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Cost and Performance Report

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High Efficiency – Reduced Emissions Boiler Systems for Steam, Heat, and Processing

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ACRONYMS AND ABBREVIATIONS

ALC	Automated Logic Corporation
BLCC	Building Life-Cycle Cost
BS	British Standards
CIBO	Council of Industrial Boiler Owners
CO	carbon monoxide
CO_2	carbon dioxide
COTS	commercial off-the-shelf
DoD	(U.S.) Department of Defense
DOE	(U.S.) Department of Energy
ECIP	Energy Conservation Investment Program
EIA	(U.S.) Energy Information Administration
EISA	Energy Independence and Security Act
EO	Executive Order
ESCO	Energy Service Company
ESTCP	Environmental Security Technology Certification Program
FEMP	Federal Energy Management Program
Fireye	Fireye, Inc.
FRPC	Federal Real Property Council
GUI	graphical user interface
IRR	internal rate of return
MMBtu	one million British thermal units
NAVFAC	Naval Facilities Engineering Command
NIST	National Institute of Standards and Technology
NO_x	nitrogen oxides ($NO+NO_2$).
NPV	net present value
O_2	oxygen
OMB	Office of Management and Budget
ORNL	Oak Ridge National Laboratory
PI	proportional-integral
PID	photoionization detector
SIR	savings to investment ratio

SoA	state-of-the-art
TECHVAL	Navy Technology Demonstration and Validation
TRL	Technology Readiness Level
UESC	Utility Energy Service Contract
USEPA	U.S. Environmental Protection Agency
UFC	Unified Facility Criteria
USACE	U.S. Army Corps of Engineers
UTC	United Technologies Corporation
UTRC	United Technologies Research Center
WSU	Washington State University
WVA	Watervliet Arsenal

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ACKNOWLEDGEMENTS

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1.0 EXECUTIVE SUMMARY

1.1 OBJECTIVES OF THE DEMONSTRATION

The demonstration of a cost effective solution to the problem of improving boiler efficiency and reducing emissions by means of a novel combustion control system and a sensor package was the main objective of the Environmental Security Technology Certification Program (ESTCP)-funded project, High Efficiency – Reduced Emissions Boiler Systems for Steam, Heat, and Processing. United Technologies Research Center (UTRC) and Fireye, Inc. (Fireye), worked together to bring the new combustion control and monitoring system from Technology Readiness Level (TRL) 4 to TRL6 and demonstrate its effectiveness in a retrofit of the 30-year-old Trane 25 one million British thermal units (MMBtu) dual fuel boiler (natural gas and No. 2 oil) at Watervliet Arsenal (WVA) in New York state. The demonstration occurred in three phases, aiming at assessing efficiency performance with the legacy mechanical system, the commercially available state-of-the-art (SoA) oxygen (O_2) trim solution, and the newly demonstrated carbon monoxide (CO)/O_2 trim solution. In this way, a comparison among technologies and benefits associated with adoption of the proposed solution could be precisely quantified.

1.2 TECHNOLOGY DESCRIPTION

The demonstrated control solution is intended for retrofit of hot water or steam generation boilers with capacities larger than 10 MMBtu/hr. The developed technology includes continuous monitoring of flue gas concentrations of O_2 and CO to improve the boiler fuel-to-steam efficiency by means of regulation of the burner inlet fuel valve and air damper. The new boiler efficiency control system incorporates a novel control algorithm, low cost sensors to monitor exhaust composition and a user friendly tool for visualization of boiler performance. The controller continuously maintains the optimum proportion of fuel and air feeding the burner in order to reduce inefficiencies arising from excess air content while preventing unsafe operation arising from incomplete combustion. This new system is an evolution of a commercially available O_2 trim solution developed on the Fireye PPC4000 product platform and contrasts with legacy systems with preset mechanical linkage by using electronic driven servomechanisms to set the ratio of fuel to air.

1.3 DEMONSTRATION RESULTS

During a one-year testing campaign between February 2011 and March 2012, it was demonstrated that the new system would enable fuel savings of 4% for typical utilization with natural gas, and an equivalent reduction of carbon dioxide (CO_2) emissions. Stated performance objectives (5% fuel costs savings) were not met for the demonstration boiler when fired with natural gas. Nevertheless, the investment in the new technology on a similar boiler burning natural gas would pay back in slightly more than 2 years with expected fuel savings of $17,000 yearly. Although the new system was not tested with No. 2 oil, it was demonstrated that 7% fuel savings are achievable with a SoA efficiency control product on which the new technology is based.

Boiler performance on all configurations was assessed in terms of combustion efficiency, fuel-to-steam efficiency, and emission levels, and compared with preset performance objectives. As

performance is dependent on the specific operating point of the boiler, the evaluation was performed at different steady state conditions corresponding to levels of steam output and corresponding firing rates. The following was observed for operation with natural gas:

- Combustion efficiency improved with the adoption of O_2 trim technology by 1% to 2% across the firing range. An additional improvement of 0.5% to 1% was observed by introducing CO/O_2 trim at an operation range below 60% of maximum fuel utilization. Measured performance did not meet originally stated objectives (more than 6% improvement over baseline).
- The improvements above had an impact on overall fuel-to-steam efficiency, with improvements of 2% to 3% with the introduction of O_2 trim over baseline, and an additional 0.5% to 1% with CO/O_2 trim for operating ranges below 60% of fuel utilization. Measured performance did not meet originally stated objectives (more than 5% improvement over baseline).
- Throughout the demonstration, CO and nitrogen oxides ($NO+NO_2$) (NO_x) levels remained within target boundaries.

Based on standard utilization assumptions and at current fuel prices, economic performance was quantified and compared to pre-demonstration targets (system payback of less than one year for the demonstration boiler). It was calculated that for a 25 MMBtu/hr boiler fired by natural gas:

- The adoption of O_2 trim would enable yearly savings exceeding 2400 MMBtu of gas, about 3%, or $13,500 cost savings. The further upgrade to CO/O_2 trim technology would enable yearly savings exceeding 3000 MMBtu of gas, about 4%, or $17,000 cost savings.
- Payback for upgrading to O_2 trim technology would be 2 years with an net present value (NPV) of $77,000 over 10 years. For the CO/O_2 trim solution, 2.4 years payback and NPV of $88,000 was estimated.
- Every year, 144 tons of CO_2 emissions would be avoided with O_2 trim, 181.5 with CO/O_2 trim technology.

During the demonstration, the controller performance was observed relative to ease of use, installation, and maintainability, and positive feedback relative to its deployment was collected.

1.4 IMPLEMENTATION ISSUES

When adopted for all 10 to 100 MMBtu/hr oil and natural gas boilers older than 10 years across the U.S. Department of Defense (DoD), the demonstrated technology has the potential to save $150 million of fuel costs annually and avoid the emission of 768,000 tons of CO_2.

Other findings impacting broad implementation include:

- Savings and economic indicators would be much more favorable for larger boilers. Estimates for a natural gas-fired 100 MMBtu/hr boiler showed payback of 4 months and fuel cost savings in the order of hundreds of thousands of dollars.

- Fuel-to-steam efficiency improvements of 7% to 8% were measured across the firing range when No. 2 oil was used as fuel, but demonstration was limited to O_2 trim technology. Estimates for operation with oil are of 7% ($140,000) fuel savings and payback of 0.2 years for a 25 MMBtu/hr boiler.
- An estimate of potential overall savings across DoD, based on the demonstration results, indicate potential savings of $150 million of fuel costs annually and avoid the emission of 769,000 tons of CO_2.

In summary, it was demonstrated that combustion control technology is a viable solution to achieve substantial fuel savings and reduced carbon footprint and easy to install for boiler retrofit, enabling quick return on investment. In particular, it has been shown how CO/O_2trim technology can lead to substantial energy savings. The new CO/O_2 control solution was tested at its prototype stage (TRL6) and further development, testing, and certification is needed for product release (TRL8). Adoption across DoD will be facilitated by this study and will enable further engagement with key decision makers in installations and energy service companies.

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2.0 INTRODUCTION

2.1 BACKGROUND

In the United States there are approximately 163,000 industrial and commercial boiler systems delivering steam for industrial processes, space heating and hot water. Boilers with capacity larger than 10 MMBtu/hr account for 28% of the total and provide 85% of the overall U.S. boiler capacity. Ninety three percent of all such systems are more than 10 years old (Oak Ridge National Laboratory [ORNL], 2005) and typically operate at efficiencies between 70% and 80% (Harrold, 1999). Under the pressure of rising fuel costs and increasingly stringent policies limiting the emissions of polluting gases and overall carbon footprint, boiler owners are looking at cost effective ways to renovate legacy systems.

Reducing boiler inefficiencies, fuel expenditures and emission output is key towards meeting DoD goals on energy security and environmental impact in line with DoD Instruction 4170.11 (DoD, 2005). This directive includes efficient boilers among the recommended solutions for facility energy conservation. Of the $3.5 billion per year the DoD spends on facility energy consumption, ~$850 million (25%) of it is estimated to be for fuel consumption in boilers larger than 10MMBtu/hr, based on an equivalence to the U.S. inventory (U.S. Energy Information Administration [EIA], 2003). The Army owns 214 sites with >10 MMBtu/hr oil/gas boilers for a total capacity of almost 34,000 MMBtu/hr, more than 90% of which are older than 10 years. The total boiler capacity for DoD can be estimated at 82,000 MMBtu/hr by scaling proportionally with total owned building area (data from the Federal Real Property Council [FRPC], 2006 and Andrews, 2009). Clearly, the DoD objective to increase energy efficiency and reduce carbon footprint must include solutions targeted to large boilers.

Combustion of fossil fuels is still by far the most utilized technology for generating hot water and steam in industrial and commercial applications. Cleaner alternative energy technologies lack the flexibility and availability required for most near-term applications. High efficiency, low emission combustion is therefore considered the most viable approach to reduce fuel cost and mitigate undesired environmental effects.

Three possible paths to renovation are currently available: (1) replacement with new boilers (either condensing boilers allowing efficiencies above 90% or noncondensing ones with improved heat exchanger, burner, and control system); (2) replacement of the burner for better air/fuel mixing and combustion; or (3) adoption of SoA combustion control systems. While the first and second paths lead to the highest efficiency gains, they are capital investment intensive with paybacks of several years (Durkin, 2006), and often require significant infrastructural changes, which further add to cost. An upgrade of the combustion control system is a more cost effective solution (Eoff, 2008), often generating payback in less than 1 year (Wright, 2001) due to lower first cost and significant recurring fuel savings associated with more efficient boiler operation.

The SoA approach to upgrading the combustion control systems consists of substituting the mechanical linkage between the air inlet damper and the fuel inlet valve with a digital controller acting on electromechanical positioning servomechanisms. The controller sets the opening of fuel and air inlets at all working conditions (firing range) of the boiler as imposed by the installer

during a commissioning phase. In addition to this so-called parallel positioning controller, an O_2 trim function ensures that the O_2 concentration measured in the exhaust gases is kept at a pre-set low value (generally 4%, depending on the burner installed), thus allowing efficient operation under all boiler working conditions.

