Economics of Spray Cooled Off Gas Ducts

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INTRODUCTION

Spray cooling, a proven alternative to tubular pressurized cooling of electric arc furnace equipment, has been successfully employed in EAF steel making for the past 18 years. First appearing in a furnace roof commissioned in September 1986, the primary design intent of spray cooling has been to minimize downtime associated with the maintenance and repair of furnace equipment. Spray-cooled equipment realizes increased life resulting from better management of thermal stress fatigue cracking, improved maintainability resulting from welded steel plate repair procedures, and lower maintenance costs resulting from the reduced cost to rebuild versus alternative equipment replacement. This paper will discuss increased life expectancy, maintainability and the maintenance economics of spray cooling, a patented technology.

LIFE EXPECTANCY

Spray-cooled technology has brought increased life and equipment availability to EAF roofs, sidewalls and sumps, DES roof elbows, off gas ducts, LMF roofs, BOF hoods and most recently to Consteel® furnace connecting cars and pre-heater hoods. Distinct to the spray-cooled process, a spray system incorporating overlapping sprays creates a high degree of water turbulence at atmospheric pressure on the cooled surface. Droplet impingement turbulence results in efficient cooling yielding heat transfer coefficients on the order of ten times greater than for laminar flow. Water distribution rates are varied to match known heat load demands affecting system efficiency and reliability.

Thin-walled plate construction of the independent inner shell incorporating minimal welds, rounded or chamfered corners, and mechanical forming make spray-cooled equipment less susceptible to thermal induced stress fatigue cracking – a common nemesis of this type of equipment. The off gas duct inner shell is the exposed hot plate and is in direct contact with the 3300°F furnace off gas stream. A minimal amount of constraint is built into the inner shell, which undergoes cyclic thermal expansion and contraction due to this exposure. Combined with a plate thickness optimized based on known heat loads, the construction methods employed serve to minimize thermal fatigue cracking.

The primary material used for the inner shell of a spray-cooled off gas duct is carbon steel; pressure vessel quality ASTM A-516 Grade 70 plate. Properties such as thermal conductivity, allowable stress, workability and cost have made this grade of steel the material of choice. This plate grade is readily weldable, formable, and machinable.

Thickness of the inner shell is a function of two considerations. One thickness will be considered based on its effectiveness in minimizing thermal stress fatigue cracking. Another thickness will be considered based on its effectiveness in resisting corrosion and abrasive wear.

Fatigue Life:

As a sample analysis, using known off gas duct cooling water ΔT's, an average heat flux of 194,490 Btu/hr x ft^2 was calculated. Thermal induced stress in 1/2", 3/8" and 1/4" thick plate were found to be 44,158 lb/in^2, 33,118 lb/in^2, and 22,079 lb/in^2 respectively.

