Spray-Cooling, Staying Cool in Hot Places

Stanley Smith, Maintenance Supervisor, Severstal USA 145 Airport Road Columbus, MS 39703 Phone (662) 245-4260 Fax (662) 245-4295, Email ssmith@severstalna.com

Troy D. Ward, Technical Director, Systems Spray-Cooled, Inc. 311 Plus Park Blvd., Ste. 280, Nashville, TN 37217, Phone (615) 366-7772, Fax (615) 366-7755, Email tward@tsg.bz

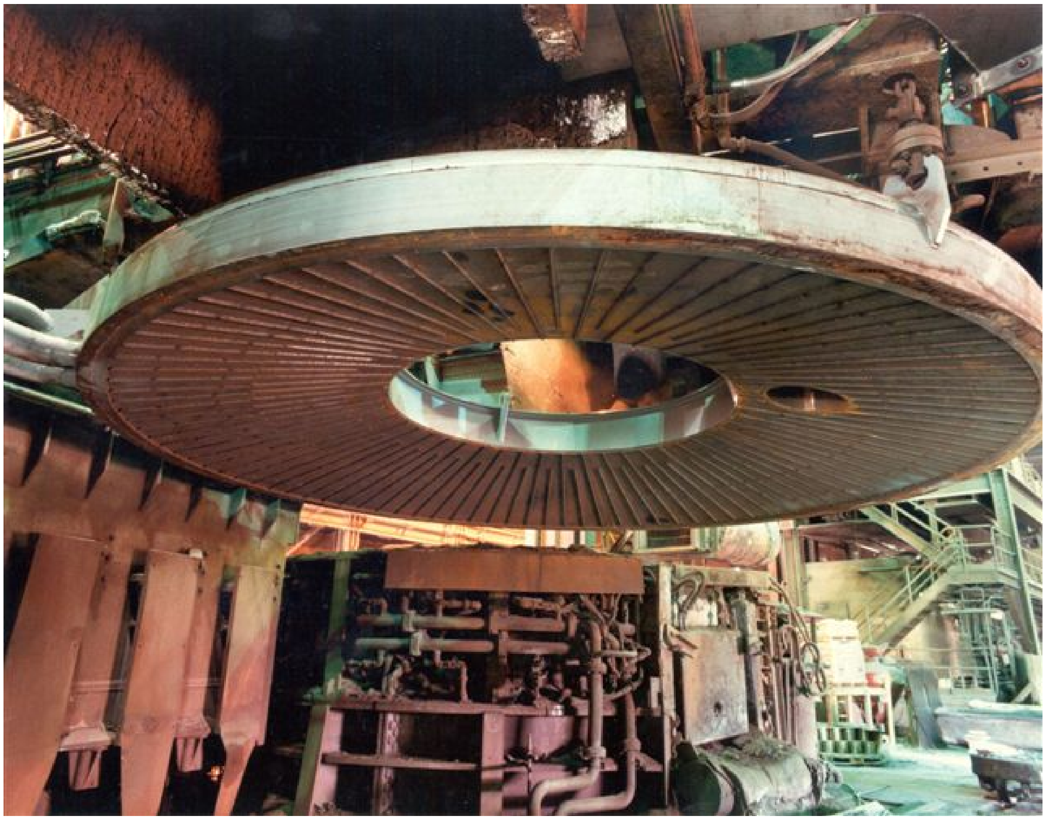
Key words: Minimized downtime, Manageable stress cracking, Improved maintainability, Lower maintenance costs, Inherently safer

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 25 years. First appearing on a furnace roof commissioned in September 1986, the primary design intent of spray cooling has been to minimize furnace 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 construction repair procedures, and lower maintenance costs resulting from the reduced cost to rebuild versus alternative equipment replacement. This paper will discuss design improvements and the increased life expectancy of this patented technology.

DISCUSSION

First commissioned on an EAF furnace in September 1986, the design has been continuously improved. From its beginning as a furnace closure element, e.g. a roof, which is formed and assembled into one-piece, being generally frustum conical shaped including an exposed consumable bottom wall (hot plate), a vertical peripheral outside diameter (O.D.) wall, a parallel covering top wall (dust cover) and a central wall (delta) defining a closed volume wherein spray means are positioned to direct sprays of water for cooling the center, bottom and peripheral walls the Spray-Cooled™ roof design has since evolved.

