A Practical Engineering Approach to Improving the Reliability of Blast Furnace Tuyeres

This paper is the 2012 Gold Reliability Achievement Award winner. For more information about AIST awards, visit AIST.org.

At Severstal Dearborn, an employee involvement program team was assembled to focus on improving the reliability of blast furnace tuyeres. A practical engineering approach was adopted for the project. To date, the reliability project has been deemed a success. By implementing lessons learned from early failures, and through willingness to trial new designs, productivity lost to tuyere failures has decreased 95%, resulting in savings in excess of US$7 million to date.

Authors

Charles Copeland
senior process technologist, Ironmaking Department, Severstal Dearborn, Dearborn, Mich., USA
ccopelan@severstalna.com

Stuart Street
ironmaking technology manager, Ironmaking Department, Severstal Dearborn, Dearborn, Mich., USA
stuart.street@severstalna.com

The original research for this work was presented in "Tuyere Failures: Cause and Effect," in the December 2011 issue of *Iron & Steel Technology.*

Made predominantly of cast copper, with water-cooled channels, the tuyere is the device that allows heated air to be blown into the combustion raceway of the blast furnace. Exposed to a harsh and turbulent operating environment, the tuyere region is dynamic and complex, containing combustion gases, molten oxides (slags), molten iron, coke, pulverized coal, char and temperatures frequently exceeding 4,000°F (2,204°C). Although recognized as a key component, an indestructible tuyere has yet to be developed. Poor tuyere reliability is not a recent phenomenon. Despite being the dominant ironmaking route, and after several centuries of development, blast furnaces are still prone to suffering tuyere failures.[1] A tuyere failure introduces a state of affairs that all operators try to avoid, typically furnace instability, increased costs and fuel rate, lost productivity, and increased safety and environmental exposure.

Recognized as a critical component, tuyere reliability is frequently tracked as a key performance indicator (KPI) in blast furnace operation. A review of tuyere performance indicated high failure rates and found that unplanned outages to replace tuyeres were becoming routine. This paper reviews Severstal's investigation into tuyere reliability and discusses the practical engineering approach, along with resulting changes to operating practice and tuyere design. Key characteristics of Severstal Dearborn's Ironmaking Department are listed in Table 1, and referenced in detail elsewhere, while details pertinent to the tuyere system are listed in Table 2.[2,3]

In the most general terms, reliability is the absence of failure, within defined limits. Going further, Yang asserts, "...the function of reliability engineering is to avoid failures."[4] There are many methods to avoid failures. Redundancy and over-engineering can provide reasonable results in certain circumstances. In his work on reliability engineering, O'Connor shows that one must "...apply engineering knowledge and specialist techniques to prevent or to reduce the likelihood of failures." He continues, "...practical engineering must take precedence in determining the causes of problems and their solutions."[5] With

This article is available online at AIST.org for 30 days following publication.

Table 1

Severstal Dearborn Ironmaking

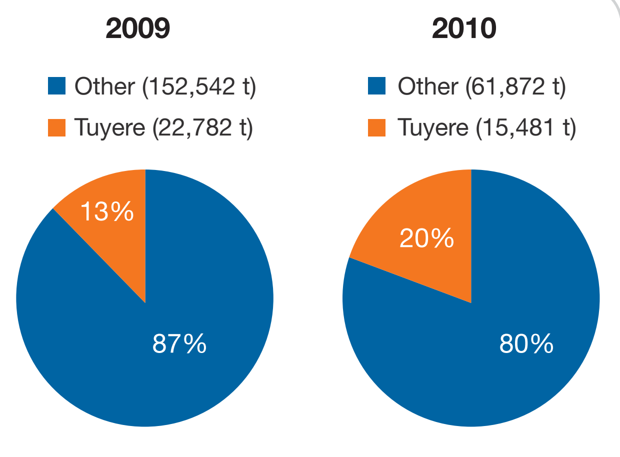
Characteristic	Detail
No. of blast furnaces	1 operating – "C"
Raw material handling	Automated stockhouse, belt-fed top
Iron feedstock	100% fluxed pellets
Working vol./ht.	63,472 ft^3/79 feet 8.75 inches
Hearth vol./dia.	7,824 ft^3/30 feet 4 inches
Tapholes	2 (90° separation)
Furnace charging	2 material hoppers, P-W bell-less top
Fuel injection	Pulverized coal injection and natural gas
Furnace cooling	Closed-loop system; underhearth; bosh/tuyere plates; 4 rows Cu staves; 4 rows Fe staves.
Productivity (design)	9.8 tpd/100 ft^3 w.v. (design), frequently >10.0 tpd/100 ft^3 w.v.

Table 2

Tuyere System Details

Characteristic	Detail
No. of tuyeres	20
Design characteristics	Double compartment with gas injection port
Tuyere diameter	6.75 inches
Tuyere length	19 inches
Tuyere angle	6°
Cooling system	Closed loop
Pumping system	2 x 500 hp electric motors Backup natural gas engine Pressurized mill water secondary backup
System cooling flow	5,150 gpm
Individual tuyere flow	257 gpm
Nose loop flow	125 gpm
Body loop flow	132 gpm
System pressure	142 psi
Leak detection system	Multiple stage
Smallest detectable leak	0.20 gpm

Figure 1



Production lost to tuyere failures in 2009–10; tuyere failures were the largest individual source of delays.

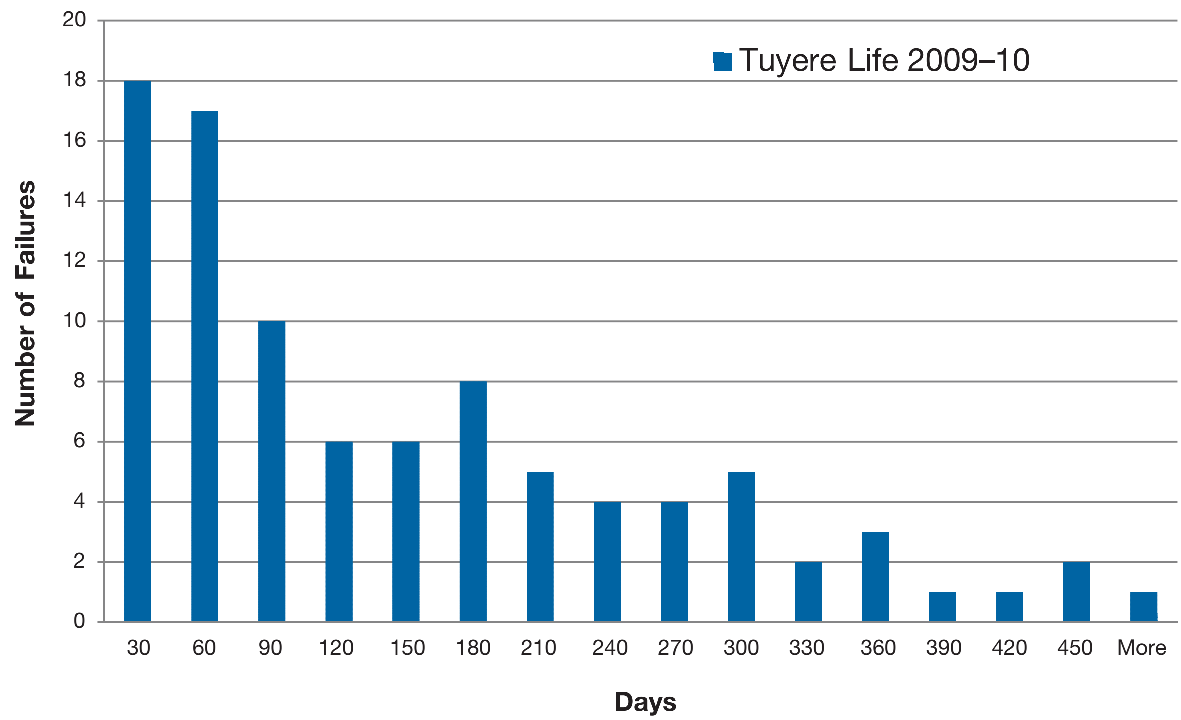
relatively few failures and a lack of robust laboratory testing methods, this practical engineering approach was adopted for the tuyere reliability project.

Project Drivers

Two drivers focused the team: increasing profitability and reducing negative furnace impact from tuyere water leaks. With increasing pressure to reduce costs and improve productivity, Ironmaking delays became subject to additional management scrutiny and analysis. Early in the delay analysis process, it became apparent that poor tuyere reliability accounted for a significant fraction of total delay time. In fact, during 2009–10, tuyere failures were the largest single source of Ironmaking internal delays (Figure 1), and average tuyere life was less than 120 days. The current benchmark life of 460 days was rarely achieved. Figure 2, a tuyere life chart, illustrates poor performance and the high early failure rate.

When a tuyere fails, high-pressure water, which cools the tuyere, is allowed to enter the blast furnace. This water ingress sets in motion a chain of events that will upset furnace operation: furnace instability, increased fuel and material costs, lost productivity, and increased safety and environmental risks (Table 3). Taken to an extreme, a tuyere failure can result in the destruction of the blast furnace with ominous safety impacts.[6,7] The effects of tuyere failures

Figure 2



Tuyere life in days, 2009–10. Note the high early failure rate.

were the topic of discussion at many early technical society meetings.