While the current technology can ensure efficiencies around 80%, it has the following shortcomings, which prevent reaching the highest possible efficiency gains through combustion control:

- Flue gas O_2 concentration cannot be further reduced because of safety concerns associated with incomplete combustion. For this reason, efficiency is not increased further, limiting gains to ~5%.
- The commissioning of the system is performed manually, which can lead to configuration errors and variability leading to suboptimal operation, as well as progressive mistuning.
- Continuous emission monitoring is unavailable, preventing minimum emission operation and real-time verification compliance with air permits.
- Calibration for a specific fuel is necessary so adopting fuels other than oil and gas is not practical.
- Commercially available O_2 sensor stack probes are expensive (~$10,000 per sensor, installed cost), thus decreasing the economic attractiveness of the retrofit.

Hence there is a need for a safe, low cost, robust approach that can be easily retrofitted into legacy boiler systems, with continuous optimization of air/fuel controls to attain maximum efficiency while monitoring and controlling operation to meet local emission regulations. Satisfying this need will reduce fuel consumption and carbon footprint in older boiler systems enabling them to be operated at the highest efficiencies possible through tight closed-loop control while maintaining low CO and NO_x emissions.

2.2 OBJECTIVE OF THE DEMONSTRATION

The project's objective was to mature boiler controls technology that enables higher efficiency operation of boilers via a simple changeover of the current legacy air-fuel mechanical linkage.

The objective of the demonstration at WVA was to evaluate and quantify performance of the new boiler control technology relative to baseline and SoA boiler control solutions. Performance in terms of energy savings benefits was characterized relative to the following innovation elements:

1. *CO-, NO_x-, and O_2-based boiler feedback control.* By using online feedback based on flue gas concentration measurements in addition to O_2, the new technology can enable improved boiler efficiency over SoA while maintaining a margin of safety under a broad set of conditions (e.g., varying air humidity, fuel composition, plant variability).

2. L*ow-cost sensors for CO, NO_x, and O_2 concentrations.* Commercial off-the-shelf (COTS) sensors configured to robustly measure target gas species concentration. Sensor robustness of the technology under demonstration includes the ability to operate under typical boiler room settings, to operate over time within an acceptable accuracy and limited drift, and to operate for safety critical applications by means of diagnostic functions.

3. *Assisted commissioning.* By utilizing assisted commissioning technology, which automates the boiler setting across the operating range, a reduction of commissioning time by 30% is achieved. NOTE: Evaluation of commissioning times was only partially performed during the demonstration, and assisted commissioning algorithm technology was not evaluated due to implementation problems during the execution of this demonstration program. See Section 6.0 for additional details.

Ease of use of the new boiler control technology during boiler set up and operation was also validated during the demonstration. Such attributes had to be ensured for plant managers and operators to fully benefit from the new technology as intended. To that end a visualization interface was deployed, displaying key performance metrics and operator tunable system parameters allowing boiler operators to visualize boiler operation online.

2.3 DRIVERS

Regulations and directives driving the need for demonstrating advanced boiler control technology are as follows:

- **Energy Policy Act of 2005.** Directs federal agencies to purchase Energy Star and Federal Energy Management Program (FEMP)-designated products when procuring energy-consuming items covered by the Energy Star program. Agencies must also incorporate energy-efficient specifications in procurement bids and evaluations. Energy Independence and Security Act (EISA) 07 Section 525.
- **Energy Independence and Security Act of 2007 (Title IV Subtitle C).** Requires that U.S. federal agencies improve energy efficiency and reduce greenhouse gas emissions by 30% by 2015 relative to a 2003 baseline. It also requires (sec 433) that new federal buildings must reduce fossil fuel-generated energy consumption, with 2003 as baseline, by 65% in 2015 and 100% by 2030. Provisions require federal procurement to focus on Energy Star and FEMP-designated products.
- **National Energy Conservation Policy Act (42 U.S.C. 8254(a)(1)).** Mandates the use of practical and effective present value methods for estimating and comparing life-cycle costs for federal buildings, using the sum of all capital and operating expenses associated with the energy system of the building involved over the expected life of such system or during a period of 40 years, whichever is shorter, and using average fuel costs and a discount rate.
- **Emergency Economic Stabilization Act of 2008.** Contains provisions for incentives relative to replacing equipment with high efficiency technology.

- **Executive Order 13423.** Mandates that new construction, major renovations, and repairs/alterations must comply with Guiding Principles (Optimize Energy Performance: energy efficiency, on-site renewable energy, measurement and verification and benchmarking) and 15% of existing building inventory by the end of FY2015 and incorporates outlined sustainable practices (sec 2(f)/OAA 09, sec 748).
- **Instruction 4170.11.** Provides procedures for DoD installation energy management and pertains to all phases of administration, planning, programming, budgeting, operations, maintenance, training, and material acquisition activities that impact the supply, reliability, and consumption of energy at DoD installations. This includes directives for upgrade to low energy solutions for new construction as well as renovation under the Energy Conservation Investment Program (ECIP).

If implemented across DoD, the technology demonstrated in this project would contribute to the increase of energy efficiency towards meeting EISA's stringent energy efficiency requirements and adopting more sustainable practices as instructed by Executive Order (EO) 13423. The proposed technology in combination with others aimed at reducing energy demand and making supply more efficient would enable meeting those goals. The application of the CO/O_2 trim control technology, if applied to new boilers, would enable energy saving necessary for obtaining Energy Star certification for the whole boiler system. Widespread boiler control updates could be possible by mandating their adoption and incentivizing upgrades via the DoD ECIP. The adoption of this technology would become even more relevant in the short term, as ramp up of renewable energy heating solutions on a large scale would occur in much longer term. Finally, whenever combustion-based renewable solutions are adopted (biofuels, biomass systems), the technology demonstrated in this project would find direct applicability.

3.0 TECHNOLOGY DESCRIPTION

3.1 TECHNOLOGY OVERVIEW

The boiler control technology consists of the following innovative elements:

1. **Control function update.** A novel control algorithm based on CO and O_2 emissions and that ensures safe operation using less than 2% excess O_2 concentration.
2. **Sensing devices.** In situ, low-cost gas sensors of O_2, CO, and NO_x for continuous emission monitoring of the exhaust composition and feedback to the combustion controller.
3. **Easy commissioning features.** Simplified manual commissioning procedures enabled by the new PPC4000 menu-based interface for quick setting of the air/fuel ratio across the boiler operating range.
4. **Graphical user interface (GUI).** A monitoring and data logging device providing real-time visualization of boiler performance metrics to the operator.

Advanced commissioning procedures were initially proposed to reduce installation and recalibration times, the occurrence of mistuning, and the need for frequent recalibration. However, those were not implemented in the final demonstration.

The technology was demonstrated on a legacy, single burner, 25 MMBtu/hr boiler located at the WVA central steam plant. The existing legacy combustion efficiency controller, based on mechanical linkage technology, was replaced with Fireye's SoA solution with O_2 trim. This controller was then updated with the novel control logic making use of additional measurements of flue gas CO and NO_x concentrations. COTS exhaust sensors were utilized making the proposed system cost effective compared to commercially available systems.

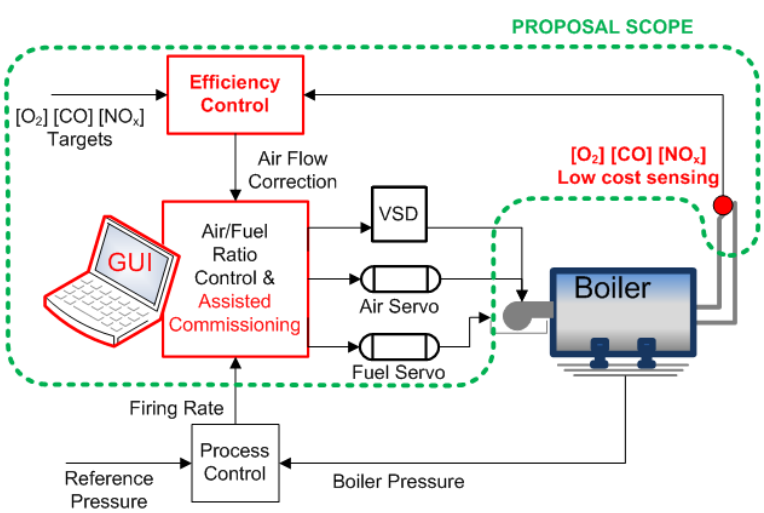

Figure 1. Schematic of the technology demonstrated.

Boiler fuel efficiency can be controlled by setting the correct proportion of fuel and air feeding the burner and depends on the unburned fuel, the inlet and outlet temperature of the gases, and the O_2 content of the exhaust (British Standards [BS], 1987). Boiler efficiency decreases as the air/fuel ratio increases; this change is accompanied by increase in the exhaust O_2 concentration. In contrast, very low air/fuel ratios result in incomplete combustion and potentially unsafe conditions manifested by a sharp increase in exhaust CO concentration. In legacy systems, the fuel-air ratio is maintained by a mechanical linkage, while SoA solutions are based on parallel positioning, O_2 trim technology. The lack of information on flue gas composition and relatively imprecise positioning of air and fuel opening require linkage systems to be set to operate often with 8%-10% excess O_2 (U.S. Department of Energy [DOE], 2006)(Washington State University [WSU], 2003) to guarantee an adequate safety margin (Eoff, 2008). Part load operation, variable environmental conditions, system drift, and linkage hysteresis over time cause performance degradation towards either more inefficient operation or potentially unsafe conditions (Figure 2). For this reason, legacy boiler efficiencies often degrade over time, resulting in estimated efficiencies of about 75%.

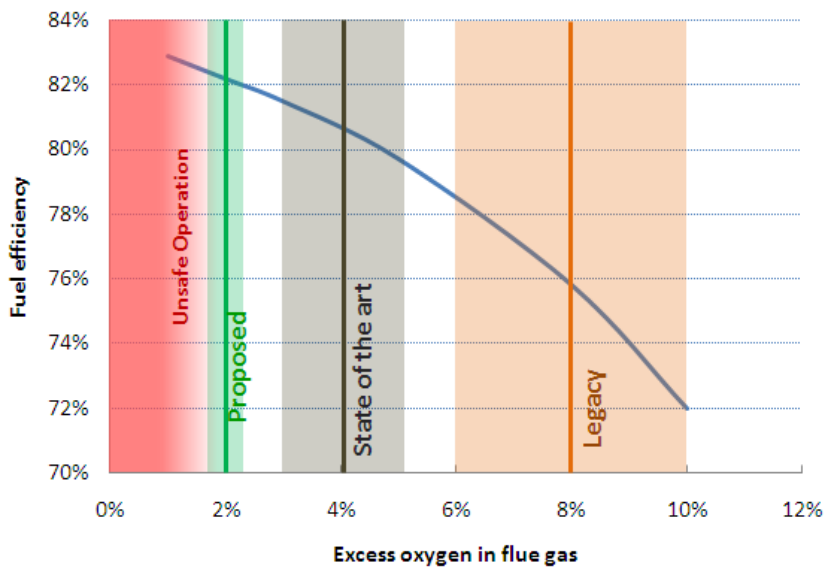

Figure 2. Efficiency gain enabled by reduction of excess air and variability.
(Harrold, 1999)
Evolution from legacy to SoA to proposed new technology.

