High-Conductivity Copper in the Blast Furnace

Among all pure metals, copper has the second highest thermal and electrical conductivity, next to silver. These properties, coupled with a reasonable cost, make copper ideal for use in metallurgical vessels as a conductor of electrical current, as well as a lining material and protector of refractories and steel superstructures.

Copper is ideal for use as a lining material for refractories and steel superstructures. This paper covers the evolution of copper to its current form, particularly its superior performance in water-cooled blast furnace cooling elements.

This paper will cover the evolution of copper to its current form, the influence of impurities in pure copper, and offer comparisons to other materials. Some aspects of producing high-conductivity copper castings in a typical non-ferrous foundry will be discussed. Foundries producing copper castings must follow strict standard operating procedures to obtain acceptable casting quality, and castings that will perform well in harsh service environments. To produce *high-conductivity* copper castings requires even more stringent control. Finally, in addition to basic theoretical discussions and modeling, some empirical evidence and typical failures with general recommendations will be covered which can lead to superior performance in water-cooled blast furnace cooling elements such as tuyeres, tuyere coolers, cooling plates and staves.

Historical Perspective

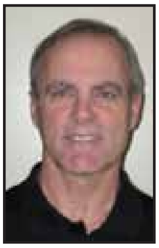
Before there were metals, there were rocks. Rocks and stones were important to early man as tools and weapons. But once metals were discovered, everything changed. The historical progression of these materials was so important that scholars divided ancient history into the Stone Age, followed by the Bronze Age, then the Iron Age. The first smelting of copper may have been performed in pottery kilns as early as 8,000 years ago. Iron smelting followed a few thousand years later, first in China. Like the copper smelters, the ironmaking furnaces were made of earth and stone, then bricks, and now in modern times are lined with water-cooled components and ever-changing refractory materials.

Refractories have their limitations in many practical uses as insulating materials, but their combination with cooling elements have improved productivity and extended the life of furnace linings. Cast iron and steel have been used for cooling members, and shower-cooled steel-shelled cupola melting furnaces are still used in high-production iron foundries all over the world today. In blast furnaces, cast-iron members were used in many variations for structural and cooling elements. Bethlehem Steel Corp. operated five foundries in their home plant in Pennsylvania, some of them predating their incorporation in 1904. The plant's original stone building was constructed for the Bethlehem Iron Works in the 1860s, and housed early ironmaking facilities. It later became the plant's iron foundry, where cast-iron staves were produced for many of the corporation's blast furnaces. The plant also operated a brass foundry, built in 1904, which produced brass and bronze parts, and copper castings for relines and maintenance at its five blast furnaces, as well as those at all the sister plants in Johnstown and Steelton, Pa., Lackawanna, N.Y., Sparrows Point, Md., and the newest in Burns Harbor, Ind.

It is interesting to note that the first use of bronze cooling plates in the United States is alleged to have occurred in Pittsburgh. James Gayley was a noted iron and steel expert and inventor with an international reputation, working at the Edgar Thomson plant of U. S. Steel. Gayley is credited with many innovations, including the invention of the bronze cooling plates for blast furnace linings, in the 1880s.[1] Other materials were used in attempts to keep the refractory cool in the blast furnace, including cast-iron plates, but eventually copper became the standard material for superior cooling.

Why Copper?

A Little on Conductivity — Pure copper is a very good conductor of both electricity and heat, and most of its applications are based on these properties. If ceramics and other non-metallics could take the heat of the blast furnace, then there would be no need for metallic materials. But they can't, and consequently, metallics are utilized. However, most metals would lose their strength in the 3,000°F blast furnace environment, or become liquid, like the pig iron being produced. That's why



Authors

Trevor Shellhammer (left), metallurgist, Shellhammer Consulting, Lehighton, Pa. (tshellhammer@live.com), and **Rick Walsh** (right), Alabama Copper & Bronze Co. Inc., Birmingham, Ala. (alabamacopper@bellsouth.net)

thermal conductivity is so important. The more perfect that conductivity, the better the service life will be.

The International Annealed Copper Standard (IACS) is used as an electrical conductivity standard for metals, and measures conductivity in % IACS, with pure copper essentially as 100%. It is easy to measure using special eddy current testers. Thermal conductivity is measured in metric units of Watts per meter per kelvin, W/m-K, or U.S. units BTU-ft/hr-ft^2-°F, and is more difficult to determine, especially in the field. Since both properties are based on the movement of free electrons, there is a proportional relationship between them. At a given temperature, the thermal and electrical conductivities of metals can be described by the Wiedemann-Franz Law[2]:

