Electric Arc Furnace Explosions: A Deadly but Preventable Problem

Hazards are ever-present in the steel plant environment, and a heightened awareness and emphasis on safety is a necessary priority for our industry. This monthly column, coordinated by members of the AIST Safety & Health Technology Committee, focuses on procedures and practices to promote a safe working environment for everyone.

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Over the past 30 to 40 years, electric arc furnaces (EAFs) used in steelmaking and other processes have been running longer, harder and faster as facilities make it a priority to ramp up production. In addition to more demanding operating schedules, many furnaces have been equipped with larger electrodes, oxygen lances, or secondary chemical energy sources to generate more power and boost furnace ratings. As EAFs are increasingly pushed and stretched to the limits, the goal of ensuring safe and reliable operation has never been more challenging.

During this period of escalating production demands, EAF furnace accidents have unfortunately been widespread and do not seem to be abating. Table 1 includes a sample listing of serious EAF accidents caused by steam explosions during the past two decades. The following sections will highlight a few examples of the most highly publicized incidents, listed chronologically:

Tamco Steel Inc., Rancho Cucamonga, Calif., USA, March 2004 — A safety technician and three coworkers were attempting to stop a water leak on an EAF used to convert scrap metal into new reinforcing bars for construction. The furnace exploded and emitted hot steam and flying debris, blowing out the front observation glass and the back window of the control room. The technician suffered severe burns and required surgery and hospitalization.

ArcelorMittal Plate (formerly called ISG Plate), Coatesville, Pa., USA, May 2007 — Three steelworkers were working adjacent to a 165-ton rated EAF when, according to the U.S. Occupational Safety and Health Administration (OSHA) report, it is believed that a stray electrical arc created a significant internal water leak on one of the water-cooled shell panels. The pressurized leak accumulated within the furnace and when the temperature of the molten steel was finally up to pouring temperature (approximately 3,000°F), the employees found that the furnace's taphole was blocked. When they succeeded in unblocking the taphole, the EAF violently erupted. One worker was killed and two others injured as a result.

Despite measures to improve safety following this accident, another very similar incident occurred in Coatesville in May 2013. Three workers were injured, two critically, when water again leaked into an EAF, leading to an explosion.

Carbide Industries, Louisville, Ky., USA, March 2011 — Two employees were killed and two others injured by a steam explosion. According to the Chemical Safety Board (CSB), "The deaths and injuries likely resulted when water leaked into the electric arc furnace causing an overpressure event, ejecting furnace contents heated to approximately 3800°F." The CSB reported that the explosion occurred after the company failed to investigate similar but smaller explosive incidents over many years, while deferring crucial maintenance of the EAF. In February 2013, as part of its final investigation report on the incident, the CSB cited the need for a standard mechanical integrity program for electric arc furnaces that would include preventive maintenance based on periodic inspections and timely replacement of furnace covers.

Comments are welcome. If you have questions about this topic or other safety issues, please contact safetyfirst@aist.org. Please include your full name, company name, mailing address and email in all correspondence.

Gerdau Long Steel North America, Knoxville, Tenn., USA, May 2014 — One steelworker was killed and five others injured by a hydrogen explosion that occurred when a leak caused more than 1,000 gallons of water to pour into a 2,900°F electric arc furnace, tossing out "fragments of molten metal and debris," according to a report by the Tennessee Occupational Safety and Health Administration (TOSHA). Workplace procedures call for employees to shut off the water and evacuate the area when there is a leak. But on the day of the accident, employees did not leave the area and a pump directed 200 gallons of water per minute into the furnace for at least seven minutes before it was shut off.

The examples described above and the additional incidents listed in Table 1 comprise many of the more serious incidents. Smaller explosions or "near misses" sometimes occur in which there may be no injuries, yet there will invariably be property damage, sometimes extensive. These lesser incidents are often not reported to the media or to regulatory agencies, but they may nonetheless be costly and disruptive to facility operations as well as pose a serious threat to safety.

EAFs are used in a wide range of other extreme heat load applications in iron and steel foundry works, in addition to steelmaking industries that produce steel from iron and ferrous ores and steel scrap; non-ferrous industries (including aluminum, bronze, brass, copper, zinc titanium, tin and lead); mining/ore smelting; carbide and other specialty chemical manufacturing; and powdered metallurgy.

