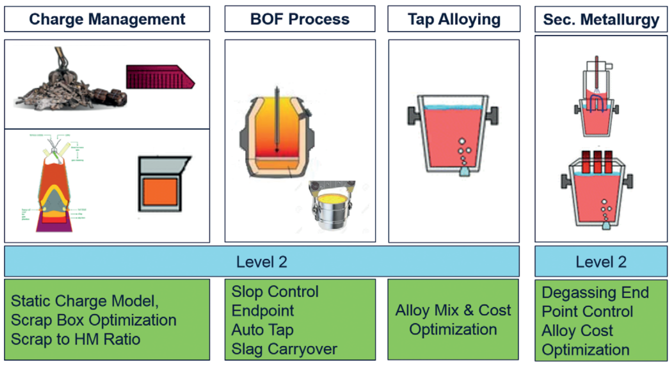

Fig 1. Tenova's i BOF® platform provides control and optimization across all BOF steelmaking process steps

i BOF® control modules

Slop Control

Slopping occurs when molten slag foams uncontrollably and spews from the converter mouth. Unless a deliberately conservative blowing practice is employed, most BOF shops will encounter slopping once the rate of CO generation peaks after silicon oxidation. **Table 1** outlines the substantial savings attainable with better slop control [1,2,3,4].

Fig 3 illustrates how Tenova's slop control module functions [4];

- an accelerometer attached to the lance carriage, continuously monitors lance vibration;
- proprietary software analyzes the vibration data in real-time;
- specialized cameras facilitate tuning of the slop detection model;
- the System is tuned to alarm 20-40 seconds before visible slopping with minimal false alarms;
- the slop alarm triggers dynamic mitigation (lance height, O_2 blowing rate, CaO); and,
- once the slopping threat has ended, the system dynamically returns to standard blowing conditions (**Fig 4**).