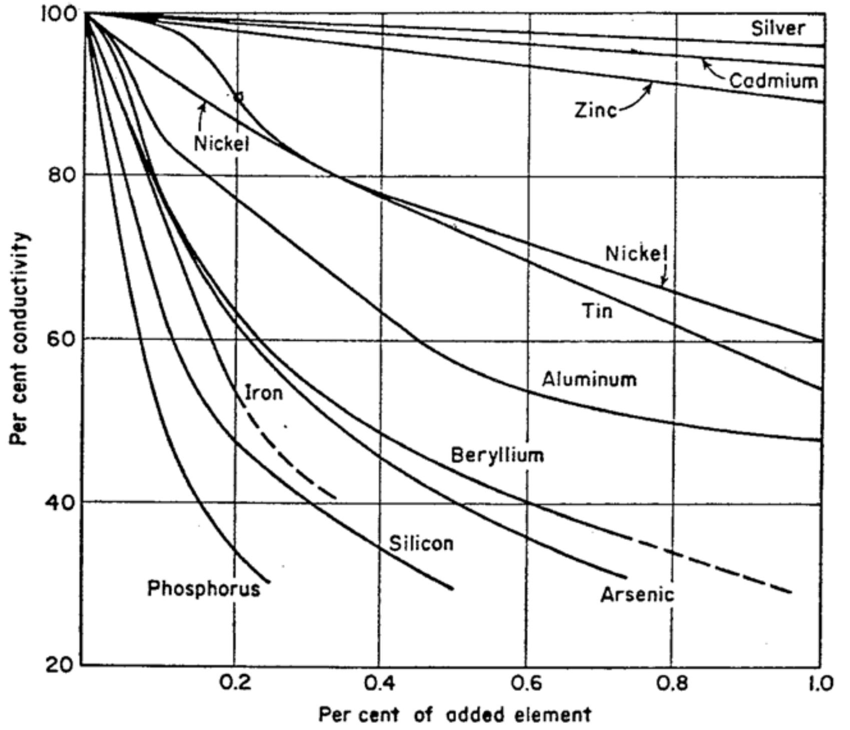
$$\frac{\kappa}{\sigma} = LT \quad or \quad L = \frac{\kappa}{\sigma T}$$

(Eq. 1)

where

κ = thermal conductivity,
σ = electrical conductivity and
L = the Lorenz number, the constant of proportionality.

Figure 1



The effect of alloying elements or impurities on the electrical conductivity of copper.[3]

Since the electrical conductivity is easiest to measure, it is generally used to specify and test the quality of copper. The best way to increase the electrical and thermal conductivity of copper is to decrease the impurity levels. The existence of impurities and all common alloying elements, except for silver, will decrease the electrical and thermal conductivity of copper. As the amount of the second element increases, the electrical and thermal conductivity of the alloy decreases.

As shown in Figure 1, zinc has a very minor effect on the thermal conductivity of copper, followed by increasing effects from nickel, tin, aluminum, and serious effects from iron, silicon and phosphorus. Phosphorus, unfortunately, is often used to deoxidize copper, which can increase the hardness and strength but severely affect the conductivity. This will become important in discussions on foundry practices.

Electrical and thermal conductivity of most metals can vary widely with temperature. It is interesting to note that, while copper is not technically considered a superconductor, its electrical conductivity at cryogenic temperatures can exceed 1,000% IACS.[4] On the opposite end of the temperature range, where we are most concerned, thermal conductivity of metals can vary widely with temperature, decreasing as temperature increases. Fortunately, the thermal conductivity of copper does not vary much with temperature in the range of interest, from ambient temperatures up to the melting point (Figure 2). Therefore, as it is exposed to high temperatures in the blast furnace, not only does it remove heat very efficiently, but its heat transfer does not suffer at elevated temperatures.

A Little on Heat Transfer — Considering that heat transfer can take place by conduction, convection and radiation, we will look mainly at conduction. Conduction will take place if there is a temperature gradient in a solid (or stationary fluid) medium. And energy, or heat, is transferred from more energetic (high temperature) to less energetic (low temperature) molecules when neighboring molecules collide. Fourier's Law expresses conductive heat transfer[5] as:

$$q = k\,A\,dT\,/\,s$$

(Eq. 2)