In SoA solutions, improved positioning and O_2 concentration measurement enable the reduction of safety margins to a typical value of 4% and reduction of variability due to environmental factors and degradation, allowing efficiencies around 80%. The boiler and burner characteristics affect the efficiency curve and the region of safe operation and consequently the achievable efficiency. As SoA systems are based on microcontroller technology, the setting of the desired air and fuel servomechanism positions across the boiler's operating range can be performed manually during commissioning by operating a menu-based digital interface. It is imperative that menu-assisted procedures are intuitive enough to enable fast and precise setting.

Advancement to date of the demonstration technology can be summarized as follows:

2006: Fireye and UTRC developed SoA algorithm.

2007: Development of assisted commissioning algorithm on Fireye experimental boiler.

2008: Demonstration of efficient boiler operation with monitoring of CO concentration.

2009: Low cost multi-sensor system prototyped at Fireye.

June 2010: 4 different algorithms of CO/O_2 trim controls conceived at UTRC and demonstrated on Fireye's experimental boiler.

September 2010: Fireye PPC4000 parallel positioning boiler control system is released.

November 2010: A multisensor box prototype is designed and built to enable stack exhaust gas sampling and continuous monitoring of O_2, NO_x, and CO.

March 2011: CO/O_2 trim algorithm finalized, including the fuel micropulsing feature to anticipate CO spikes and increase control operation safety.

April 2011: Fireye PPC4000 with SoA O_2 trim control product is released.

June 2011: An improved CO sensor system prototype is designed and built.

November 2011: The CO/O_2 trim control is implemented on PPC4000 and tested at Fireye's boiler experimental facility.

January 2012: The new control system is installed at WVA.

A block diagram of the overall system is illustrated in Figure 3. The efficiency algorithm communicates with air/fuel positioning controls to dispatch optimal settings for the air and fuel servomechanisms actuating the air damper and natural gas supply valve. Information on the concentrations of O_2 and CO is provided to the controller by a continuous emissions measurement unit. Two additional gas monitoring devices (not used for control purposes) were installed to provide additional information on NO_x emissions, gas emissions redundancy, as well as evaluation of alternative CO sensing. The system also includes a GUI that reports all boiler operation information to the boiler operator.

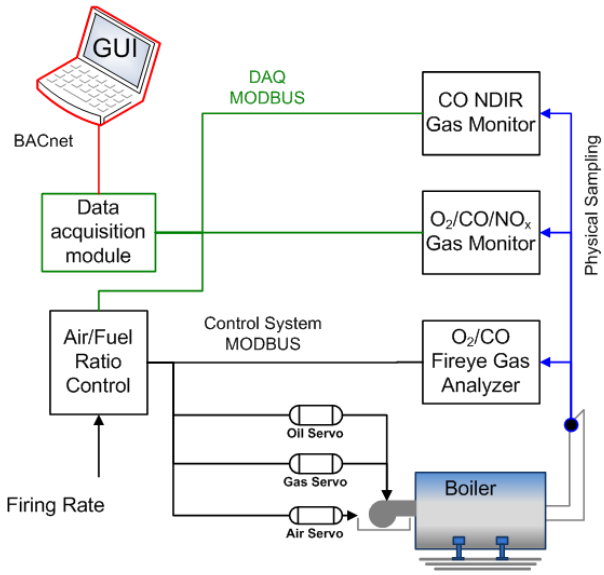

Figure 3. Block diagram of the system.

A detailed description of all the components can be found in Sections 2.1.1 through 2.1.3 of the Final Report.

3.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

The boiler control technology enables fuel savings while ensuring safe operation. Fuel efficiency improvements translate into reduced CO_2 emissions and fuel costs, which are the main drivers of boiler operating costs. By directly measuring concentrations of O_2, CO, and NO_x, the technology enables environmentally friendly operation and identifies maintenance needs as they arise. Additional benefits include robust operation in the face of varying environmental conditions and system degradation, adaptability to different boiler and oil/gas burner configurations, and extensibility to operation with nonconventional fuels (e.g., biogas and syngas).

Applicability of the technology is limited to single burner, noncondensing boilers fueled with gaseous or liquid fuel with capacities between 10 and 100 MMBtu/hr. Larger, single burner boilers use flow metering instead of simple positioning for air and fuel supply (fully metered controls). Modifications to the technology, including fully metered systems are possible. The technology can be implemented on smaller size boilers as well, but it may not be an attractive investment because of high first costs in relation to achievable fuel savings. The technology does not address the direct control of emissions and treatment of flue gases.

Expected efficiency improvements are generally of the order of 4-7% for noncondensing boilers, typically operating below or slightly above 80%. Higher efficiency improvements can certainly be obtained via boiler replacement and adoption of condensing systems often operating above 90%. Full boiler replacement, however, requires a greater investment, orders of magnitude higher than a control system upgrade. Whether full boiler or control system upgrade is preferable would mostly depend on availability of capital investment and the need of a complete infrastructural overhaul, for example, a migration from a centralized to a decentralized architecture of the heating system, from oil to natural gas, or from conventional to part renewable. Nonetheless, because of the short payback time, combustion control overhaul can provide short-term benefits even if a heating plant update is expected later.

Technology feasibility relies on the availability of robust, low-cost gas species sensing components. This is a quickly evolving technology and it is expected that costs will drop and more COTS sensors with the required accuracy and reliability will enter the market over the next few years. Future product enhancements will leverage new sensors based on emerging technologies with improved performance (e.g., drift compensation, faster response, and reduced maintenance) at lower cost while allowing sufficient component flexibility.

During the demonstration, it was noted that the algorithm is effectively able to maintain operation close to stoichiometric conditions by sensing the insurgence of CO spikes, therefore maintaining safe operation at the highest possible efficiency. This translates into significant improvement in terms of efficiency, especially at low firing rate conditions, where O_2 trim systems are typically commissioned in a conservative fashion imposing high O_2 target levels. On the other hand, the CO/O_2 trim technology adds some complexity to the commissioning of the boiler, as it requires:

- A new mindset: the installer should set commissioning points at lower O_2 target levels than for an O_2 trim system.
- Tuning of additional parameters, which determine the amplitude of fuel pulses and thresholds for triggering adjustments of the target O_2 levels.
- Very careful tuning of the air trim proportional-integral (PI) controller. Indeed, the CO/O_2 trim works adequately only if the PI controller is tuned so that the system does not react to rapid changes of O_2 and CO concentrations, and does not generate unwanted oscillations of the O_2 concentration. Gross mistuning of controller parameters can lead to reduced performance in terms of efficiency gains.

Benefits and drawbacks of the demonstration technology are summarized in Table 1.

Table 1. Table of benefits and drawbacks.

	Description	Typical excess O_2	Benefits	Drawbacks
Legacy	Fuel and air positioning set by means of mechanical linkage. Flue gas composition not measured.	8%	Low cost, familiar technology.	Large safety margin on excess O_2, performance drift due to linkage degradation, no emission monitoring.
SoA	Replacement of linkage with parallel positioning of inlet fuel and air. Flue gas O_2 concentration measured to trim excess air.	4%	Precise fuel and air modulation, lower excess air required, excess air is controlled and maintained.	Wide safety margin required to account for variable environment conditions and part load operation, especially at lower firing rates. No emission monitoring, high cost.
Demonstration	Parallel positioning system using measurements of flue gas CO and NO_x concentrations in addition to O_2. Availability of assisted commissioning feature for boiler tuning and setup.	2%	Detects unsafe operation via direct CO monitoring, improves part load performance, monitors and responds to high emissions. Adapts to degradation, changing conditions, and fuel properties.	Cost of additional sensing devices (to be reduced by leveraging sensors from automotive applications). Need for more careful tuning of the system parameters to ensure efficiency gains.

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4.0 FACILITY/SITE DESCRIPTION

The main boiler plant at WVA, Watervliet, New York was the site of the demonstration of the advanced boiler control technology. The demonstration was carried out on a 30-year-old 25 MMBtu/hr boiler manufactured by Trane.

The demonstration occurred at WVA's central boiler plant. The plant supplies steam to the Arsenal between the months of October and May, and it is available for maintenance only during the cooling season.

The central plant has three large boilers providing steam for heating and industrial use and a smaller auxiliary 25 MMBtu/hr water-wall, dual fuel boiler that is used during plant startup and in periods of peak demand. Boilers similar in size and age to the one selected for demonstration are in use at many DoD installations. For example, the Army owns 214 sites with >10 MMBtu/hr single burner oil/gas boilers, more than 90% of which are older than 10 years.

Figure 4. The demonstration boiler.

The boiler at WVA is duel fuel capable although it operates primarily on natural gas. Since the auxiliary boiler is not required to be continuously online, it offered the opportunity to perform off-line installation and calibrations during the heating season with minimal interference.

Data collection was conducted during the 2010-2011 and 2011-2012 heating seasons. The boiler plant personnel kindly agreed to make changes to the operating conditions of the boiler to fulfill the requirements of the test plan, greatly facilitating the task of data collection. For demonstration of the CO/O_2 trim algorithm, 24/7 data collection was not pursued as the prototype algorithm was largely untested and not UL certified. As collection sessions required frequent switching between operating modes and boiler shutdowns, those had to be performed carefully to avoid inducing unwanted oscillations in the operation of the other boilers. No major event at the boiler plant occurred that would have disrupted data collection, except for the planned summer shutdown.

The WVA boiler facility and in particular the auxiliary boiler to be used for the demonstration is fully accessible once the WVA point of contact submits a visitor request to security. The facility is staffed 24/7 and open year-round allowing for efficient installation, modification, and troubleshooting. Weather conditions are typical of the U.S. Northeast where boilers see maximum utilization during the October to May heating season.

Due to warm weather during the 2010-2011 heating season, the boiler plant was shut down one week earlier than planned, limiting the collection of SoA data. The 2011-2012 heating season was also characterized by unusually warm weather. This limited the possibility to operate the boiler at maximum capacity during many days. Also, switchover to oil did not occur for similar reasons (the gas utility forces WVA to switch to oil in situations of high natural gas demand). For this reason, collected data was limited to that acquired at low capacity operating points, thus reducing the confidence in performance across the entire firing range. Filling this gap by acquiring additional data at WVA would have required extending the project to the 2012-2013 heating season and hoping for colder weather conditions.

5.0 TEST DESIGN AND ISSUE RESOLUTION

5.1 CONCEPTUAL TEST DESIGN

The existing boiler control and monitoring setup was modified incrementally in three phases. In Phase I, instrumentation and a data acquisition system were installed to baseline system performance. Phase II included the installation of the SoA controller to quantify benefits of switching to that technology. In Phase III, the controller software was updated with the installation of the new sensor box (Fireye box) and benefits of CO/O_2 trim were quantified.

Phase I: Setup for boiler monitoring and baseline with legacy control (February 2010)

- The boiler was instrumented with metering devices to measure airside and waterside properties and enable precise quantification of boiler efficiency. Direct measurement of sufficiently accurate air flow measurements turned out to be impractical.
- Flue gas composition was measured to monitor combustion characteristics and emissions.
- Boiler process variables, i.e., water/steam pressure were also measured.

Phase II: Setup for tests with SoA control (October 2011)

- The setup was upgraded with the Fireye PPC4000 (UL listed) control system.
- The controller was connected to a safeguard system to ensure safe boiler shutdown.
- The fuel inlet valves and air damper were actuated by new Fireye servomechanisms.
- Steam flow and inlet temperatures sensors were repositioned to improve measurements.