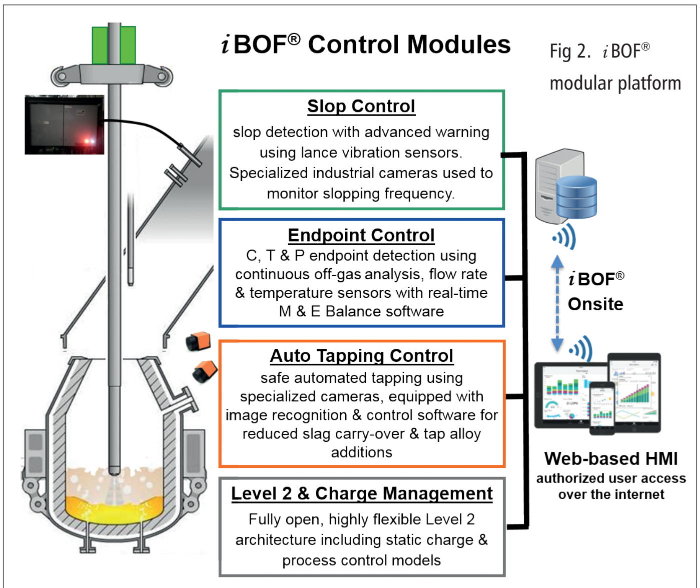

Fig 2. *i* BOF® modular platform

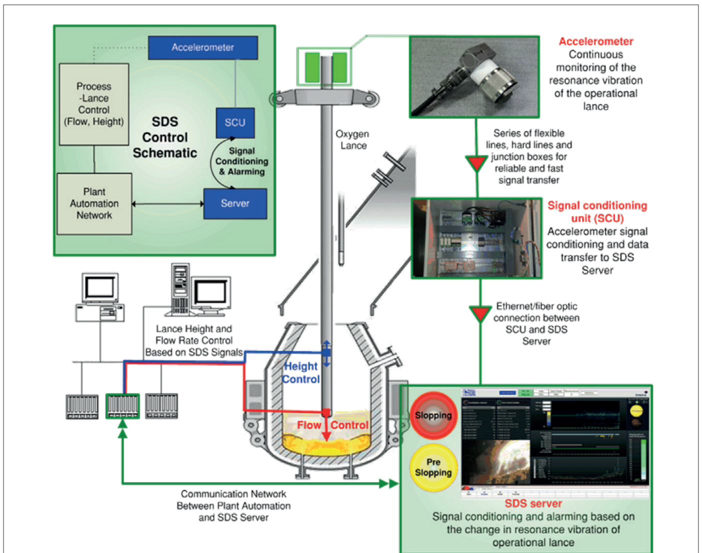

Fig 3: Schematic of Tenova's slop control module

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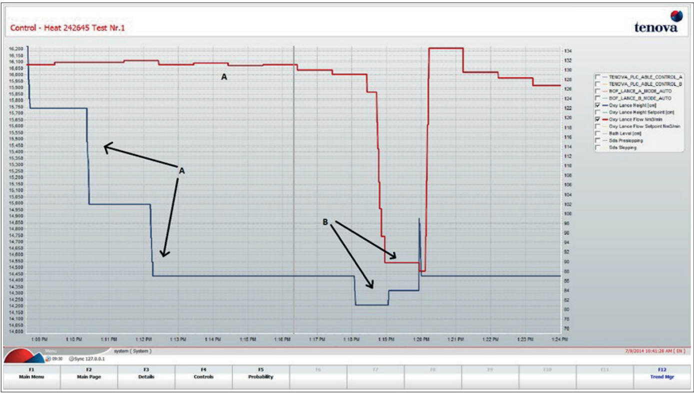


Fig 4. Lance profile (bottom line) and oxygen flow (top line); normal conditions (Region A), dynamic slop mitigation (Region B) with dynamic return to normal blowing

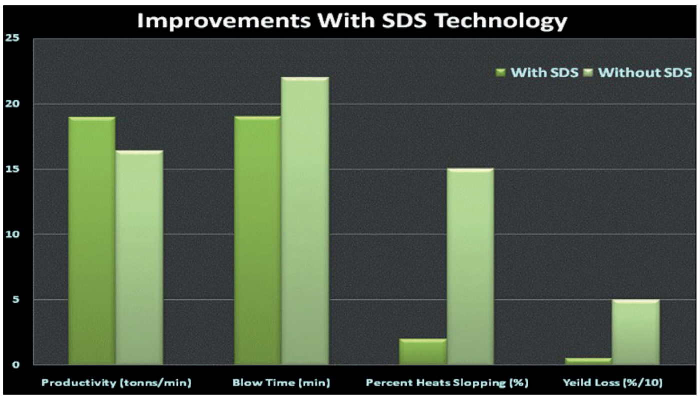


Fig 5. Slop detection and mitigation benefits verified in five European BOF vessels [2]

Item	Specific Details	Total Savings per yr ***
Mouth Cleaning	$200 per day (labor & equipment)	$72,000
Lime Shots	1,000 lbs "lime shots"** used on 40% of heats to control slop	$200,000
Yield Loss	1,600 short tons per year of additional steel not in the pit based on 16% reduction in mid to heavy slopping heats *	$175,000
Pit Cleaning	$200 per day (labor & equipment)	$72,000
Production Loss	2 heats per day lost for pit cleaning. Assume only 1/2 additional heat per day can be realized **	$1,380,000
Roof Violations	Reduced emissions by 15%	Intangible
TOTAL SAVINGS		$1,899,000

NOTES:
* Assumes additional yield valued at $110 per short ton
** Assumes incremental profit margin of $30 per ton on productivity gains
*** Assumes BOF shop operates 360 days per year operation producing 9,500 heats with a mid to heavy slop frequency reduced from 20% to 4% with i BOF® Slop Detection Technology

Table 1. Savings with effective slop control (USA steel plant)

Cost Item	Typical Savings per Heat (200 MT)	
	US Units	Metric Units
Oxygen	2902 scf	77.9 Nm^3
Aluminum	56 lbs	25.4 kg
Manganese	210 lbs	95.3 kg
75% FeSi	5 lbs	2.3 kg
Carbon	57 lbs	25.9 kg
Probes	1.25	1.25
Gunning Refractory	111 lbs	50.3 kg
Tap-to-Tap Time	- 0.2 min	- 0.2 min
Yield	+ 0.33%	+ 0.33%

Table 2. Verified savings on low carbon heats using Tenova's endpoint detection system

The benefits of Tenova's slop control module are summarized in **Fig 5**; to date, 10 Tenova slop detection systems have been successfully installed in North America and Europe with six additional systems currently pending. **Fig 5**.