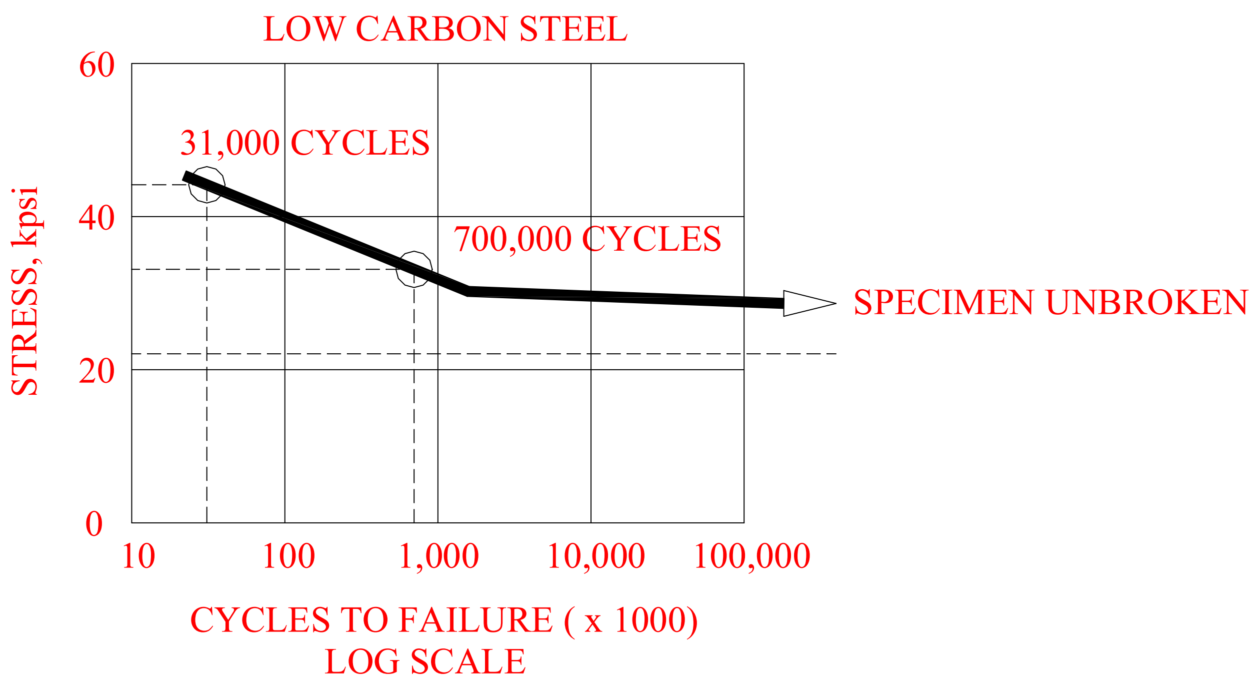

Figure 1

If a large number of specimens are tested to failure, at different values of stress amplitude, the resulting plot is called the S-N diagram. For steels, it is usually found that above 1,000,000 cycles to failure the plot levels off, i.e. there is a value of stress amplitude below which fatigue failure does not occur. This is known as the endurance limit or fatigue limit for the material.

In Figure 1, the cycles to failure for the sample with a 0.50" thick inner shell is approximately 31,000 cycles. The cycles to failure for the sample with a 0.375" thick inner shell is approximately 700,000 cycles. A 0.25" thick inner shell would have a fatigue life that would exceed 100 million cycles. If based solely on fatigue life expectancy, the recommended thickness for the carbon steel inner shell would be 0.25".

Wear:

Corrosive deposit oxidation, and the repetitive formation and removal of these oxide scales by gas stream entrained particles can accelerate metal removal or thinning of the exposed surface. This chemical/physical attack, resulting from the presence of impurity elements and the gas stream velocity, can accelerate wear and effectively reduce the number of cycles to plate failure. The exposed surface of the spray-cooled off gas duct inner shell is smooth and its topography lends no residence to the corrosion causing gas stream components. However, should corrosion/erosion wear be identified as the predominant mode of premature failure, life can be extended directly proportional to an increase in plate thickness. All other things being equal, doubling the plate thickness should double the life expectancy.

Fatigue and wear life are designed into spray-cooled equipment with the proper selection of the inner shell plate thickness.

Stress concentration points are also taken into account. Welded corners present a point of high potential for the initiation of thermal stress fatigue cracking. Corners should be allowed to expand and contract freely by being unrestrained by their geometry or by nearby welds, reinforcements or attachments. Rounding or chamfering is employed as an effective means of minimizing stress concentration at corners. Seam welds are kept to a minimum when forming the rolled inner shell and weld seam intersections are avoided if possible.

This prescription plate selection is a tested recipe for increased life expectancy leading to reduced downtime and lower maintenance costs.

MAINTAINABILITY

Spray-cooled equipment is designed for maintainability. The inner shell wears out, but can be replaced in whole or in part. Since there are minimal attachments from the outer shell or the spray system to the inner shell, replacement of the inner shell is quick and inexpensive. The inner shell is simply cut free from the duct end flanges and removed and replaced. The outer shell and spray system, allowing for normal wear and tear should last indefinitely.

The critical component in spray-cooled equipment is the carbon steel plate inner shell. Proper maintenance begins with recognizing the importance of protecting the inner shell and understanding the operating functions of the equipment providing the protection. For this reason, a preventative maintenance program focusing on the constant performance of these functions is integral to maximizing shell life and minimizing downtime for repair.