Initially, prior to the advent of water cooling, many tuyere failures related to a tuyere "ironing."[8–12] With the invention of hot blast in 1828, tuyere design evolved to eventually include water cooling.[13–15] By the close of the 19th century, the benefits of a water-cooled tuyere were accepted within the industry, as was recognition of the effect of a failure. Reported effects of tuyere failures were: lower grades of iron (higher sulfur and lower silicon), chilled hearths, explosions, "wild gas" for the stoves (presumably high hydrogen contents), increased safety risks (changing tuyeres while on blast), increased costs and lost production.[12,16–17] By 1918, J.E. Johnson Jr., in his text on blast furnace principles, advised operators of the "…ruinous effect of water on the operation of the furnace…," while also quantifying the heat loss in terms of fuel for a leak ($^{1}/_{2}$ gpm leak corresponding to a 2% loss in hearth heat).[19] Nearly 100 years later, tuyere reliability is still a topic of interest at technical meetings. Tuyere reliability is still a modern issue, as discussed in papers and presentations at recent technical meetings by Yaniga, Shellhammer, etc.[21,23]

Project Approach

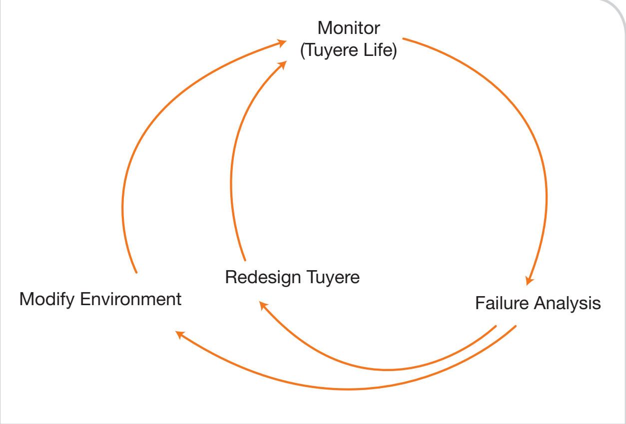
The tuyere reliability project started simply, with operators observing what was thought to be a

Table 3

Impact of Tuyere Failure

Impact	Single site, outage to change 1 tuyere	North America 2010
Lost production time	90 minutes	42,210 minutes (29 days)
Reduced production time	2 x 30 minutes (in/out of shutdown)	28,140 minutes
Lost production	260 t/hour x 90 minutes = ~520 tons	243,880 tons
Increased coke rate	2 coke blanks and 40# coke rate increase = ~20.5 tons	9,615 tons
Greenhouse gas increase	61.3 tons (based on 91%[C] in coke, all oxidized to CO_2)	28,432 tons

Figure 3



Production lost to tuyere failures in 2009–10; tuyere failures were the largest individual source of delays.

common failure location on leaking tuyeres. This practical observation developed into progressively more detailed failure analyses. Information gleaned from failure analysis fed tuyere redesigns and practice changes to modify the furnace environment around the tuyere, creating a reliability cycle and the project (Figure 3). With relatively few failures, a small data set and lacking a robust testing method, a statistics-intensive methodology — which is common in reliability projects — was not feasible. Instead, a practical engineering approach, using existing in-house knowledge, was adopted.

Failure Analysis

Five activities encompassed the failure analysis project portion; literature survey, tuyere sectioning and metallography, electrical conductivity testing, failure concentration mapping and data monitoring/analysis. Results of these activities enter the reliability cycle, driving tuyere redesign and environment modifications.

Literature Survey — Attempts to improve tuyere reliability have continued to challenge blast furnace operators and tuyere manufacturers. As blast furnaces have been developed to run higher productivity, at lower coke rates — primarily through pulverized coal injection — activity investigating the causes of poor tuyere reliability has focused on burden, operating practices and tuyere design. Table 4 summarizes recently published work concerning blast furnace tuyeres. To prioritize actions to improve tuyere reliability, failure causes indicated in the literature review and from operating experience are listed in Figure 4 in order of ascending criticality. In practice, Severstal's reliability improvement team found tuyere failures

Table 4

Recent Investigations Concerning Blast Furnace Tuyeres

Author(s)	Reference	Year	Comments
Stepanov, et al.	20	2011	Influence of coke quality on tuyere reliability.
Copeland and Street	21	2011	Tuyere design, operating practice, industrial scale testing.
Shellhamer and Walsh	22	2010	Tuyere manufacturing and design influence on tuyere life.
MacRae	23	2010	Computational fluid dynamics (CFD) modeling of water flow with respect to tuyere design.
Yaniga and Francis	24	2010	Industrial study of tuyere failures (burden, operating practices, water flow).
Shen, et al.	25	2009	Computer modeling study of air-cooled tuyere design.
Li, et al.	26	2008	Computer modeling study of tuyere nose failure (copper purity and scale).
Yang, et al.	27	2007	Coating to increasing tuyere life.
Wan, et al.	28	2007	Gradated multi-layer coating to increase tuyere life.
Roldan, et al.	29	2005	CFD modeling investigating industrial tuyere failures related to cooling.
Zhao, et al.	30	2005	Tuyere failures due to insufficient cooling in nose region.
Huang and Liao	31	2005	Coated tuyere to increase life.
Qian, et al.	32	2004	Coke quality degradation and increase in tuyere failures.
Radyuk, et al.	33	2002	Aluminum-based spray coating of tuyeres to increase life.
Dalley	34	2001	Coating (hardfacing, ceramic, calorizing) tuyeres to increase life.

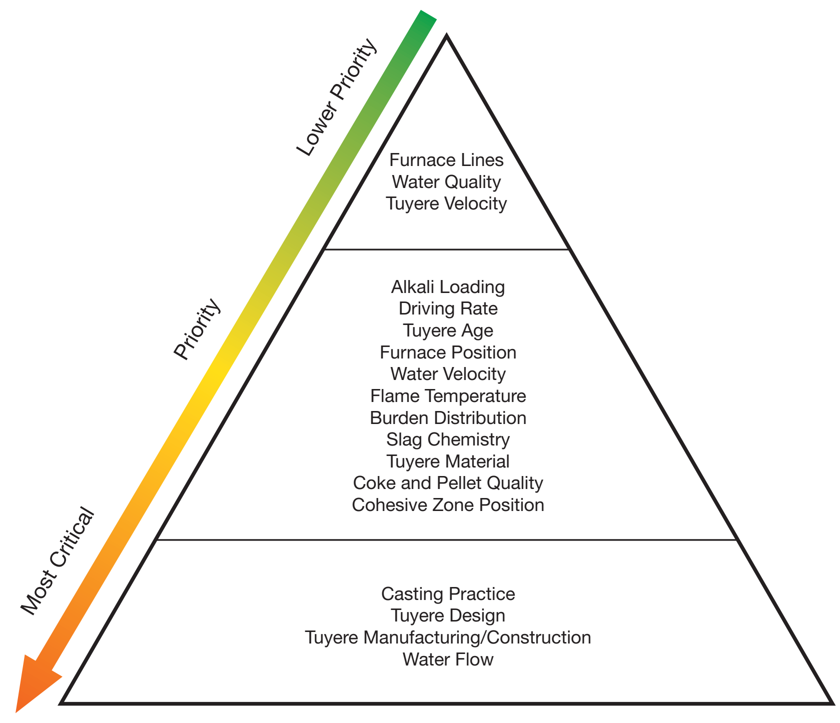
stemming from issues with burden distribution, operating practice, tuyere design and manufacturing defects.

Tuyere Sectioning/Metallography

— Frequently, causes of tuyere failures are self-evident. Erosion, abrasion and hot metal burns are all readily discernible from a cursory visual inspection. However, greater detail is needed to complete the analysis. By cutting sections from failed tuyeres, casting and manufacturing defects become obvious.

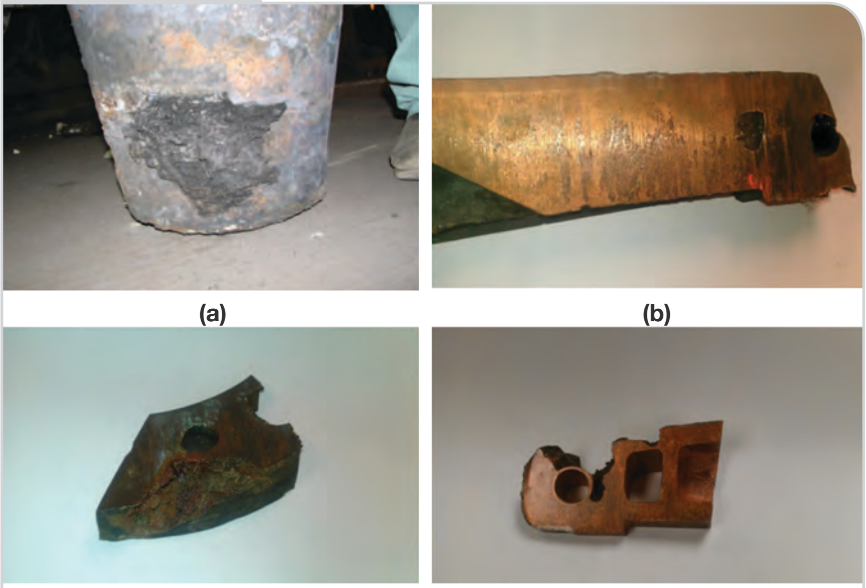
Two manufacturing flaws, seriously affecting reliability, were uncovered upon examination of failed tuyere sections. The first issue found occurred during an effort to secure a domestic tuyere supplier. A design was chosen that included a cast-in copper pipe that created the nose loop. A copper pipe is formed to the shape of the nose loop, cleaned and set into position in the core box, along with the sand cores that create the body passages. Molten copper is then poured around the preformed nose loop pipe and sand cores, forming the tuyere. The benefit in such a design is that the nose loop can be preformed into relatively smooth shapes, helping to prevent water flow eddies. Shortly after installation, tuyeres featuring the cast-in copper nose loop pipe began to fail. Failures were commonly seen after only a few days or weeks of service. The nose copper was burnt away to the point where the copper pipe became exposed to the furnace (Figure 5). In extreme cases, the tuyere nose tip was missing 1.5 inches of copper. Upon removal and inspection, the casting was found lacking a consistent and complete metallurgical bond to the cast-in copper pipe. Sections taken bisecting the nose loop allowed the pipe to simply fall from the casting. A black, powdery substance was

Figure 4



Tuyere reliability hierarchy.

