Technical Paper:

Electric Arc Furnace (EAF) Explosions: A Deadly but Preventable Problem

By Scott Ferguson and Nick Zsamboky, Systems Spray-Cooled™

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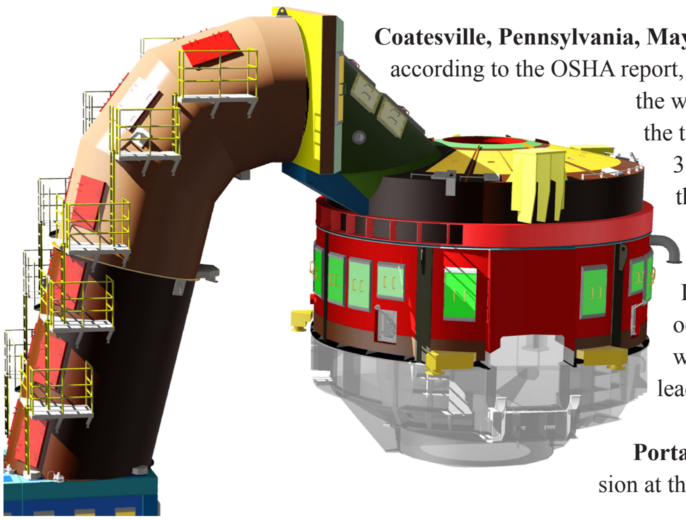
Over the past 30-40 years, electric arc furnaces (EAFs) used in steelmaking and other processes have been running longer, harder and faster as facilities make it a priority to ramp up production. In addition to more demanding operating schedules, many furnaces have been equipped with larger electrodes, oxygen lances or secondary chemical energy sources to generate more power and boost furnace ratings. The fact is, regardless of furnace age, most of today's EAF operations tend to run hotter, have shorter tap to tap times and produce more heats (batches of molten steel) per day than ever before. 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. To cite a few examples of the most highly publicized incidents, listed chronologically:

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 prod.	1 hospitalized injury	Explosion occurred as technician was trying to stop EAF water leak
2004	U.S.	Smelting plant	1 killed	Worker burned by 3000 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
2010	U.S.	Steel pipe mfg	1 killed, 2 injured	Workers exposed to 2000 F molten metal and steam in EAF explosion
2011	U.S.	Carbide mfg	2 killed, 2 injured	Water leak in EAF caused over-pressure event ejecting 3800 F furnace contents
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 melt shop 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 3000 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 1000 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
2016	U.S.	Steel mill	2 injured	Reaction in a 175-ton EAF triggered an explosion: Cause is under investigation.

Rancho Cucamonga, California, 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.



Coatesville, Pennsylvania, May 2007: Three steelworkers were working adjacent to a 165-ton rated EAF when, according to the 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 degrees F), the employees found that the furnace's tap hole was blocked. When they succeeded in unblocking the tap hole, 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 a 3,000 degree F electric arc furnace containing molten steel, leading to an explosion.

Portage, Indiana, January 2010: One person was killed and four others injured in an explosion at this northwest Indiana steel mill, officials said. It was the second at the Portage facility since the previous November, when eight workers were injured. Water mixing with molten slag in one of the mill's furnaces caused the explosion, Portage Mayor Olga Velazquez said. Four workers, who were investigating a water leak in the electric arc furnace when the explosion occurred, were taken to nearby hospitals.

Louisville, Kentucky, 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 over-pressure event, ejecting furnace contents heated to approximately 3800 degrees F." The CSB reports 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.

Knoxville, Tennessee, May 2014: One steelworker was killed and five others injured by a hydrogen explosion occurring when a leak caused more than 1,000 gallons of water to pour into a 2,900 degree 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 as a pump directed 200 gallons of water per minute into the furnace for at least seven minutes before it was shut off.

While the reporting articles used different terminology for the causes of the above incidents, they were all a result of water being introduced into the molten steel inside the furnace and causing an explosion. These few examples described above and the many additional incidents listed in Table 1 comprise many of the more serious incidents. However, it is believed that these represent just the tip of the iceberg. 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 posing a serious threat to safety. The authors of this paper have been often called in following these "lesser" incidents and have witnessed serious property damage even when no injuries occurred.

Getting an accurate handle on the frequency of EAF explosions is made more difficult by the diverse applications for these furnaces. Though they are typically associated with steelmaking, EAFs are actually used by a variety of industries; and while the degree of risk varies with the application, there is always the potential for explosions to occur – as seen with the fatal Louisville accident, which occurred in a furnace used in the production of calcium carbide.

EAFs are used in a wide range of other extreme heat load applications in iron and steel foundry works, in addition to steelmaking industries which 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. When you consider that there are estimated to be thousands of EAFs in use on a global basis across these industries, the potential for disaster becomes very evident.

A number of U.S. agencies are concerned with the issue of EAF explosions – among them the Occupational Health & Safety Administration (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 Louisville 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 this time no industry or regulatory group is spearheading a safety program or standard targeted at the specific problem of electric arc furnace explosions.