Same as for all other water-cooled equipment, an uninterrupted supply of cooling water to the heat affected area is essential. This water is supplied from nozzles in spray-cooled equipment making this particular function easily verifiable through inspection openings present in the equipment outer shell. United States Patent No. 6,092,742 describes the patented nozzles incorporated in spray-cooled equipment for this purpose. A lack of water or an irregular spray pattern suggests attention to the nozzle is needed and is correctible by cleaning or replacing the nozzle. Occasional inspection of the spray nozzles reduces the potential for burn-through and premature degradation of the carbon steel inner shell.

Periodically, the interior of the spray chamber should be examined to verify properly functioning nozzles and the absence of mineral deposits on the spray surface. No deposits suggest the system is operating correctly. Deposits on the surface of a noted area suggest an operational hot spot or a plugged nozzle.

Auxiliary equipment strainers, a part of the spray-cooled system, are employed to minimize the likelihood of plugged nozzles. Consistent with other process auxiliary equipment, periodic inspection and maintenance are required. On a regular basis, observe the pressure drop across the strainer and perform necessary maintenance and/or cleaning if the pressure differential across the strainer exceeds the recommended setting. Inspect for holes or tears in the baskets or screens.

Instrumentation, ensuring vital operations are functioning properly is employed to assist with monitoring spray-cooled equipment. In addition to the routine inspection of the various components, an alarm system alerts operators of too low or too high cooling water supply conditions, too large pressure differential across the strainer, and discharge water too high temperature signaling a potential system upset condition.

Under optimal operating conditions and an effective maintenance program, a crack or hole will eventually occur in the inner liner. Distinctive to spray-cooled equipment is its operation at atmospheric pressure. Water that leaks from a stress crack or burned hole is minimal offering improved safety over pressurized systems by limiting the amount of water entering furnace evacuation system.

Repair of a crack or hole can be performed relatively quickly because the inner shell is made from rolled carbon steel plate. Repairs are accomplished by welding, and where replacement material is required, standard carbon steel plate can be used.

Temporary repairs can be made during production. This generally consists of welding up a crack or installing a patch plate at a location where a hole has occurred. Typically this is accomplished from the outside of the equipment by accessing the inner plate from the water side through external hatches provided or a temporary hole cut in the outer shell. Cutting- your-way-in and welding-your-way-out is another spray-cooled equipment distinction that improves maintainability. The affected area is isolated from the cooling water by the temporary removal of a spray bar and capping of the supply nipple.

A temporary repair of a burned hole is typically performed by first cutting out the damaged material. Remove material to the extent sufficient to assure the inner shell where the patch is being installed is at its original base metal thickness, usually cutting 1”-2” outside of the hole (Figure 2). Use the cut out piece as a template for fabricating the patch. Using the best available grade of carbon steel, make the patch slightly larger than the removed piece being careful not to exceed 1/4" on any side (Figure 3). Position the prepared patch over the hole and attach with a 1/4" fillet weld.

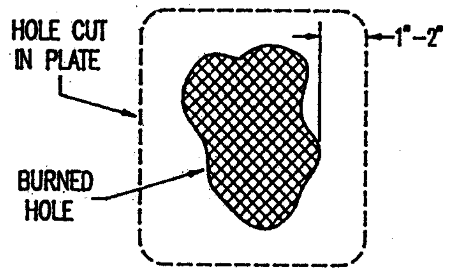

Figure 2

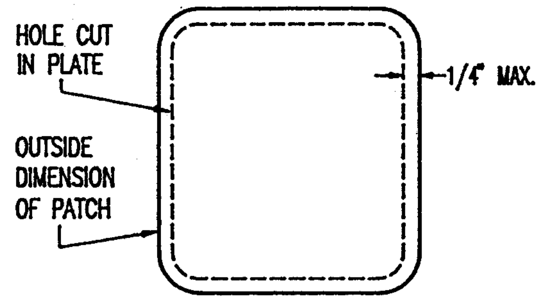

Figure 3

Cracks are repaired by first arc gouging the entire length of the crack plus 1" beyond on each end to remove the damaged material (Figure 4). Beveled weld preparations are made to the sides of the crack to ready the joint for welding (Figure 5). The joint is then welded using a stringer bead process for the entire thickness of the base metal.