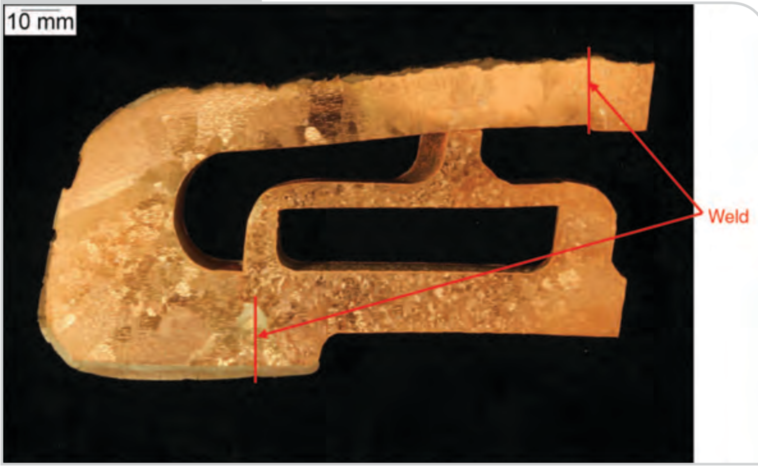
Figure 5



(a) (b) (c) (d)

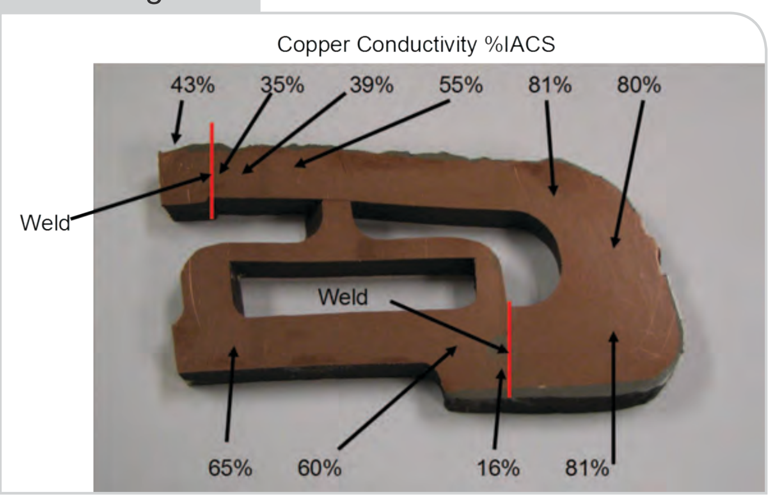
Failures and casting defects: hot metal attack due to iron dripping on tuyere surface, damage above low water velocity area (a); voids in casting, manufacturing defect (cast-in pipe); nose erosion (b); hot metal attack, manufacturing defect (cast-in pipe) (c); and manufacturing defect (cast-in pipe), hot metal attack penetrating hard surface coating (d).

Figure 6



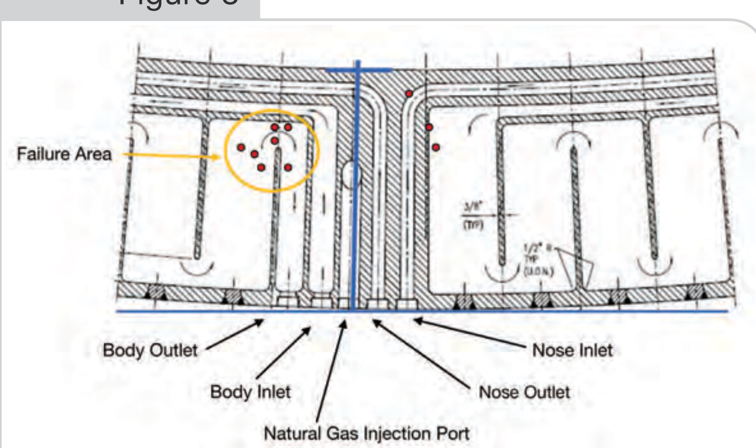
Welds and heat-affected zones in spiral tuyere.

Figure 7



Spiral tuyere electrical conductivity study.

Figure 8



Original tuyere failure concentration map.

present between the pipe and casting. Even a minute gap between the casting and copper pipe nose loop creates a barrier to heat transfer.[22] When insufficient heat is removed from the casting, the copper melts away. Exposed to the raceway, the thin-walled pipe (0.125-inch wall thickness) is not robust enough to survive inside a blast furnace.

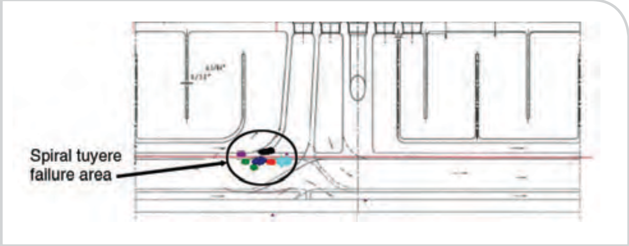
A later, more insidious manufacturing flaw was discovered after polishing and etching a section from a failed spiral nose tuyere. Revealed were weld joints created by using dissimilar filler metal and heat-affected zones on the outer tuyere surface (Figure 5). This design, characterized by its three-piece construction, is detailed in the Failure Concentration Mapping section, below.

Electrical Conductivity Testing — To aid in the failure analysis of the second manufacturing flaw listed above, electrical conductivity tests were performed. Focusing on the common failure point, conductivity of the casting was measured across the weld line (Figure 12). According to the Wiedemann-Frantz law, electrical conductivity is proportional to thermal conductivity.[33] Electrical conductivities as low as 16% International Annealed Copper Standard (IACS) were observed. At the outer circumferential weld, where failures were most common, the thermal conductivity of the weld zone was only about one-third of the thermal conductivity of pure copper. This forms a weak point where the casting is not sufficiently cooled and simply melts away to eventual failure. Electrical conductivity specifications were increased, and more rigorous testing was required of tuyere manufacturers as Severstal realized the significance this parameter plays in tuyere performance.

Failure Concentration Mapping — As part of the standard failed tuyere analysis process, each point of failure was plotted on a drawing that illustrated water passages within the tuyere. In time, a concentration map was developed, indicating a common failure point in the original tuyere design. Although the failure rate varied with changing operating parameters, the common failure point and apparent mechanism remained the same (Figure 8). The body passage outlet, where the cooling water reached its maximum temperature and an abrupt change in cross-sectional water passage area occurs, lay directly below the common failure point. A practical observation, later confirmed by computer flow modeling, was made that indicated possible low water velocity and flow eddies in this area. Increasing water velocity will help prevent tuyere burnout, and efforts were made to improve water velocity in the common failure location.[36,37]

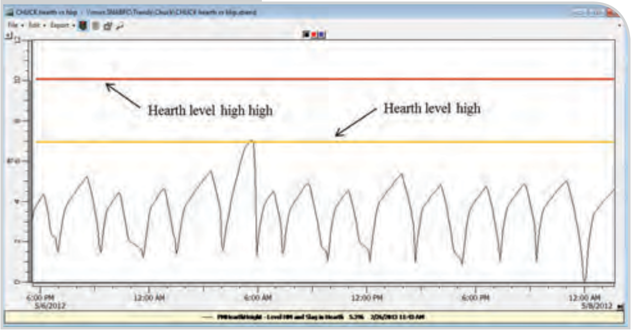
Failure mapping continued as new designs were trialed. A second failure concentration point was noted in a third-generation design. Circumferential water-cooling passages across the tuyere nose characterized this third-generation "spiral" tuyere. It was assumed that greatly increased water velocity in the original common failure location, as noted earlier, would prevent reliability issues. In operation, this design performed worse than the original lower water velocity tuyere. Spiral tuyeres at Severstal are manufactured from three pieces of copper: a nose casting, body casting and an internal piece that creates the spiral flow. Two circumferential welds, attaching the body to the nose casting, characterize the spiral-type tuyere. Severstal Dearborn also employs a natural gas port in the tuyere, which forced the outer circumferential weld close to the tuyere nose. The failure concentration map indicated failure points on the outer circumferential weld line. Incidentally, the failure pattern was almost identical to the burns Amber Dalley reported in 2001.[34]

Figure 9



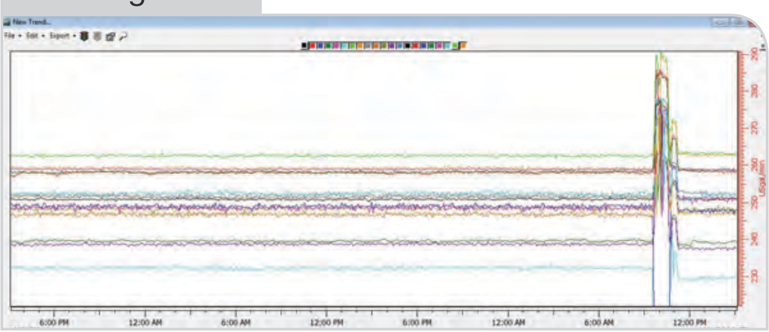
Failure concentration map, spiral nose design.