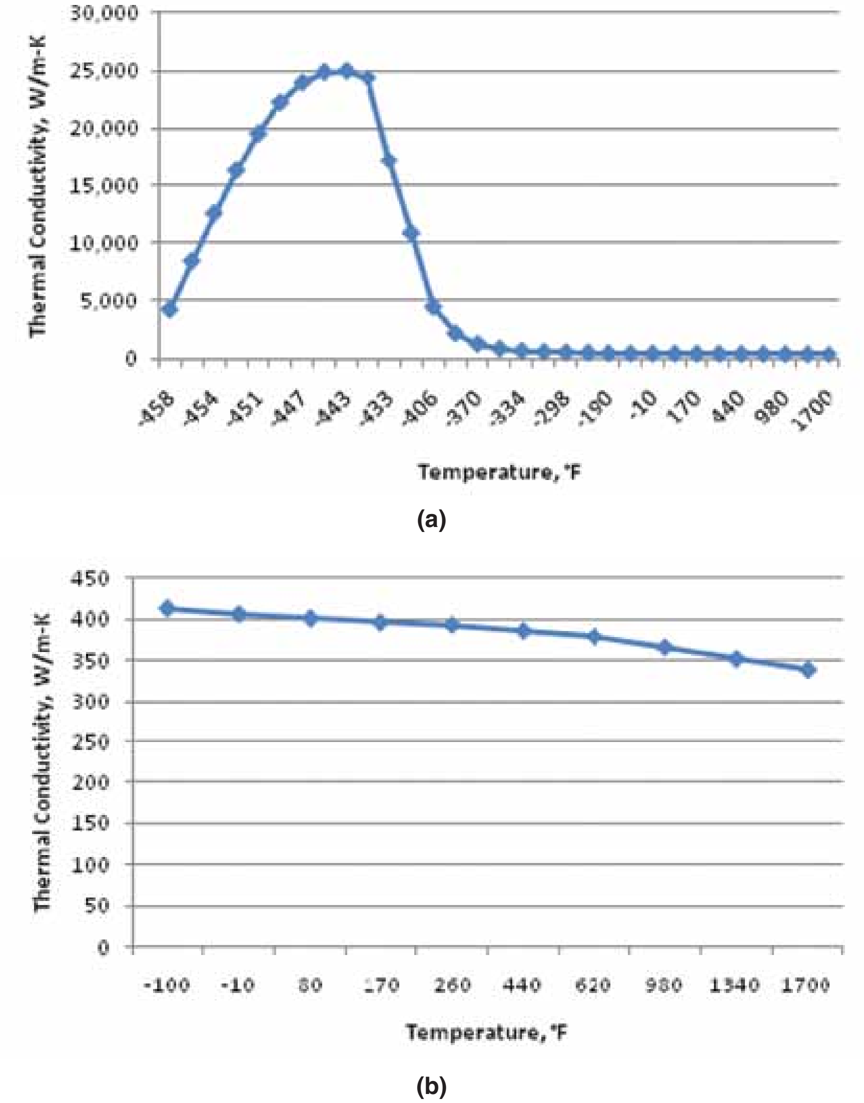
where

q = heat transferred per unit time (W, Btu/hr),
k = thermal conductivity of the material (W/m-K or W/m-°C, Btu/(hr °F ft^2/ft)),
A = heat transfer area (m^2, ft^2),
dT = temperature difference across the material (K or °C, °F) and
s = material thickness (m, ft).

The largest variable in heat transfer, as explained above, is the thermal conductivity of the material. The properties of some common materials show a striking difference in their ability to conduct heat (Table 1). These materials are important in calculating the conduction of heat in a copper casting in the blast furnace.

Based on the properties listed and some simple calculations, Table 2 shows the approximate maximum heat transfer through a system described, analogous to a

Figure 2



Ultrahigh conductivity of copper at low temperatures (a), and stable thermal conductivity of copper at ambient temperature to near melting point (b).

tuyere wall, per square inch of surface, in a 3,000°F furnace environment, with 70°F cooling water.

To further show the drop in thermal conductivity of the different systems, the schematics in Figure 3 show that the loss of thermal conductivity results in less heat transfer through a wall, the result of which is higher surface temperature on the furnace side, with the temperature profile shown by the dark arrow.

In the case of the tuyere with a cast-in copper pipe, even though the pipe is a high-conductivity copper material, the air gap hampers heat transfer, analogous to a thermal-pane window. For the hard-surface weld overlays, a variety of materials are used, mainly with combinations of nickel and/or chrome, for the primary purpose of abrasion resistance. All these weld overlays reduce the conductivity of the system. When further considering the three-dimensional heat transfer, this reduction can result in tremendous lateral thermal differences that can lead to localized hot spots to the point of melting. Some examples will be shown later of the consequences of these arrangements.

Foundry Aspects of Producing High-Conductivity Copper

Prior to the 1980s, it was common to find blast furnace copper alloyed with materials such as tin, zinc and phosphorous for various reasons. The main reasons were for castability, soundness and increased tensile strength.[6–7] Tin made the copper easier to cast, since pure copper has a very short freezing