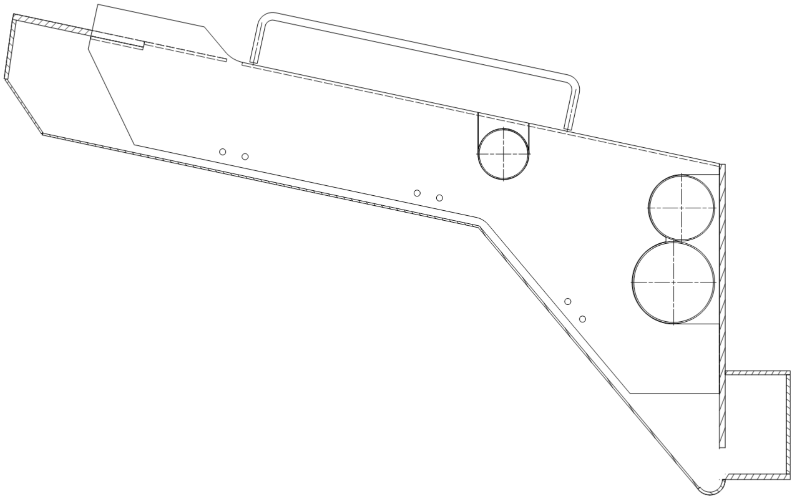


The frustum conical shape that grew in popularity both in the states and abroad incorporated various forms of protective slag retention devices on the hot plate. From radially installed re-bar first commissioned to the more conventional C-cup slag retainers used today, maintaining a depth of slag coverage is pivotal to prolonged equipment life. With the introduction of chemical energy in the EAF, oxygen, fossil fuels and carbon, to facilitate more rapid scrap melting, enhance bath decarburization, and promote refining and production of foamy slag all to the benefit of reduced power on time and reduced electrical energy consumption the roof design too has continued to change.

A dual frustum conical shape was next prototyped. The original frustum conical shape was formed to sit concentrically atop a steeper frustum conical shape to provide more vertical separation from the furnace charge scrap heap. This roof profile later became known as a steep cone roof. Several variations of this type were tried, each to address specific concerns that arose during its in-service trials. Originally, the bottom frustum conical shape adjoined a flat bottom plate connecting the inside hot plate of the roof to the vertical peripheral O.D. wall outside. Temperature differential between the inside of the roof and the outside of the roof would cause the flat bottom flange to crack. The crack would propagate outward toward the vertical peripheral O.D. wall and inward into the hot plate. Premature maintenance resulted.

Next the bottom of the roof was modified to add a quadrant of a small diameter pipe, tangent to the steep slope of the bottom frustum conical shape and tangent to the flat bottom flange. The concept was that the pipe would serve as a round between the two surfaces and serve to reduce/relieve the stresses that are induced by the furnace heat load at welded corners. Improvement was realized and equipment life extended.

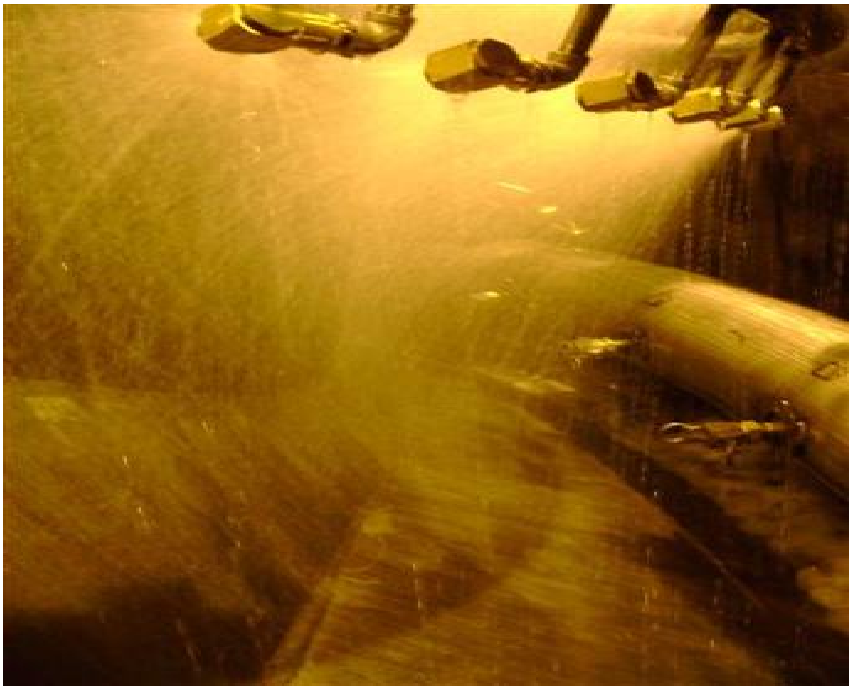
This was followed by a narrowing of the bottom of the roof such that a quadrant of a drawn-on-mandrel tube could be used that was tangent to the steep slope of the bottom frustum conical shape and tangent to the vertical peripheral O.D. wall. Manufactured to ASTM A513, the drawn-over-mandrel product selected had tensile properties that are comparable to cold-drawn seemless steel tubing of the same steel analysis and nominal size. It also has a high degree of uniformity in wall thickness as it is formed from high-quality, flat-rolled steel with very little gauge variance. Seam weld quality is assured by ultrasonic, flux leakage, and eddy current testing. Additional improvement was realized and additional equipment life was gained.



