

EXTENDING CONDENSING BOILER DURABILITY

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INTRODUCTION

Withstanding the harsh, unforgiving conditions amidst frigid air purges to hot flames, seldom-maintained hydronic loops, and acidic flue gas condensate demands a pressure vessel heat exchanger engineered with higher durability margins. This whitepaper serves as an introduction to condensing boiler heat exchanger designs, the potential modes of failure, and how Fulton has solved these engineering challenges to significantly extend boiler operational longevity.

CONDENSING BOILER TECHNOLOGY

Condensing boilers achieve ultra-high fuel-saving efficiencies by making use of the latent heat released during condensation of the H_2O formed as a byproduct of the combustion process. This phase change capture recovers energy in the flue gas water vapor that would otherwise be lost in a conventional non-condensing boiler.

Flue gas condensate forms along surfaces of the boiler heat exchanger as combustion gases are cooled below their dewpoint temperature. This is typically around 137°F (58°C) and will vary by fuel type and the amount of excess Oxygen in the flue gases. Because the heat exchanger is a counter-flow design, achieving ultra-high condensing efficiencies requires the return water from the heating system be below this temperature. As return water temperature further decreases, more condensate is formed, more latent heat captured, and greater fuel cost savings are realized. Condensing boilers are built with these lower water temperatures and larger temperature differentials in mind.

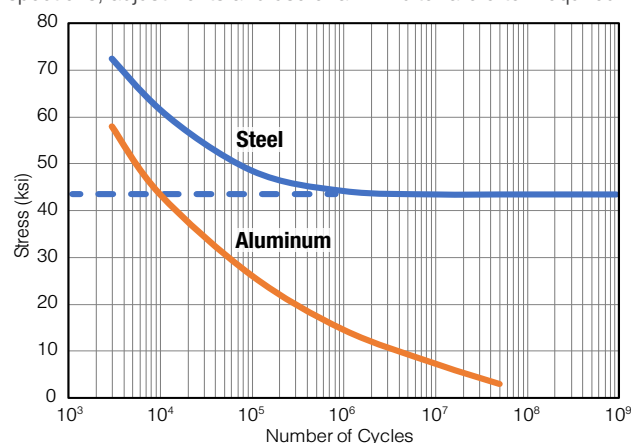
MATERIALS OF CONSTRUCTION

Multiple considerations will be made by the Specifying Engineer when rigorously selecting the right condensing boiler for a heating plant. Prominent among them for a facility with long-life demands is choosing a heat exchanger built with stronger and more forgiving materials.

Certain materials, such as cast iron and copper, will corrode when exposed to flue gas condensate due to its mild acidity with a typical pH of 3 to 5. This corrosion causes rapid deterioration of surface enhancements, decreasing heat flux. As a result, stack temperatures rise, and thermal efficiencies continually decline over the life of the boiler. Eventually, corrosion breaches through the heat exchanger, requiring costly leak repairs or complete replacement.

Aluminum is an alternative corrosion-resistant material with the favorable properties of relatively high thermal conductivity and low weight. However, cast aluminum is a very brittle material with a finite fatigue life. Its Stress-Cycle (S-N) curve does not become horizontal at an endurance limit, meaning even when operating under low stress, it is not a question of if aluminum experiences a cyclic fatigue failure but rather when.

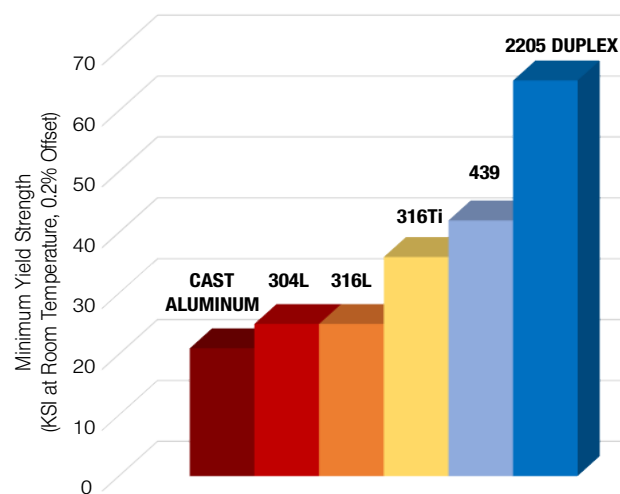
Operators must also remain vigilant in their water chemistry regimen, else risk permanent damage to the self-passivating aluminum heat exchanger by dissolving the sensitive oxide layer. To protect the oxide film, the water must have a pH between 6.0 to 8.5, a range conflicting with that typical of steel piping which favors a pH of 8.5 to 10.5. This is particularly problematic as the pH can drift up over time. Regular inspections, adjustments and use of an inhibitor are often required.