Figure 10



Hearth liquid level.

Figure 11



Tuyere water flows.

Data Monitoring/Analysis — Ironmakers at Severstal Dearborn are fortunate to have extensive instrumentation and monitoring capabilities available. Tuyere reliability improvements depend in part on providing operators with practical tools, helping to indicate when conditions are such that a tuyere failure may occur. Two examples are shown in Figures 9 and 10. Figure 9 is a chart in which the hearth liquid level is monitored. High liquid level in a blast furnace hearth will distort raceway gases in a manner that may increase heat load on the tuyere or promote wall working — two conditions that will decrease reliability.[35] A failure can also occur when high levels are taken to an extreme and liquids contact the tuyere bottom (Figure 10).

Water flow is of obvious importance. The most fundamental step to tuyere integrity is to have water flow. System water flow and pressure, as well as individual tuyere water flows, are continuously monitored and alarmed. Water supply to tuyeres is redundant, with spare electric and diesel pumps in place to ensure constant water flow. In the event of a catastrophic pipe break or total loss of pumping capability, pressurized mill water will flood the system as a tertiary backup. Tuyere water flows are shown in Figure 11. Additional continuous monitoring activities also include actively watching wall heat loading and gas flow.

After a tuyere failure, event analysis often begins with data mining and a high-level review of furnace conditions prior to the event. Table 5 is a summary of common parameters used in determining furnace conditions that may affect tuyere reliability. In-depth operating data analysis, together with literature, burdening and operating practice review, led to awareness that the operating environment can negatively impact tuyere reliability. Changes to operating and burden practice are detailed later.

Table 5

Parameters Monitored in Relation to Tuyere Reliability

Parameter	Deviation	Relationship to tuyere reliability
Water flow	Low or no flow	Failure to provide sufficient cooling
Liquid level	High level (over 7 feet)	Raceway distortion, possible wall working and high heat load on tuyere
	High high level (over 10 feet)	Liquid contact with tuyere bottom
Bosh and stack stave thermocouples	General rapid increase in bosh and stack	Wall working, increased hot metal generation above tuyere
	Local, very rapid temperature increase in bosh or stack	Peeling, scab may hit or melt above tuyere
Above-burden probe thermocouples	High wall and low center temperatures	Wall working, more iron generated above tuyeres

Tuyere Redesigns

Computer flow modeling, combined with practical in-house testing and failure analysis methods, described above, guided tuyere redesigns. As stakeholders in Severstal's success, tuyere manufacturers played a significant role by introducing new design concepts and developing Severstal's in-house knowledge base. The following sections describe tuyere design modifications and tools used in redesign decision making.

CFD Modeling — Concentration failure mapping indicated a common failure point in the original tuyere. This common failure point was over an area where low water velocity and flow eddies were thought to occur. Low water velocity will decrease a tuyere's resistance to failure.[37,38] A computational fluid dynamics (CFD) model confirmed suspicion of low water velocity and recirculation design (Figure 12a). A subsequent and ultimately unsuccessful (due to manufacturing issues) design revision was made to improve water velocity. A second CFD model confirmed the improve water velocity (Figure 12b). Figure 12c is a CFD model created as part of the review process before a new design is approved. The model indicated less recirculation and higher water velocity in the known failure area. The design in Figure 12c ultimately proved successful. Proving to be a useful evaluation tool, CFD modeling is now required before any design changes are approved.

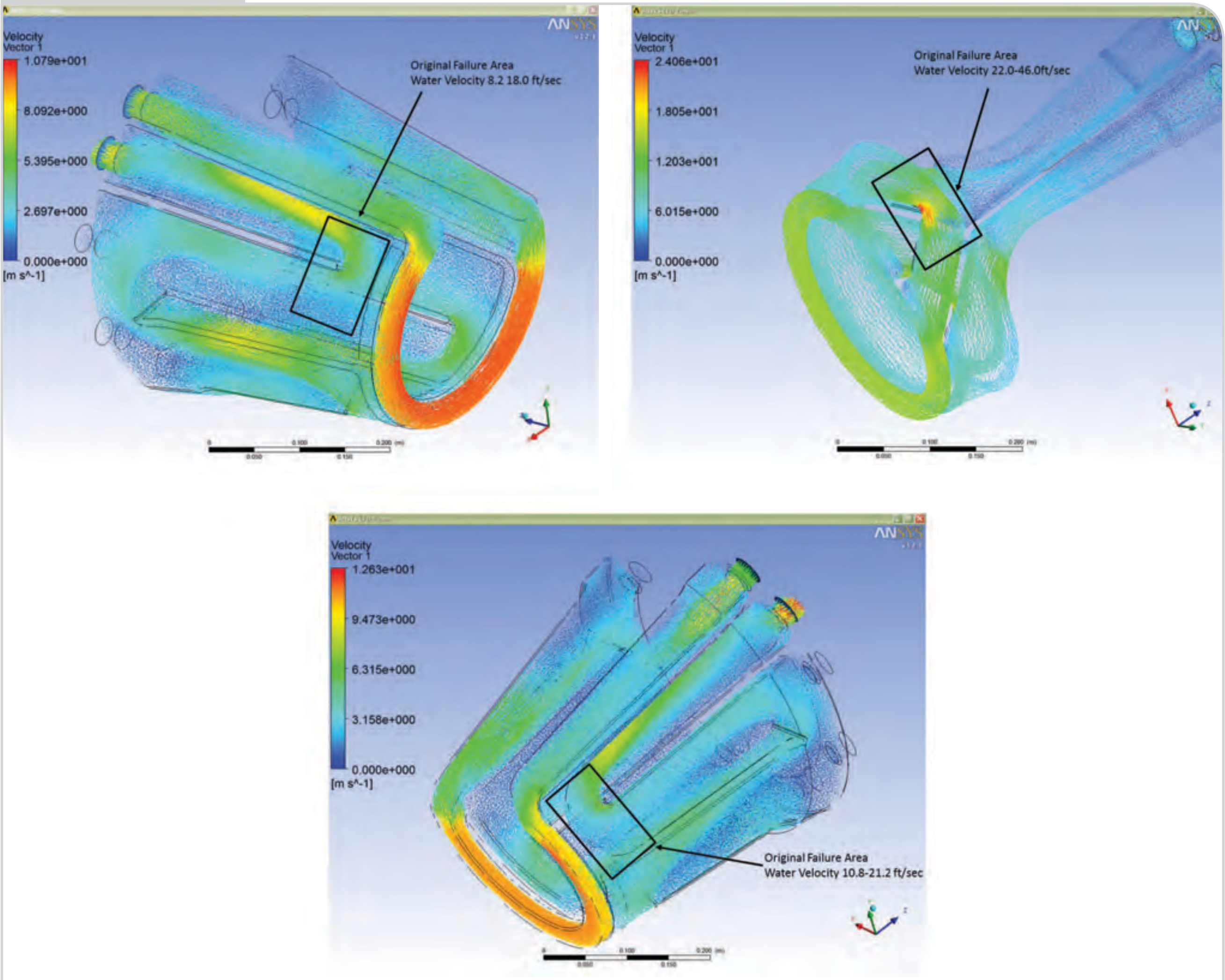
In-House Testing — Tuyeres are commonly coated with a variety of materials.[34] Severstal traditionally used tuyeres coated with a hard-surface, nickel-chrome weldment with the intent that hot metal burns would be prevented. Failure analysis indicated this hard surfacing did not withstand hot metal attack (see Figure 5a). A decision was made to trial tuyeres with a new, calorized coating instead of a hard-surface weld. Calorizing is a pack diffusion process where the copper casting is placed in a sealed retort containing aluminum powder. The casting is heated and aluminum is diffused into the surface, creating a copper aluminide inner layer and an aluminum oxide outer layer.[39,40] The various layers can be seen in Figure 13. This is not a new technology; publications from the 1910s and 1920s assert calorizing as beneficial to tuyere life.[41,42] A Russian article goes so far as to say "…tuyere life is increased by 3–4 times… ."[42]

The early 20th century enthusiasm for calorizing seems to have dampened somewhat until recently; calorized tuyeres were available but unadopted in Dearborn until 2010 and appear to be more common following successful implementation at Severstal.[34] Reports in recent literature vary from poor to excellent burn resistance and good erosion resistance[34] to "…calorized copper is superior to bare copper on exposure to hot metal splash…" and "…it is up to six times harder than bare copper, which means it [the calorized layer] is more abrasion resistant… ."[32] Internally, questions were raised regarding the performance of calorized tuyeres, based on past operating experience. A set of in-house tests, similar to Dalley's and Shellhammer's previous work, were undertaken to determine the present-day validity of calorized tuyeres.[32,34]

Before complete adoption of the calorized coating, validation of the coating's effectiveness, as well as the futility of hard surfacing, was needed. In-house testing began with a simple, practical experiment on the casthouse floor (Table 6). Three tuyeres were heated to 700–800°F, and iron from the trough well at 2,740°F was poured on the surface until the outer skin was penetrated. The point of penetration appeared similar to hot metal "bullet-hole" burns (Figure 14). Testing ceased on the calorized tuyere after 102 lbs. of iron had been poured (Table 7) and the surface remained undamaged.