Endpoint control

Poor endpoint control manifested as reblows, overblows or blowing down high/ mid-carbon grades to ~0.04%C before ladle recarburization causes yield and productivity losses, elevated tap ppm [O], increased slag FeO and excessive tap alloy consumption. To ensure a robust, low cost endpoint solution, Tenova's latest generation endpoint control module includes:

- real-time mass and energy ('M&E') balance software incorporating fundamental thermodynamic and kinetic

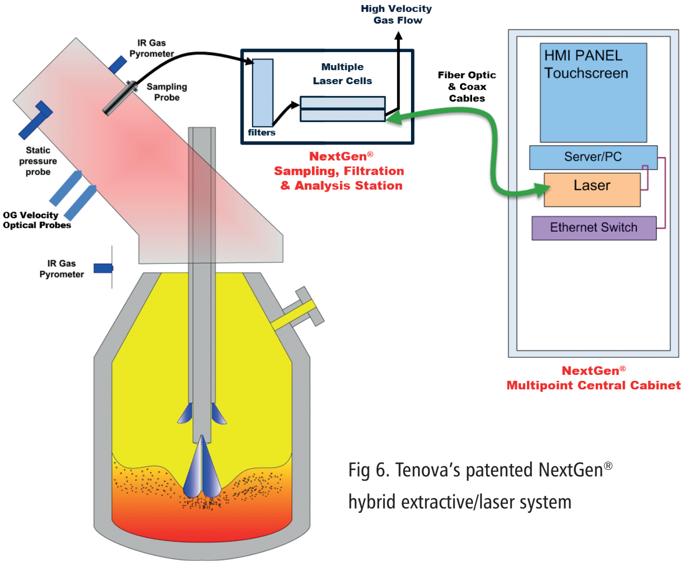
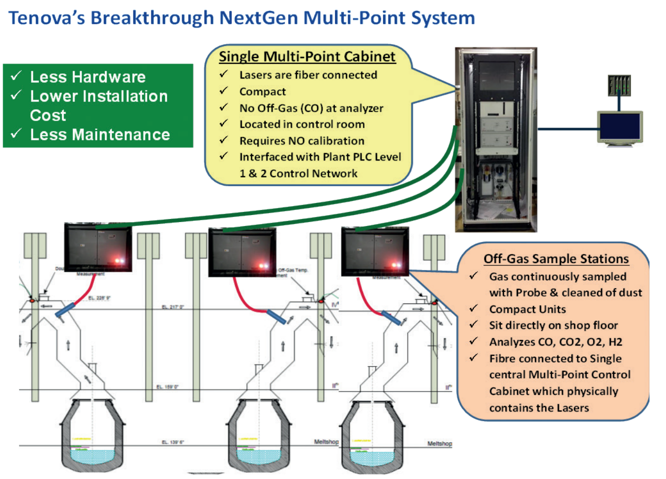
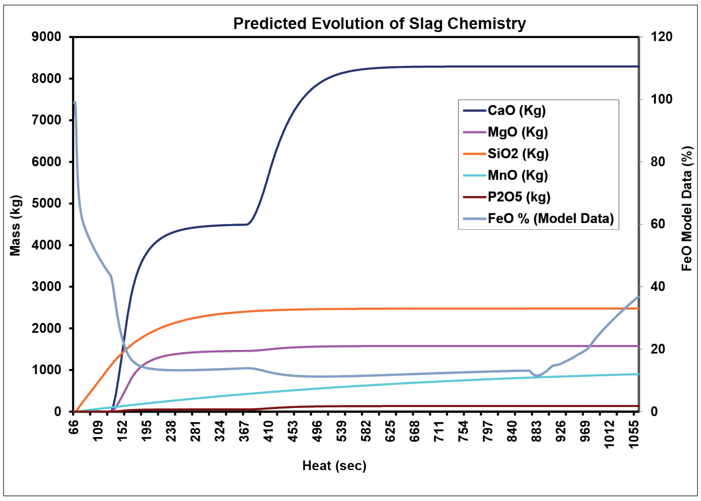