▲ **FIGURE 1: S-N Curve (Cyclic Fatigue Life)**

Steel and stainless steels on the other hand may achieve an infinite fatigue life, meaning cyclic fatigue failure does not occur provided the stress is lower than the endurance limit, the horizontal asymptote of the S-N curve. This property, among others, has helped make stainless steel become the material category of choice in the industry.

Yet stainless steel is not a single alloy, but rather a large family of alloys. There are hundreds of grades and subgrades of stainless steel, each designed for a special application, and each with vastly different properties. It is important to understand why the different grades exist to avoid material failures due to misapplication of the wrong grade.

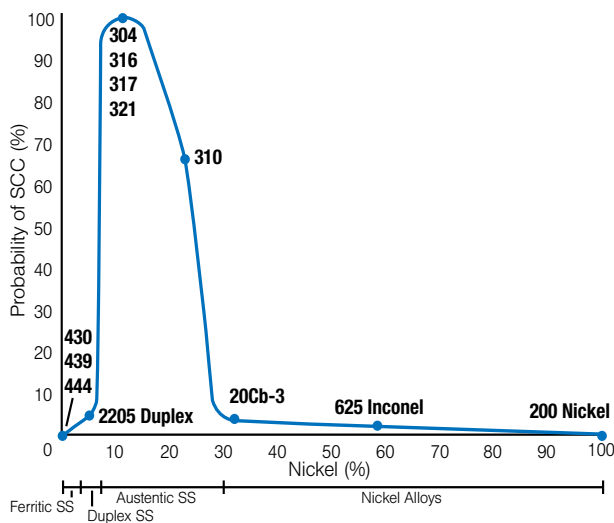


▲ **FIGURE 2: Heat Exchanger Material Yield Strengths**

Fulton has over 30 years' proven experience designing and manufacturing rugged condensing boilers, and uses only high-quality materials that are carefully selected for the application for instance duplex stainless steel (2205). Duplex has a microstructure containing both ferrite and austenite grains. The existence of both provides superior corrosion resistance, reduced thermal expansion, and a minimum yield strength that is more than double that of conventional austenitic ("300-series") stainless steels, and triple that of cast aluminum. Class 25 gray cast iron is so brittle the yield strength is unspecified.

One of the most commonly used stainless steel boiler heat exchanger materials is 316L, which experiences relatively higher rates of thermal expansion and therefore higher stresses, while at the same time has reduced strength to deal with these increased stresses. 316L will have a shorter operating life than heat exchangers built with duplex.

Some boilers, typically lower-end products only, are principally constructed using 304 as the heat exchanger material. 304 is a particularly poor choice because it is highly susceptible to Stress Corrosion Cracking (SCC); a mode of cracking failure instigated without warning and can be catastrophic in pressurized equipment. Stainless steels containing between 7 to 20% nickel are the most prone to this mode of failure, which includes 304, 316L and 316Ti.



▲ **FIGURE 3: Probability of Stress Corrosion Cracking (SCC)**

The formation and propagation of SCC is dependent on multiple factors including corrosive environments, higher temperatures and the presence of tensile stress. SCC will not form below what is known as the Critical Pitting Temperature (CPT). 304 has poor pitting resistance where SCC can occur even at room temperature. Molybdenum is used to improve pitting resistance which is why 316L with a composition containing typically 2.0% Molybdenum increases CPT to around 115°F (50°C). Although 316L is considered a slight improvement, boilers built with either 304 or 316L both still have an elevated risk of SCC failure even when operating under normal heating mode temperatures with only a small presence of chlorides of just a few parts per million. 2205 and 439 are not subject to SCC in hydronic heating systems.

While 304 or 316L may be reasonable choices for a short-term installation where frequent replacement is accepted, it is not prudent to employ these as the dominant heat exchanger materials for applications where boiler longevity and durability are concerns.