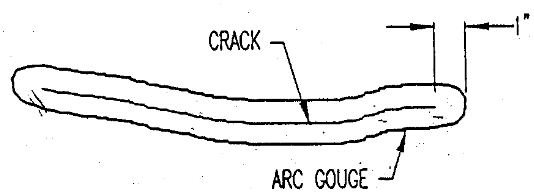

Figure 4

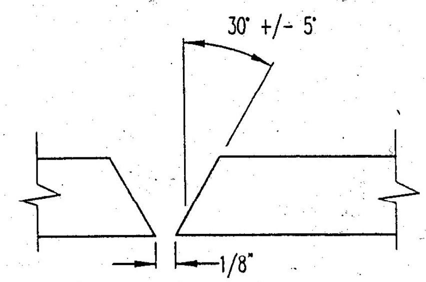

Figure 5

Permanent repairs to the inner shell can be postponed until the end of a production cycle or when downtime is scheduled for maintenance on other equipment to minimize unscheduled downtime. A permanent repair is done similarly, but entails removal of damaged material and replacement with new original base metal patch material installed flush in the cut-out (A516 Grade 70). Steps are taken to ensure that a full penetration weld is achieved by using a root pass weld and dye checking it before finishing the weld with stringer beads.

Operator awareness is equally important in maintaining spray-cooled equipment. As usual, production personnel play a vital role in maintaining their equipment. Inspection and emergency action plans are all aspects of operation that have significant effect on the overall reliability and performance of the equipment.

This information is intended to be used only as a guide in providing general information with respect to the maintenance of spray-cooled equipment and should only be utilized by persons trained and experienced in the operation and maintenance of related steel making furnace systems. Because the operator's specific use, application and conditions of use are all outside of the control of Systems Spray-Cooled, Inc., same makes no warranty or representation regarding the results which may be obtained by the operator in using this information. It shall instead be the responsibility of the operator to determine the suitability of any of the maintenance methods discussed for the operator's specific application.

ECONOMICS

To this point, this discussion has dealt briefly with distinct spray-cooled benefits that promote improved life expectancy and increased maintainability. These and other benefits can be substantiated by years of consistently good performance in related EAF, BOF, AOD and Consteel® furnace steel making applications.

Lower maintenance costs is another goal of spray-cooled technology. Whether its associated periodic maintenance or complete inner shell rebuilds, spray-cooled off gas ducts have afforded users lower maintenance costs resulting from the reduced cost to rebuild versus alternative equipment replacement.

In September 2001, Nucor Yamato Steel in Blytheville, Arkansas installed 2,032 SF of spray-cooled off gas duct during conversion of their D1, D2 and D3 duct sections to spray cooling on both furnaces.

This facility in Arkansas has two 22 ft., 120 ton AC furnaces equipped with a 90 MVA transformer, a 1,100 volt secondary, 24" electrodes turns 40 minute heats. The melt shop produced 2.7 million tons in 2000, 2.3 million tons in 2001, 2.2 million tons in 2002, 2.3 million tons in 2003 and is on pace to produce 2.6 million tons in 2004. Table I is a summary of the furnace operating parameters.

Table I - Furnace Operating Parameters

Furnace No.	Average Power	Average Power Factor	Average Secondary Current
1	80 MW	0.83	60,000 amps
2	79 MW	0.83	61,500 amps

- Average Tap-Tap Time .... 39.9 Minutes
- Average Tap Tons .... 121.3 Tons
- KWH/Ton 335.0
- Oxygen Usage .... 1,440 SCF/Ton
- Electrode Consumption .... 2.78 Lbs./Ton

In 2001, the decision to replace the water-cooled tubular duct sections was due to pipe stress cracking and the accompanying high-pressure water leaks. Nucor was already an experienced spray-cooled equipment user and had documented success with spray-cooled ductwork at their Plymouth, Utah and Berkeley County, South Carolina facilities. They were already familiar with the improved safety aspects offered by the non-pressurized spray-cooled technology and anticipated the same reduced downtime and maintenance costs they experienced after conversion to spray-cooled equipment on their roofs and roof elbows, sidewalls and sumps and LMF's. Based on their earlier conversion experiences with spray cooling, hopes were equally as high that the results would be the same as they expanded the use of the technology into the off gas ducts. Table 2 is a summary of their conversions to spray cooling in chronological order.

