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FINAL REPORT

GTI PROJECT NUMBER 15311

DOE Contract DE-FC36-00ID13904

Super Boiler: Packed Media/Transport Membrane Boiler Development and Demonstration

Reporting Period:
May, 2000 – September, 2009

Prepared For:
U.S. Department of Energy
Mr. Bill Prymak
DOE Project Officer, Golden Field Office
303-275-4931
bill.prymak@go.doe.gov

GTI Technical Contact:
Mr. David Cygan
R&D Manager
847-768-0524
david.cygan@gastechnology.org

Gas Technology Institute

1700 S. Mount Prospect Rd.
Des Plaines, Illinois 60018
www.gastechnology.org

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EXECUTIVE SUMMARY

Gas Technology Institute (GTI) and Cleaver-Brooks developed a new gas-fired steam generation system—the Super Boiler—for increased energy efficiency, reduced equipment size, and reduced emissions. The system consists of a firetube boiler with a unique staged furnace design, a two-stage burner system with engineered internal recirculation and inter-stage cooling integral to the boiler, unique convective pass design with extended internal surfaces for enhanced heat transfer, and a novel integrated heat recovery system to extract maximum energy from the flue gas.

With these combined innovations, the Super Boiler technical goals were set at 94% HHV fuel efficiency, operation on natural gas with <5 ppmv NOx (referenced to 3%O_2), and 50% smaller than conventional boilers of similar steam output. To demonstrate these technical goals, the project culminated in the industrial demonstration of this new high-efficiency technology on a 300 HP boiler at Clement Pappas, a juice bottler located in Ontario, California.

The Super Boiler combustion system is based on two stage combustion which combines air staging, internal flue gas recirculation, inter-stage cooling, and unique fuel-air mixing technology to achieve low emissions rather than external flue gas recirculation which is most commonly used today. The two-stage combustion provides lower emissions because of the integrated design of the boiler and combustion system which permit precise control of peak flame temperatures in both primary and secondary stages of combustion.

To reduce equipment size, the Super Boiler's dual furnace design increases radiant heat transfer to the furnace walls, allowing shorter overall furnace length, and also employs convective tubes with extended surfaces that increase heat transfer by up to 18-fold compared to conventional bare tubes. In this way, a two-pass boiler can achieve the same efficiency as a traditional three or four-pass firetube boiler design. The Super Boiler is consequently up to 50% smaller in footprint, has a smaller diameter, and is up to 50% lower in weight, resulting in very compact design with reduced material cost and labor costs, while requiring less boiler room floor space.

For enhanced energy efficiency, the heat recovery system uses a transport membrane condenser (TMC), a humidifying air heater (HAH), and a split-stage economizer to extract maximum energy from the flue gas. The TMC is a new innovation that pulls a major portion of water vapor produced by the combustion process from the flue gases along with its sensible and latent heat. This results in nearly 100% transfer of heat to the boiler feed water. The HAH improves the effectiveness of the TMC, particularly in steam systems that do not have a large amount of cold makeup water. In addition, the HAH humidifies the combustion air to reduce NO_x formation. The split-stage economizer preheats boiler feed water in the same way as a conventional economizer, but extracts more heat by working in tandem with the TMC and HAH to reduce flue gas temperature. These components are designed to work synergistically to achieve energy efficiencies of 92-94% which is 10-15% higher than today's typical firetube boilers.

INTRODUCTION AND MARKET OVERVIEW

Natural gas is widely used in the industrial sector, most prominently for process heating, steam generation, power generation (including combined heat and power systems, CHP), space heating, and other uses (Figure 1). Boilers represent a key application for natural gas in the industrial sector, consuming an estimated 1.5 quadrillion Btu's of energy each year.

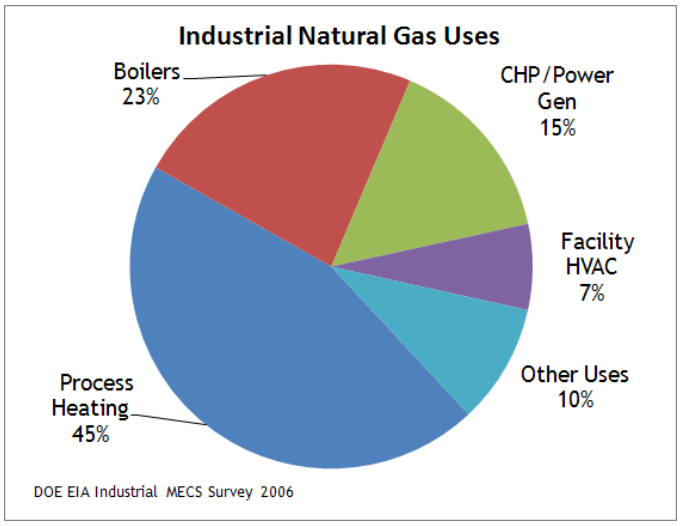

Figure 1: Industrial Natural Gas Uses (DOE-EIA MECS)

Waste heat recovery opportunities in process heating and steam generation represent a key opportunity for energy efficiency improvements in the industrial sector. For industrial boilers, efficiency improvements of 15 percent could yield annual energy efficiency improvements of nearly 225 Trillion Btu.

Table 1 provides an overview of the industrial boiler population, broken down by size range. Boilers up to 50 MMBtu/hr comprise the largest portion of boiler population. Many of these are industrial firetube boilers, typically less than 1200 boiler horsepower (about 40 MMBtu/hr). These are widely used in all segments of the industrial market, including food processing, paper, chemicals, metals, and other manufacturing operations.

Table 1: Industrial Boiler Population (Source: DOE/ORNL - EEA)

	Food	Paper	Chemicals	Refining	Metals	Other Industrial	Total
< 10 MMBtu/hr	6,570	820	6,720	260	1,850	7,275	23,495
10-50 MMBtu/hr	3,070	1,080	3,370	260	920	3,680	12,380
50-100 MMBtu/hr	570	530	950	260	330	930	3,570
100-250 MBtu/hr	330	540	590	200	110	440	2,210
>250 MMBtu/hr	70	490	350	220	120	110	1,360
Total	**10,610**	**3,460**	**11,980**	**1,200**	**3,330**	**12,435**	**43,015**

The current stock of industrial steam boilers in the U.S. is rapidly aging (Figure 2), and there is a clear need for advanced technologies to enable more efficient, cost-effective, and environmentally clean steam generation.