Phase III: Setup for demonstration of proposed technology (January 2012)

- The setup was further upgraded by uploading the new controller software on the PPC4000 system and installing the Fireye Box to enable CO measurements and execution of the CO/O_2 trim control algorithm.

During each phase, the boiler was operated either in commissioning mode or in controlled mode. Automatic startup and shutdown procedures were executed anytime the boiler was brought online or off-line. Standard procedures did not change in the three phases of the demonstration.

A data acquisition system was installed prior to baseline testing. A detailed description of all sensors is available in Section 5.1.1 of the Final Report. The sensors were installed at the beginning of the demonstration prior to testing of the baseline configuration. Later, new sensors were added for the legacy, SoA, and CO/O_2 trim demonstrations.

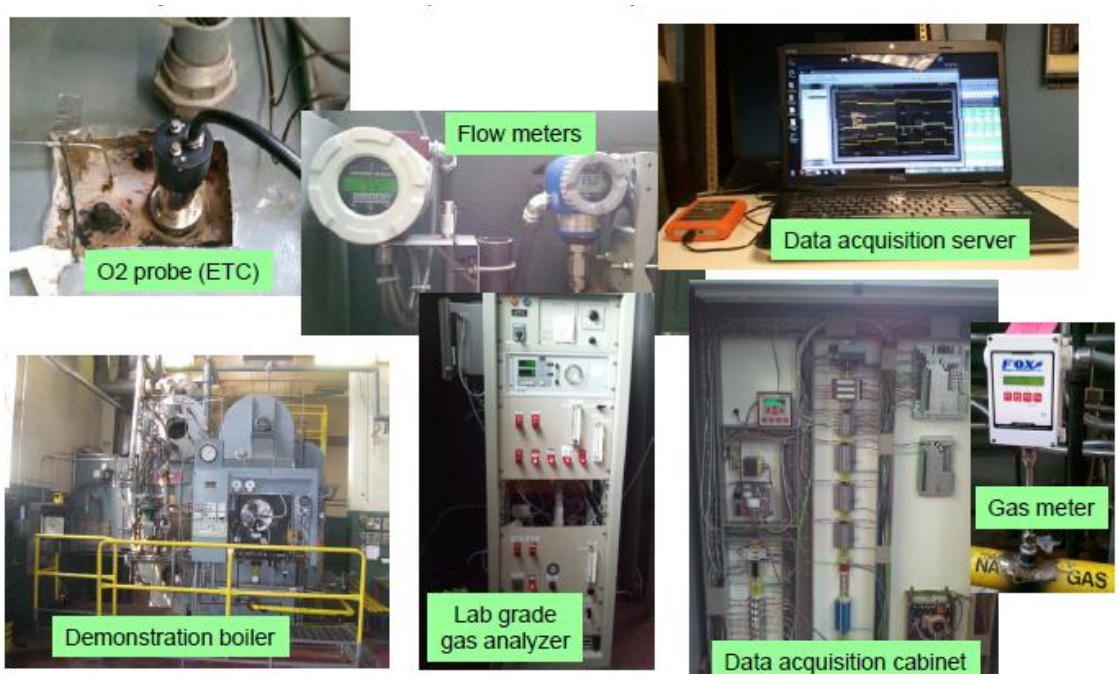

Figure 5. Baseline sensors and data acquisition overview.

For demonstration purposes, the boiler was operated at pre-set firing rates, with boiler plant pressure regulated by the master boiler.

5.2 BASELINE CHARACTERIZATION

Baseline characterization was carried out by operating the boiler with existing linkage-based controls. Data was collected to evaluate baseline performance under a number of distinct characterization scenarios, as described in detail in Section 5.2 of the Final Report.

Boiler operation characterization across the firing range. The boiler was operated at fixed, predefined firing rates or operating points ("low fire," 25%, 50%, 75%, and "high fire") for a predefined period of time.

Boiler characterization during regular operation. Extended operation tests were conducted to monitor the boiler operation across an extended period of time of more than 24 hours.

Commissioning. Baseline data on commissioning time for the linkage-based system was collected by performing a retuning session. Time to set the fuel-air linkage system across the firing range was assessed. It should be noted that what was performed was a fine tuning of an already installed device. This did not enable the evaluation of duration of first time commissioning.

Since WVA almost exclusively runs on natural gas, experiment repeats were done using that fuel. A few experiment sets relative to firing range characterization were performed using No. 2 oil. Performance evaluation with natural gas is also most relevant, as approximately 80% of DoD boilers use that fuel. The use of oil for heating will decline over time because of boiler conversion programs. Nonetheless, the application of combustion control technology to existing

boilers remains a worthwhile investment that will generate immediate energy savings. The adoption and diffusion of liquid biofuels will present efficiency improvement potential similar to those observed with oil.

Information on past year boiler performance was also obtained by WVA personnel. Information relative to steam output and stack oxygen concentrations were recorded. Of particular interest are historical daily averages of O_2 stack concentrations, as this measure is directly related to combustion efficiency. Data between 2007 and 2011, before the demonstration started, are reported in Figure 6. The chart shows all data between the 2007-2008 and 2010-2011 heating seasons. The cause of sudden drop of O_2 concentration is associated with retuning of the linkage system that was performed prior to start on the testing sessions.

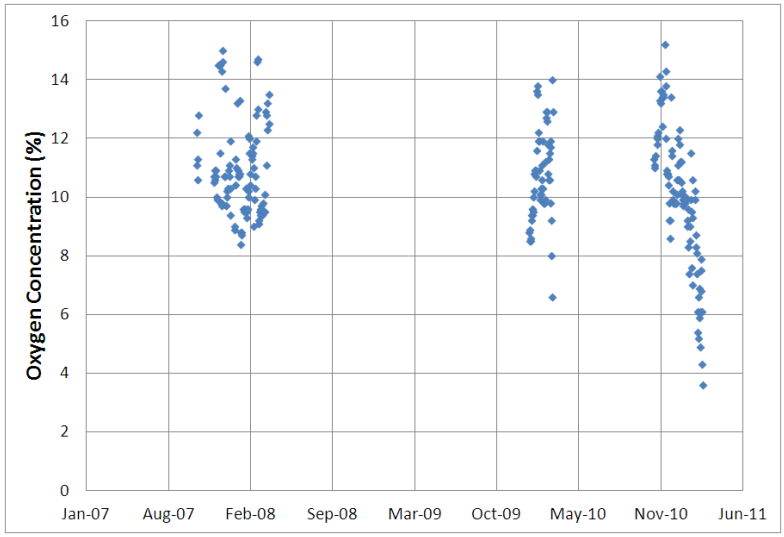

Figure 6. Historical daily average O_2 concentrations measured at the stack.

5.3 DESIGN AND LAYOUT OF TECHNOLOGY COMPONENTS

The advanced boiler control makes use of standard components that are part of the PPC4000 efficiency control system and builds advanced functionality by modifying some of them. The overall architecture and safety features do not change compared to the SoA solution. The reader should refer to Section 5.3 of the Final Report for a complete description of the layout. Some of the main components are illustrated in the Figures 7, 8, and 9.

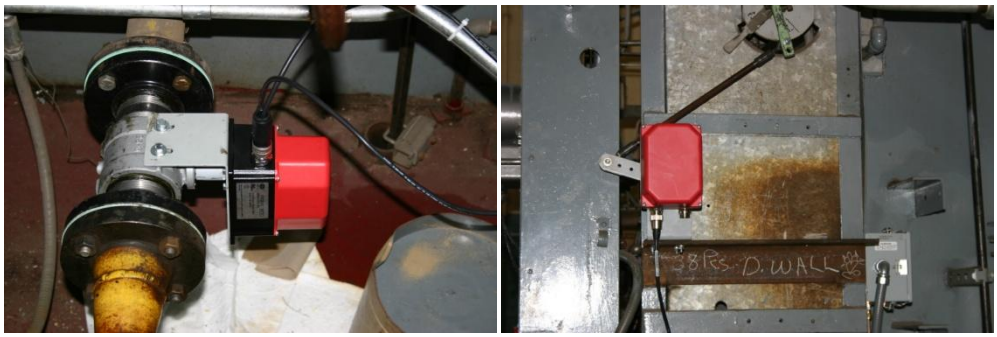

Figure 7. Fuel/air positioning electromechanical actuators.
Fuel servomotor on left, air servomotor on right.

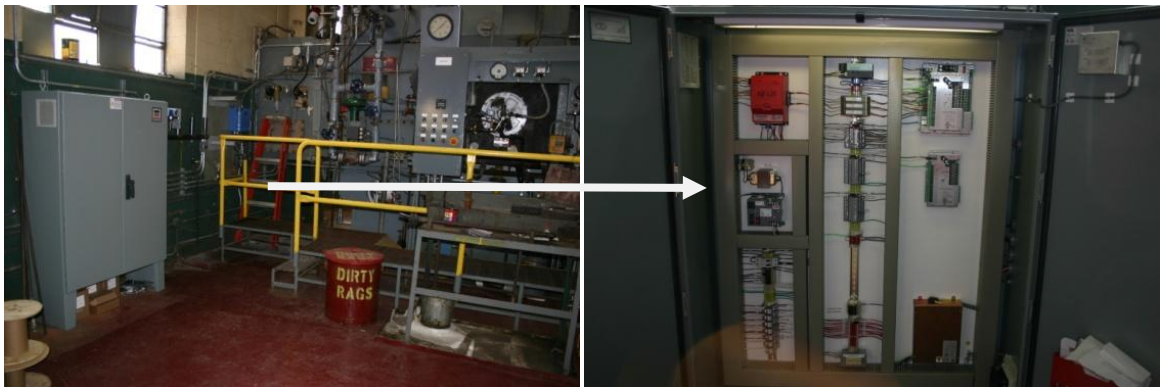

Figure 8. The boiler control system, located in an enclosure near the boiler.

Figure 9. The prototype multisensor box used for CO/O_2 trim closed loop control.

5.4 OPERATIONAL TESTING

Demonstration activities occurred between February 2011 and April 2011, resumed in October 2011, and were completed in March 2012. The following testing activities (described in detail in the Final Report, Section 5.4), were conducted:

1. Instrumentation and data acquisition system installation (December 2010 to January 2011)
2. Baseline characterization with linkage control (February 2011 to March 2011)
3. SoA characterization with PPC4000, O_2 trim mode (March 2011 to April 2012)
4. SoA characterization with PPC4000, O_2 trim mode (October 2011 to December 2011), with repositioned instrumentation
5. Legacy characterization with PPC4000, open loop parallel positioning mode calibrated to match boiler historical data (November 2011)
6. CO/O_2 trim characterization (February 2012 to March 2012)

7. Decommissioning (March 2012 to April 2012).

Activity 5 was not originally planned as part of the demonstration but was deemed necessary to measure boiler performance associated with the operation observed during the previous years' heating seasons as illustrated in Figure 6. Necessity of this step arose from the finding that, before activity 2, the boiler was retuned to operate at lower O_2 concentrations by plant maintenance personnel. It was therefore decided to collect data associated with both the retuned linkage and with operation reflective of legacy pre-demonstration O_2levels.