Fig 6. Tenova's patented NextGen® hybrid extractive/laser system

Fig 7. Application of the multipoint NextGen® analyzer system to a 3 BOF shop





Parameter	Catch Carbon Trial** (29 Heats)	Baseline (180 Heats)
Endpoint Carbon	0.052	0.043
Endpoint Temperature °F	2985	2997
Endpoint [O] ppm	521	685
Slag % FeO	19.4%	22.1%
Total Savings Range $ per tls	$1.64 - $3.16 **	NA

Table 3. Confirmed savings with a catch carbon practice using Tenova's endpoint detection system

Fig 8. Left. Predicted sec-by-sec evolution of slag chemistry

Fig 9a and 9b. Upper – turn down too early at high [%C] when using 0.1%P hot metal can result in [%P] exceeding the 0.015% max spec. Lower – overblowing the heat can result in [P] revision

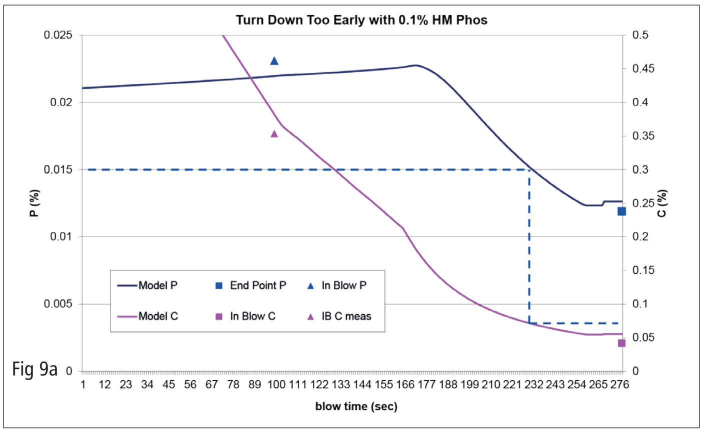


Fig 9a

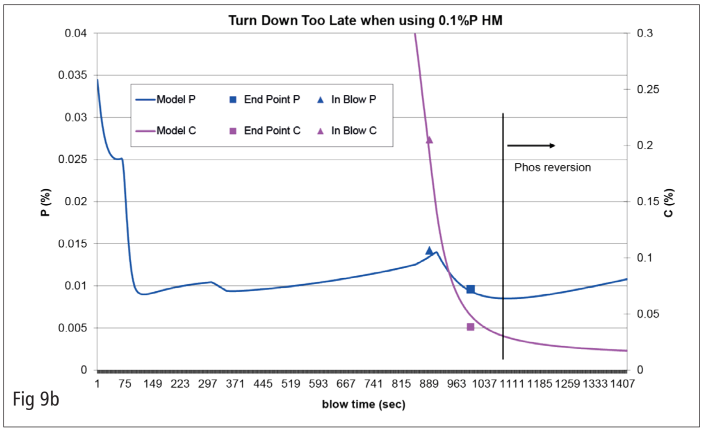


Fig 9b

equations to better model the non-equilibrium near-end of blow conditions when carbon, iron and phosphorous oxidation can occur concurrently;

- patented NextGen® hybrid extractive/laser off-gas analysis technology, proprietary off-gas velocity and temperature sensors and a PLC link provide all the measurements needed to close a precise real-time M&E balance (**Fig 6**). NextGen®'s multipoint capability reduces hardware, installation costs and maintenance by enabling continuous, simultaneous off-gas analysis on multiple BOFs with a single central cabinet (**Fig 7**).