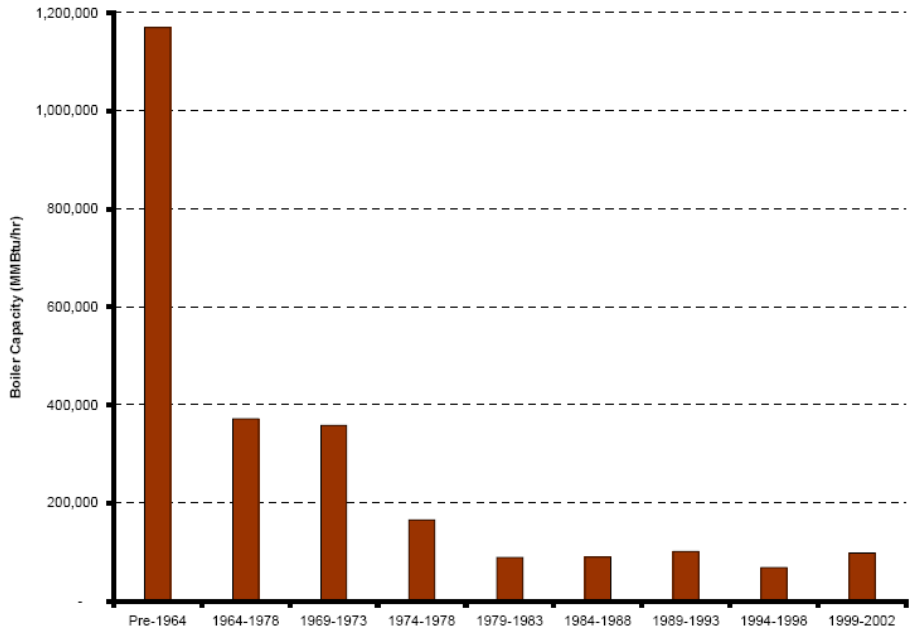

Figure 2: Age Distribution of US Industrial Boilers (DOE/ORNL – EEA)

To address this opportunity, the project undertook the development of a "Super Boiler" technology platform in cooperation with the US natural gas industry and other industry partners and stakeholders. The goal of this program was to achieve the following goals:

- 94% energy efficiency (higher heating value, HHV)
- 5 vppm NO_x
- 50% reduction in footprint and weight
- Reduced life-cycle costs

SUPER BOILER TECHNOLOGY

Studies have estimated the breakdown in useful energy delivered in steam systems and the myriad of ways in which energy losses occur (Figure 3). Only about 56% of input energy ends up as delivered energy, while up to 44% of the energy that goes into producing and delivering steam can end up in losses. The most significant inefficiencies come from exhaust energy losses from the boiler flue gases.

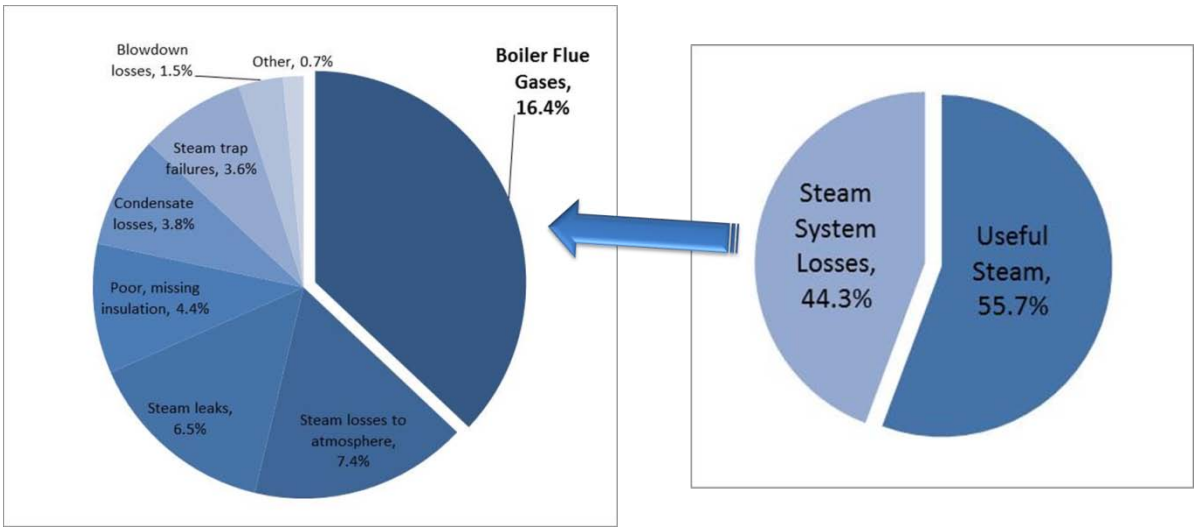

Figure 3: Steam System Useful Output and Source of Losses

The energy in boiler flue exhausts includes the sensible energy related to temperature as well as a significant portion that is related to water vapor; condensation of water vapor can release significant amounts of energy that can be recovered (while also potentially recovering and re-using water derived from combustion byproducts in the steam generation process). Sensible heat recovery can achieve up to 88% efficiency. Going beyond this level of efficiency requires water vapor condensation. Natural gas exhaust systems have about 18% water vapor by volume – which is related to about 10% of the fuel energy input. To achieve on the order of 93-95% higher heating value (HHV) efficiency requires water condensation and latent heat recovery.

In traditional condensing equipment, this results in a corrosive condensate due to the absorption of carbon dioxide into the water condensate (yielding a pH of about 3-5). This can be problematic due to its corrosive nature, impacting metal materials or requiring treatment prior to disposal. The method of heat and water developed and proven in this program, however, uses a unique nano-porous membrane technology to achieve high-performance, yet low-pressure drop, extraction of energy and water from natural gas exhausts. The transport membrane condenser (TMC) technology was a key technological outcome of this program.

Figure 4 depicts the efficiency and exhaust temperatures of a conventional boiler (around 410°F, depending on steam pressure/temperature) along with a series of heat-recovery options including economizers and the TMC technology. Combined with other elements of the Super Boiler technology, boiler efficiency levels of 94-95% are possible (depending on make-up water conditions and other factors).

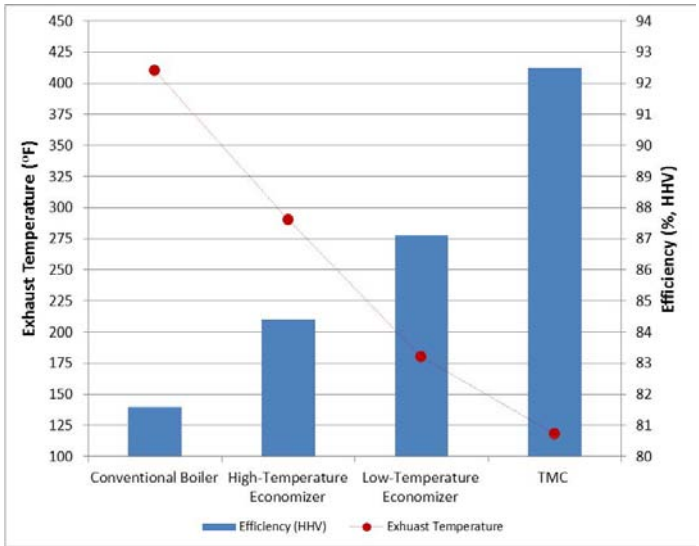

Figure 4: Example Exhaust Temperature and Efficiency of Boilers

In this program, GTI and Cleaver-Brooks developed a new gas-fired steam generation system, the Super Boiler, for increased energy efficiency, reduced equipment size, and reduced emissions. The system consists of a firetube boiler with a unique staged furnace design, a two-stage burner system with engineered internal recirculation and inter-stage cooling integral to the boiler, unique convective pass design with extended internal surfaces for enhanced heat transfer, and a novel integrated heat recovery system to extract maximum energy from the flue gas (Figure 5).