WHY FIRETUBE? VARIABLE PRIMARY FLOW

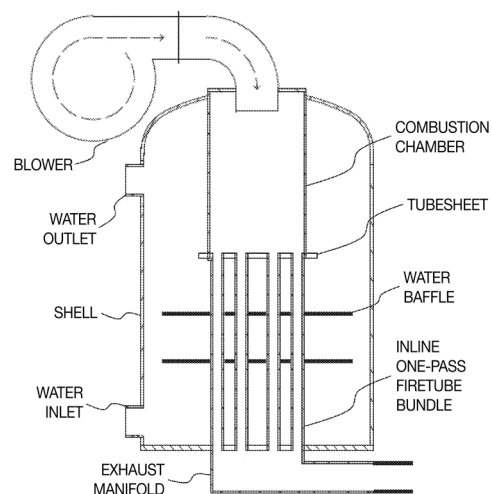
Consulting engineers tasked with specifying longer-lasting equipment show preference for heat exchanger platforms that offer benefits such as longer useful operating life, low water pressure drop and built-in buffer volume. These are the characteristics of stainless steel firetube boilers built with durable materials and greater water content, lending to more forgiveness of unpredictable system conditions such as swings in flow rate, rapid slugs of cold water slamming a hot boiler ("thermal shock"), and water chemistry or particulate issues. The large water passageways also lowers pump head requirements, thus reducing initial spend on pumps and life cycle electrical operating costs.

From a design engineer's perspective, these pressure vessel attributes also constitute favorable benefits in their application relative to hydronic piping methods. A well-designed firetube condensing boiler includes proper support of variable primary flow systems, a type of piping arrangement where the system (secondary) loop flows directly through the boiler plant without the need for decoupling. This strategy completely eliminates the primary loop and associated dedicated boiler pump(s), piping, valves and related ancillaries.

One of the most fundamental errors in development is to stick to a complicated design, and to not strive to delete parts. Variable primary flow not only greatly simplifies the hydronic design, but it saves on installation, operation and maintenance costs. Additionally, and perhaps the most appealing benefit, the problematic blending that occurs in primary-secondary systems is completely eliminated. Return water may only travel directly to the boiler inlet, it cannot blend with heated supply water, thereby optimizing for the lowest possible return water temperatures the heating coils can provide. This offers the greatest condensing potential and maximizes boiler plant thermal efficiency.

INLINE ONE PASS HEAT EXCHANGERS

Heat exchangers with multiple passes incorporate turn-around elements where combustion byproducts change direction. A well-engineered design may effectively "cancel" opposing thermal expansion growth of each pass resulting in near net zero expansion, thus low or negligible thermal expansion stress. In contrast, the combustion flow inside an inline one pass heat exchanger does not complete any full turns.



▲ **FIGURE 4: Inline One-Pass Firetube Heat Exchanger**

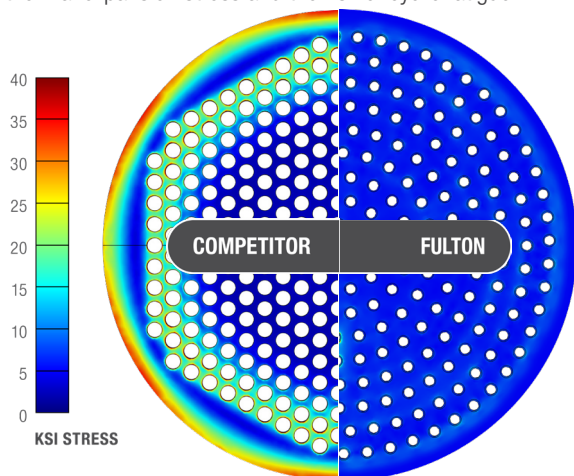
As building space allocated to the boiler room has continued to decrease, the heating boiler has needed to shrink in size. It became clear to the industry that a single pass heat exchanger architecture was conducive to satisfying compact dimensional constraints. The challenge with this design has historically been the mitigation of stress on the tubes and tube-to-tubesheet welds caused by axial (longitudinal) thermal expansion. Manufacturers have implemented a variety of stopgap solutions from bent tubes to corrugated combustion chambers or internal bellows. The problem with all of these conventional methods is that the compliant mechanism, the flexible member that absorbs cyclic deflection, is inside the pressure vessel shell.

In other words, if and when a fatigue failure occurs, the repair requires costly cutting and welding by a code certified worker, or as is more typical in practice: the purchase of a new replacement boiler.

HOW DO WE GET TO INFINITE FATIGUE LIFE?