With the real-time M&E balance, Tenova's technology provides a precise endpoint solution:[5]

- *Reliable [C] and temperature endpoint control for low carbon grades:* By eliminating assumptions or statistical models, Tenova's M&E balance approach is capable of predicting endpoint carbon to within 0.01% and temperature within 17 °C on about 90% of low carbon heats, thereby generating significant operating cost benefits (**Table 2**). Typically, low carbon heat savings range from $1.00 - $1.25 per tls.
- *Catch carbon practice for mid- and high- carbon grades:* Stopping a blow with precision at higher carbon levels is difficult; Tenova's catch carbon endpoint detection system has demonstrated a 60% reduction in endpoint standard deviation on mid/high carbon grades thereby avoiding recarburization in the ladle, higher operating costs, higher tap oxygen levels and increased tap alloy consumption. **Table 3** shows using a 0.05% 'catch carbon' practice instead of an 0.04% recarburization practice reduces endpoint [O] ppm and tap alloy consumption with savings between $1.65- 3.15 per tls.
- *Complete slag and bath chemistry prediction from start-to-end of heat:* Tenova's fundamental model predicts the evolution of both slag and bath chemistries from start-to-end of heat providing a valuable data base for *i* BOF® digitalization advanced analytics and continuous improvement. **Fig 8**.
- *Improved phosphorous endpoint control:* Tenova's endpoint model predicts near-end of blow [P]. With 0.04%, HM [P], the endpoint carbon window to hit < 0.015% [P]max is quite wide and phosphorous reblows are rare. However, **Fig 9** shows that, at 0.1% HM [P], early turn-downs and over-blowing can both result in over spec [P].

i. Auto-tapping

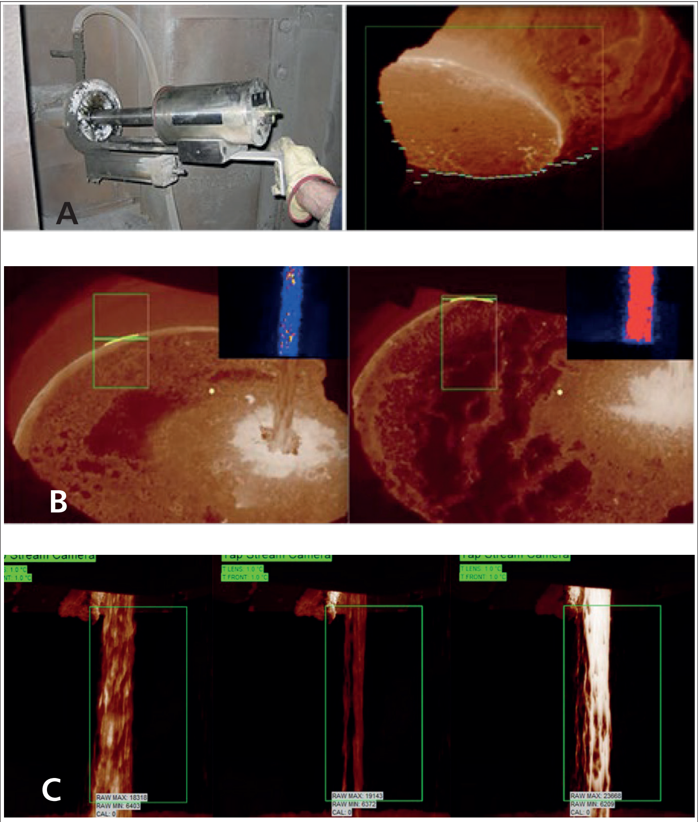
Tenova uses specialized software, cameras and image recognition to automatically and safely control BOF tapping. The aim is to maintain the optimum tilt angle, maximize the ferrostatic head over the taphole, delay the onset of a vortex and minimize slag entrainment in the tap stream.