Somewhat simultaneous to this improvement, United States Patent No. 7,625,517 was applied for and received. In it, the interior cooling system comprised of an intake manifold, a plurality of spray bars attached to the intake manifold, and a plurality of distribution nozzles positioned along each spray bar is described that works in unison with a collection manifold that is positioned to collect the spent coolant for evacuation. Nozzles are oriented to direct the fluid coolant towards the collection point by using the kinetic energy of the coolant exiting the nozzle and striking the surface at an obtuse angle as measured in the direction of the collection point. A predetermined temperature range between 40 to 300 degrees Fahrenheit is maintained on the hot plate. This patent supersedes others that cover this technology while still including claims to the existing technology.

Parallel to this improvement, the roof profile continued to change. Current design still is frustum conical shaped. The roof keeps the concentric dual cone height and maximum vertical separation above the furnace scrap heap while the hot plate becomes a single steep frustum conical shape. Elevated temperature spent coolant runoff and evacuation is expedited by the steep slope toward the collection point at the roof O.D. Colder, fresh spray nozzle droplet impingement cooling can continuously impact the surface of the frustum conical shape hot plate. Much improvement has been realized. Equipment life has been extended.

An uninterrupted supply of cooling water to the hot plate is essential. United States Patent No. 6,092,742 describes the nozzles that best provide this cooling. Larger nozzle free passages reduce potential nozzle blockage. Under optimal operating conditions and an effective maintenance program, a crack or hole will eventually occur in the bottom wall or hot plate. 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 that can enter the furnace. Operation at atmospheric pressure reduces the amount of water that escapes the roof enclosure when there is a leak. A typical spray-cooled furnace component operating at 6 gallons per minute per square foot would dispense only 11 ounces per minute through a 2 square inch hole. In contrast, a typical tubular water-cooled furnace component operating at 60 psi would discharge more than 270 gallons per minute through the same size hole.



Usage of supplied cooling water is kept efficient by distributing it according to the requirements of the varying heat load areas identified throughout the roof; less water per square foot being required in cooler areas and more water per square foot being required in hot spots. Distribution of cooling water within the roof is via stainless steel piping that is not a part of the heated surface. Fouling of the water-cooled distribution piping, which can adversely affect the heat transfer rates in tubular water-cooled roofs, is not a factor with spray cooling. Cooling water is distributed throughout the roof at the same inlet water temperature so that cooling rate remains constant. This distribution method could potentially reduce pumping costs by not wasting water where it is not needed. Lower water volumes at lower pressures reduce pumping costs. Pumping the same volume of cooling water at one-half the pressure reduces pumping costs by 50%. Pumping one-half the volume of water at one-half the pressure reduces pumping costs by 75%.

The thin-walled plate construction of the independent frustum conical shaped hot plate with minimal welds, rounded or chamfered corners at penetrations, and mechanical forming make it less susceptible to thermal induced stress fatigue cracking – the common nemesis of this type of equipment. Thermally induced stresses are directly proportional to the thickness of the plate seeing the furnace heat load. Plate construction enables repairs to be made from the outside of the roof, rather than the inside. Operation at atmospheric pressure permits leaks to be temporarily repaired by an easy “weld-a-patch” technique with the roof still in service. Permanent repairs can be scheduled around production needs. These benefits equate to reduced furnace downtime due to improved equipment availability.