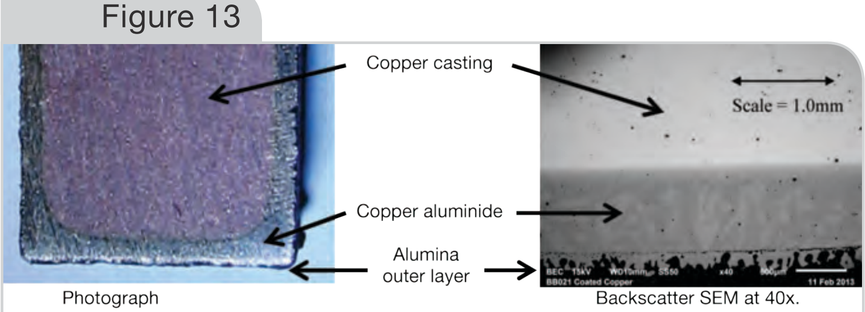
The experiment was repeated, in a more controlled manner, using unheated, high-conductivity, 6 x 6 x

Figure 12



CFD models of tuyeres.

Figure 13



Photograph of a calorized copper plate cut in half.

1-inch cast copper blocks. Tuyere failure concentration mapping indicates that tuyeres are most susceptible to burns in the 3 and 9 o'clock positions. The test samples were held at 45° to simulate the most susceptible position. A sand-filled box sat below the test pieces so that all the poured iron could be collected and weighed. Again, iron was poured onto the test block surface until failure by complete penetration occurred. A thermal imaging camera was positioned on the cold side of the plates to document the failure process. The bare copper (Figure 15a) and hard-faced plate (Figure 15b) burned through quickly, while the calorized plate survived undamaged (Figure 15c). Pouring on the calorized plate was stopped after the container used to hold the iron filled up. The calorized surface is an insulating, non-wettable coating that provides significant protection from hot metal contact.[39] Infrared video footage captured the failing plates (Figure 16).

Table 6

Initial Pour Conditions	
Tuyere replicant sample	700–800°F temperature
Hot metal temperature	2,740°F
Hot metal silicon	0.67%

Figure 14

Bare copper tuyere completely penetrated with iron after pour test.

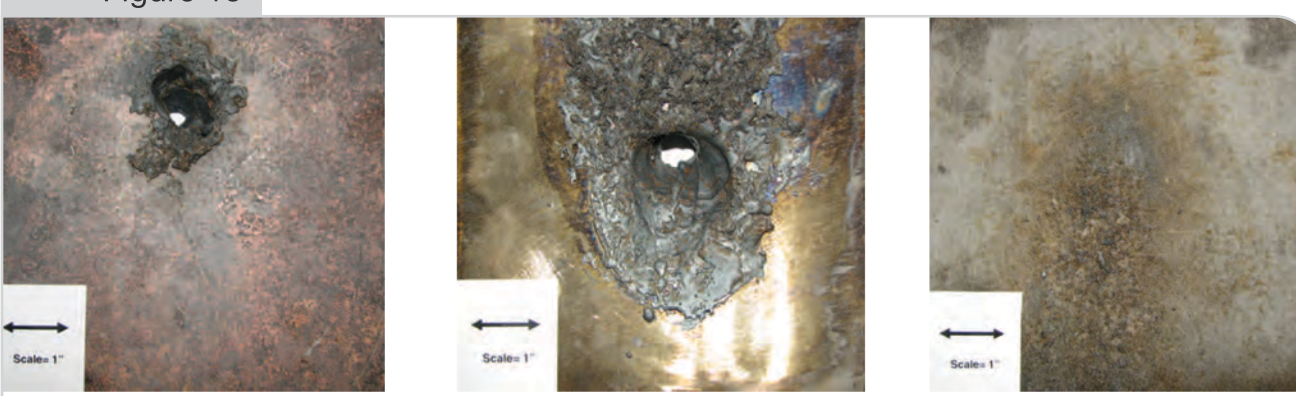
Before adopting a tuyere with acceptable performance, six design generations were trialed. A calorized, high-conductivity copper tuyere with hard-surface weld on the nose tip is currently in service. Resistance to hot metal penetration has increased sevenfold, and the average life more than doubled. Reliability has improved to the point where tuyeres are replaced on a scheduled basis during quarterly maintenance outages, and failures requiring unplanned outages are rare. Iterations of tuyere design are listed in Table 9.

Modified Environment

Investigations into charging and operating practice began, as failure analysis indicated a possible relationship with tuyere reliability. Along with a concurrent study looking at iron ore degradation, these investigations produced several practice changes that improved tuyere reliability.[43]

Standard charging practice at Severstal Dearborn includes the use of nut coke. Nut coke, a small-size fraction that is segregated by screening, is normally charged with the ore layer. With varying coke quality, nut coke generation rates can increase to the point

Figure 15



(a) (b) (c)

Photographs of copper plates after second pour test.

Table 7

Initial Pour Test Results

Tuyere coating	Characteristic	Weight of iron poured (lbs.)	Result
Bare copper	90% IACS	17	Complete penetration
Hard faced	Ni-Cr weld overlay	43	Penetration through weld overlay
Calorized	Aluminum diffusion coating	102	Surface unblemished

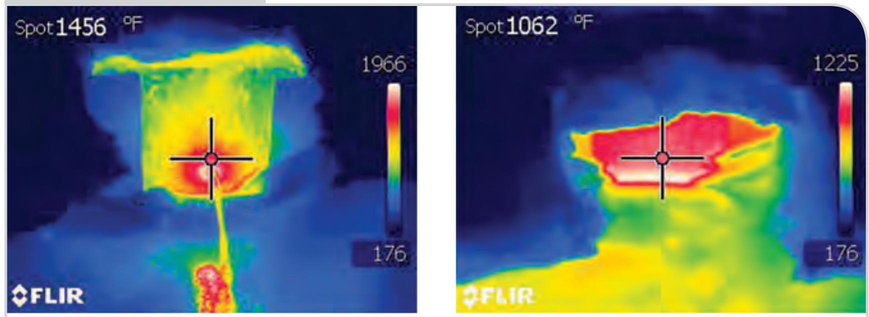
Table 8

Results of Iron Pour Test Onto Copper Plates

Tuyere coating	Weight of iron poured (lbs.)	Test duration	Result
Bare copper ~90% IACS	12	2 minutes, 50 seconds	Complete penetration
Hardfaced (Fe/Cr weld overlay)	16	3 minutes, 30 seconds	Complete penetration
Calorized (aluminum diffusion)	130	14 minutes, 0 seconds	Surface undamaged

where more nut coke is generated than could be consumed within the ore layer. During periods with lower coke quality, large quantities of nut coke are stockpiled on-site. Severstal's operating scheme sought to consume these stockpiles of excess nut coke. A decision was made to replace larger furnace coke on the walls with nut coke (Figure 17b). Ultimately, the "wall" nut coke reached a rate of 55 lbs./nthm, or 1.5 chute revolutions. Tuyere failures increased during this

Figure 16



Hard-faced plate at the moment of failure.

Calorized plate after 14 minutes of continuous pouring.

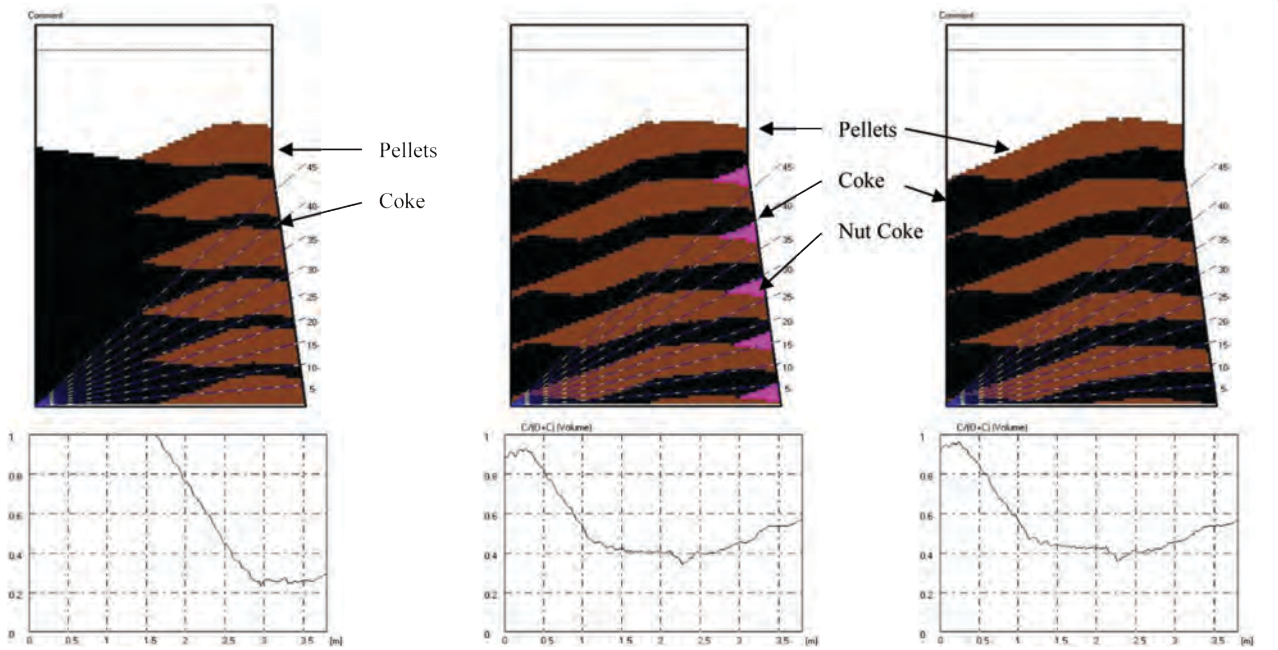
Infrared images of second test plates.