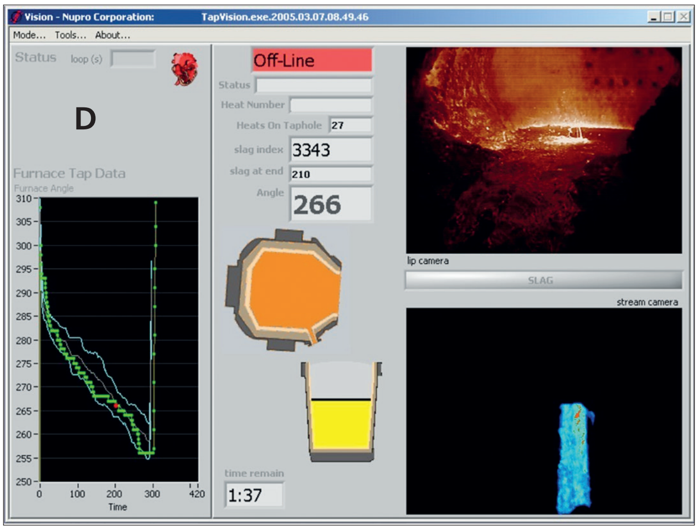
Typical auto-tapping benefits are summarized in **Table 4**.

The *i* BOF® Auto-tapping solution incorporates many specialized technologies which can be configured to either enable fully automated tapping without operator intervention or to provide an optimum tilt angle guidance curve for the operator to follow. In both cases, the aim is to maximize the ferrostatic head over the taphole and avoid an early slag vortex which causes excessive slag carryover.

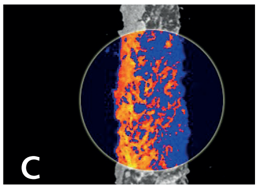
Furnace lip camera for 'slag on the lip' detection

A ladle view camera and car positioning algorithm confirm ladle positioning and freeboard.





A. Furnace lip camera for ‘slag on the lip’ detection
B.Ladle view camera, car positioning algorithm confirm ladle positioning and freeboard
C. Stream and slag detection camera
D.HMI display – system information, tap-time calculation and optimum furnace trajectory



Auto-Tap Tangible Benefits	Annual Savings	Comments
Increased Productivity	~ $900,000	Reduced tap time plus improved pacing for alloy additions, furnace & ladle movement
Aluminum Consumption	~ $300,000 - $500,000	Shorter vortex time reduces slag/metal emulsification and lowers dissolved [Al] oxidation in bath
Tap Alloys Recovery	~ $1,000,000	From less slag carry-over and reduced slag raking losses
Increased Fe Yield	To be quantified	Optimized tilt angle allows more drained steel prior to onset of slag
Auto-Tap Non-Tangible Benefits	**Comments**	
Safety	Auto-Tapping reduces/eliminates operators on the floor during metal pouring	
Improved Consistency	Reduces variability in steel chemistry, temperature, slag consistency & process time	
Fewer Process Upsets	Reduces operator error and delays	

Table 4. Tangible and non-tangible benefits with Tenova’s auto-tap technology

Charge management with optional level 2

Charge management is critical – it balances raw material costs against productivity, yield and steel quality requirements. *i* BOF® charge management properly evaluates all these factors and provides a comprehensive management tool that includes a static charge model together with scrap optimization and ferro-alloy optimization models to maintain the lowest cost scrap mix while ensuring correct steel chemistry. Tenova’s optional level 2 is a fully open, flexible supervisory system that executes the charge management models in the correct sequence using the correct data to properly account for production delays, changes in HM temperature and chemistry, changes in scrap densities and chemistry, flux requirements and grade specifications. **Fig 10**.

Effective charge management is critical to the BOF process from defining the HM/scrap ratio, optimizing the scrap mix, trim additions and tap alloys and defining the end of the blow. **Fig 11**.

The *i* BOF® static charge model allows the steel plant to tailor its specific operating constraints from ‘must have’ to ‘high priority’ to ‘relaxed’ – the model uses a least squares method to find the optimum solution; if it is unsolvable, the best suboptimal solution will be calculated. **Fig 12**.