A number of U.S. agencies are concerned with the issue of EAF explosions, among them OSHA, the National Fire Protection Association (NFPA), the CSB, and industry groups such as the Association for Iron & Steel Technology (AIST) and the American Foundry Society. In 2013, when the CSB published its final report on the Carbide Industries investigation, they called for development of a standard that "will provide guidance for industry on the safe handling of hazardous processes that may not otherwise be regulated by other safety regulations, such as OSHA's Process Safety Management (PSM) Program." However, at the time of this writing no industry or

Table 1

Partial List of Accidents

Year	Country	Facility	Injuries	Description
1994	Germany	Steel mill	7 injured	EAF explosion caused by water leak from sidewall cooling system
1995	Germany	Steel mill	1 killed, 1 seriously injured	EAF explosion caused by water leak in cooling system
2003	U.S.	Steel mill	2 seriously injured	Half-ton EAF explosion caused severe burns
2004	U.S.	Construction products manufacturing	1 hospitalized injury	Explosion occurred as technician was trying to stop EAF water leak
2004	U.S.	Smelting plant	1 killed	Worker burned by 3,000°F steam when EAF exploded
2007	U.S.	Steel mill	1 killed, 2 injured	Stray electrical arc created an internal leak on a water-cooled shell panel
2008	Germany	Steel mill	None	Water leak in the EAF caused six-figure damage but no injuries
2010	U.S.	Steel mill	1 killed, 4 injured	Leak in EAF caused water to mix with molten slag
2011	U.S.	Steel pipe manufacturing	1 killed, 2 injured	Workers exposed to 2,000°F molten metal and steam in EAF explosion
2011	U.S.	Carbide manufacturing	2 killed, 2 injured	Workers exposed to 2,000°F molten metal and steam in EAF explosion
2011	Australia	Steel mill	4 injured, 1 seriously	Water accidentally entered EAF as workers were removing partly melted scrap
2012	Canada	Steel mill	1 injured	Injury occurred from a small steam explosion in the meltshop EAF
2012	U.S.	Steel mill	2 injured	EAF steam explosion injured two workers
2013	U.S.	Steel mill	1 killed	EAF explosion fatally injured one worker
2013	U.S.	Steel mill	3 injured, 2 critically	Water leak into 3,000°F EAF caused severe explosion
2013	Mexico	Steel mill	4 killed, 10 injured	Explosion occurred during routine maintenance at DRI intake of EAF
2014	U.S.	Steel mill	2 killed, 17 injured	Deaths and injuries resulted from violent EAF explosion
2014	U.S.	Steel mill	1 killed, 5 injured	Leak caused 1,000 gallons of water to pour into EAF, creating a hydrogen explosion
2014	U.S.	Steel mill	1 killed	Pipe exploded in a BOP furnace, fatally injuring one worker

regulatory group is spearheading a safety program or standard targeted at the specific problem of EAF explosions.

How EAF Steam Explosions Occur

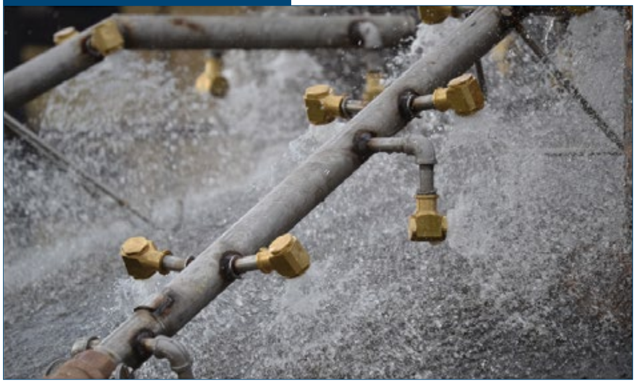
In the fatal accidents described earlier, and in many others documented as well, there is a common denominator: Water leaks into a hot furnace in large enough quantities to become superheated and trigger a violent steam explosion. To understand how this occurs, it is first necessary to look at how EAF cooling technology has developed over time.

Older-style EAFs used refractory brick liners to help the furnace withstand the extremely high operating temperatures within. Though the bricks did not melt, they tended to break apart as furnaces began operating at higher capacities with much higher temperatures and pressures, and with the added use of supplemental chemical energy.