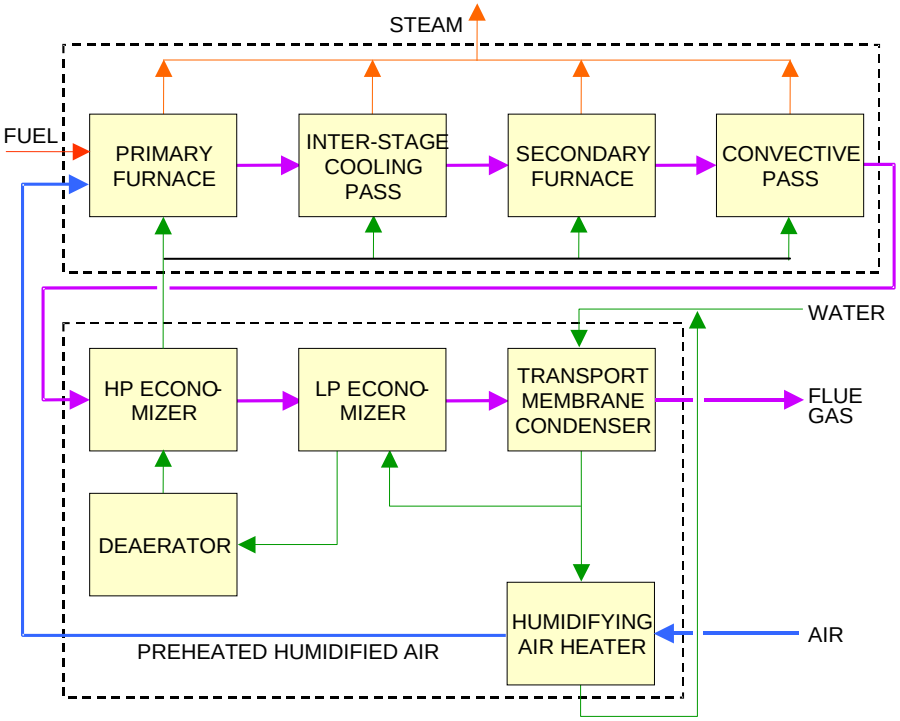

Figure 5: Schematic Diagram of Two-Stage Super Boiler System

For enhanced energy efficiency, the heat recovery system uses a transport membrane condenser (TMC), a humidifying air heater (HAH), and a split-stage economizer to extract maximum energy from the flue gas. The TMC is a new innovation that pulls a major portion of water vapor produced by combustion from the flue gas along with its sensible and latent heat. This results in nearly 100% transfer of heat to the boiler feed water. The HAH improves the effectiveness of the TMC, particularly in steam systems that return a significant amount of condensate to the boiler. In addition, the HAH also humidifies the combustion air to reduce NO_x formation.

The split-stage economizer preheats boiler feed water in the same way as a conventional economizer, but extracts more heat by working in tandem with the TMC and HAH to reduce flue gas temperature. These components are designed to work synergistically to achieve energy efficiencies of 92-95%, which is 10-15% higher than the typical firetube boiler technology that operates around 80-82% efficient.

To reduce equipment size, the Super Boiler's dual-furnace design increases radiant heat transfer to the furnace walls, allowing shorter overall furnace length, and also employs convective tubes with extended surfaces that increase heat transfer by up to 18-fold compared to conventional bare tubes. In this way, a two-pass boiler can achieve heat transfer from the combustion gases that previously required a three or four-pass design. The boiler is consequently up to 50% smaller in footprint, has a smaller shell diameter, and is up to 50% less in weight, resulting in savings in material cost and boiler room floor space.

Finally, the Super Boiler combustion system combines deep air staging, internal flue gas recirculation, inter-stage cooling, and unique fuel-air mixing technology to achieve low emissions rather than the most widely used method of external flue gas recirculation. This kind of clean combustion is made possible because of the integrated design of the boiler and combustion system which permits precise control of peak flame temperatures in both primary and secondary stages of combustion. The two-stage combustion consists of two combustion chambers with a fuel rich primary zone and a staged air secondary zone. The two stages are separated by a convective heat transfer pass that lowers the temperature of the fuel rich primary gases before the combustion is completed in the secondary zone. The typical low-NOx technology used today has limitations because it tries to control the peak flame temperatures in one stage with external flue gas to achieve below 9 ppmv NOx, making combustion hard to maintain and more prone to combustion instability, unless a method of stabilization is employed. Furthermore, this performance is achieved at low excess air throughout the firing range, less than 3% O_2, for optimal energy efficiency, which also distinguishes this technology from current that requires stack oxygen as high as 6%. This further benefits efficiency.

The individual components of the Super Boiler went through a series of laboratory testing and field testing programs prior to commercialization. This culminated in a key field demonstration at Clement Pappas in Ontario, California that showcased this cutting edge technology in an industrial setting. In the following sections, we highlight key elements of this system and the results of the field demonstration at Clement Pappas.

KEY TECHNOLOGY SUBSYSTEMS AND TESTING

The status of the Super Boiler technology is described in terms of the status of the two components of the Super Boiler: the two stage firetube boiler and the TMC-based heat recovery system.

The boiler is of firetube design. However, unlike a conventional firetube boiler with one combustion chamber, the Super Boiler has two separate combustion chambers with an inter-stage cooling section between the two combustion chambers (Patent # 6,971,336 B1); thus the

term two-stage firetube boiler. These two separate combustion chambers provide for the two-stage combustion system of fuel rich (1/6 air to fuel ratio) combustion in the primary zone and a secondary combustion zone where the remaining combustion air is provided to complete the combustion (Patent # 6,289,851). Figure 6 shows a depiction of the two-stage boiler and burner configuration.