Table 1

Electrical and Thermal Conductivities of Selected Materials

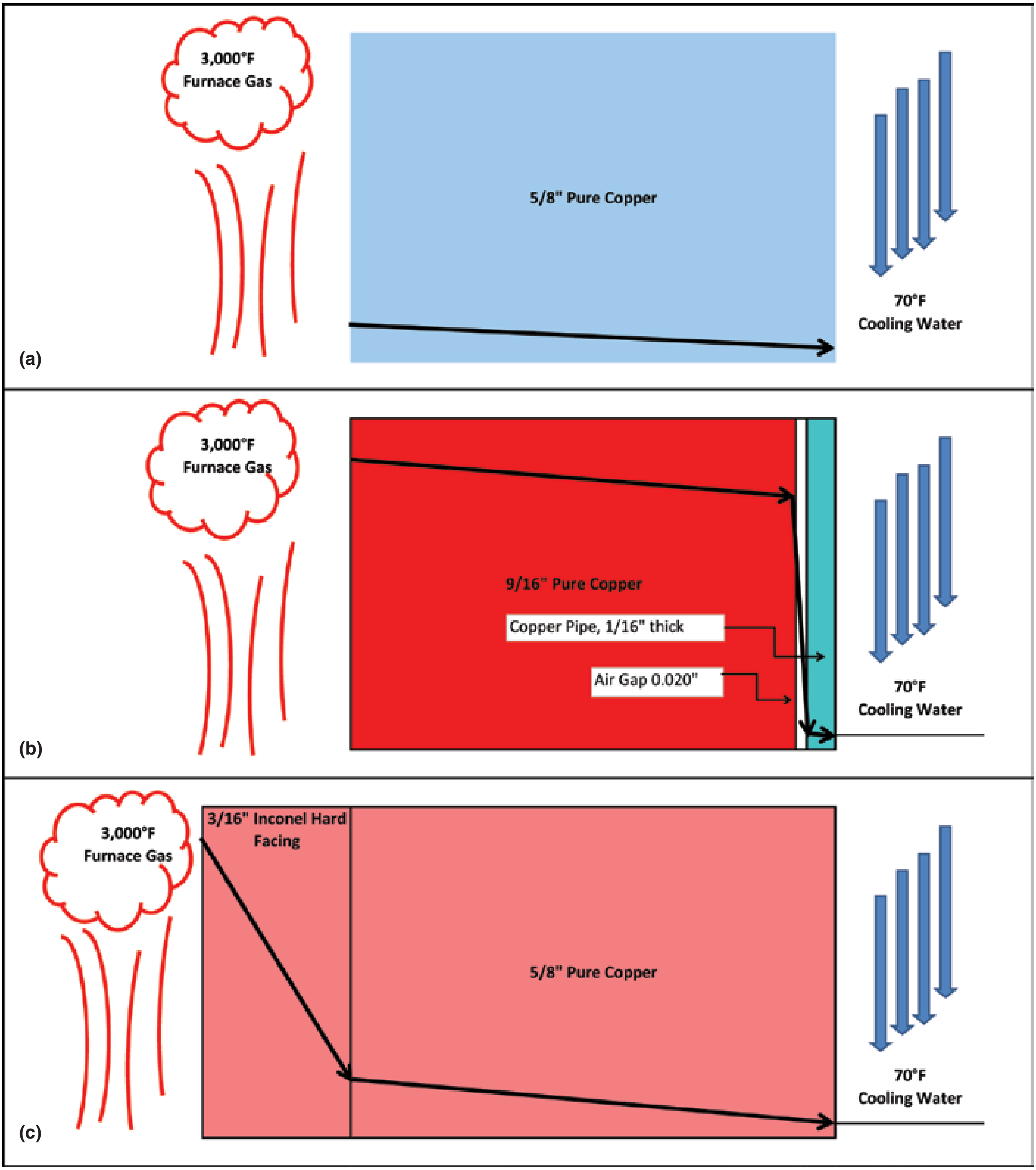
Material	Electrical conductivity %IACS	Thermal conductivity W/m-K
High-conductivity copper	95%	401
"Contaminated" copper	65%	279
Inconel/stainless steel	10%	16
Fire brick	—	1
Air	—	0.025