The solution was to protect EAF roofs and other components with a system of tubular panels with high-pressure water pumped through them to provide cooling. Most of the tubular systems used to cool EAF upper shells and roofs consist of an external support structure or "spider" that doubles as the cooling water supply and return headers, with an arrangement of multiple tube panels hung on the inside of the spider. Although pressurized water is an effective coolant, it becomes problematic when leaks crop up — a fairly regular occurrence in highly stressed furnaces.

Most leaks begin as small cracks caused by thermal fatigue, which is inherent to the heavily welded construction required to build these panels. Alternatively, leaks are sometimes caused when an errant arc strike or mechanical puncture during operation creates holes, in which event water at very high pressure and possibly high volumes may enter the furnace even more rapidly.

Figure 1



Spray bars in a non-pressurized spray cooling system.

Water pouring into a furnace will not in itself generate an explosion if it sits on top of the molten bath of steel and boils off. The problem occurs when the furnace rocks or tilts for pouring out steel or impurities. This action can cause the sloshing molten metal to encapsulate the water, immediately converting it into steam. It then expands to more than 1,700 times its original volume, generating a violent explosion that can blow the roof off a furnace and send steam, molten steel and debris flying hundreds of feet and placing people and equipment at risk.

The primary approach for avoiding explosions with tubular systems has been to install an electronic monitoring system to measure the water content of the offgas and detect irregularities.

Non-Pressurized Cooling — A Safer Alternative

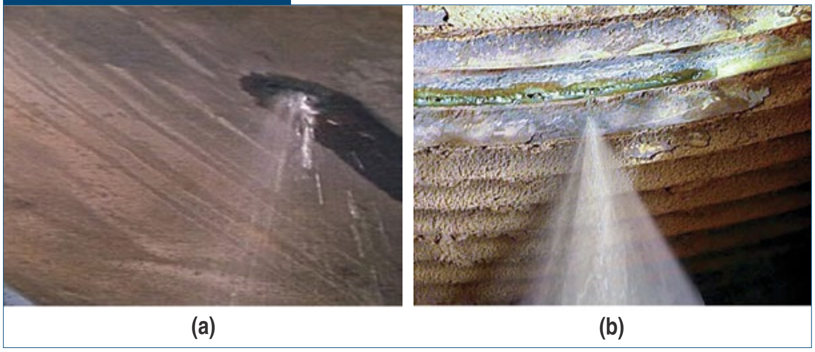
In the early 1980s, the introduction of a new non-pressurized cooling technology offered a safer, more maintenance-friendly alternative to pressurized tubular water cooling. The first commercial EAF roof using this technology, known by the trade name of Spray-Cooled™, was installed at Timken Steel in Canton, Ohio, USA, in 1986 and is still in service today. The general configuration of equipment used in spray cooling is a double-walled design that includes a replaceable inner carbon steel hot face, an outer structural carbon steel dust cover, and an inner stainless steel and brass spray system in the annulus space that sprays water on the backside of the hot face.

The spray system is an arrangement of non-corrosive piping and spray nozzles, which are removable using detachable spray bars that connect to a water supply header with cam locks (Fig. 1). A single inlet feeds the header. The entire piping network is attached to the outer shell so that the hot plate may be replaced without affecting the spray system. Cooling capacity can be readily changed by adjusting the amount of water distributed in a particular area of the equipment.

With a non-pressurized system, it is droplet impingement produced by the spray nozzles rather than water velocity that provides the turbulence required for optimal heat transfer. Liquid droplet spray and jet impingement cooling have been widely used in the metal-making industry and have been proven capable of high heat removal rates. Cooling water is distributed according to the varying heat load demands identified: cool spots = less water, hot spots = more water. Cooling water is supplied at the same supply inlet temperature to every square inch of the hot plate throughout the equipment. All of the available water is thereby used efficiently and effectively.

With non-pressurized spray cooling, equipment operates at a roughly 30 psi cooling water supply pressure at the nozzle heads; however, when the water

Figure 2



Leak in a non-pressurized spray cooling system (a) vs. leak in a pressurized tubular system (b) (5 gallons/hour vs. 16,000 gallons/hour).

leaves the spray system it is at atmospheric pressure, as compared to typically 60 psi for pressurized tubular equipment. The significance is that, in the event of a crack or leak, spray cooling will not force high volumes of water into the furnace as a pressurized tubular system does. For a comparable cooling supply flowrate, tubular equipment will introduce more than 3,000 times more water into a furnace than a spray cooling system.