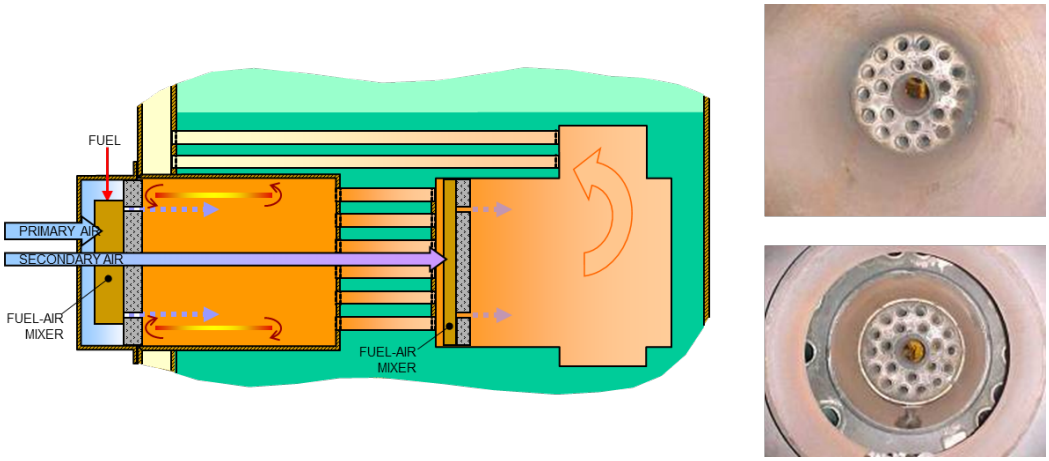

Figure 6: Two-Stage Firetube Boiler Design for Low Emissions and Compactness

The firetube design is also a two-pass design, i.e. the first pass is achieved in the combustion sections and the second pass is within the convective section where multiple small convective tubes are employed. The Super Boiler employs Cleaver-Brooks “AluFer” (aluminum fins) inserts into a portion of the convective tube length to extract additional heat from the flue gases in the convective section of the boiler. The Super Boiler also uses a rear water cooled door to eliminate refractory in the back of the boiler and this rear door provides for complete access to the secondary combustion chamber and the turning section from the first to the second pass of the boiler.

The first boiler of the Super Boiler two-stage, firetube design was a laboratory 75 HP 150 psig steam design (3 MMBtu/hr firing rate) unit and was tested from July 2004 to July 2005 at GTI. The burner was of gun style with external combustion air fan. This laboratory experimental boiler was fired as high as 5 MMBtu/hr natural gas flow and achieved less than 5 ppm NO_x and less than 10 ppm CO over the range of 1 to 5 MMBtu/hr input with oxygen in the flue gas in the range of 1-3 % at steady state conditions.

Figure 7: First-Generation Super Boiler Lab Test at GTI

The first-generation heat recovery system employed microchannel economizer panels supplied by Pacific Northwest National Lab (PNNL). These are shown in Figure 8. This economizer design was tested up to full boiler load, confirming ability to reduce flue gas from 380°F to 160°F with gas-side pressure drop at design value of 2.0"wc.

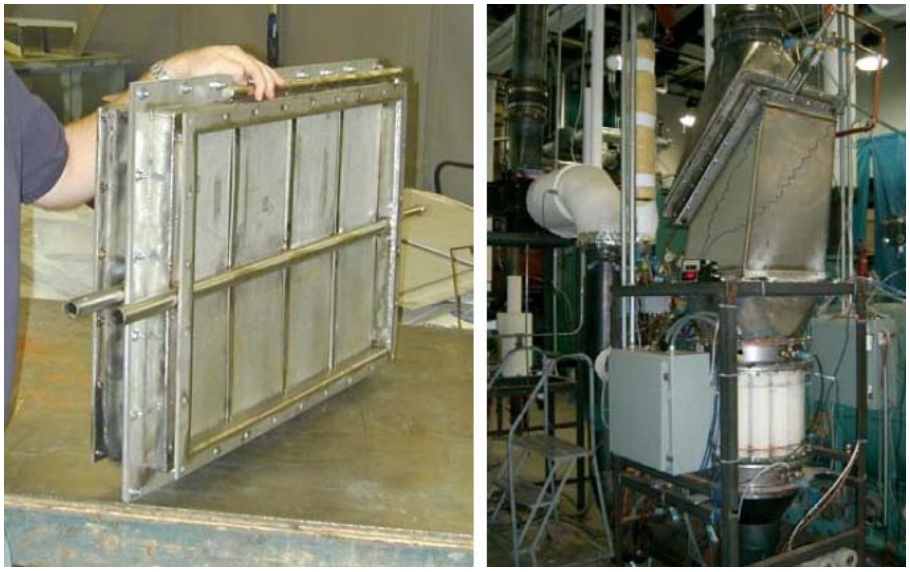

Figure 8: First-Generation Economizer Using PNNL Microchannel Heat Exchanger

Located downstream of the microchannel heat exchanger was the first-generation TMC module (Figure 9). This low-pressure-drop device became a key feature of the program, enabling simultaneous recovery of low-temperature heat as well as condensation and recovery of pure water from the exhaust stream. The ability to selectively condense and recover water that could be used as part of the steam loop was a key development that resulted from the Super Boiler program. Within the tubular heat recovery module is a nano-porous membrane that is key to the achieving: (1) high selectivity, (2) high water flux rates, and (3) low pressure drop.

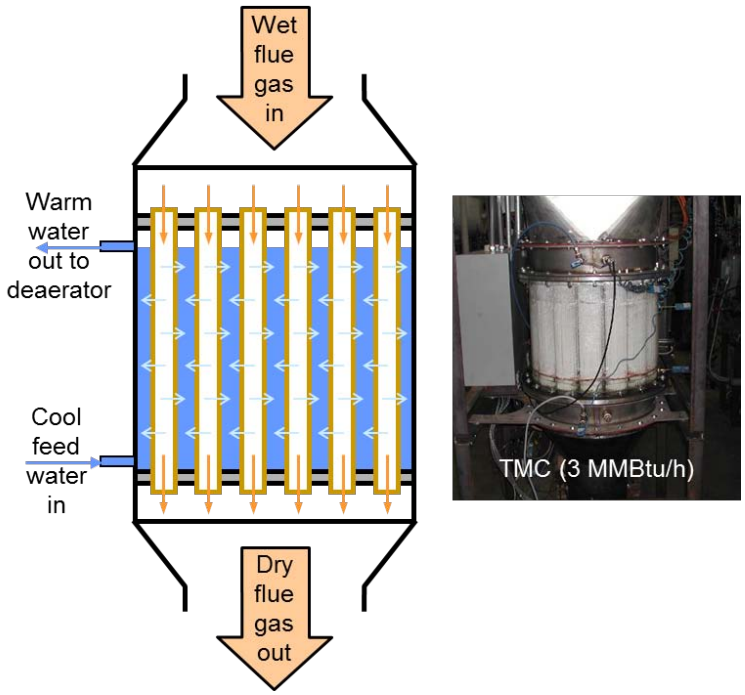

Figure 9: First-Generation Transport Membrane Condenser (TMC) Module

Figure 10 shows the complete set-up for lab testing of the first-generation Super Boiler technology. The results of this testing confirmed the ability of the core two-stage burner and TMC-based heat recovery system to meet the overall program goals for low emissions and high efficiency. These results enabled movement to an initial field test of an integrated system at a suitable industrial setting.