Table 2

Heat Transfer Through a Hypothetical Tuyere Wall

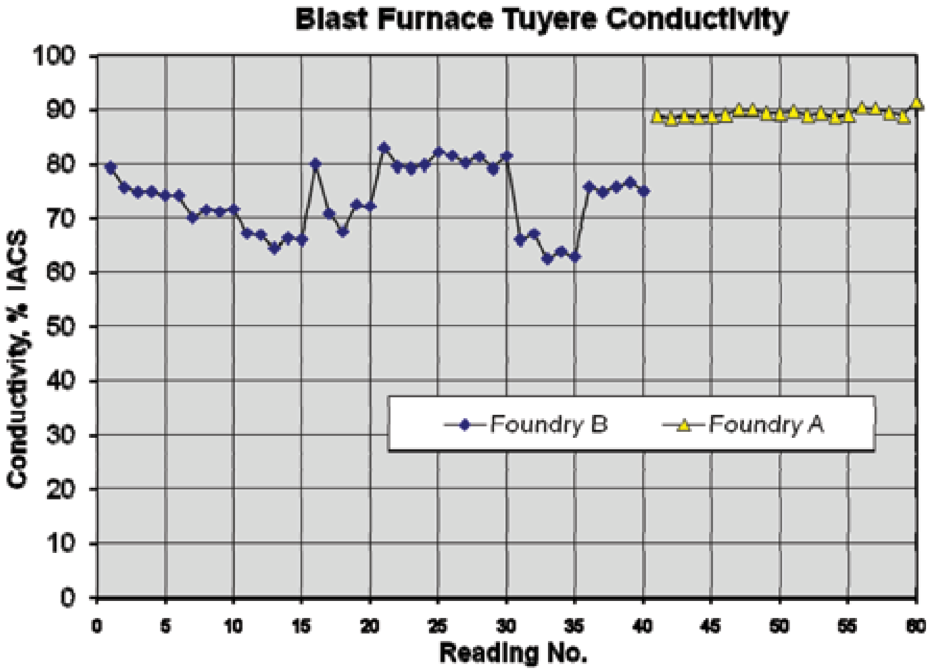
Heat transfer, BTU/hr	Material comprising tuyere wall
95,000	Pure copper, 95% IACS, 5/8 inch thick
68,500	Contaminated copper, 65% IACS, 5/8 inch thick
9,800	3/16-inch Inconel weld, on pure copper, 5/8 inch thick
1,700	Pure copper, 95% IACS, 9/16-inch thick with a 1/16-inch-thick copper pipe cast-in, and an air gap of 0.020 inch (poor bond)

Figure 3



Schematics of thermal profile through a copper wall, with cast-in copper pipe layer (a), with air gap due to poor bonding (b) and with Inconel overlay (c).

Figure 4

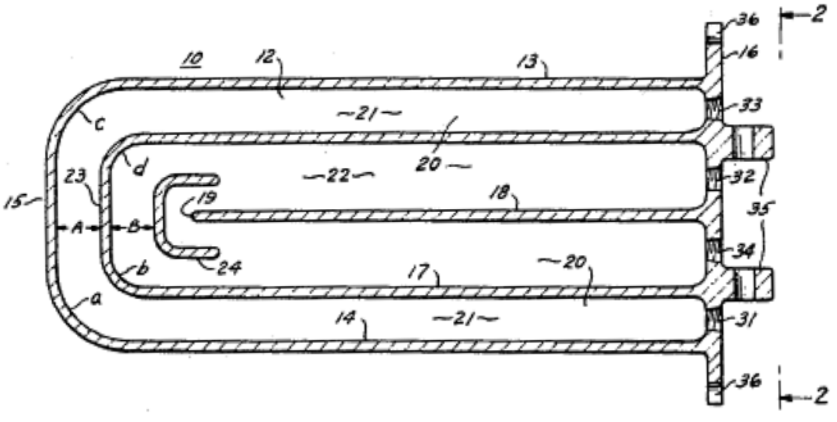


Comparison of actual tuyere conductivities from two different suppliers.[10]

range and can be difficult to feed during solidification, leading to shrinkage. Pure copper is also subject to hot tearing and porosity, which can cause leaks during pressure testing. Tin gave the metal more strength to withstand the stresses during contraction, as the casting cooled around the sand water jacket cores. And phosphorous was added as a phos-copper alloy to deoxidize the melt. Much like in steelmaking, it is best to melt a copper heat under oxidizing conditions, as this keeps the hydrogen to a minimum, and then simply deoxidize. Once in the melt, hydrogen, unlike oxygen, is very difficult to remove, and causes serious porosity. The combination of tin and phosphorus meant it was common to have blast furnace copper with electrical conductivity in the range of 50% IACS. Removing the tin as an alloying agent, and deoxidizing with phos-copper, will yield some improvement in conductivity, but since a phos residual is usually present, conductivities may approach only 75% IACS and can be erratic, depending on an unpredictable residual level.

Sand Binders — Foundry practices have changed over the years, and new sands and binders have been developed which allow foundries to produce high-conductivity copper without the need for tin to strengthen the metal, thereby preventing hot tears. Foundry suppliers worked to develop chemical binders to replace the common oil-based core binders that required baking in ovens. These new binders were called "no-bake," since they hardened without baking through the use of catalysts to cure the binders. For copper castings, sand cores must not be too strong, or hot tears will result, and therefore binders were developed for these special applications with low hot strengths. Testing confirmed that casting high-conductivity copper without hot tears was possible.[8] Today, in making water jacket cores for tuyeres, tuyere coolers and cooling plates, conventional baked cores having core oil binders mixed with sub-angular silica sands have been replaced with no-bake furan or phenolic resin binders and round-grained silica sands. This allows low binder levels, e.g., <1%, which break down to allow the copper to contract during cooling, without cracking. While these practices work well, they add cost to the casting process.

Figure 5



Section of patented stack plate design with improved water flow derived from physical modeling.