For example, a 2-square-inch hole in a tubular panel operating at 60 psi will force approximately 16,000 gallons per hour into the furnace. By comparison, the same 2-square-inch hole in the spray cooling practice will introduce less than 5 gallons into the furnace in the same hour. In minimizing the chance of excess water entering the furnace, non-pressurized spray cooling addresses the root cause of EAF accidents in a proactive and preventive manner (Fig. 2).

Explosion prevention is not the only safety benefit of non-pressurized cooling. Another key advantage is the ability to make repairs from outside the equipment. When a crack or leak in a tubular panel needs to be repaired, the maintenance crew is typically required to suppress the heat within the furnace, put down insulating boards, and enter the furnace in thermal suits to attempt the repair.

With spray cooling, this scenario is eliminated — the thin-walled plate construction of the hot plate utilizes minimal welds (unlike the heavily welded tubular panels), rounded or chamfered corners, and mechanical forming that make equipment less susceptible to stress fatigue cracking. If small holes or cracks appear, they can be temporarily patched or welded from the outside with no need for furnace downtime. Permanent repairs to the hot plate can be postponed until the end of a production cycle or when downtime is scheduled for maintenance on other equipment to minimize unscheduled downtime.

Reduced Operating Costs, Greater Longevity

Furnace roof life varies greatly depending on operating conditions. The life of the cooling system and basic structure is virtually indefinite. The hot face of a roof (or any piece of equipment) is a wear item, so with spray cooling the equipment is designed to be rebuilt with only the hot face being periodically replaced — a key advantage over pressurized tubular equipment, which must be completely discarded and replaced when it is worn out. Typically a customer can save 65–85% by rebuilding versus replacing as would be required with tubular. The ability to repeatedly rebuild equipment at a fraction of the cost of replacement, coupled with the decreased downtime, typically makes return on investment extremely attractive and the payback period very short — usually 1 year and sometimes as little as 6 months.

The life of the hot face is directly related to the application. For example, a southern U.S. steel mill using spray cooling on two 165-ton, 170-MVA furnaces reported using the roofs continuously for more than 10,000 heats over roughly 16 months with no downtime and virtually no maintenance required. An off-furnace duct using spray cooling in the same meltshop is still in continuous operation after more than 50,000 heats and 8+ million tons without any associated downtime or appreciable maintenance. Other world-class ultrahigh-power (UHP) furnace operators have routinely experienced well over 5,000 heats on their EAF roofs before requiring a rebuild. Equipment life spans of 10–15 years are quite normal, though some roofs have been in service for more than 26 years.

By contrast, a tubular EAF roof might typically last 1–2 years, though the life span can be even shorter in severe applications. With some designs, it is possible just to replace the inner panels when they wear out

Figure 3

Typical spray cooling roof.

(generally in 6–12 months), and the spider or superstructure at less frequent intervals, but even in these cases 5 years is about the maximum life expectancy.

One example of non-pressurized spray cooling resulting in cost savings for a mill involves a major steel mill that was experiencing very short service life with pressurized tubular ducts due to increased oxygen usage and production. Duct life was averaging only 2–3 months, with some new ducts lasting as little as 6 weeks. This resulted in average production downtime of 40 hours per month per furnace and average monthly maintenance of 64 man-hours per month. The mill replaced the pressurized tubular duct sections (D1/D2 section = 10 feet 0 inches x 7 feet 9 inches inside diameter (ID), D3 section = 10 feet 8 inches x 8 feet 5 inches ID) with ducts utilizing non-pressurized spray cooling. The mill has found that the non-pressurized ducts are lasting over 4 times longer and can be rebuilt and placed back in service at a fraction of the cost of new tubular ducts. They estimate that the payback on this project was less than 6 months considering reduced downtime and maintenance costs. They have reported that their duct maintenance costs decreased from US$0.25 per ton to US$0.05 per ton after converting to spray cooling, for an annual savings of US$440,000 per year, totaling US$1,320,000 over a 3-year period (Table 2).