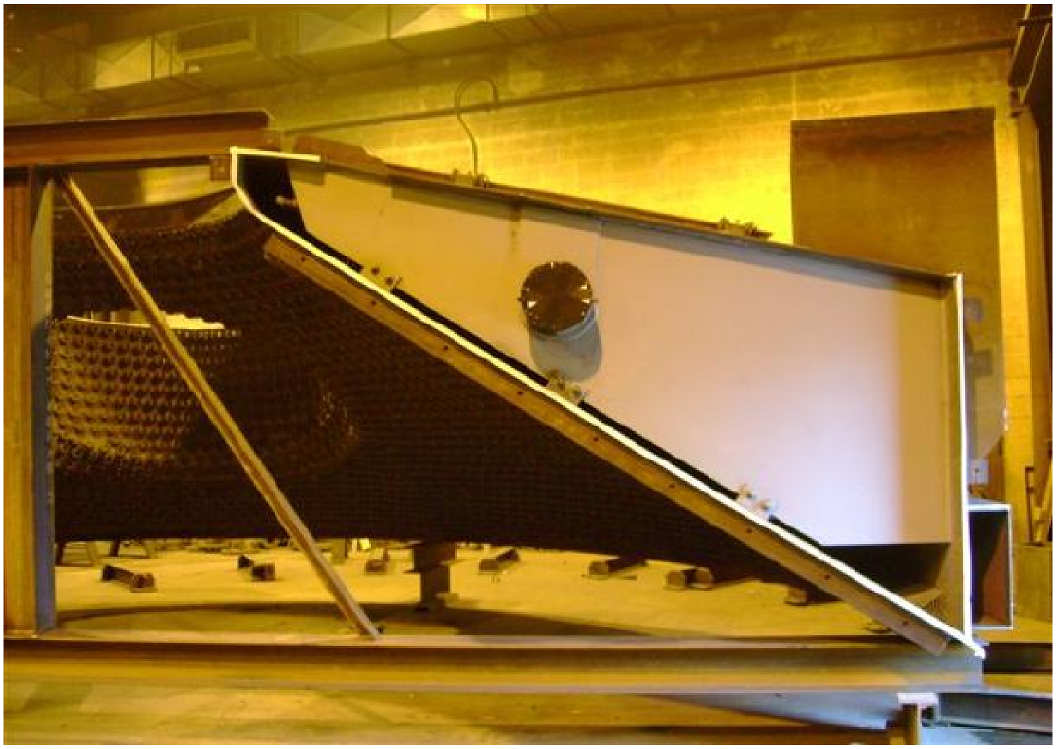
The primary material used for the consumable bottom wall of a Spray-Cooled™ roof is carbon steel; pressure vessel quality ASTM A-516 Grade 70 plate. The bottom wall (hot plate) and central wall (delta) wears out, but can be replaced in whole or in part. The vertical peripheral O.D. wall, the covering top wall (dust cover) and the internal cooling system, allowing for normal wear and tear should last indefinitely.

Recently, one such Spray-Cooled™ roof installed at Severstal USA in Columbus, Mississippi completed an 8,000 heat, 1.4 million ton campaign on furnace with no maintenance required. Visual inspection revealed good slag coverage still present and visible slag retainers were unworn. But for some superficial minor stress cracking of the vertical peripheral outside diameter (O.D.) wall that threatened to propagate into the hot plate, the operator suspects that the roof may have gone 10,000 or more heats. Based on historical averages for this equipment on similar size UHP EAF’s, 8,000 heats translates to better than a 300% life increase.

Commissioned operationally in October of 2007, this prototype was one of three (3) purchased for the facility in Columbus, Mississippi – Phase I. The facility combines mini-mill steelmaking and integrated finishing technology. It features a scrap-based electric arc furnace, feeding a thin-slab caster coupled with a high-powered hot-strip mill. Thin-slab output is further processed in a highly sophisticated cold-rolling mill and galvanizing line.

A group of industry veteran operators and maintenance personnel previously experienced with the Spray-Cooled™ technology elsewhere specified it at Severstal for the upper shell, the roof, the roof elbow, the fixed duct, the dropout chamber and in several sections of the off gas ductwork downstream of the dropout chamber. Operators say that they would not have anything else.