Spray bars in a non-pressurized spray cooling system

HOW EAF STEAM EXPLOSIONS OCCUR

In the fatal accidents described above, 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. Although refractory-lined furnace roofs are still used in some applications such as copper smelting, where the arc is submerged beneath the molten level of the metal, they are no longer sustainable for modern iron and steelmaking processes.

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. Multiple supply and drain hoses and flow control valves are required from the headers to the individual tubular panels. The individual panels are typically made from either carbon steel, copper or aluminum bronze material and utilize multiple pieces of heavily welded pipe and welded return elbows. 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. When the furnace is in heating mode, the steel is expanded and compressed enough that the crack doesn't open up, so only a small amount of cooling water can enter the furnace. But when the surface cools down and the steel contracts between heats, the crack opens up and the highly pressurized system literally forces cooling water to infiltrate and basically flood the furnace with water. 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.

A pressurized tubular cooling system typically operates at 60 psi water pressure, which is enough pressure to allow water buildup to occur very quickly. A two-square-inch hole in a tubular panel results in more than 16,000 gallons of water spilled into the furnace in just one hour, an amount equal to the water in a typical backyard swimming pool.

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 usually occurs during normal steel-making operation when the furnace tilts or rocks to tap and slag either to pour 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 over 1700 times its original volume, which happens very rapidly -- 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 off-gas and detect irregularities. While such a monitoring system is an important part of any overall safety program, depending solely on this approach is rather like sticking one's finger in the dike to avert catastrophe. It is a reactive rather than proactive response that fails to prevent the root cause of the problem: too much water in the furnace.

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 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.

Leak in a non-pressurized spray cooling system (left) vs. leak in a pressurized tubular system (5 gal/hr vs. 16,000 gal/hr)

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. 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. This is determined by the size and quantity of the nozzles used.

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. Very effective heat transfer can thereby be obtained at virtually any flow rate. 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 most efficiently and effectively.

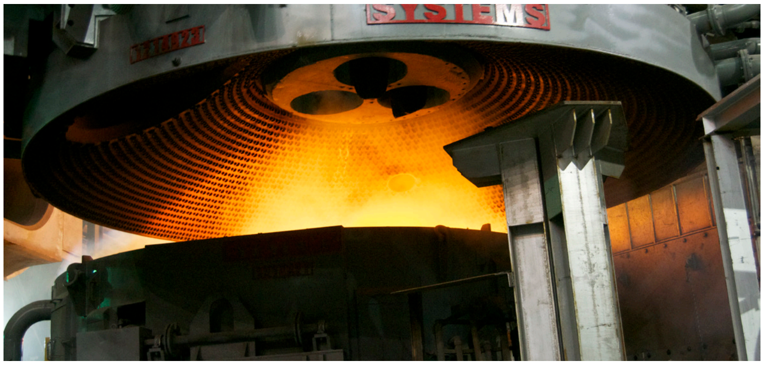
With non-pressurized spray cooling, equipment operates at a roughly 30 psi cooling water supply pressure at the nozzle heads; however, when the water leaves the spray system it is at atmospheric pressure, as compared to typically 60 psi for pressurized tubular equipment. The significance is that, in 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 flow rate, tubular equipment will introduce over 3,000 times more water into a furnace than a spray cooling system.

For example, a two 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 two square-inch hole in the spray cooling practice will introduce less than five gallons into the furnace in the same hour. Looking at it during a one-minute time span, the tubular panel will force 266 gallons per minute into the furnace whereas spray cooling will introduce less than eleven ounces per minute. This greatly reduces the risk of dangerous and possibly deadly steam explosions. In minimizing the chance of excess water entering the furnace, it thereby addresses the root cause of EAF accidents in a proactive and preventive manner.

Explosion prevention is not the only safety benefit of non-pressurized cooling. Another key advantage is the ability to do repairs from outside the equipment.

When a crack or leak in a tubular panel needs repair, 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. This is a very hot and hazardous environment in which to work and also entails significant downtime.

With spray cooling, this scenario is eliminated. For one thing, 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.



Typical spray cooling roof

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 from 65-85 percent by rebuilding vs. 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 one year and sometimes as little as six months.

The life of the hot face is directly related to the application. For example, a southern U.S.A. 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 melt shop 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 Ultra High Power (UHP) furnace operators have routinely experienced well over 5,000 heats on their EAF roofs before requiring a rebuild. Equipment lifespans 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 (generally in 6-12 months), and the spider or superstructure at less frequent intervals, but even in these cases five years is about the maximum life expectancy.

Since spray cooling operates at half the pressure of tubular equipment, it also cuts cooling water pumping energy costs in half. It is also a more efficient method of cooling, so the equipment typically requires less cooling water than pressurized tubular. Systems may be custom designed to operate within a facility's current water usage restrictions, or possibly use even less water.

Cost-saving example: A major steel mill 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 six weeks. This resulted in average production downtime of 40 hours per month per furnace and average monthly maintenance of 64 man-hours per month.