Figure 10: Lab Test of First-Generation Super Boiler

A subsequent 300 HP 150 psig steam design of a two-pass, firetube boiler (conventional single combustion chamber) with AluFer tube inserts in convective pass tubes and the rear water cooled door was then field tested with a first-generation TMC-based heat recovery system in Alabama (at Specification Rubber) beginning in 2005. It confirmed the successful application of the AluFer tubes to provide a compact boiler footprint for the 300 HP size with boiler flue gas temperature of 50°F above saturated steam temperature and successful operation of the rear water cooled door.

Figure 11 shows a picture of the boiler and high-pressure economizer (HPE) being installed at Specification Rubber in Alabama. Figure 12 shows the low-pressure economizer (LPE) and transport membrane condenser (TMC) heat and exhaust water recovery system at the field test site.

Figure 11: Super Boiler and High-Pressure Economizer at Alabama Field Test Site

Figure 12: Low-Pressure Economizer and Transport Membrane Condenser at Alabama Site

A comprehensive data acquisition system was installed at the Alabama field test site to gather data on system performance and efficiency. Under these conditions, the unit met 93.9% (HHV) efficiency, with an exhaust temperature of 123°F. Note that the exhaust temperature and the dewpoint temperature are essentially identical. The TMC module has successfully extracted water content from the exhaust stream, allowing the exhaust gases to leave at saturated conditions. Typically, exhaust water vapor recovery on the order of 40-60% are possible using the TMC technology (depending on make-up water conditions and other factors).

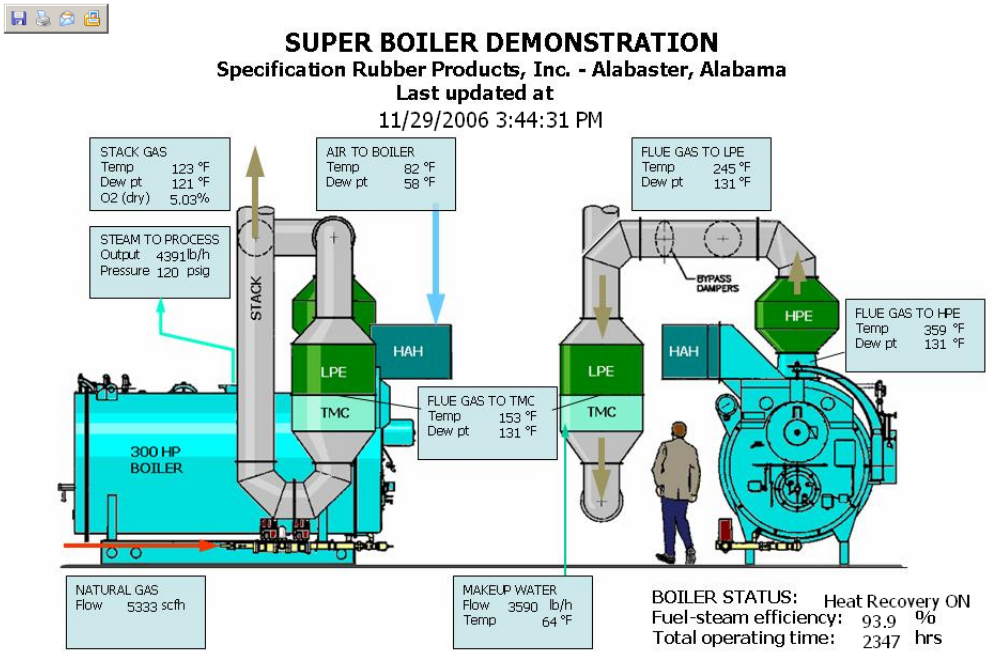

Figure 13: Example System Operating Data at Alabama Field Test Site

The next-generation 300 HP Super Boiler was designed and fabricated in 2006, and tested as part of the development of the two-stage combustion system at the Cleaver-Brooks Thomasville, GA plant from the fall of 2006 to the spring of 2007. It should be noted that the primary zone burner on the 300 HP Super Boiler is applied as part of the Cleaver-Brooks standard integral front head design of the boiler which includes the combustion air fan in the integral head.

GTI worked through R.F. MacDonald (RFM), authorized sales/service rep for project partner Cleaver-Brooks, Inc. to install the second-generation Super Boiler at a juice bottling plant in Ontario, California, operated by Clement Pappas & Company (CPC). The facility (Figure 14) had one 600-HP boiler but had space for a second boiler. The Clement Pappas site operated 24 hours a day, 7 days a week, thus offering a good opportunity for annual fuel savings.

Clement Pappas Entrance | Boiler/Compressor House | Boiler Room Interior

Figure 14: Clement Pappas Pictures of Host Site

GTI and Cleaver-Brooks completed design and fabrication of the Super Boiler system for field demonstration. The system consisted of the following components:

1. Firetube boiler, staged/intercooled design rated for 300 horsepower steam (150 psig)
2. Two-stage natural gas combustion system including flame safety system
3. Hawk ICS control panel with parallel positioning FAR controls
4. Blow down valves and piping
5. Feed water valves and piping
6. Steam spool piece, non-return valve, and steam stop valve
7. Level Master water level control
8. Modulating feed water control valve and bypass loop
9. Gas train and regulator
10. Cain high-pressure economizer
11. Bypass damper
12. Cain low-pressure economizer
13. Transport membrane condenser (TMC)
14. Humidifying air heater (HAH)
15. Heat recovery control panel
16. Required pumps, sensors, and control valves for heat recovery system
17. Sample coolers
18. Chemical feed system

The boiler was designed jointly by GTI and Cleaver-Brooks and fabricated by Cleaver-Brooks at their production facility in Thomasville, Georgia. The combustion system was designed by GTI and integrated by Cleaver-Brooks with their integral head design, and was fabricated by their Industrial Combustion division in Monroe, Wisconsin. Economizers were supplied by Cain Industries per specifications by Cleaver-Brooks. The TMC and HAH were designed and manufactured by GTI. Remaining components were purchased from various vendors. Photographs of the TMC and HAH are shown in Figure 15.

TMC HAH

Figure 15: Pictures of TMC and HAH

Figure 16 shows a series of pictures taken during the system installation at Clement Pappas.