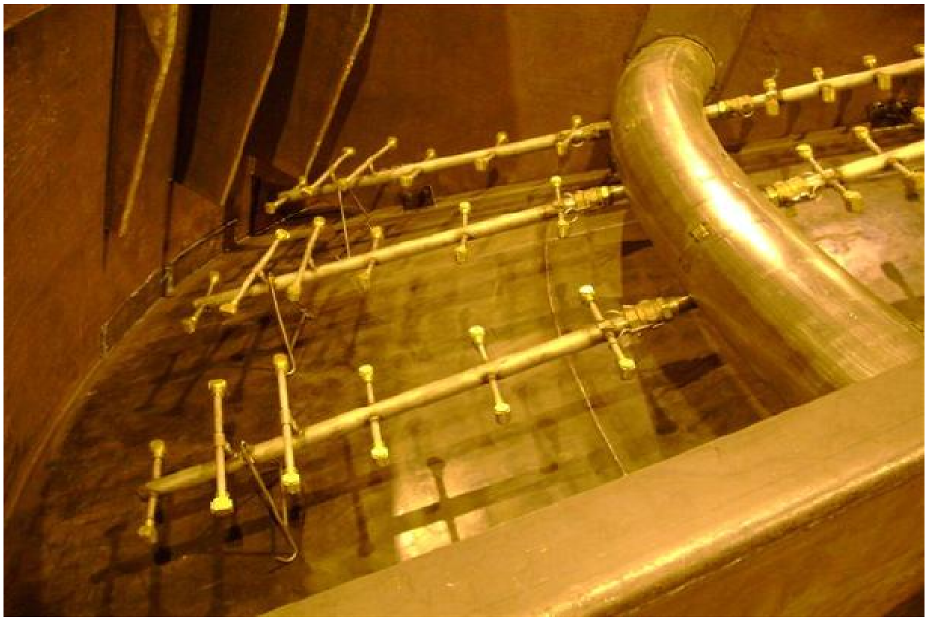
Initially skeptical of the purported improvements to the vintage Spray-Cooled™ equipment that they were familiar with, the Severstal Columbus production and maintenance personnel were quick to acknowledge the technological advancements that have been made after an 8,000 heat campaign. Stanley Smith, the veteran Maintenance Supervisor at Severstal offers high praises for the latest design. He emphasized that the Spray-Cooled™ roof was only taken off the furnace after the 8,000 heats because he preferred not to have to weld the superficial exterior cracking that had occurred on an otherwise scheduled down day as he had a spare. He acknowledged that the equipment was still in great shape considering the amount of energy that they put into their furnace over a short duration to produce 180 ton heats in around 30 minutes. He thought these improvements in design and the performance results should be encouraging for lower power furnace operators as well.



First, the steep frustum conical shape provides for a welcome separation above the furnace scrap heap helping to prevent damaging arcs and/or arc flare. Initially, an intermediate voltage is selected until the arc ignites and the electrodes begin to bore into the scrap. After a while, the electrodes will have penetrated the scrap sufficiently so that a high voltage (long arc) can be used. As the furnace heats up, the arc stabilizes and the power input can be increased. The increased head room provided by the latest design permits a quicker, less destructive bore in practice.

Second, the steep frustum conical shape facilitates the quick runoff and evacuation of the spent cooling water so that fresh cooling water can be immediately applied to the cooled surface without interruption from collecting surface water. Found more common in the predecessor roofs with less steep profiles after the cooling water supply was increased to address the increased heat load due to the introduction of chemical energy into the furnace, accumulating surface water was found to cancel the surface cooling. Boiling occurs, the surface temperature rises, bubbles coalesce and a vapor film is formed and the heat must be conducted through the film before being quenched by the cooling water. Heat transfer is reduced by the added thermal resistance. The heated surface must dissipate the applied heat load, or its temperature will rise catastrophically above the melting temperature of the metal. The steep frustum conical shape encourages the spent cooling water runoff eliminating any surface accumulation.

Third, the interior cooling system with its plurality of nozzles oriented to direct and flush the fluid coolant down the steep frustum conical shape toward the O.D. collection manifold and around the roof delta insures that uniform cooling is available continuously and there is no collection of water on the cooled surface. Before directing the nozzles down the slope was employed, downstream pairs of nozzles could dam up the runoff from the nozzle pairs upstream of them causing water to accumulate on the surface instead of advancing to be evacuated. Cooling was lost. Nozzles oriented to flush fluid coolant down the steep frustum conical shape has prevented this from happening.



Next, the decision to incorporate the use of 1/4" ASTM A-516 Grade 70 plate in the manufacture of the steep frustum conical shape exposed hot plate proved to be valuable by minimizing thermal stress fatigue cracking due to the furnace heat load on the exposed surfaces. The thermally induced stresses caused by the furnace heat load causes cyclic fatigue cracking that cannot be repaired successfully. The stress amplitude is directly proportional to plate thickness. For the same heat load, the stress amplitude increases with plate thickness. Increased stress amplitude shortens the number of cycles to failure.