They replaced the pressurized tubular duct sections (D1/D2 section = 10'-0 x 7'-9 ID, D3 section = 10'-8 x 8'-5 ID) with ducts utilizing non-pressurized spray cooling. They have found that the non-pressurized ducts are lasting over four 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 six months considering reduced downtime and maintenance costs. They have reported that their duct maintenance costs decreased from $0.25 per ton to $0.05 per ton after converting to spray cooling, for an annual savings of $440,000 per year, totaling $1,320,000 over a three-year period **(Table 2)**.

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 hrs./month per furnace	0 hrs./month per furnace
Average maintenance labor	64 man-hrs./month	2 man-hrs./month
Duct replacement/relining cost	$1,650,000 (3-year period)	$330,000 (3-year period)
Cost per ton of steel produced (2.2 million tons/year)	$0.25 per ton	$0.05 per ton
Total savings		**$440,000/year x 3 years = $1,320,000**

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

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 melt shop, such as upper EAF sidewalls, EAF roofs, fourth-hole elbows, off-gas ducts, drop-out chambers, Consteel® preheater and connecting car hoods, spray chambers, BOF hoods and ductwork, AOD hoods, and LMF roofs and hoods.

Non-pressurized spray cooling is being used successfully by some of the most recognized steelmakers in the world including Nucor Steel, Severstal, Arcelor-Mittal, AK Steel, Gerdau, Timken, US Steel, Daido, Daehan Steel, Hyundai Steel, BHP (OneSteel, Smorgen), SDI, ProfilARBED, Acerinox, Badisch Stahlwerke (BSW) and many others. In the smelting industry, roofs and off-gas duct installations have been in continuous operation since the 1990's 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 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."

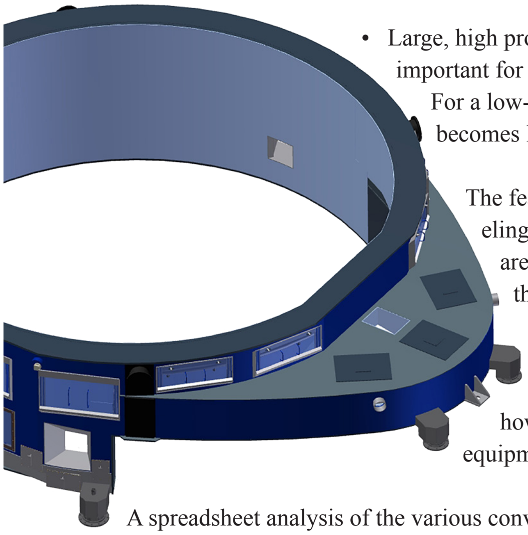
Similarly, a paper on steel mill safety by attorney Joseph Lipari of The Sultzer Law Group (New York, N.Y.) references a lawsuit in which litigants alleged that manufacturers of the EAF and pressurized panels should have provided information about "the use of EAF spray cooling as a 'safer alternative'."

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.

DETERMINING VIABILITY

Though it may always be the safer alternative, is non-pressurized spray cooling economically viable for every application? As a general rule of thumb, this technology offers the greatest benefits for:

- Severe applications: The more severe the application, the greater the potential for development of leaks that may lead to a violent steam eruption. By minimizing the amount of water that enters the furnace, the clear-cut safety advantage of non-pressurized cooling in these situations is well established.



- Large, high productivity shops: The ability of spray cooling to maximize furnace uptime becomes exponentially more important for melt shops with "24/7"operations, where an unplanned interruption will entail a sizable financial hit. For a low-production shop where the furnace is only running three days a week, the issue of unwanted downtime becomes less relevant.

The feasibility of converting existing equipment to spray cooling may also vary. Recently introduced 3D modeling capabilities now allow easier retrofits: A design team can perform an onsite 3D laser scan of the furnace area to determine clearance issues, location of equipment and other factors -- generating a customized plan that precisely fits spray cooling into the existing space.

Since the spent cooling water is at atmospheric pressure, vacuum pumps must be incorporated into the system to siphon the cooling water out of the roof. For most installations this does not pose a problem; however, some systems are designed with a closed-loop, fully pressurized supply and return system off the equipment, and higher conversion costs may apply in these situations.

A spreadsheet analysis of the various conversion factors involved, and the anticipated payback, is the best way to determine the economic justification for any given application. Though in all cases, safety will trump economics as the deciding factor.

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 above. 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.
- 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 plain old common sense. Here are some general recommendations for optimizing safety in any facility:

- Instrumentation that ensures that vital operations are functioning properly should be employed to assist with monitoring water levels.
- Periodic visual inspections during routine walk-downs should be performed to look for cracks, holes, or indications of water build-up on the furnace roof or other surfaces.
- Small holes or cracks should be patched or welded immediately to prevent them from growing larger. With non-pressurized spray cooling, temporary repairs can generally be done from the cold side without incurring furnace downtime or exposing operators to the hot furnace.
- Check gravity drains regularly to make sure they are functioning properly.
- Use metalized jackets or other safety apparel to protect workers from harmful burns.
- Be mindful of other water sources that might create problems. For example, during winter months, scrap that is stored outside may become caked with snow or ice. If it is added to the furnace in this condition, the moisture content is potentially high enough to trigger an incident.
- As obvious as it may sound, don’t use the furnace as a trash receptacle.

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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Charging of a 170 Ton EAF

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