Heat Recovery Skid Set In Position

Boiler Set In Place Below Heat Recovery Skid

Wiring Heat Recovery Junction Box

Humidifying Air Heater Connected

TMC, Stack, and Reheat Line

View From Behind Existing Boiler

Figure 16: Boiler Installation Pictures

Front of Boiler and Access Stairway

Heat Recovery Skid Viewed from Left Side

Boiler and Heat Recovery Skid Viewed from Back

Welcome Banner from Clement Pappas

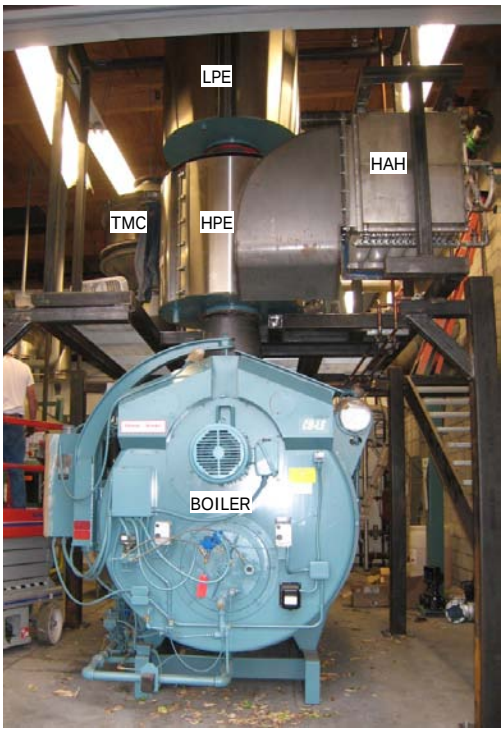

Figure 16: Boiler Installation Pictures (continued)

Emissions performance was one of the key parameters during the testing program in Southern California (due to more stringent NO_x emissions in that region). Figure 17 shows the corrected NO_x emissions monitored continuously for nearly 28 hours. The data points were recorded at five second intervals. The average and standard deviation for all the continuous data recorded during this 27.9 hour time period was 4.0 ppmv and 0.9 ppmv, respectively.

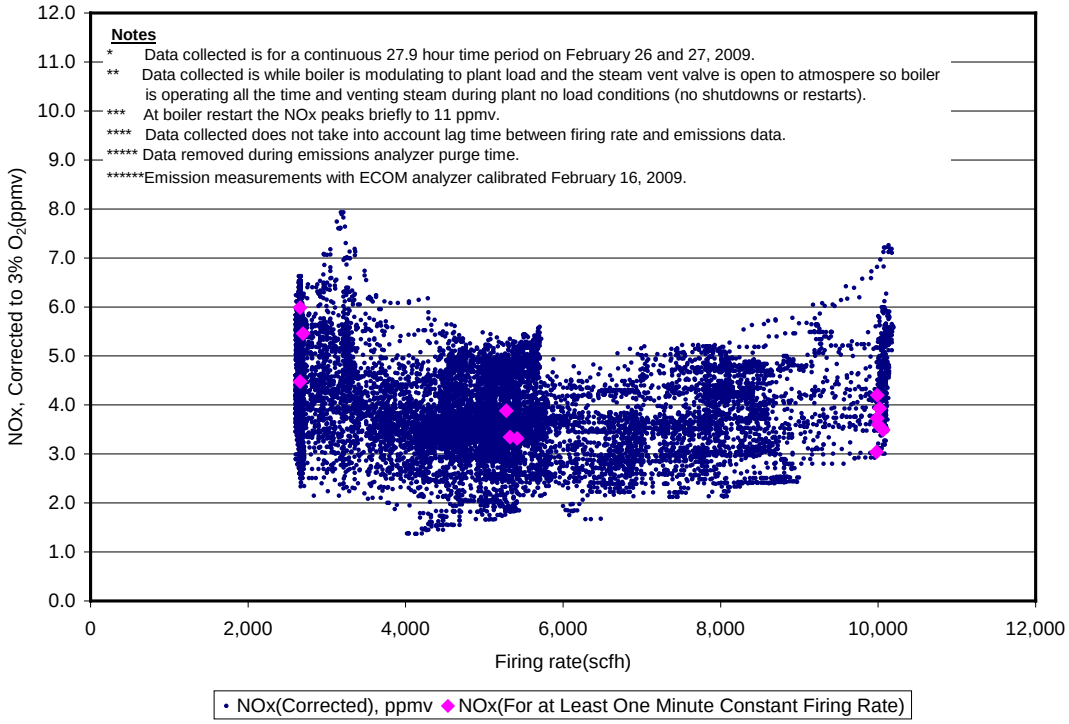

Figure 17: NO_x Emissions Data at Different Firing Rates, February 27, 2009

At the Clement Pappas site, the efficiency of the Super Boiler with the advanced heat recovery skid (AHRS) consistently operated between 92-93% (HHV). The lower-than-anticipated efficiency was due to makeup water conditions – both the volume of make-up water and its temperature. One of the original requirements during the job site selection was to have a makeup water requirement greater than 25% for optimal TMC operation. This is important so the water temperature in the TMC stays cold enough so that the vapor will condense on the membrane tubes for transport through the membrane. The amount of makeup also impacts the amount of water going through the low pressure economizer (LPE) to the makeup tank. If makeup is low then the LPE cannot lower the flue gas temperature to an acceptable dew point before it goes into the TMC. The amount of makeup water in this test ended up around 12-15%.

Overall, the testing of the Super Boiler technology at Clement Pappas was successful in demonstrating the low-emission capability of the two-stage combustion technology and the ability of the TMC-based heat recovery system to deliver acceptably high efficiency (92-93%) despite less-than-optimal make-up water conditions. As with the Alabama field test, the TMC module demonstrated very good robustness over an extended operating period.

The following is a list of results from the Clement Pappas testing:

- The two-stage combustion system proved to be stable and reliable through the firing range.

- Initial operation of the Super Boiler showed a 24% reduction in fuel usage compared to existing boiler operation.
- The heat recovery system worked well despite a low makeup water requirement of only 12-15%.
- The Super Boiler followed the site's steam load and was able to meet quick steam load demands.
- The HRS has handled the large and relatively short steam loads and extensive on and off cycling well.
- The low makeup water conditions caused more reliance on the HAH to dissipate heat from the TMC.

In parallel with the Clement Pappas field testing, GTI worked on a next-generation design of the TMC technology to achieve improved performance, more compactness, lower assembly cost, and improved accessibility for field maintenance. The next section delves into the TMC technology and the final design configuration that resulted from this program.

TMC Heat Recovery System

The TMC Heat Recovery System is based on GTI (Patent # 6,517,607) transport membrane condenser (TMC), which recovers both sensible and latent heat from flue gases to achieve energy efficiency up to 94 % (HHV). The TMC recovers a portion of the sensible heat in addition to recovering up to about 50% of the flue gas water vapor from boiler flue gases which then can be reused in the system.

The key to the TMC technology is based up a concept called capillary condensation. Using this approach, it is possible to achieve high water selectivity, high water transport rates, and low pressure drop (which is particularly critical to exhaust heat recovery). Figure 18 shows the substantially higher flux rates possible with capillary condensation compared to conventional diffusion-based processes.