Table 9

Tuyere Redesigns

Identifier	Current status	Reason for adoption	Failure analysis techniques used to determine performance	Reason abandoned
OEM 1	Abandoned	OEM design	Concentration failure mapping, sectioning, modeling, literature survey, data mining	Concentrated failures (Figure 8), known water flow issues
OEM 2	Abandoned	OEM design	Concentration failure mapping, sectioning, modeling, data mining	Concentrated failures, known water flow issues
Mod 1	Abandoned	Two additional body passages added, to improve velocity in known OEM tuyere failure area	Concentration failure mapping, sectioning, modeling	Manufacturing defect, nose loop pipe not bonded to casting
Mod 2	In service, being phased out	Spiral design, higher velocity in known failure area	Concentration failure mapping, sectioning, modeling, conductivity analysis, data mining	Hot metal penetration at weld line causing failures (Figure 9)
Mod 3	In service, being phased out	Domestic manufacturer, calorizing to improve life	Sectioning, pour test, modeling	Nose erosion causing failures
Mod 4	Phased in	Domestic manufacturer, nose tip hardfacing in addition to calorizing	Sectioning, pour test	Currently in service
Mod 5	In development	Domestic manufacturer, calorized, with advanced hard surface		

Figure 17



Ore/Coke Ratio (By Volume)
Center Wall

A

Large Coke Chimney, ore on the wall

Many Bullet-Hole Tuyere Failures

Ore/Coke Ratio (By Volume)
Center Wall

B

Smaller Coke Chimney, Nut Coke on Wall

Many Bullet-Hole Tuyere Failures

Ore/Coke Ratio (By Volume)
Center Wall

C

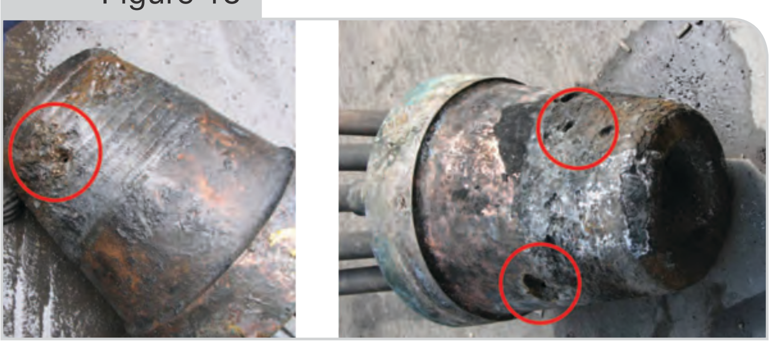
Smaller Coke Chimney, No Nut Coke on Wall

Fewer Tuyere Failures

Current Operating Burden Pattern

Burden distribution patterns.

Figure 18

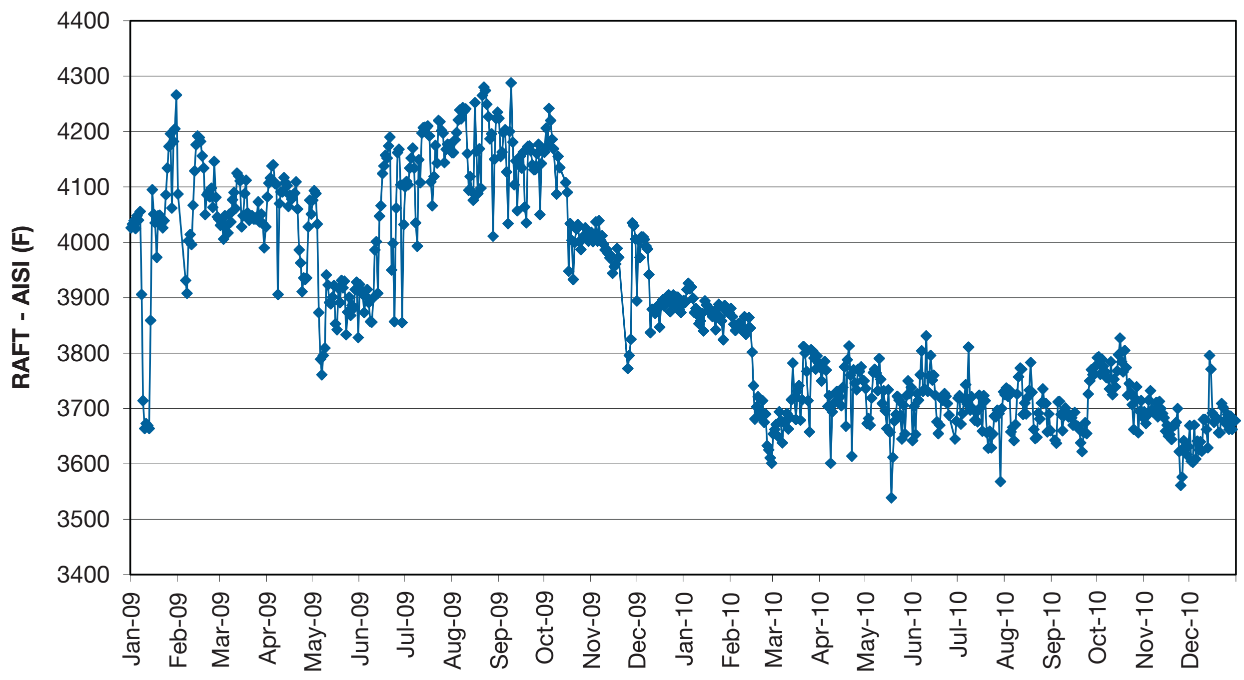


Typical bullet-hole burns (circled) in failed tuyeres.

period, with bullet-hole hot metal burns common. The authors propose that nut coke on the furnace wall somehow changes the permeability above the tuyeres, causing hot metal to occasionally flood the top of the tuyere, resulting in a bullet-hole-type burn. Examples of bullet-hole burns are pictured in Figure 18. This strategy was abandoned when the excess nut coke was consumed.

Another operating path sought to minimize "short circuits" and "channeling" (events of excessive gas flow on the walls resulting excursions of high top pressure) by increasing the ore loading at the wall, while simultaneously operating with high oxygen levels (targeted blast oxygen up to 34%) to boost productivity. Figure 17a illustrates the high wall ore loading, with Figure 19 showing a two-year raceway adiabatic flame temperature (RAFT) graph. While using this practice, the blast furnace experienced high flame temperatures, (speculated) low cohesive zone position and increased hot metal production at the wall — all variables that increase a tuyeres susceptibility to failure. This operating scheme culminated in an extended outage to replace three tipped tuyeres. The high flame temperature practice was abandoned after repairs were made replacing tipped tuyeres. The target RAFT temperature was reduced 400°F, from 4,100°F, and the ore-to-coke ratio at the wall was increased to 55% from 30% (Figure 17c).

Figure 19



"C" blast furnace RAFT temperature (AISI), January 2009 to December 2010.

This change resulted in fewer bullet-hole-type hot metal burns on the tuyere tops. Ultimately, tuyere failure rates have been greatest during periods of radical burden changes.

Results

Tuyeres fail in varying manners. Types of failures, in the context of reliability, are noted in Table 10. At the project's inception, tuyere failures were catastrophic in nature, requiring abrupt unplanned outages. As redesigns and practice changes took effect, tuyere reliability improved, pushing failures from sudden to gradual. Currently, of the few failures seen, degradation failures are most common. Indicating failure rate over time, the classic bathtub graph (Figure 20), with three distinct phases — early failure, useful mid-life and wear-out[45] — is a useful tool to visualize reliability improvements.