Melting and Deoxidation

As stated previously, all alloying elements and impurities reduce copper's conductivity, and therefore there must be closer control over raw materials at the furnace. Certain copper ingot (electrolytic tough pitch, or fire refined), wire bar, or copper wire chops are good charge materials, along with a limited amount of foundry returns (gates and risers). Recycling scrap, from blast furnaces for example, is not acceptable due to potential pickup from bronze or steel pipe fittings, slag and iron burns, and hard-surface weld overlays. Over the years, many studies have been conducted, and some new and/or proprietary materials were developed for deoxidation of the copper melt.[9] Alternatives to phos-copper must be used, such as boron, calcium boride, magnesium and lithium, for example. These are generally more expensive materials, but allow conductivities routinely exceeding 90% IACS to be possible. A 1997 comparison of two domestic foundries producing identical copper tuyeres for a North American blast furnace is shown in Figure 4. Utilizing special high-conductivity copper practices in the foundry, it is now possible to get much more reproducible results at higher levels of conductivity.

Bethlehem Steel's brass foundry, mentioned earlier, switched from producing conventional copper castings to high-conductivity copper in 1976. This required different melting and deoxidation practices, as well as molding and coremaking procedures. While the foundry closed with the shutdown of the hot end of the plant in 1995, the graph in Figure 4 shows that other foundries have similarly improved their procedures and can consistently produce high-conductivity copper castings.

Improving Performance by Modeling

Excellent work has been done over the years to predict, simulate and test the burnout of copper components, mainly tuyeres.[11–13] Predicted optimum water velocity of 15 m/second has been viewed as the standard to reduce copper burn-through. This is fine if the water flow is uniform across the water passage. But more often than not, the water flow is not uniform, and the presence of baffles and sharp corners in the water jacket creates streams of higher velocity, along with eddy currents and backflow and recirculation zones. In the 1970s, Bethlehem Steel performed water modeling using actual castings, with exterior walls machined away and replaced with Plexiglas windows. A bead injection apparatus was built to introduce plastic beads of differing specific gravities into the water stream, to more clearly show water flow. Alterations were made to the internal configuration to improve flow. Figure 5 shows this early modeling work, which led to the patented design for a cooling plate with improved water flow.[14]

For tuyeres, the same model construction was used, albeit slightly more difficult due to the tuyere configuration. In the same manner as the stack plate, poor water flow was easily detected and modifications could be made to the tuyere water jackets to reduce stagnant areas (Figure 6). These stagnant areas contained suspended plastic beads which were "stuck" in place, essentially having a velocity of zero. The heat transfer here being very low can result in the creation of "hot spots." With the advent of computational fluid dynamics (CFD) packages for the computer, the same designs could be investigated and confirmed on a PC. Figure 7 shows an overview of water flow in a tuyere cooler using CFD, and a close-up of the recirculation at the nose.