Fatigue life is defined as the number of load cycles until failure. All else being equal, as stress increases the number of cycles the boiler will tolerate before failure decreases. The exception being conditions below the endurance limit where cyclic fatigue failure does not occur; this is considered infinite fatigue life. Methods for increasing fatigue life include using higher yield strength materials and/or those with less thermal expansion, and designing for lower operating stress.

The fatigue failure issues that plague other inline one pass designs are solved on Fulton's Endura+ (EDR+) through the use of duplex stainless steel and the patented tube stress relief expansion joint. This uniquely innovative design pins the heat exchanger to the pressure vessel shell at one end only, allowing for free expansion and contraction at the other. As the heat exchanger is brought up to operating temperature, growth is absorbed at the expansion joint, virtually eliminating longitudinal thermal expansion stress and the risk of cyclic fatigue.



▲ **FIGURE 5:** Finite Element Analysis (FEA) of Tubesheet Stress

In comparative designs lacking the tube stress reliever, Finite Element Analysis (FEA) modeling reveals tube-to-tubesheet stresses of up to 22,000 psi (152 MPa) for duplex stainless steel which has endurance limit of around 17,000 psi (117 MPa). This translates to an estimated lifespan of approximately 9.5 years under normal operating conditions. This lifespan will be significantly shorter for lower grade materials such as 304 and 316L due to their higher rates of thermal expansion (higher stresses) and lower strength (diminished fatigue limit).

The expansion joint couplings used on Endura+ are an established technology with decades of proven performance in similar applications of pipe alignment and thermal expansion. Unlike bent tubes or internal bellows, the expansion joint is external to the pressure vessel, easily inspectable and designed to last many decades. In the extremely unlikely event the expansion joint needs to be replaced, the simple procedure takes little time, and requires no cutting and no welding. This is an industry first, and a Fulton exclusive.

ELIMINATING LOCALIZED BOILING

Despite the name, a condensing boiler operates in a pressurized hot water system that should ideally never experience any phase-change boiling. Should boiling occur within the heat exchanger, the violent process of steam forming and collapsing in small pockets causes scale to build as impurities precipitate out. This phenomenon is known as localized boiling. Deposits decrease efficiency, and worse, scale and steam pockets act as insulative barrier preventing the water from performing its task of cooling the heat exchanger tubes. As a result, metal temperatures and stress further increase, accelerating fatigue, eventually leading to a heat exchanger failure.

Water-side scale and corrosion is generally not covered under any manufacturer's heat exchanger warranty, making the elimination of localized boiling a paramount long-term durability concern for boiler owners and operators.

The occurrence of localized boiling is a consequence of lack of engineering paid to water flow management inside the pressure vessel. Flow hallways in conventional tubesheet patterns experience poor mixing and cannot provide adequate cooling to the tubes. A bad situation made worse, an unsealed water baffle allows flow to shortcut through gaps in baffle openings around the tubes, depriving design path areas of the heat exchanger of much-needed flow. The resulting dead-zones create metal hot spots where the vaporization temperature is exceeded, consequently, localized boiling occurs.

Fulton has solved these concerns through multiple breakthrough inventions. To eliminate flow hallways, the Endura+ uses a unique tubesheet pattern, a patent pending concentric staggered ring configuration. While patent pending gasketed baffles seal around the tubes to ensure water travels only along the intended engineered flow paths. The combination of these advancements comprehensively solves the challenge of protecting the heat exchanger from localized boiling, ensuring many more years of efficient and reliable service.

CONCLUSION

Through the use of duplex stainless steel, the external tube stress reliever, a state-of-the-art tube pattern, and advanced water baffling techniques, Fulton has made it possible to significantly extended the operating life of the condensing boiler. The Endura+ is backed by a lifetime thermal shock warranty, the best in the industry.

Fulton is a premier provider and innovator of heat transfer solutions backed by over 70 years' of expertise manufacturing boilers, and 30 years' experience in condensing boilers. Fulton are the technical experts when it comes to revolutionary clean-slate heat exchanger designs simultaneously optimized for durability, efficiency and reliability.

SOURCES

- Stainless Steels Technical Data Sheets, Allegheny Technologies Incorporated (ATI Metals)
- Aluminum Casting, AZO Materials
- Compliant Mechanisms Research, Brigham Young University, Dept. of Mechanical Engineering
- "Stainless Steel in the Brewery", John C. Tverberg, Technical Quarterly
- Mechanical Properties Creep and Fatigue, European Space Agency