Confirmed *i* BOF® charge management benefits include:

- 1.5% reduction in reblows;
- 0.15% increase in yield
- 62% of heats stopped within 10% of target
- Improved ppm [O] and [P] endpoint control
- Offline optimization analysis

i BOF® DIGITALIZATION

Fig 13 shows that individual steel plants can install one or more *i* BOF® control modules and then add the corresponding *i* BOF® digitalization which enables each module’s process control computer to connect to Tenova’s digital diagnostic centre via the internet.

To comply with each steel plant’s data security protocols, data from the onsite *i* BOF® control modules can be transferred either in batches, continuously, or on demand/request to a remote server. Tenova offers two data storage options to meet each plant’s highest security requirements: the highly secure Microsoft Azure Cloud, or a secure dedicated Tenova server.

In compliance with each steel plant’s data security protocol, *i* BOF® digitalization creates a large data pool for the installed *i* BOF® control module(s).

As shown in **Fig 13**, Tenova created a digitalized programme, Service 4.0, that provides ongoing service, support and continuous improvement functionality for each *i* BOF® control module – each steel plant can tailor the level of Service 4.0 coverage that best meets its priorities. Service 4.0 is designed to provide each steel plant with the following functionality:

- *Performance monitoring:* Tenova uses the incoming data to monitor each *i* BOF® control module including both hardware and process control model performance.

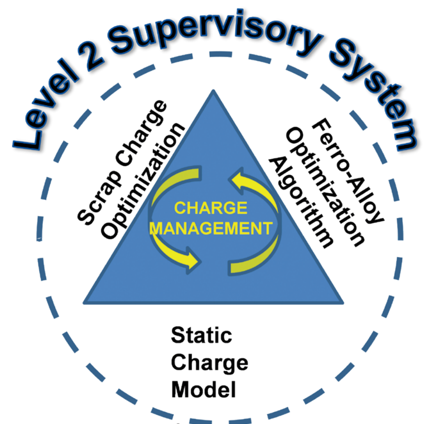


Fig 10. Tenova's *i* BOF® Charge Management and level 2 supervisory system

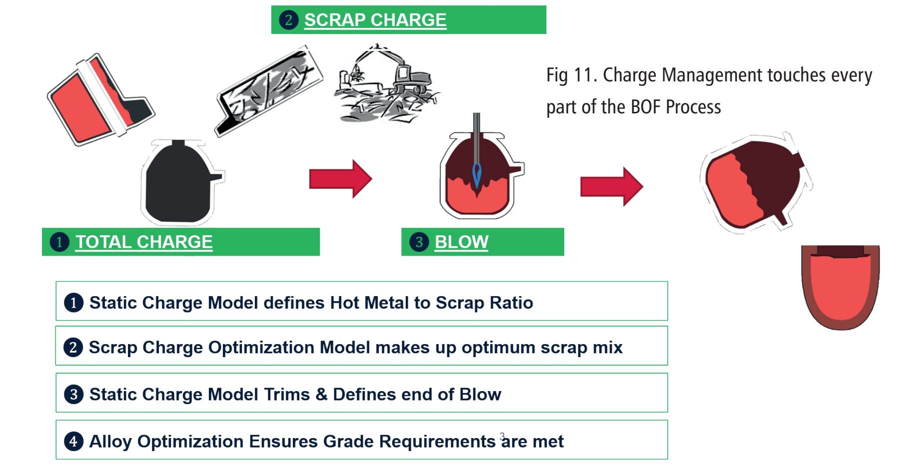


Fig 11. Charge Management touches every part of the BOF Process

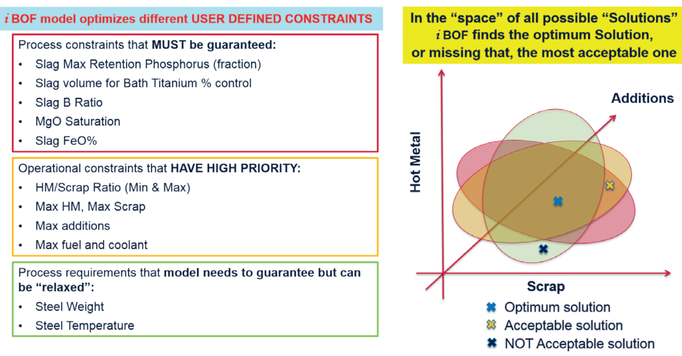


Fig 12. *i* BOF static charge model provides the optimal charge mix solution with complete user flexibility