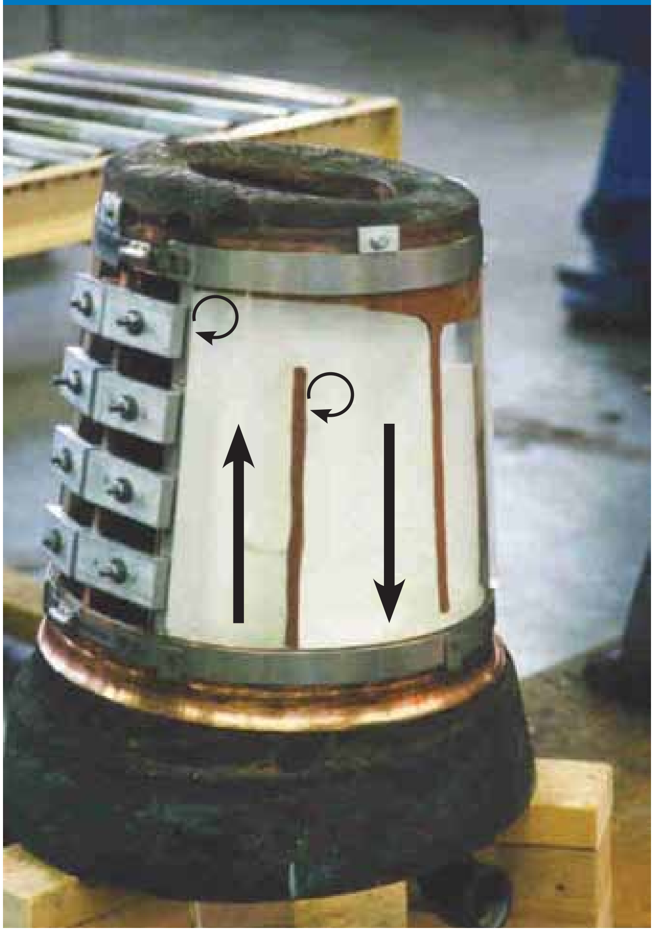
Coatings

Again, much work has been done in the area of coatings for copper blast furnace components. Some of the most recent work was by U. S. Steel Research & Technology Center, in performing hot metal tests on copper samples with and without an array of coatings.[15] Previous work performed at Bethlehem Steel has shown similar results.[16] Several conclusions were made from their work. First, it was very easy to simulate a tuyere burn with hot metal in the lab. The resulting burns appeared very similar to actual failed tuyeres. Second, ceramic coatings of alumina and zirconia were very effective in preventing burns in the lab. In the field, however, they are easily abraded from the casting surfaces, and can even be seriously damaged before getting into the furnace, by normal handling in storage and at tuyere change. Abrasion testing in the lab proves this, and their longevity in the furnace was questioned. To prevent abrasion, weld overlays have been used, and more recently, calorizing. Testing of weld overlays or Inconel coatings has shown mixed results in hot metal resistance testing.

A more compelling case can be made for calorizing, or pack cementation. This is a diffusion treatment that yields a far more durable layer which extends into the copper.[17] It has shown two main benefits. First, it is up to six times harder than bare copper, which means it is more abrasion-resistant in service. Some test results of average microhardness measurements from five locations in both a calorized area and the copper substrate are shown in Table 3. The average is the Vickers hardness numbers, HV, with a 200-gram load.

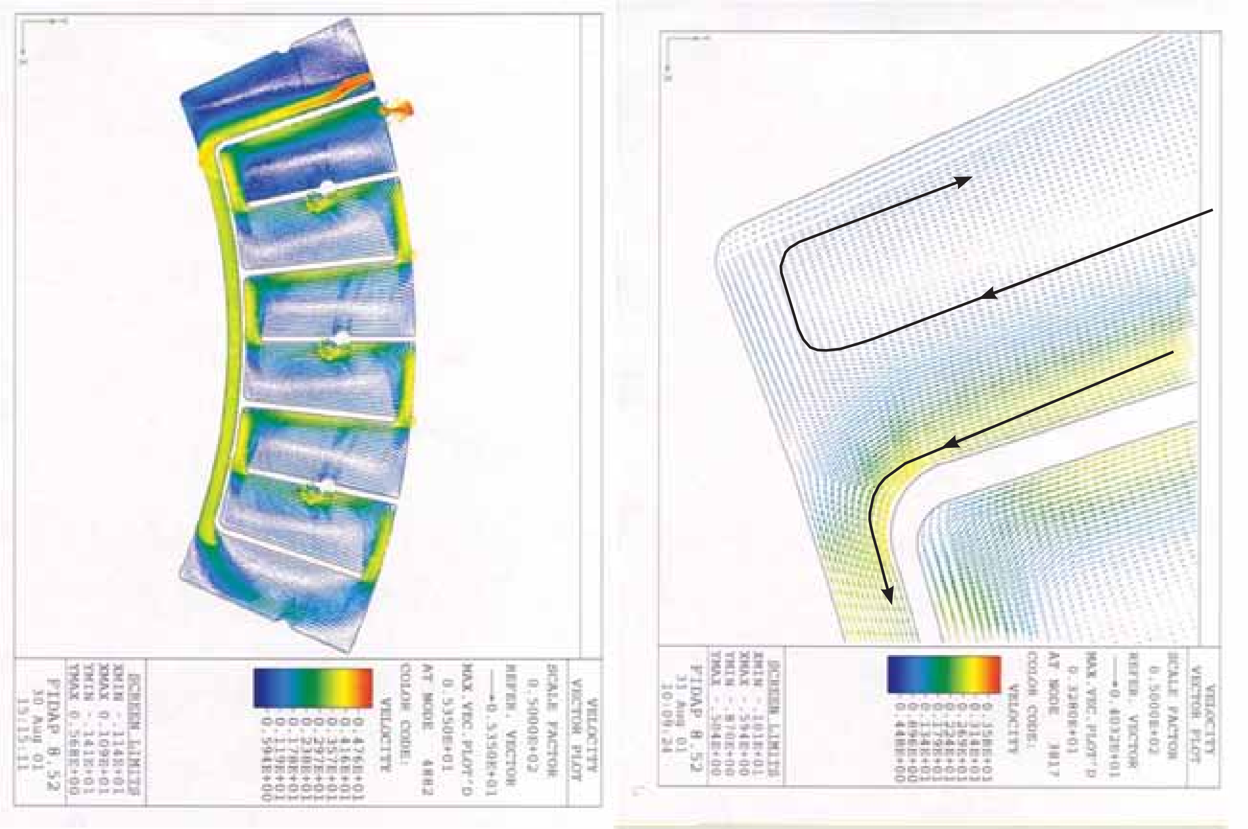
Second, and more importantly, calorized copper is superior to bare copper on exposure to hot metal

Figure 6



Water model of tuyere body, with stagnant zones shown.