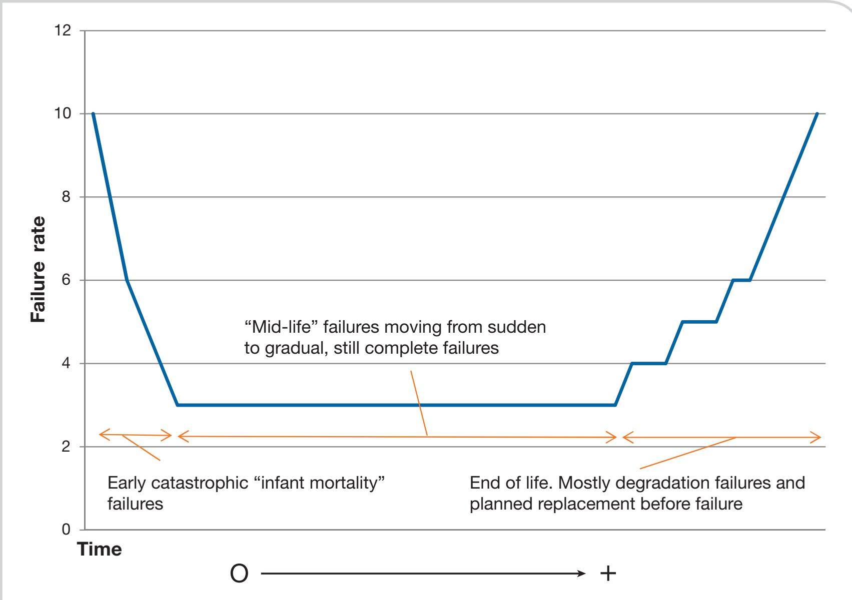
Success of the tuyere reliability project lies in shifting the distribution of failures to the right of the bathtub, eliminating early and mid-life (sudden and complete) failures, and pushing to "degradation failures" (Figure 22). These degradation failures are predictable so tuyere replacement can be managed

Table 10

Types of Failures, Derived From Aggarwal[44]

Failure	Description
Sudden failure	Failures that cannot be predicted
Gradual failure	Failures that can be predicted
Complete failure	Failures that result in deviation beyond specific limit (requiring an unplanned shutdown)
Partial failure	Failures that result in deviation beyond specific limit but do not cause complete lack of function (shutdown for replacement can be delayed and planned)
Catastrophic failure	Failures that are both sudden and complete
Degradation failure	Failures that are both gradual and partial

Figure 20



Classic reliability bathtub graph.

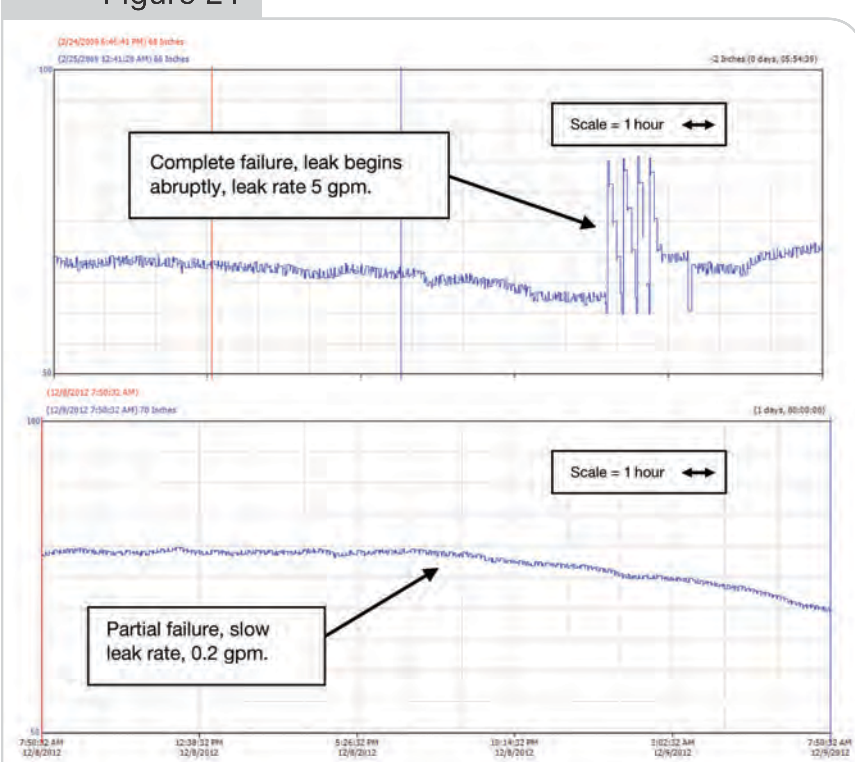
during planned maintenance outages before a failure becomes "complete." Figure 21 shows an example of a complete failure and a "partial" failure.

Improved tuyere reliability has had a very positive business impact. Preventing unplanned outages improves productivity and yields a savings in coke and nitrogen usage. Additionally, with reduced tuyere failures, fewer tuyeres need to be purchased. During the reliability project's most active period, a US$3.5 million year-to-year (2010–11) improvement was realized. Figure 23 and Table 11 detail advances in tuyere reliability. Extending this most active period to date, the tuyere reliability project has currently produced a US$7 million positive business impact.

Success of the new tuyere design has resulted in sourcing solely from a U.S. manufacturer, and other North American operators have shown interest in tuyere reliability and have begun adopting the current design. Work undertaken to date has provided a direction for the next stage of development: more intricate water passage design and more advanced coatings. Trials, particularly pour testing, have resulted in coating application being explored in other applications.

Additional and less quantifiable impacts from increased tuyere reliability are also noted. Since outages to replace failed tuyeres are generally abrupt and unscheduled, maintenance resource allocation is disturbed. As with all unscheduled outages, a general shift from preventive/predictive maintenance to a "firefighting" maintenance approach is common. Scheduling disruptions and delays with normal preventive maintenance activities are seen up to 48 hours after an unscheduled tuyere change.[46] Also, avoiding unscheduled tuyere changes gave a bit of relief to the maintenance and operating groups. The sense of goodwill was another pleasant result for the authors.

Figure 21

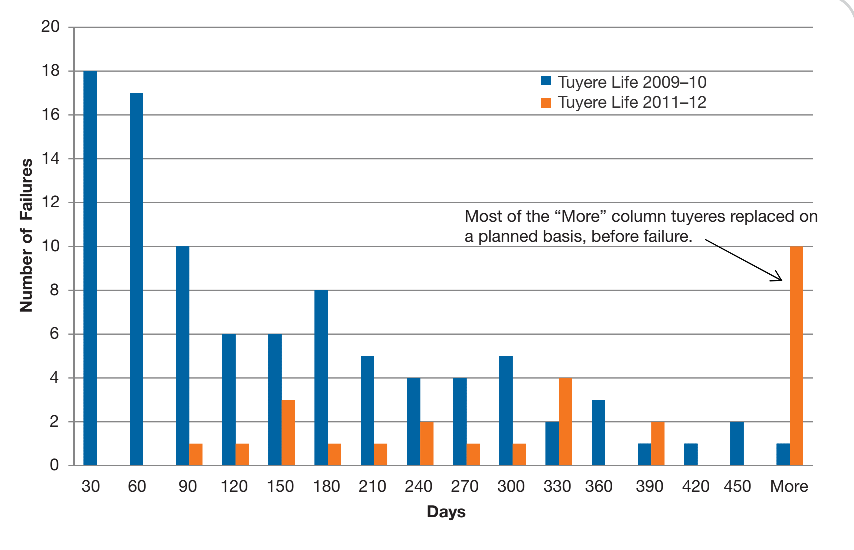


Examples of tuyere failures.

Conclusions

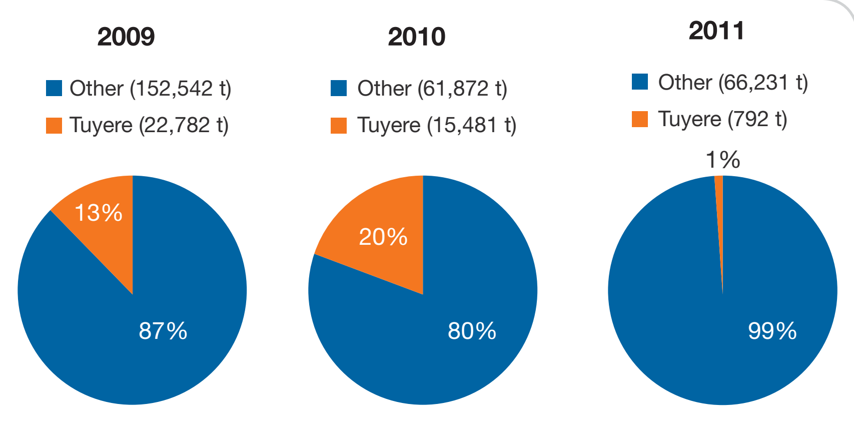
A comprehensive, multi-faceted study was undertaken to improve tuyere reliability. Following a simple cycle of monitoring reliability,

Figure 22



Tuyere life graph.

Figure 23



Tonnage lost to tuyere failures over a three-year period.

Table 11

Reliability Project Impact

	2010	2011
Tuyeres replaced	19	1
Coke usage	390 tons	16,696 Mcf
Purge nitrogen	21 tons	878 Mcf
Lost production	15,481 tons	792 tons
Business impact	US$3,459,009	

analyzing failure, redesigning and environment modification, this practical study has achieved significant results. To date, a 95% improvement in tuyere life and 19-fold reduction of lost productivity has been realized. Through savings from decreased usage of coke, nitrogen and tuyeres, as well as increased productivity, improved tuyere reliability has generated a positive business impact of US$7 million to date. Going forward, the techniques outlined in this work will be used to tackle new reliability challenges.

Acknowledgments

The authors wish to extend their appreciation to the Reliability Achievement Award audit team: Colleen Reeves, Jay Ondrovic, Bill Bennett and Brian Finnicum, who successfully presented the tuyere project to the AIST Maintenance & Reliability Technology Committee.