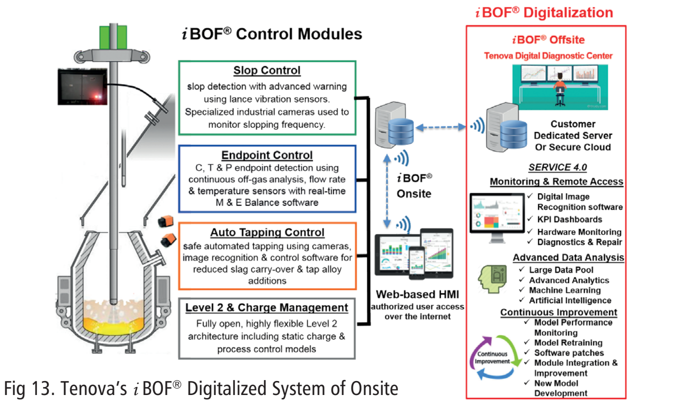


Fig 13. Tenova's *i* BOF® Digitalized System of Onsite Process Control Modules connected to Tenova's Off-Site Digital Diagnostic Centre

Where appropriate, monitoring also uses Tenova's proprietary digital image recognition software to seamlessly provide image acquisition, analysis, event confirmation, severity recognition, image registration, registered image comparison, and improved performance. As noted above, data is transferred from each *i* BOF® control module to the Tenova digital centre cloud or steel plant dedicated server either in batches, continuously or on request;

- *Dashboards:* The incoming data are used to generate real-time KPI-driven dashboards that are displayed on each *i* BOF® control module's web-based HMI. These dashboards are designed to provide steel plant management with a rapid assessment of hardware health, maintenance and repair status, and process control model performance;
- *Model tuning portal:* Tenova provides a web-based portal for steel plant users to upload data to retrain an existing *i* BOF® model whenever the dashboards indicate declining performance. Data can be quickly uploaded, the model is automatically retrained on the new data set, and a performance report is issued to assess the new model. If desired, the newly tuned model can be downloaded, quickly installed, and used on the next heat;
- *Remote access:* When required, Tenova engineers can request remote access to an *i* BOF® control module to enable prompt, low-cost technical support and rapid system diagnostics and repairs;
- *Advanced cross-correlation data analysis:* Tenova's data scientists use advanced analytics and machine learning on the large *i* BOF® data pool to assess the performance capabilities of each *i* BOF® control module. In addition, the entire data pool is analyzed to identify cross-correlation between various installed control modules – for example, determining the cross-correlations between slop frequency and endpoint prediction, or correlating the rate of CO generation with slop initiation;
- *Continuous performance improvement: i* BOF® digitalization allows monitoring of each process control model's performance to identify when adjustments are required, to maintain peak performance by rapidly and retraining process models, to install software patches as required, and to develop cross correlation algorithms that further improve system performance.

References

1. Shakirov, M., Boutchenkov, A., Galperine, G.; Schrader, B., "Prediction and Prevention of Slopping," ISSTech 2003 Conference Proceedings, p. 655-666, 2003
2. Scipolo, V. Zuliani, D., Todorovic, I., "Update on Tenova's Intelligent *i* BOF® Technology and Slop Detection System (SDS)", AISTech Conference, Indianapolis In, 2014
3. Evestedt, M; Medvedev A.," Model-Based Slopping Detection in a Top-Blown Steel Converter," Department of Informational Technology, Uppsala University, Sweden, 2007
4. Kafie, J.; Babaei, B.; Scipolo, V., " BOF Slop Detection – Savings Potential with Real-Time Slop Detection & Mitigation Technology", AISTech Conference, Cleveland, OH, 2015
5. Zuliani, DJ; Scipolo, V., "*i* BOF® Technology Improves BOF Process Control, Endpoint Detection & Slop Mitigation", AISTech Conference, Pittsburgh PA, 2016