Market Update

Since its inception in the 1980s, the acceptance of spray cooling has grown, and this equipment can now be found in new and retrofit applications on furnaces worldwide across six continents. The technology has expanded to include basically every type of water-cooled equipment in a meltshop, such as upper EAF sidewalls, EAF roofs, fourth-hole elbows, offgas ducts, dropout chambers, Consteel® pre-heater and connecting car hoods, spray chambers, basic oxygen furnace (BOF) hoods and ductwork, argon oxygen decarburization (AOD) hoods, and ladle metallurgy furnace (LMF) roofs and hoods.

Non-pressurized spray cooling is being used successfully by some of the most recognized steelmakers in the world, including Nucor Corp., Severstal, ArcelorMittal, AK Steel Corp., Gerdau, Timken, United States Steel Corporation, Daido, Daehan Steel, Hyundai Steel, BHP (OneSteel, Smorgen), Steel Dynamics Inc., ProfilARBED, Acerinox, Badisch Stahlwerke (BSW) and many others. In the smelting industry, roofs and offgas duct installations have been in continuous operation since the 1990s at Namakwa Sands, ISCOR Vaal Works, ISCOR Kumba, Richards Bay Minerals and ISCOR Heavy Metals.

Though tubular systems still dominate the market, many industry experts regard non-pressurized spray cooling to be the best available technology today. David Kobernuss, an independent

Figure 4

Spray-cooled furnace and duct.

Table 2

Cost-Saving Example: Duct Replacement Economic Analysis

	Pressurized/tubular duct sections	Non-pressurized ducts with spray cooling
Average production downtime due to water leaks	40 hours/month per furnace	0 hours/month per furnace
Average maintenance labor	64 man-hours/month	2 man-hours/month
Duct replacement/relining cost	US$1,650,000 (3-year period)	US$330,000 (3-year period)
Cost per ton of steel produced (2.2 million tons/year)	US$0.25 per ton	US$0.05 per ton
Total savings		US$440,000/year x 3 years = US$1,320,00

Notes:
Duct dimensions, D1/D2 section: 10 feet 0 inches x 7 feet 9 inches inside diameter (ID)
Duct dimensions, D3 section: 10 feet 8 inches x 8 feet 5 inches ID
Non-pressurized spray cooling, first campaign: 9,350 heats
Non-pressurized spray cooling, second campaign: 9,410 heats

consultant who has served as an expert witness in accident investigations, states: "The better and safer state-of-the-art equipment is to use a low-pressure water spray that cools the shell walls from the outside. Any errant electric arc that would hit the wall, that results in a crack in the wall, will only cause a 'dribble' of water to enter the furnace. This low volume will be easily evaporated by the hot furnace atmosphere. Also, any crack can be easily repaired from outside the furnace with little associated downtime."

As recognition grows for the safety advantages of non-pressurized cooling, several of the facilities that have experienced explosions in the past are working toward solutions that utilize spray cooling.

Safety Strategies

A review of reports on EAF explosions reveals that a variety of conditions have led to OSHA fines and/or litigation from injured employees or their families in incidents like the ones reported earlier. Among these are:

- Failure to have a supervisor on the shift at the time of the explosion.
- Lack of a monitoring system in the furnace to detect accumulation of water or explosive gases.
- Failure to properly maintain the furnace.
- Failure to require furnace operators to wear aluminized jackets or other protective gear.
- Failure to investigate similar but smaller explosive incidents where there were no injuries.
- Failure to apply best available technology to safeguard employees.

Even the safest equipment does not preclude the need for an overall preventive safety program that includes, among other things, ongoing monitoring, vigilance and common sense. Here are some general recommendations for optimizing safety in any facility:

- Periodic visual inspections during routine walkdowns should be performed to look for cracks, holes, or indications of water buildup on the furnace roof or other surfaces.
- Small holes or cracks should be patched or welded immediately to prevent them from growing larger.
- Check gravity drains regularly to make sure they are functioning properly.
- Use metallized jackets or other safety apparel to protect workers from harmful burns.

In conclusion, the use of safer operating technologies such as non-pressurized spray cooling offers a win-win proposition. It helps to keep workers out of harm's way while reducing the potential for property damage, costly fines and litigation. As an added benefit, such technologies can increase furnace uptime and reduce operating costs for improved production yields and greater profitability.

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