The authors would also like to thank Severstal Dearborn management for allowing them to publish this work, and acknowledge Ed Asbury, the Severstal Dearborn Ironmaking crew, Dennis Webb of Alabama Copper and Bronze, Trevor Shellhammer of Shellhammer Consulting, Andrew Park of Quantum Ceramalloy, and Garrett LaFata for their assistance and input.

Disclaimer

References

1. www.worldsteel.org, Statistics for DRI and BFI Annual Production.
2. B. Edwards, A. Cheng, S. Street, B. Ebner and L. Hausmer, "Severstal NA 'C' Blast Furnace 2007 Revamping: Equipment Design Transforms C BF Into a World-Class Operation," *Iron & Steel Technology,* Vol. 6, No. 3, Mar. 2009, pp. 65–75.
3. P. Bond and M. Smith, "Pulverized Coal Injection at Severstal North America 'C' Blast Furnace Using Acquired Pulverized Coal," *AISTech Conference Proceedings,* Vol. I, 2009, pp. 375–386.
4. G. Yang, *Life Cycle Reliability Engineering,* Wiley, 2007.
5. P. O'Connor, *Practical Reliability Engineering,* Wiley, 2011, pp. 1–5.

6. Anon., “Blast Furnace Breakouts, Explosions, and Slips and Methods of Prevention” U.S. Department of the Interior, Bureau of Mines, 1917, p. 174.
7. Anon., “The Explosion of No. 5 Blast Furnace, Corus UK Ltd., Port Talbot, United Kingdom,” *Health and Safety Executive,* 2001, p. 47.
8. F. Overman, *The Manufacture of Iron,* Trubner and Co., London, U.K., 3rd edition, 1854.
9. N. Neal Solly, “Description of a Gunmetal Tuyere for Blast Furnaces,” *Institution of Mechanical Engineers,* 1865, pp. 256–277.
10. Taws and Hartman, *Tuyeres,* Lehman and Bolton, Philadelphia, Pa., 1886.
11. Taws and Hartman, “Tuyeres,” *The Metallurgical Review,* Vol. 2, Mar.–Aug., 1878, pp. 487–492.
12. J. Hartman, “Notes on Tuyeres in the Iron Blast Furnace,” *Transactions of American Institute of Mining Engineers,* Vol. 28, Feb.–Oct., 1898, pp. 666–673.
13. B. Fackenthal, “Tuyeres in the Iron Blast Furnace,” *Transactions of American Institute of Mining Engineers,* Vol. 28, Feb.–Oct., 1898, pp. 673–678.
14. J. Percy, *Metallurgy: The Art of Extracting Metals From Their Ores, and Adapting Them to Various Purposes of Manufacture: Vol. 2, Iron and Steel,* John Murray, London, U.K., 1864, pp. 394–395.
15. Anon., “Art III — Metallurgy,” *London Quarterly Review — American Edition,* Vol. 120, Jul.–Oct., 1866, p. 44.
16. T. West, *Metallurgy of Cast Iron: A Complete Exposition of the Processes Involved,* The Cleveland Printing and Publishing Co., Cleveland, Ohio, 1897, pp. 52–55.
17. H. Allen, “A New System of Cooling Tuyeres for Blast Furnaces,” *The Journal of the Iron and Steel Institute,* Vol. 61, No. 1, 1902, pp. 79–87.
18. W. Foster, “Method of Supplying Water to Furnace Tuyeres and Coolers,” *American Manufacturer and Iron World,* Vol. 70, No. 1, 1902, pp. 494–497.
19. J. Johnson, *The Principles Operation and Products of the Blast Furnace,* McGraw-Hill Co., New York, N.Y., 1918, pp. 347–372.
20. E. Stepanov, V. Borisenko, D. Mezin, V. Shevchuk, O. Chuirkina and I. Mel’nikov, “Influence of the Blast Furnace’s Operating Conditions and Coke Quality on the Life of Air Tuyeres,” *Coke and Chemistry,* Vol. 54, Issue 12, pp. 464–468.
21. C. Copeland and S. Street, “Tuyere Failure — Cause and Effect,” *AISTech Conference Proceedings,* Vol. I, 2011, pp. 605–619.
22. T. Shellhammer and R. Walsh, “High Conductivity Copper in the Blast Furnace,” *AISTech Conference Proceedings,* Vol. I, 2010, pp. 437–452.
23. A. MacRae, “Eddy-Free Tuyeres for a Blast Furnace,” *AISTech Conference Proceedings,* Vol. I, 2010, pp. 489–498.
24. S. Yaniga and W.P. Francis, “Tuyere Life Improvements and Operating Enhancements on Great Lakes B-2 Blast Furnace,” *AISTech Conference Proceedings,* Vol. I, 2009, pp. 365–373.
25. Y-S. Shen, Z-M. Liu, T. Zhu, F-S. Yan, H-N. Xin and R-L. Sun, “The New Technology and the Partial Thermotechnical Computation for Air-Cooled Blast Furnace Tuyere,” *Applied Thermal Engineering,* Vol. 29, No. 5–6, 2009, pp. 1232–1238.
26. C. Li, L. Cao and N. Xu, “Preventing Method for Erosion of Blast Furnace Tuyere,” *Journal of Shenyang University of Technology,* Vol. 30, No. 1, 2008, pp. 60–63.
27. D. Yang, Y. Guan, Y. Zhang, J. Li, J. Hu, W. Li, “Application of Ceramic Coat Synthesized by In-Situ Combustion to BF Tuyere,” *Journal of Iron and Steel Research International,* Vol. 14, No. 2, 2007, pp. 70–72.
28. X. Wan, X. Liu and M. Zhang, “Experimental Research on ZrO_2 Coating for Single Tuyere of Small Blast Furnace,” *Naihuo Cailiao Refractories,* Vol. 41, No. 3, 2007, pp. 220–222.
29. D. Roldan, C. Tetrault, Y. Zhao, M. Atkinson and C. Zhou, “Heat Transfer Analysis in a Blast Furnace Tuyere Nose,” *Proc. ASME Summer Heat Transfer Conference,* 2005, pp. 179–183.
30. Y. Zhao, M. Atkinson, H. Crosman, C. Tetrault, D. Roldan and C. Zhou, “Investigation of Tuyere Nose Failures at U. S. Steel – Great Lakes Works B2 Blast Furnace,” *AISTech Conference Proceedings,* Vol. I, 2005, pp. 491–496.
31. X-Y. Huang and X-W. Liao,”Study on Effect of Thermal Barrier Coating of BF Tuyere on Its Service Life,” *Iron and Steel (Peking),* Vol. 40, No. 10, 2005, pp. 18–20.
32. K. Qian, W. Zhu, Y. Wang and W. Zhang, “Production of Shougang BF After Deterioration of Coke Quality,” *AISTech Conference Proceedings,* Vol. I, 2004, pp. 269–275.
33. A. Radyuk, A. Titlyanov, A. Yakoev and S. Pedos, “Improvement in Service Life of Blast Furnace Tuyeres Due to Thermal Gas Spraying,” *Stal’,* Vol. 6, 2002, pp. 11–12.
34. A. Dalley, “Protective Coatings for Copper Blast Furnace Tuyeres,” *Iron & Steel Society Ironmaking Conference Proceedings,* 2001, pp. 453–259.
35. B. Desai and S. Lenka, “Quantification of Blast Furnace Hearth Drainage Parameters Through Physical Model Study,” *Iron & Steelmaking,* Proquest, 2007, p. 269.
36. W. Jones and N. March, *Theoretical Solid State Physics,* Courier Dover Publication, Mineola, N.Y., 1985.
37. N. Ukai, H. Uneo and M. Tsukamoto, “Experimental Studies on Burnout of Tuyere,” *Tetsu-to-Hagane,* Vol. 62, No. 9, 1976, pp. 1151–1158
38. M. Mitsutsuka, H. Morise and K. Tsuda, “Study on the Burnout Mechanism of Tuyere,” *Tetsu-to-Hagane,* Vol. 57, No. 2, pp. 201–212.
39. Private communication, Andrew Park, Quantum Ceramalloy Inc., Nanticoke, Ont., Canada, to Charles Copeland, February 2011.
40. Private communication, Trevor Shellhammer, Alabama Copper and Bronze, to Charles Copeland, 2010–11.
41. Anon., “Protection of Metals From Oxidation at High Temperatures,” *Journal of the Institute of Metals,* Vol. 26, No. 2, 1921, pp. 536–537.
42. G. Valvilovskaya, D. Tarasko, P. Zhigulev, N. Yarmolindsky and G. Pleshakov, “Increasing the Lives of Blast Furnace Slag Tuyeres by Calorizing,” *Steel in the USSR,* Vol. 1, 1971, pp. 851.
43. S. Street, “An Investigation of Unstable Blast Furnace Operations Caused by Stockpiled Iron Ore Pellets,” *AISTech Conference Proceedings,* Vol. I, 2011, pp. 515–529.
44. K. Aggarwal, *Reliability Engineering,* Kluwer Academic Publishers, Dordrecht, The Netherlands, 1993, pp. 1–9.
45. R. Fries, *Reliable Design of Medical Devices,* CRC Press, Boca Raton, Fla., 2012, pp. 41–42.
46. Private communication, Shawn Kalcevic, Severstal Dearborn, to Charles Copeland, January 2013. ✦

This paper was presented at AISTech 2013 — The Iron & Steel Technology Conference and Exposition, Pittsburgh, Pa., and published in the Conference Proceedings.