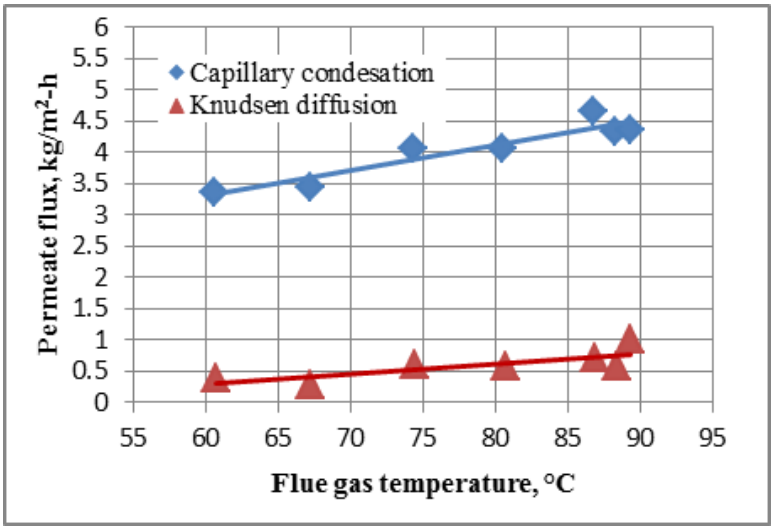

Figure 18: TMC Flux Rate Comparison

Figure 19 shows a depiction of the TMC tube and the layered elements contained within the tube. This includes a proprietary nanoporous layer that provides the key function of achieving selective water condensation and high-transport rates using capillary condensation. The condensation of water within the nanoporous membrane pores prevents the transport of carbon dioxide or other non-condensible gases such as nitrogen through the membrane. The tubes simultaneously transport water as well as the latent heat that evolves during the condensation process. This highlights the unique simultaneous ability of the TMC technology to capture heat and water, with very low pressure drop.

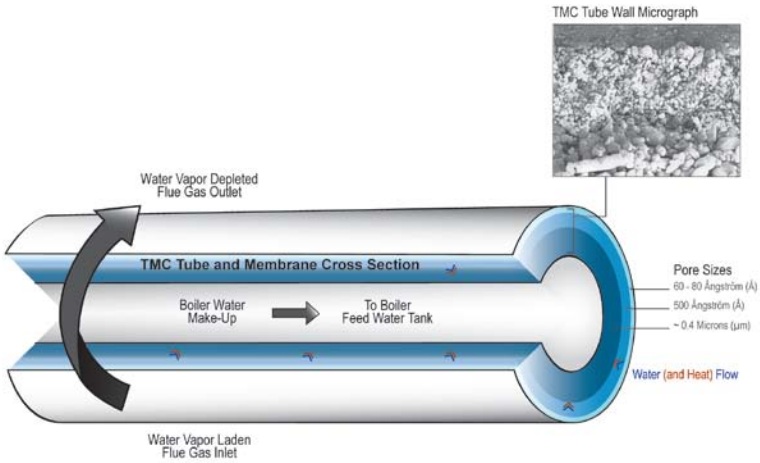

Figure 19: TMC Tube and Nanoporouos Membrane

During the course of this project, the configuration of the TMC tube bundle module (Figure 20) evolved from the first generation (where exhaust gases passed through the TMC tube) to the second generation (where the exhaust gases passed through the exterior of the tubes). The second-generation design improved overall performance, cost, and reduced pressure drops in the system.

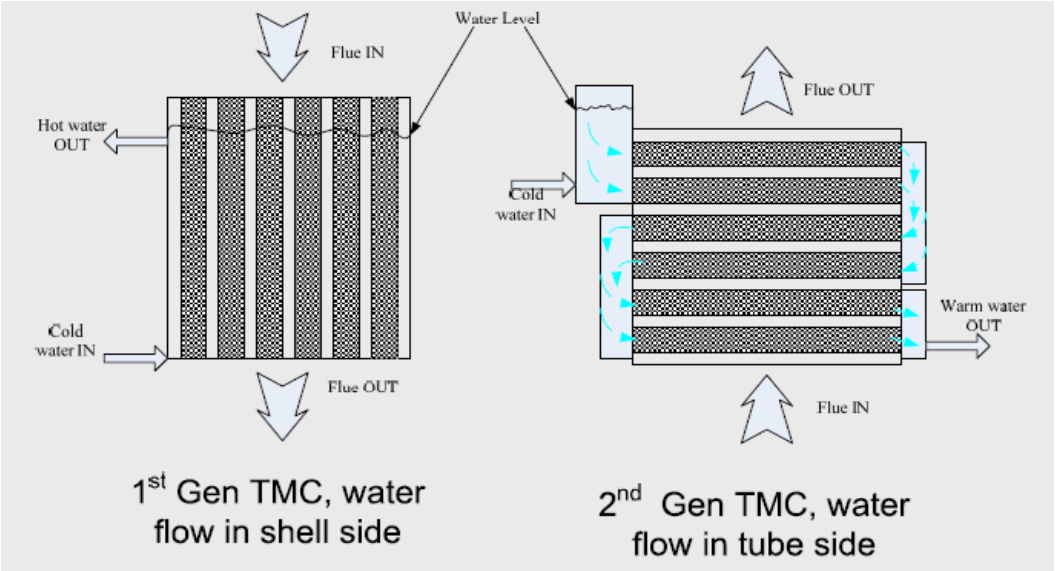

Figure 20 First and Second Generation TMC Module

The 2nd generation TMC heat recovery system employs “drawer-type” TMC modules that allows for easy access for maintenance. A standard 33 HP TMC module is presently being utilized on a number of additional Super Boiler applications. Figure 21 shows an example of this latest design approach. In this configuration, exhaust gases pass vertically up through the module and release sensible and latent heat, while a portion of exhaust water vapor condenses and is transported to the annular part of the tubes. In the annular section is flowing boiler make-up and pre-heat water that is raised in temperature prior to going into the firetube boiler. With this approach, pure water from natural gas combustion products is mixed with water in the steam loop to offset fresh water needs.

Figure 21: Latest Generation TMC Tube Assembly/Module

Figure 22 shows the latest configuration of the TMC-based heat recovery system. Boiler feedwater is introduced into the top row of TMC modules and cascades downward where it increases in temperature before leaving the advanced heat recovery system for introduction into the boiler.

Figure 22: Latest Generation TMC-Based Advanced Heat Recovery System

ENERGY AND ECONOMIC BENEFITS OF TMC-BASED HEAT RECOVERY SYSTEM

The advanced heat recovery system (AHRS) using the transport membrane condenser (TMC) technology provides energy efficiency, water savings, and energy cost saving benefits for consumers. Figure 23 shows the potential annual energy savings as a function of firing rate and annual operating hours for a nominal 300 hp boiler. Energy savings as high as 10,000-12,000 MMBtu/year are possible on a 300 hp boiler operating at high firing rates for 8000 hours per year.