5.5 SAMPLING PROTOCOL

Data collection for each phase was initially planned for 2 months but was shorter for some configurations because of additional time required for development and installation. Equipment, particularly gas analyzers, was periodically calibrated to ensure correct reading of gas species. Redundant measurements of gas compositions were collected. Natural gas heating values and composition were obtained by the local utility and were compared to those of extracted gas samples. Generally, good agreement between data sets was observed.

Most of the data are for natural gas combustion. The Arsenal has an interruptible fuel service contract, whereby they are told when to switch over to oil operation. Due to weather conditions, during the testing time of this program, oil was used for a limited number of days. Data within 40-80% of maximum fuel flow rate was captured, providing an indication of system performance, which was extrapolated to calculate overall performance metrics. The acquisition of additional data would have required an extension of the demonstration to the 2012-2013 heating season but would have provided information across the full firing range and, if taken during different weather conditions, provided a better idea of the effect of weather variability on performance with oil.

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6.0 PERFORMANCE RESULTS

Performance assessments were based on data collected during the February 2011 – March 2012 testing period. During preliminary analysis it was observed that some of the instrumentation required repositioning to avoid inconsistencies. Repositioning and modifications to sensors occurred in August and September 2011. Two sets of performance data are therefore available (pre and post September 2011), and performance results for both sets are presented in Section 6 of the Final Report. The second data set includes performance data each boiler control configuration tested and thus enables a consistent assessment of system performance. CO/O_2 trim operation with oil was not collected because plant switchover to oil did not occur during the demonstration.

Most performance data were collected as a function of the boiler operating conditions across its firing range. Each boiler operating point is expressed in terms of percent of the boiler maximum fuel flow rate, thus enabling consistent comparison. An assessment of all performance metrics is summarized in Table 2 and discussed in detail in the remainder of this section.

Table 2. Performance objectives assessment summary.

Performance Objective	Metric	Pre-Demonstration Success Criteria	Assessment Summary
Quantitative Performance Objectives			
Improve energy efficiency	Short- and long-term fuel-to-steam efficiency	>5% improvement over baseline; >1.8% improvement over SoA	Natural gas: +2-4% over baseline, +0.5% and 1.5% over SoA observed at lower firing rates for well maintained boiler. Oil: observed for SoA only. Improvement of 6% to 8% over baseline.
Reduce carbon emissions	Short- and long-term fuel-to-steam efficiency	>5% improvement over baseline; >1.8% improvement over SoA	Natural gas: CO_2 yearly emissions reduction estimated at 363,000 lb (181.5 ton), or 4%. Oil with O_2 trim, CO_2 yearly emissions can be reduced by 784,000 lb (392 ton) on a 25 MMBtu/hr boiler, or 7%.
Increase combustion efficiency	Combustion efficiency over entire operating envelope (firing range)	>6% improvement over baseline; >2% improvement over SoA	Natural gas: +1.5-3% over baseline, +0.5% and 1.5% over SoA observed at lower firing rates for well maintained boiler. Oil: observed for SoA only. Improvement of 6% to 8% over baseline.
Meet CO, NO_x regulatory emission requirements	Measured exhaust gas composition (CO, NO_x)	Meet or exceed emission targets.	Met emission targets for NO_x (below 120 ppm) and CO (below 15 ppm), on average basis.
Reduce controls commissioning time	Measured time to set air/fuel positions over boiler firing range	30% reduction over baseline	Not measured directly. Qualitative assessment of setting the PPC4000 via graphical interface was observed. Overall, commissioning procedure lasted less than 2 hours, but was not typical of actual commissioning.

Table 2. Performance objectives assessment summary (continued).

Performance Objective	Metric	Pre-Demonstration Success Criteria	Assessment Summary
Reduce system operating costs	Fuel costs, yearly operating costs for maintenance, tuning, and commissioning	>5% improvement over baseline; >1.8% improvement over SoA	3.6% over baseline, 0.6% over SoA for natural gas. Not quantified for operation with oil (6.5% improvement SoA over baseline).
Verify sensor reliability	Measurement errors and drift over time	Drift of sensors (CO, NO_x) less than 5%/demo period (full range), no failures during demonstration time	Measured drift was always below 5% so that recalibration was not needed. The CO sensor did not fail during operation.
Ensure system availability	Equipment operational or ready to operate	>95% after installation completed (for prototype)	System was available throughout the demonstration, which lasted 1 year. Downtime of 12 hours was experienced because of servomechanism failure.
Evaluate years to payback	National Institute of Standards and Technology (NIST) building life-cycle program	<1 year (typical 25 MMBtu/hr boiler)	Payback of 2.4 years observed for natural gas operation (also associated with lower natural gas prices). For operation with oil, payback is 2.5 months.
Qualitative Performance Objectives			
Ensure ease of installation and configuration	Ability of average service technician to configure and deploy successfully	A single service technician able to deploy at least as quickly as baseline or SoA	Positive feedback gathered during interviews with boiler installers and operators, both at WVA and with Fireye customers.
Ensure ease of use for boiler operator	Ability of average boiler operator to use interface effectively and achieve necessary daily operational changes	Boiler operators understanding features and able to take action for all regularly occurring events	Boiler operators easily acquired knowledge of controller operation and interface and were able to operate it and take action.
Ensure system maintainability	Number of service calls and parts replacements	Within expectations of typical operator	Because of the short demonstration time, maintenance was not performed on system, and it was not necessary. PPC4000 is easy to maintain based on feedback from Fireye customers.

6.1 BOILER EFFICIENCY

Fuel-to-steam efficiency was observed as function of the boiler operating points.

Performance analysis showed that:

- For natural gas operation, efficiency improved by 1.5% to 4% over baseline depending on the operating point. Improvement of +0.5% to 1.5% over SoA was also observed at lower firing rates. Success criteria were not met.
- For No. 2 oil operation, improvement of 6% to 8% over baseline was observed for SoA controls. Efficiency improvement objective relative to baseline was met.

Figure 10 shows boiler efficiency as a function of both firing rate and stack O_2 concentration for each control mode. The top plot demonstrates efficiency improvements for both O_2 trim and

CO/O_2 trim control systems. This boiler efficiency profile is characterized by a drop in fuel-to-steam efficiency in the mid firing range, independent of the operation mode. This profile is common, as boiler manufacturers often guarantee an efficiency level for a specific fuel at a standard operating point (Council of Industrial Boiler Owners [CIBO], 2003). Efficiency of new gas-fired boilers range between 70% and 75%. The WVA boiler's lowest efficiency is at 55% of maximum fuel flow. Heat exchanger geometry, length, and turbulence level of the burner flame at different firing rates, and orientation with respect to the water tubes closest to the flame may influence the efficiency curve's shape.

Figure 10 shows that upgrading the control system to O_2 trim and to CO/O_2 trim allows operation at progressively lower O_2 concentrations, thus improving boiler efficiency. Operating the boiler with CO/O_2 trim shows improved performance ranging between 0.5% and 1.5% at lower firing rates over O_2 trim, and improvement of 2% to 4% over legacy baseline. The reason reductions in O_2 concentrations do not translate into larger efficiency gains could include the effect of several other uncontrollable factors (e.g., changing weather, varying demand) on boiler performance.

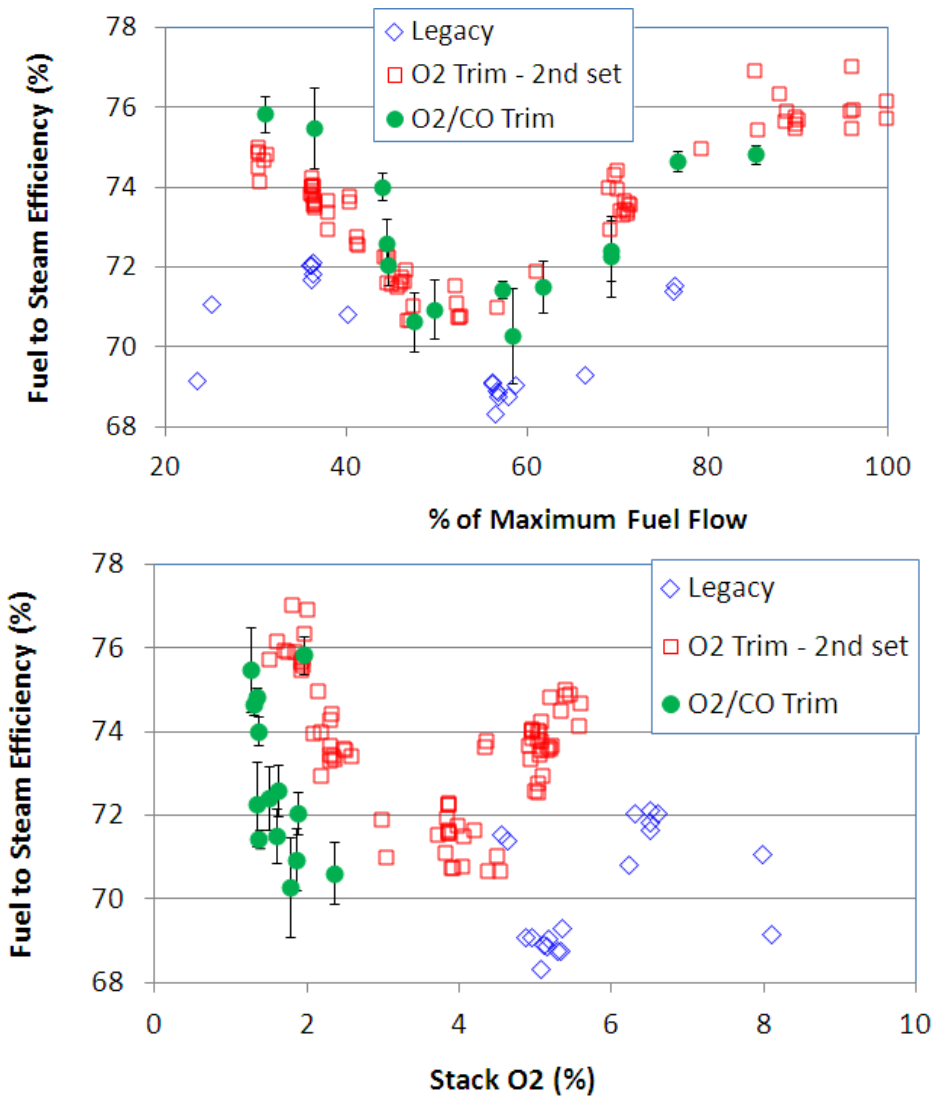

Figure 10. Second set of burner control system boiler efficiency comparisons—2011/2012.

An additional test was conducted to reduce the impact of environmental and weather variation by manually changing the air servomechanism position to sweep through a range of fuel/air rates. The test confirmed that reduction in O_2 concentrations has a positive impact on boiler efficiency, showing a gain of 1.5% for reduction of O_2 concentration from 4% to 2%. The results also confirm that lowest efficiency levels correspond to operation at 55% of maximum fuel flow.

Performance quantification associated with No. 2 oil operation was assessed but under a limited data set. The top plot of Figure 11 shows the number and duration of each steady state interval analyzed for oil-fired operation, and the plot on the bottom reports fuel-to-steam efficiency for changing fuel flow. Data was collected for baseline linkage and O_2 trim controls, showing efficiency gains of 6% to 8%. Higher absolute efficiency levels were also observed. Natural gas has a higher relative water vapor content in its exhaust and carries away a greater amount of latent heat, yielding increased heat losses. While oil fuel enables higher efficiency, it requires increased maintenance and has higher cost and emission levels.