Figure 7



CFD lateral development of tuyere cooler with velocity profile (left) and recirculation at nose (right).

splash. Splash testing has shown that it will resist multiple hot metal hits without burn-through. Figure 8 shows samples tested under lab conditions, where bare copper samples easily burned through. Plasma-applied ceramic coatings were able to resist the hot metal, but showed some flaking, and calorized samples were not penetrated.

Examples of Copper Tuyere Failures

This final section will describe some typical tuyere failures and offer, where possible, suggestions for improvement. These are anonymous examples for review and discussion, with no specifics on furnace design or operations. It should be noted that there are many reasons for copper failure due to operational problems and furnace events which cannot be solved by copper quality improvement or design modification. The tuyere shown in Figure 9 had a bullet hole in the body circuit, and had hot tears below it. It burned through along a body baffle, and poor water flow is suspected. While the hot tears did not cause the failure, it would be only a matter of time until they leaked through the wall. This casting was not made of high-conductivity copper.

The two tuyeres shown in Figure 10 were produced by the same foundry from high-conductivity copper. They came from the same blast furnace, in close proximity to each other, and were installed roughly at the same time. The uncalorized tuyere failed after 685 days due to a bullet hole, and also had excessive abrasion to the body, almost through the wall. The calorized tuyere was in the furnace for more than 2 years (774 days) and did not fail, but was pulled to change a leaking tuyere cooler. The abrasion seen on the plain copper tuyere is not present on the calorized tuyere. This is typical of calorized high-conductivity copper tuyere performance in a high-production blast furnace operation.

The two dual-chambered tuyeres shown in Figure 11 are designed with a cast-in copper pipe for the nose passage. In this case, the copper pipe is not metallurgically bonded to the copper casting, and has separated from it in the furnace. In the extreme case on the right, hot metal has eroded the cast copper around the pipe, and the tuyere eventually failed by melting through the body. This tuyere was also welded with a hardfacing alloy, which did not stop the hot metal. These cases highlight the loss of thermal conduction through the water-cooled tuyere, at the gap caused by the pipe-casting interface (like a thermal-pane window). To improve this tuyere performance, it is possible to investigate methods to have a better bond at this interface, or simply cast the tuyere without a pipe. Using a sand core for

Table 3

Vickers Hardness Measurements in Calorized Copper and Plain Copper

	Calorized layer	Copper substrate
Average HV	253.7	40.0
Std. dev.	43.1	4.4

Figure 8

Results of splash testing. Samples 1 and 3 = bare copper; sample 5 = ceramic coated copper; samples 2, 4 and 6 = calorized copper.

Figure 9

Typical tuyere failure, with tuyere cleaned and etched to reveal defects and grain structure.

Figure 10

Failed tuyere (left) made of bare copper, and a used tuyere (right) that was calorized.

Figure 11

Two tuyeres from different operations, both dual-chamber style with a cast-in copper pipe.

the nose pass would eliminate the need for a pipe and establish thermal continuity. In addition, these tuyeres were not considered high-conductivity copper, and the thermal conductivity was not optimized.

The two dual-chambered tuyeres in Figure 12 both failed through the hard-surface welds applied to prevent abrasive wear. The coatings are different: on the left is a chrome-based material and on the right, a nickel-based alloy, but they both failed. In both cases, the hard-surface area is peppered with hits of hot metal. Also, it should be noted that the casting on the right is a two-piece welded tuyere, designed with a high-velocity nose section that extends farther back on the tuyere body than a standard dual-chambered tuyere. A second burn is evident on the body, actually in the welded joint area. The welds on most tuyeres of this type are very low conductivity, in the range of 25–30% IACS. This is due to the filler rod used to ensure a good weld. This highlights the caveat of using a hardfacing material, as well as a welded construction — both procedures that will reduce overall thermal conductivity of the tuyere "system."

Conclusions

An attempt was made in this paper to present some basic facts surrounding the use of high-conductivity copper for blast furnace cooling castings that any operator should understand. These areas include the theory of thermal (and electrical) conductivity, and the deleterious effect of impurity elements in copper. It was also our purpose to explain how foundry practices have evolved to allow the foundryman to make these castings successfully, without leaking or defects, to ensure long life in the furnace. Finally, methods to improve copper tuyere life were discussed, along with a review of coating practices. The comparison of a calorizing treatment and traditional hard-surface overlays was made.

Extending the life of copper components has never been easy, and in recent times, the common fluctuating operations may have more of an impact on their performance than in past periods of steady, high production. Whatever the level of the iron producing operation, some common sense, good engineering principles, competent foundry operations, and quality, high-conductivity copper castings should ensure optimum performance.

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Figure 12

Two tuyeres that failed through the hard-surface welds: (a) sandblasted and (b) as removed.

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