Sample design calculations that follow support the decision. Given:

- ✓ Roof CWS flow rate = 3251 gpm
- ✓ CWS temperature = 84°F
- ✓ CWR temperature = 96°F
- ✓ Exposed surface area = 630 ft^2
- ✓ Plate Coefficient of Thermal Expansion = 6.33 x 10^{-6} in / in x °F
- ✓ Plate Modulus of Elasticity = 30 x 10^6 lb / in^2
- ✓ Plate Poisson's Ratio = 0.303
- ✓ Plate Thermal Conductivity = 25 Btu/hr x ft x °F

$$\text{Heat Flux} = \frac{\text{Mass Flow Rate x Specific Heat x Delta Temperature}}{\text{Area}}$$

$$\text{Plate Differential Temperature} = \frac{\text{Heat Flux x Plate Thickness}}{\text{Plate Thermal Conductivity}}$$

$$\text{Stress} = \frac{\text{Plate Coefficient of Thermal Expansion x Plate Modulus of Elasticity x Plate Differential Temperature}}{\text{2 x (1-Plate Poisson's Ratio)}}$$

Combining the last two equations produces the following relationship for stress:

$$\text{Stress} = \frac{\text{Plate Coefficient of Thermal Expansion x Plate Modulus of Elasticity x Heat Flux x Plate Thickness}}{\text{2 x (1-Plate Poisson's Ratio) x Plate Thermal Conductivity}}$$

----Example----

$$\text{Heat Flux} = \frac{3251\ \cancel{\text{gal}}/\cancel{\text{min}} \text{ x } 8.33\ \cancel{\text{lb}}/\cancel{\text{gal}} \text{ x } 60\ \cancel{\text{min}}/\text{hr x (1 Btu/}\cancel{\text{lb}} \text{ x } 1\cancel{°\text{F}}) \text{ x } 12\cancel{°\text{F}}}{630\ \text{ft}^2}$$

$$\text{Heat Flux} = 30{,}950\ \text{Btu/hr x ft}^2$$

$$\text{(For 0.50" Plate) Stress} = \frac{6.33 \text{ x } 10^{-6}\ \cancel{\text{in}}/\cancel{\text{in}} \text{ x } \cancel{°\text{F}} \text{ x } 30 \text{ x } 10^{6}\ \text{lb/in}^2 \text{ x } 30{,}950\ \cancel{\text{Btu}}/\cancel{\text{hr}} \text{ x ft}^2 \text{ x } 0.50\ \cancel{\text{in}} \text{ x ft /12 } \cancel{\text{in}}}{2 \text{ x } (1-0.303) \text{ x } 25\ \cancel{\text{Btu}}/\cancel{\text{hr}} \text{ x } \cancel{\text{ft}} \text{ x } \cancel{°\text{F}}}$$

$$\text{Stress} = 7{,}027\ \text{lb/in}^2$$

$$\text{(For 0.375" Plate) Stress} = \frac{6.33 \text{ x } 10^{-6}\ \cancel{\text{in}}/\cancel{\text{in}} \text{ x } \cancel{°\text{F}} \text{ x } 30 \text{ x } 10^{6}\ \text{lb/in}^2 \text{ x } 30{,}950\ \cancel{\text{Btu}}/\cancel{\text{hr}} \text{ x } \cancel{\text{ft}^2} \text{ x } 0.375\ \cancel{\text{in}} \text{ x } \cancel{\text{ft}} \text{ /12 } \cancel{\text{in}}}{2 \text{ x } (1-0.303) \text{ x } 25\ \cancel{\text{Btu}}/\cancel{\text{hr}} \text{ x } \cancel{\text{ft}} \text{ x } \cancel{°\text{F}}}$$

$$\text{Stress} = 5{,}270\ \text{lb/in}^2$$

$$\text{(For 0.25" Plate) Stress} = \frac{6.33 \text{ x } 10^{-6}\ \cancel{\text{in}}/\cancel{\text{in}} \text{ x } \cancel{°\text{F}} \text{ x } 30 \text{ x } 10^{6}\ \text{lb/in}^2 \text{ x } 30{,}950\ \cancel{\text{Btu}}/\cancel{\text{hr}} \text{ x } \cancel{\text{ft}^2} \text{ x } 0.25\ \cancel{\text{in}} \text{ x } \cancel{\text{ft}} \text{ /12 } \cancel{\text{in}}}{2 \text{ x } (1-0.303) \text{ x } 25\ \cancel{\text{Btu}}/\cancel{\text{hr}} \text{ x } \cancel{\text{ft}} \text{ x } \cancel{°\text{F}}}$$