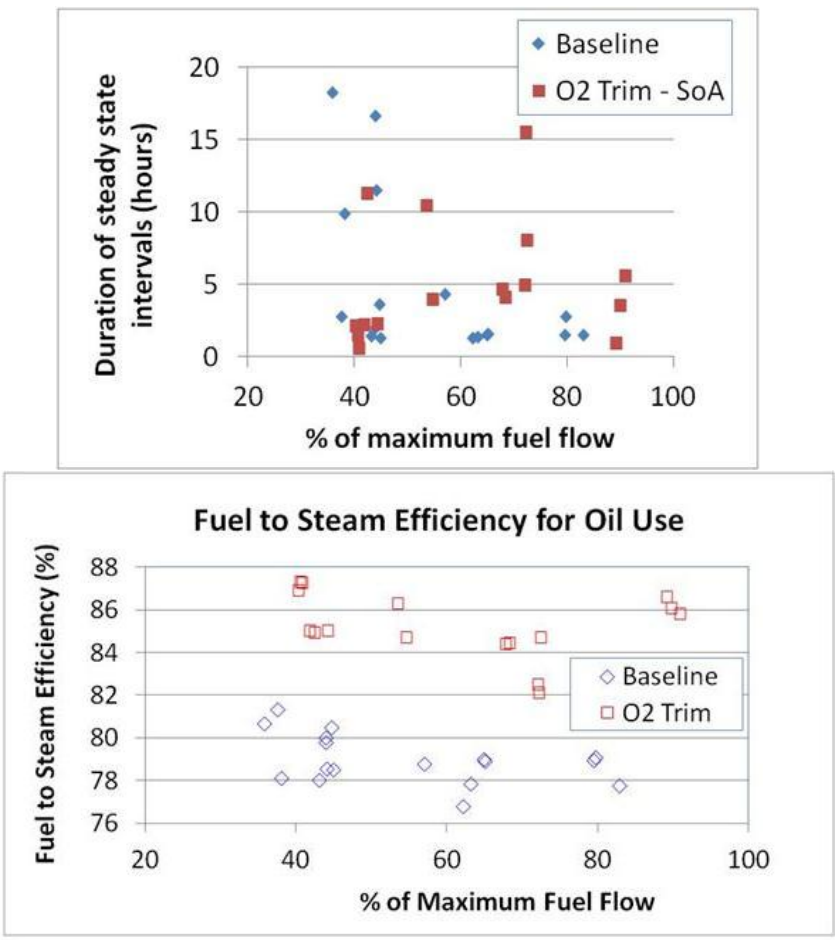

Figure 11. Fuel-to-steam efficiency gains during boiler operation on No. 2 fuel oil.

6.2 EMISSION REDUCTION (CO_2)

CO_2 emissions were calculated directly from fuel savings calculations, which depend on efficiency gains as well as utilization profiles. Based on a prescribed base utilization profile, avoided CO_2 emissions were calculated as follows:

- For natural gas operation with O_2 trim, CO_2 yearly emissions can be reduced by 288,000 lb (144 ton) on a 25 MMBtu/hr boiler.
- For natural gas operation with CO/O_2 trim, CO_2 yearly emissions can be reduced by 363,000 lb (181.5 ton) on a 25 MMBtu/hr boiler.
- For No. 2 oil operation with O_2 trim, CO_2 yearly emissions can be reduced by 784,000 lb (392 ton) on a 25 MMBtu/hr boiler.

Carbon reduction did not meet our success criteria because of the direct correlation between efficiency gains and carbon reduction.

6.3 COMBUSTION EFFICIENCY

Performance analysis showed that:

- For natural gas operation, combustion efficiency improved by 2% to 4% over baseline depending on the operating point. Improvement of +0.5% to 1.5% over SoA was also observed at lower firing rates. Success criteria were not met.
- For No. 2 oil operation, improvement of 6% to 8% over baseline was observed for SoA controls. Efficiency improvement objective relative to baseline was met.

Figure 12 reports combustion efficiency as a function of normalized fuel flow. Combustion efficiency of the two systems is similar at high firing rates, although significantly better than the legacy configuration. At lower firing rates combustion efficiency is significantly higher, 1% to 1.5% higher than levels recorded with O_2 trim.

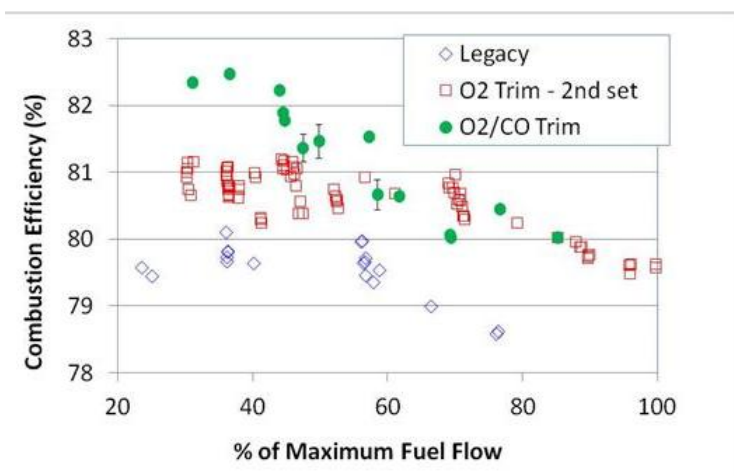

Figure 12. Combustion efficiency results of all tests from both heating seasons.

Calculations of combustion efficiency as a function of O_2 concentrations at different firing rates were also made. As seen in Figure 13, combustion efficiency increases with decreasing firing rates, and increases with decreasing O_2 concentration, about 1.5% from 4% to 2%.

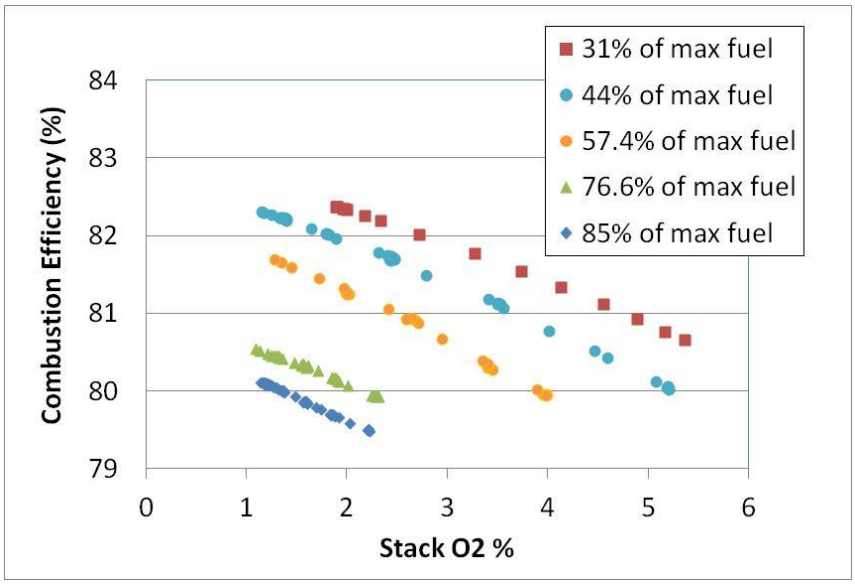

Figure 13. Effect of stack O_2 reduction on combustion efficiency.

Data relative to combustion efficiency for oil operation confirm the trends observed for natural gas.

6.4 CO AND NO_X EMISSION LIMITS

The following targets were proposed and met during tests with natural gas:

- CO (ppm, dry): <100
- NO_x (ppm, dry): <120

Operation with both SoA O_2 trim and CO/O_2 trim did not result in significantly higher CO concentration relative to baseline operation. Average levels were well within regulatory boundaries, while peak levels recorded were mostly relative to controller mistuning that was subsequently corrected. It should be noted that NO_x reduction would be mostly attainable by acting on the burner rather than on the fuel air ratio. Additional details about these performance results can be found in Section 6 of the Final Report.

6.5 REDUCTION OF COMMISSIONING TIME

A reduction of 30% of commissioning time was set as the performance objective. However, commissioning and recommissioning times were not quantified directly via ad-hoc tests for the following reasons:

- The boiler was already commissioned in a baseline state when the demonstration began.

- Commissioning with PPC4000 was performed within 2 hours, as baseline points were initially used as reference. Therefore, commissioning activities were not reflective of typical commissioning times.

Boiler installers however noticed how the use of the PPC4000 interface for commissioning was easy to use and greatly simplified the commissioning procedures. In similar installations, customers of Fireye noted that the use of PPC4000 reduced commissioning times to 30% of a baseline commissioning activity.

6.6 BOILER OPERATING COST

Annual operational savings were calculated at 3.6% over baseline, and 0.6% over SoA operational costs, for operation with natural gas. Success criteria were not met. Operational cost improvement is 6.5% for SoA over baseline for operation with oil (meeting objectives). See Section 7 for a quantification of operating costs.

6.7 SENSOR RELIABILITY

Overall, the sensor technology adopted for control purposes showed good reliability and stability during the demonstration. Failures or malfunctioning were not experienced. This met the objective of the demonstration.

6.8 AVAILABILITY

System downtime associated with the CO/O_2 trim technology was experienced only once during the demonstration. While in O_2 trim operation, one of the released product servomechanisms failed and had to be replaced. The servomechanism was quickly replaced limiting the downtime to 2 hours. Overall, the target of >95% availability was attained.

6.9 PAYBACK

The metric target was not attained for operation with natural gas, principally because of reduction of the price of natural gas (payback of 2.4 years). The target of <1 year payback was attained with oil with the SoA control (payback of 0.2 years).

6.10 EASE OF INSTALLATION

System installation involves setting up the PPC4000 product, in either O_2 trim or CO/O_2 trim mode. Since Fireye released the product in 2010, feedback from customers was collected. Some comments from installers and users are reported below.

- From a distributor: “2-1/2 hours to set up and have a boiler on-line in auto-mode.”
- From a burner OEM: “With the system we set up to use the SD card (a feature of PPC4000) to upload info, they are able to get some similar burners through their test pit in 10 minutes.”

- From a distributor: “The system is significantly easier to program and operate. The complexity has been reduced instead of 25 options there are now only 7 which is sufficient for smooth operation.”

Joe Firlet, the person responsible for boiler maintenance and upgrades at WVA submitted the following comments.

Pros:

- Nice package, easy to use
- Expandable
- Works well with the Fireye E100 BMS system (the existing flame safeguard system)
- Small in size yet powerful.

Cons:

- Display is small cannot see information from far away (A larger touch screen is going to be released, but was not yet available at the demonstration site)
- Needs markings on the actuators so we can visually see how much open/closed it is
- Needs to work in automatic with a plant master (the feature is available but was not implemented at WVA).

6.11 EASE OF USE FOR OPERATOR

Comments from Fireye’s customer base were also captured:

- From a customer: “The installation went smooth and we have not had one issue since the initial startup. We are very happy with the control.”
- From a customer: “…people were extremely pleased. I mean really ecstatic! The modulation photoionization detector (PID) was working so well they had excellent operation on their feed water which in and of itself will show less wear and tear on the feed water pump. Steam pressure was a perfect circle around the chart recorder.”