Table II - Conversion To Spray Cooling

Date	Furnace No.	Equipment
July '88	1	Roof and DES Elbow
August '88	2	Roof and DES Elbow
June '91	2	Sidewall and Sump
July '91	LMF I	Roof
June '92	1	Sidewall and Sump
January '94	1,2	Roof
May '99	1,2	DES Elbow
September '00	LMF II	Roof
April '01	1,2	Roof
April '01	1,2	DES Elbow
April '01	1,2	Sidewall and Sump
August '01	1,2	D1/D2 Duct
August '01	1,2	D3 Duct
December '01	1,2	D1/D2 Duct
December '01	1,2	D3 Duct

Normal operating schedule is 7 days/week, 24 hours/day with scheduled shutdown(s) twice a year for maintenance - one in March and one in September. While initial expectations were for vast improvement, as a part of the learning experience the duct sections were taken out of service at 6-month intervals coincidental with scheduled shutdowns for evaluation of performance until March 2003. Inner liners were replaced if needed, taking advantage of the opportunity afforded during the shutdowns so that maintenance procedures and performance expectations could be established. Between March 2002 and March 2003, the spray-cooled duct sections saw 9,350 heats experiencing only one minor incident resulting in lost production time. In March of 2003 the duct sections were removed and replaced during a semi-annual shutdown. The decision was made to replace the inner liners due to metal thinning. This was done with no loss in production. Table 3 is a summary of the duct section design and operating parameters.

Table III - Duct Design Parameters

- Diameter D1/D2 . . . . 10'-0" x 7'-9" I.D.
- Weight . . . . 22,000 Lbs.
- Nozzles 551
- Supply Water Flow . . . . 3,149 GPM
- Supply Water Pressure . . . . 20 PSIG
- Maximum Temperature Rise . . . . 40°F
- Diameter D3 . . . . 10'-8" x 8'-5" I.D.
- Weight . . . . 15,000 Lbs.
- Nozzles 360
- Supply Water Flow . . . . 2,058 GPM
- Supply Water Pressure . . . . 20 PSIG
- Maximum Temperature Rise . . . . 20°F

SUMMARY

Based on their experience, the spray-cooled duct inner liner will operate reliably with practically zero downtime during a 12-month production cycle. When a stress crack does occur, the amount of water that leaks from the duct is minimal and is a testimony to the improved safety of the non-pressurized cooling system. In addition, any repairs are quick and can generally be scheduled whenever the furnace is down for some other unrelated reason. With over 30 months of operation at Nucor Yamato, they have not had a single incident of a major water leak or downtime with this system. Table 4 is a summary of the duct section performance. Table 5 is a comparison of downtime and performance since converting to spray-cooled off gas ducts. Table 6 is a replace or rebuild cost comparison of the last three years prior to spray cooling to the performance since conversion in 2001.

Table IV - Duct Performance As Of March 31, 2004

Duct No.	Service Ending	Total No. Of Heats	Maintenance To Date
D1/D2	March '03	9,350	_
D3	March '03	9,350	_
D1/D2 (Spare)	March '04	9,410	10 Hrs.
D3 (Spare)	March '04	9,410	20 Hrs.

Table V – Duct Downtime And Performance Comparison

Topic	Prior To Spray Cooling	After Spray Cooling
• Avg. Downtime Per Month Due To Water Leaks	40 Hrs./Mo./Fce.	0 Hrs./Mo./Fce.
• Avg. Maintenance Per Month Replacing Panels; Repairing Hose Leaks; Patching Inner Liner; Plugged Nozzles	64 Man-Hours/Mo.	2 Man-Hours/Mo.
• KWH/Ton	335	335
• Tons Produced	180 Tons/Hr.	190 Tons/Hr.

Table VI - Replace Or Rebuild Cost Comparison

Event	Cost Prior To Spray Cooling	Cost After Spray Cooling
• Replace Panels, etc.; Reline Entire Section, etc.	$ 0.25/Ton	$ 0.05/Ton
• Replace Panels, etc.; Reline Entire Section, etc.	$ 1,650,000/Previous 3 Years (2.2M Tons/Yr.)	$ 333,000/Projected 3 Years (2.2M Tons/Yr.)

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