$$\text{Stress} = 3{,}513\ \text{lb/in}^2$$

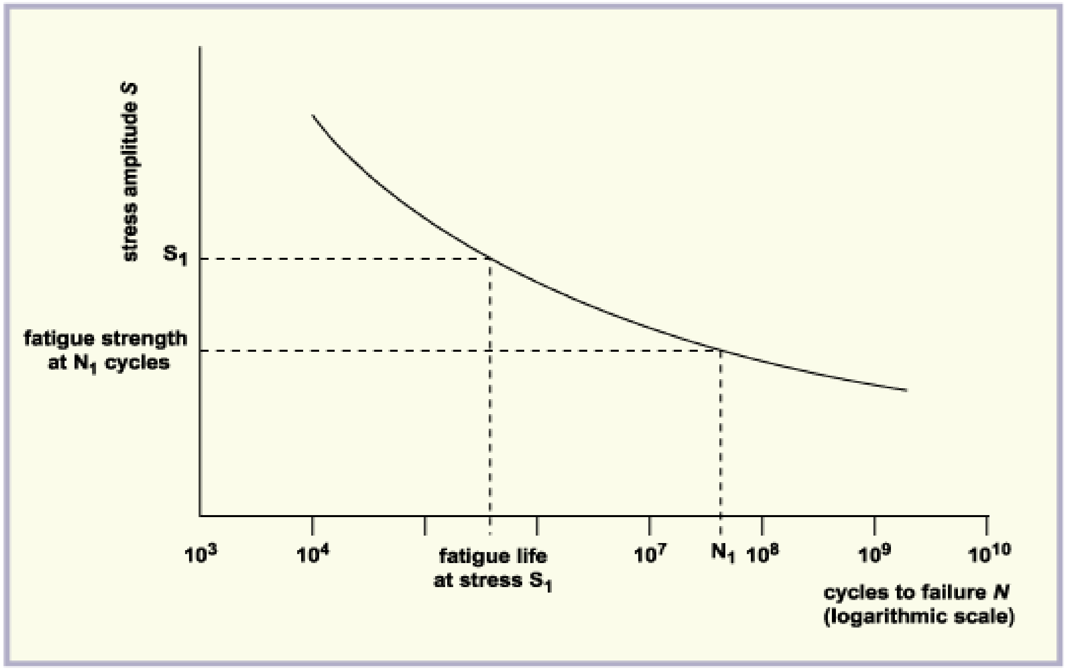
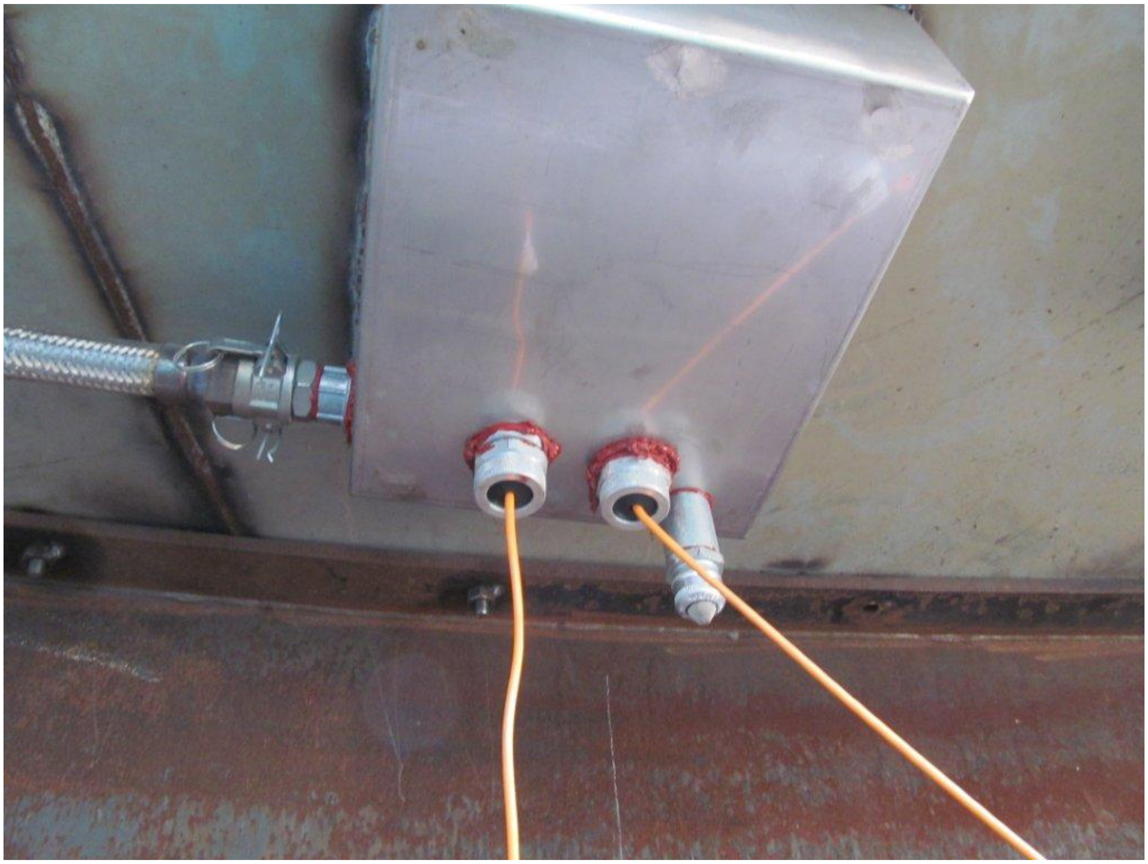