6.12 MAINTAINABILITY

See Section 7 for comments on maintenance cost estimates. During the execution of the demonstration, maintenance problems were not encountered.

7.0 COST ASSESSMENT

Costs and benefits of this new boiler control technology depend on its specific application, geographic location, and fuel type/cost. The analysis that follows provides estimates based on a number of assumptions. Whenever available, data specific to the WVA boiler were used. The cost and benefit model was implemented in an Excel spreadsheet, which can be modified to make economic benefit assessments for a specific boiler and sites.

7.1 COST MODEL

The expected life-cycle costs were calculated using the NIST Buildings Life-Cycle Cost Program. The following cost elements were collected based on prices available for the current SoA control system (PPC4000 with O_2 trim). Not all cost elements used for the model were based on tracked data obtained during the demonstration for the following reasons:

- Often, costs incurred were associated with the development of prototypes, which would be substantially different than costs of production of a finished product.
- Prices to customer need to be used to determine benefits associated with the investment in the new combustion control technology. Actual prices of new technology elements would depend on the future pricing strategies for the finished product.

See Table 19 in the Final Report for a description of the data tracked during the demonstration for each of the following cost factors.

1. **Hardware capital costs:** The upgrade cost from baseline to SoA was provided by Fireye based on an actual price quotation, as seen in Table 3.

Table 3. Cost evaluation factors and source.

Products	Item	Quan	P/N	Description	Price Ea.	Total
Basic System						
	1	1	PPC4000	UL-approved parallel positioning, controller. Operates with up to 10 FX Modbus Servo-motor outputs.	$900.00	$900.00
	2	1	NXD410	15-key, 4-line, 40-character full text display with Modbus, backlit LCD for PPC4000.	$504.00	$504.00
	3	1	PXMS-xxx (range)	Steam pressure sensor	$670.00	$670.00
	4	1	59-562-2	Display connection cable 10 ft	$61.20	$61.20

Table 3. Cost evaluation factors and source (continued).

Products	Item	Quan	P/N	Description	Price Ea.	Total
Servo Options						
	5	2	FX04	4-wire Modbus Servo-motor, 3 ft lb, 4Nm, 50/60 Hz, 24 VDC. FUEL SERVOS	$319.80	$639.60
	6	1	FX20	4-wire Modbus Servo-motor, 15 ft lb, 204Nm, 50/60 Hz, 24 VDC. AIR SERVO	$589.80	$589.80
	7	1	NXCBGO3FT	Retrofit kit brackets and couplings, gas fittings/oil cam	$1020.00	$1020.00
				TOTAL FOR BASE SYSTEMS		**$4384.60**
O_2 Trim Option						
	8	1	35-318-2	O_2 probe mounting flange	$171.60	$171.60
	9	1	NXCESO2-8	O_2 probe assembly (for flues 300 mm to 1000 mm).	$1908.00	$1908.00
	10	1	129-189	Mounting fange blank cover	$127.80	$127.80
				TOTAL FOR O_2 TRIM OPTIONS		**$2207.40**
FIELD OPTIONS						
	11	1	253-WD-2	Wiring diagrams and drawings*	$400.00	$400.00
	12	1	59-565	Belden 9940 wire 1200 ft	$1080.00	$1080.00
				TOTAL FIELD OPTIONS		**$1480.00**
	13	1	Install/ Commission	**Installation & Commissioning Works Complete System**	$16,000.00	**$16,000.00**
				GRAND TOTAL		**$24,072.00**

* Note: One set of drawings per site

Upgrading to the CO/O_2 operation requires a gas sensing package that is not commercially available. Since a pricing strategy is not yet defined, a range of prices was used ($5000-$25,000). Because the analysis includes results for a larger size boiler (100 MMBtu/hr), the cost for this boiler was adjusted to account for larger fuel and air servos. Also, $5000 was added for labor and equipment.

2. **Installation costs:** Planning, physical installation, and configuration and initial commissioning efforts were included in the estimate in Table 3.

3. **Consumables:** Consumables include replacement parts for the O_2 probe of the O_2 trim controller and for the sensor box of the CO/O_2 trim system. Costs of these components were included in the estimate of recurring annual maintenance costs.

4. **Facility operational costs:** Fuel and electric power costs, as well as personnel cost to operate the facility, represent facility operational costs. The introduction of the new combustion efficiency controls has a beneficial effect on fuel cost savings, while all other operational costs are unchanged. In conclusion, operational cost savings were calculated in terms of fuel cost savings only for both upgrades to O_2 trim and CO/O_2 trim technology. Fuel costs savings were quantified by adopting a model that requires the following information:

- *Boiler fuel-to-steam efficiency* for baseline, O_2 trim, and CO/O_2 trim configurations across the boiler's firing range. See actual data in Tables 21 and 22 of the Final Report.
- *Boiler utilization factors*, expressed in terms of total annual hours of use and percent of operation time at each discrete part load condition. A set of five utilization curves were used to reflect different typical uses of a boiler. See Section 7.1 of the Final Report for additional details.
- *Fuel type and cost.* This analysis considers natural gas as well as No. 2 oil as fuels. For natural gas, a rate of $5.5 MMBtu/hr was used. Sensitivity of economic performance indicators to fuel costs was performed by considering prices in the $1-10 MMBtu/hr range. For No. 2 oil, a price of $4/gal was considered. Fuel cost savings were calculated by subtracting the annual cost of fuel associated with new technology adoption to the annual cost of fuel of baseline, based on the data and assumptions above.

5. **Maintenance:** Maintenance costs were not tracked during the demonstration, and estimates of costs were provided by using qualitative information and the following assumptions:

   - Costs for maintenance of baseline systems are higher than those of electronic positioning control systems. Trim controllers have replacement parts that need to be periodically replaced. Instrument recalibration can add to the cost of maintaining such systems.
   - For O_2 trim, Fireye does not consider a significant increase in need for maintenance. CO/O_2 trim maintenance requirements have not been quantified with precision. However, the CO/O_2 sensor system performed well during the demonstration.

   For the above reasons, a conservative estimate for maintenance costs was made for the O_2 trim system ($1000/year) and the CO/O_2 trim system ($1500/year).

6. **Hardware lifetime:** This metric was not tracked during the demonstration. Based on how other positioning and trim systems perform in the field, lifetimes are longer than 10 years.
7. **Operator training:** Training costs were included as part of the installation cost estimates. The PPC4000 was praised for its ease of use with programming, calibration, and operation.

7.2 COST DRIVERS

There are several factors that can influence system cost and actual achievable savings. These cost drivers include:

1. *Boiler size:* System cost changes with boiler size, driven by the size of the servomechanisms for air and fuel modulation. As boiler capacity increases, servos capable of higher torque level must be employed, adding to system cost.
2. *Boiler utilization:* Attainable fuel savings will depend on the utilization factor of the boiler and the load profile, as fuel-to-steam efficiency changes with boiler load. The less time the boiler is operating, the smaller the savings will be. Utilization depends on heating demand.
3. *Boiler heat transfer effectiveness:* While the CO/O_2 trim controller will operate to achieve the highest level of combustion efficiency, how that relates to overall fuel savings will depend on the effectiveness of the boiler to transfer additional heat to the water or vapor.
4. *Type and cost of fuel:* The type and cost of fuel will influence the total savings.
5. *Local cost of manpower:* Changes in the installation and periodic maintenance costs could occur because of changes in labor rates.

7.3 COST ANALYSIS AND COMPARISON

Cost estimates for application of the O_2 trim and CO/O_2 trim technology compared to the baseline are listed in the following pages. The following assumptions were made for the life-cycle cost analysis:

- Weather conditions and boiler utilization typical of WVA were used for the analysis. five different utilization scenarios were considered, which could be applicable to other climatic conditions.
- All assumptions for calculation of the cost model elements were used.
- Life-cycle analysis adherent to the DoD ECIP guidelines was performed.[1] All NIST Building Life-Cycle Cost (BLCC) prescribed parameters for 2012 were utilized.
- The analysis assumes a 10-year life span of the system.

7.3.1 Energy Cost Savings

By applying the cost model, we made the following conclusions:

- For a typical boiler utilization profile, the application of new controls would enable fuel savings of about 3% for O_2 trim technology and 4% for CO/O_2 trim with natural gas. Savings associated with oil utilization would be 7% for O_2 trim technology.
- Fuel savings variations are limited to a few tenths of a percent when a different utilization profile is assumed.

[1] According to the Office of Management and Budget (OMB) Circular A-94 or information from Handbook 135, the Life-Cycle Costing Manual for the FEMP and its annual supplement. Parameters available in NIST's BLCC tool.

- Fuel cost savings scale linearly with boiler size as well as with fuel cost. Notwithstanding a downward trend of natural gas fuel costs, the adoption of new control technology enables significant savings. For oil, predicted savings are much higher than with natural gas.
- An increase of boiler utilization leads to increased fuel savings.

In summary, boiler size, utilization, and cost of fuel are the most important drivers to achievable fuel cost savings and on the overall value of the investment.

Energy savings calculations were conducted for the five different utilization profiles. A summary relative to all profiles is reported together with detailed calculations relative to profile #1.

Table 4. Estimated annual energy cost savings for all five profiles (25 MMBtu/hr).

Profile	Total Fuel Baseline	Fuel Saved (MMBtu)		% Fuel Saved		$ Saved		
		O_2 trim	CO/O_2 trim	O_2 trim	CO/O_2 trim	O_2 trim	CO/O_2 trim	
1	79,318	2462	3102	3.10	3.91	13,543	17,063	Degree day
2	79,515	2481	3003	3.12	3.78	13,646	16,518	Euro efficiency
3	43,795	1248	1949	2.85	4.45	6864	10,717	Low loads
4	149,756	4892	4975	3.27	3.32	26,903	27,361	High loads
5	80,852	2424	3164	3.00	3.91	13,330	17,404	NAVFAC

NAVFAC = Naval Facilities Engineering Command

Table 5. Detailed energy cost savings estimation for a 25 MMBtu/hr boiler, profile #1.

Maximum capacity	25	MMbtu/hr	Profile	1				
Operation	10%	20%	30%	40%	60%	80%	100%	TOTAL
Heating load (MMbtu/hr)	2.5	5	7.5	10	15	20	25	
Hours during heating season	1272	984	1064	1512	1192	320	8	
Cycling (20% equivalent hours)	60%	763						
Hours of operation		1747	1064	1512	1192	320	8	6352
Overall utilization								35.5%
Fuel utilization (MMbtu)								
Fuel required: baseline		6.88	10.42	14.49	21.23	27.27	33.78	79317.82
Fuel required: O2trim		6.68	10.14	14.08	20.45	26.43	32.75	76855.48
Fuel required CO/O2trim		6.56	9.91	13.95	20.45	26.43	32.75	76215.49
Fuel savings (MMbtu)								
Fuel Saved: O2 trim		0.20	0.28	0.41	0.77	0.84	1.03	2462.35
% Fuel Saved: O2 trim		2.90%	2.70%	2.82%	3.64%	3.08%	3.06%	3.10%
Fuel Saved: CO/O2 trim		0.32	0.50	0.54	0.77	0.84	1.03	3102.33
% Fuel Saved: CO/O2 trim		4.60%	4.85%	3.72%	3.64%	3.08%	3.06%	3.91%
lb of CO2 - reduction								288,341
								363,283
Cost savings								
Cost of fuel ($/Mmbtu)								5.5
O2 trim								$ 13,543
CO/O2 trim								$ 17,063

As annual fuel cost savings are highly sensitive to the cost of natural gas, a sensitivity analysis was performed to help quantify the effect of price variation on overall investment performance. Sensitivity with changing number of operation hours helps to illustrate variations with

geographical operation. In addition, utilization would depend on the number and use of boilers available in a multiboiler power plant.