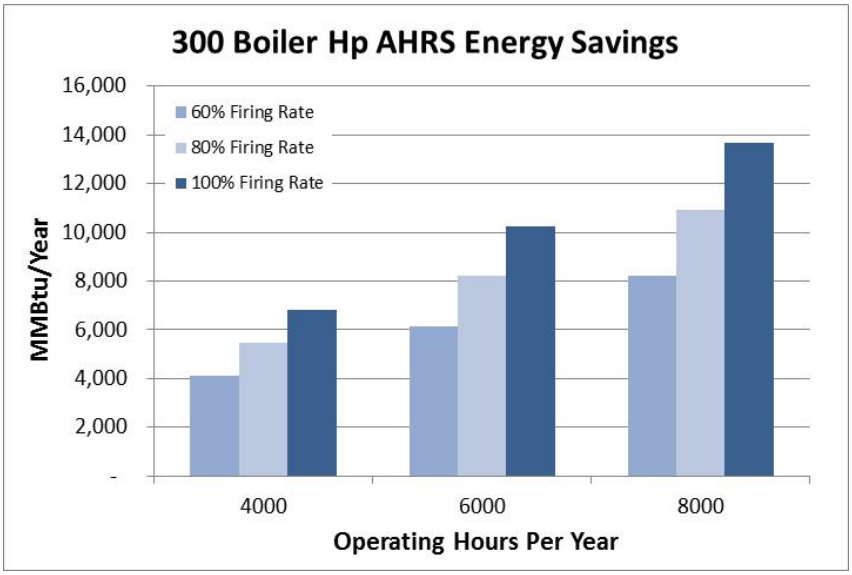

Figure 23: AHRS Energy Savings Benefits

Figure 24 shows the potential water recovery rates at different firing rates and operating hours for a 300 hp boiler (assuming a 40% exhaust water recovery rate). Annual water savings of 300,000 to 4000,000 gallons are possible at higher firing rates and operating hours. This water provides economic savings through avoided fresh water purchase, water treatment costs, and disposal.

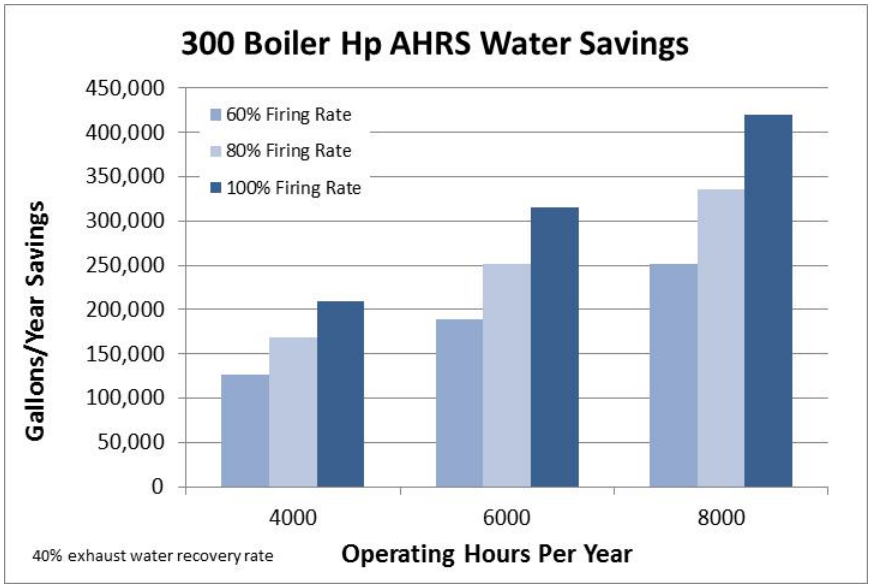

Figure 24: AHRS Annual Water Recovery Rates

Figure 25 shows the potential energy savings with ARHS, assuming $8/MMBtu natural gas costs. Energy cost savings of $80,000-$110,000 per year are possible compared to a conventional boiler.

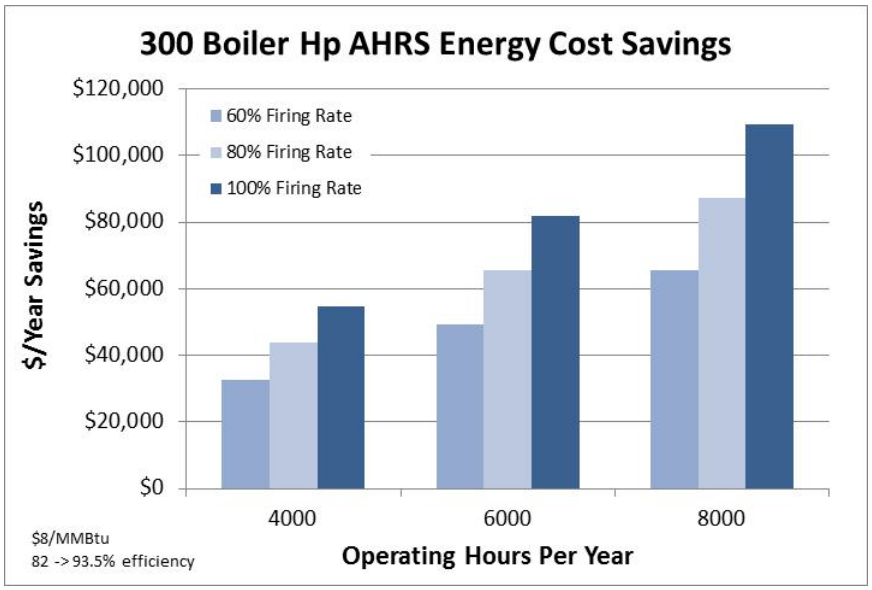

Figure 25: AHRS Energy Cost Savings

CONCLUSIONS

The technology developed within the Super Boiler program was shown in lab testing and extensive field testing capable of achieving the stated project goals:

- 94% HHV fuel efficiency
- Less than 5 ppmv NO_x
- 50% smaller footprint than conventional boilers of similar steam output

Two core technologies were developed in this program:

- A patented two-stage firetube boiler burner that is capable of achieving the program goals of less than 5 ppmv NO_x emissions
- A patented low-temperature heat recovery technology, the transport membrane condenser (TMC), that simultaneously achieves heat and water recovery from natural gas exhaust streams

The following is a list of results from the Clement Pappas testing:

- The two-stage combustion system proved to be stable and reliable through the firing range.
- Initial operation of the Super Boiler showed a 24% reduction in fuel usage compared to existing boiler operation.
- The heat recovery system worked well despite a low makeup water requirement of only 12-15%.
- The Super Boiler followed the site's steam load and was able to meet quick steam load demands.
- The advanced heat recovery system handled the large and relatively short steam loads and extensive on and off cycling well.
- The low makeup water conditions caused more reliance on the humidifying air heater (HAH) to dissipate heat from the TMC.

Continuous improvements and design enhancements were made to improve the performance, manufacturing cost, pressure drop, and serviceability of the TMC modules.

Economic analyses point to the potential for significant energy efficiency, energy cost, and water recovery benefits from using this technology on industrial boilers.