Figure 2 S-N Curve

From Figure 2, the cycles to failure for the sample thicknesses increase with the corresponding decrease in stress amplitude. If based solely on fatigue life expectancy, the best thickness for the ASTM A-516 Grade 70 plate would be 0.25”.

Next, and equally significant, is the fact that the equipment can be easily instrumented and monitored. Resistance temperature detectors (RTDs) can be simply installed through portals and strategically located to provide complete protection of the equipment including the control of energy unleashed in a specific area or in the entire furnace. Conventional pressurized water cooled equipment, typically instrumented only at the cooling water inlet and outlet, leaves the operator to accept where the problematic hot spot is located and to address it by increasing the cooling water flow to the entire panel. Increased volumes of water are supplied to areas where it is not needed just to treat the problem area. Here, an independent, enclosed cooling circuit provides the ability to vary the cooling capacity of the system according to localized demands. Strategically located RTDs installed either in known or suspect problem areas can easily be interconnected with conduits to junction boxes and communication established with the operator to effectively monitor the equipment and protect it from itself or over zealot production requests. Process instrumentation and safety interlocks are employed that are attached to electronics that perform logic operations on process conditions, and only trips (closes) in the event that exceeding those conditions will cause harm to equipment or personnel. Preventative maintenance of this type ensures that equipment is always available to manufacture products for the end customer.



RESULTS

In conclusion, veteran electric arc furnace operators emphasized that the technology and equipment is very versatile offering additional operational advantages. Spent cooling water with a minimal increase in temperature after just one pass through the equipment is available for reuse to other water cooled equipment when cooling water limitations have been met. Operation at reduced energy requirements due to lower cooling water supply operating pressures helps curb energy costs per ton. Ability to make required equipment modifications without engineering and/or redesign delays due to overall design simplicity permits onsite retrofitting to adjust to operational changes. Equipment repair costs are fractional compared to equipment replacement costs. Cooling at atmospheric pressure, accompanied with less voluminous water leaks constitutes less catastrophic consequences following an inevitable arc strike.

SUMMARY

A Spray-Cooled™ roof has inherent features that minimize many of the problems typical of pressurized water cooled roofs. As previously sited, high pressure, high volume water leaks, unmanageable thermal stress fatigue cracking and difficult and/or expensive maintenance are a few areas where spray cooling provides appreciative improvement.

In summary, the primary advantages of spray-cooling over conventional pressurized cooling are the elimination of the source of high pressure, high volume water leaks; the ability to effectively transfer heat at low flow rates; the consistency and uniformity at which cooling water is distributed; the ease at which cooling water distribution can be matched to roof heat load variations; construction that lessens the impact of thermal induced stress fatigue cracking; and a complete assembly that promotes life prolonging maintainability.

This discussion describes the features of spray cooling that has prolonged EAF roof life. These and other benefits can be substantiated by years of consistently good performance in electric arc furnace steel making.

Systems Spray-Cooled Technology is covered by one or more patents – United States Patent Nos. 4,715,042; 4,813,055; 4,815,096; 4,849,987; 5,115,184; 5,330,161; 5,327, 453; 5,444,734; 5,561,685; 5,648,981; 5,887,017; 5,999,558; 6,092,742; 6,185,242; 6,872,873; 7,452,499 pending and foreign patents.

Systems Spray-Cooled, Inc. 311 Plus Park Boulevard, Suite 280, Nashville, Tennessee 37217, (615) 366-7772, Web Site: www.spraycooled.com

ACKNOWLEDGEMENTS

The author is grateful to Severstal USA Columbus, Mississippi for their participation and to Stanley Smith, Maintenance Supervisor Severstal USA for his contributions as co-author.