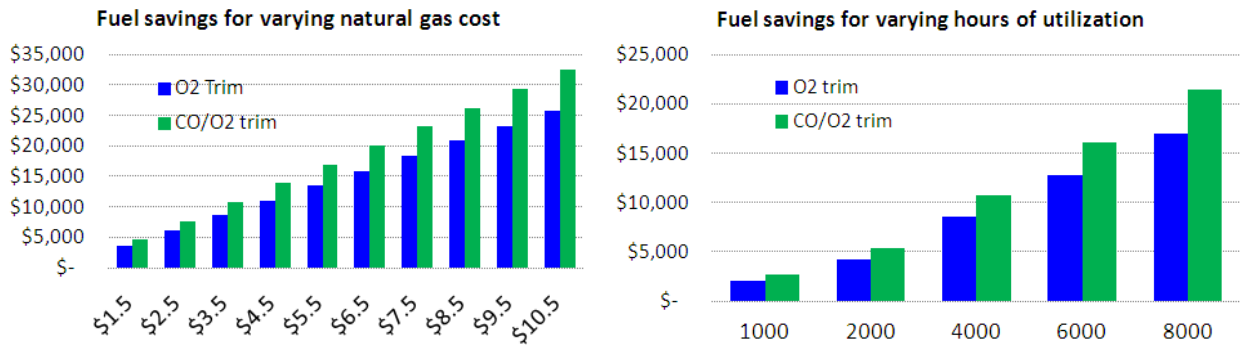

Figure 14. Sensitivity to natural gas price variation and boiler yearly hours of utilization of annual fuel savings (25 MMBtu/hr).

The analysis can be repeated for a larger size boiler, i.e., 100 MMBtu/hr by means of scaling.

Table 6. Estimated annual energy cost savings for all five profiles (100 MMBtu/hr).

Profile	Total Fuel Baseline	Fuel Saved (MMBtu)		% Fuel Saved		$ Saved		
		O_2 trim	CO/O_2 trim	O_2 trim	CO/O_2 trim	O_2 trim	CO/O_2 trim	
1	317,271	9849	12,409	3.10	3.91	54,172	68,251	Degree day
2	318,000	9924	12,013	3.12	3.78	54,584	66,072	Euro efficiency
3	175,178	4992	7794	2.85	4.45	27,457	42,868	Low loads
4	599,024	19,566	19,899	3.27	3.32	107,614	109,445	High loads
5	323,409	9694	12,658	3.00	3.91	53,319	69,618	NAVFAC

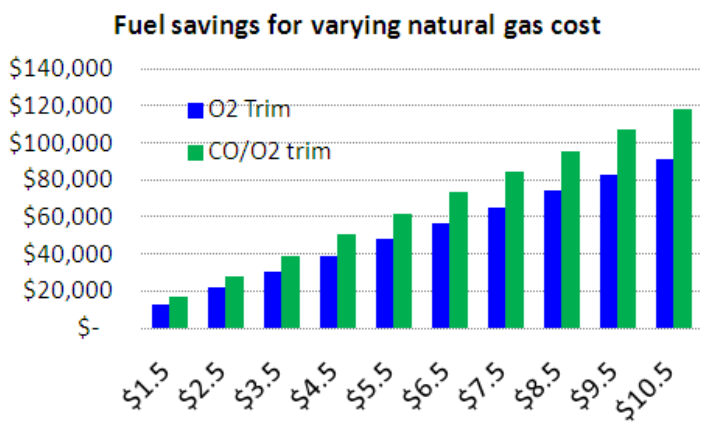

Figure 15. Sensitivity to natural gas price variation of annual fuel savings (100 MMBtu/hr).

Performance of the boiler operating with No. 2 oil is estimated in the tables and charts below. As efficiency gains and cost of fuel are higher, achievable yearly energy savings are correspondingly higher.

Table 7. Estimated annual energy cost savings for all five profiles (25 MMBtu/hr, oil).

Profile	Total Fuel Baseline	Fuel Saved (MMBtu) O_2 trim	% Fuel Saved O_2 trim	$ Saved O_2 trim	
1	509,174	35,715	7.01	142,858	Degree day
2	518,457	36,472	7.03	145,887	Euro efficiency
3	277,759	19,062	6.86	76,247	Low loads
4	994,480	70,939	7.13	283,758	High loads
5	520,499	36,464	7.01	145,855	NAVFAC

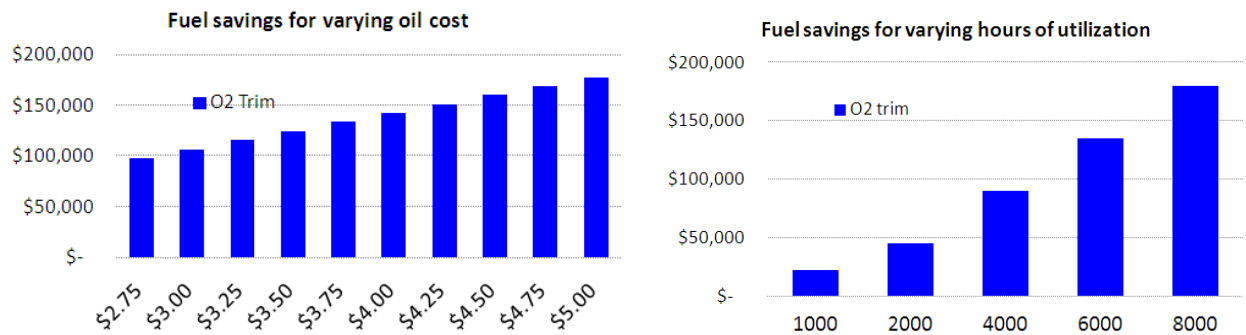

Figure 16. Sensitivity to oil price variation of annual fuel savings (25 MMBtu/hr).

7.3.2 Value of Technology Investment

To quantify economic benefits, a cash flow analysis was performed for natural gas-fired boilers. Based on the analysis, variations were calculated according to:

- Boiler size (25 MMBtu/hr or 100 MMBtu/hr)
- Utilization profile
- Annual hours of boiler operation
- Cost of natural gas fuel
- First cost of the CO/O_2 probe (the most uncertain fixed cost factor).

Attractive payback and NPV are achievable by adopting combustion control solutions. Payback time for natural gas is 2 years for a 25 MMBtu/hr boiler and less than a year for larger (100 MMBtu/hr) boilers. O_2 trim technology has lower payback times than CO/O_2 trim but also lower NPV. Variation of sensor first cost has an impact on payback times, but less so than other factors such as fuel cost. For oil, payback time is in the order of months for O_2 trim technology. See Section 7.3 of the Final Report for a detailed example of this cash flow analysis.

The following economic parameters were calculated:

- Discounted total operational savings over the 10-year utilization period
- Payback time, calculated relative to savings during the first year of operation
- NPV
- Adjusted the internal rate of return (IRR) as prescribed by the FEMP standard
- Savings to investment ratio (SIR) as ratio between the operational savings and the first cost associated with the system installation.

7.3.3 Overall Value of Investment to DoD

The Army owns 214 sites with >10 MMBtu/hr oil/gas boilers, more than 90% of which are older than 10 years.[2] Total boiler capacity for DoD can be estimated at 82,000 MMBtu/hr by scaling proportionally with total owned building area (data from FRPC, 2006, and Andrews, 2009). Since a comparison between O_2 trim and CO/O_2 trim potential energy savings was not performed for oil, the same relative efficiency gain observed for natural gas (with profile #1) was applied to oil for CO/O_2 trim operation.

Table 8. Estimate of overall DoD annual savings and carbon reduction.

DoD boiler inventory size				
DoD total area of building inventory	2112	MMsqft		
Army total area of building inventory	870	MMsqft		
Army total oil/gas boiler capacity, plants >	33,773	MMBtu/hr		
# of sites	214			
# of sites, installation >10 years old	196			
DoD est installed capacity >10MMBtu cer	**81,991**	MMBtu/hr		
Of which oil	**20%**			
	GAS	**OIL**	**TOTAL**	
Total DoD capacity	65,593	16,398	81,991	
Annual fuel consumption – baseline	208,106,497	333,980,589	542,087,086	MMBtu
Savings O_2 trim	6,460,472	23,426,150	29,886,622	MMBtu
Savings CO/O_2 trim	8,139,606	26,120,917	34,260,523	MMBtu
Energy cost savings – O_2 trim	35,532,594	93,704,601	129,237,196	
Energy cost savings – CO/O_2 trim	44,767,835	104,483,668	149,251,503	
Avoided CO_2 emissions – O_2 trim	378,261	262,139	640,399	ton
Avoided CO_2 emissions – O_2 trim	476,574	292,293	768,867	ton

The calculations above were performed for the base case with profile #1 and $5 MMBtu cost of natural gas and $4/gal for No. 2 oil. Under those assumptions, with the introduction of CO/O_2 trim technology, DoD has a potential saving opportunity of $150 million every year, as opposed to yearly $130 million for O_2 trim only. Annual reduction of more than 760 tons of CO_2 emissions can also be estimated.

[2] Information extracted from data on the Army boiler inventory as of July 2009 available from the Army Headquarters Installation Information System, courtesy of the Army Corps of Engineers.

8.0 IMPLEMENTATION ISSUES

This demonstration utilized the O_2 trim Fireye PPC4000 Air/Fuel Ratio Control, which is commercially available from Fireye. The system consists of the PPC4000 controller, servomotors, NXD410 user interface and an NXCESO2-1001 oxygen probe. These components are readily available from local distributors who are trained and familiar with their installation. All the hardware is UL certified. Full deployment was completed in 3 days, including commissioning. Upgrade from the linkage-based boiler control system required replacement of the existing butterfly valve assembly with a servomotor-driven valve assembly for both the fuel and air linkages. This process is straightforward; however, some welding may be required depending on the existing flange spacing on the fuel supply line. The PPC4000 controller can operate up to 10 servomotors so dual fuel control, for example natural gas and oil, is easily configurable. Problems were not encountered during the installation at WVA, and a scenario where the controller could not be deployed due to physical constraints cannot be envisioned.

Notwithstanding that electronic boiler controls are becoming more known in the United States, much work has to be done to diffuse the knowledge about their benefits (only an estimated 10% of boilers have electronic controls versus 60% in Europe and worldwide). User concerns over deployment of a digitally controlled O_2 trim system should be mitigated by this demonstration. Downtime during installation was at most 3 days, and full installations have been performed by Fireye trained distributors at other sites in 1 day. The PPC4000 is a proven product with a very low failure rate. The system can always revert to manual control if a problem is encountered. Through this demonstration, UTRC and Fireye did not find any reason to avoid upgrade of the burner management system to closed-loop control. Regulations that would prevent adoptions are currently not known. Emission levels observed during the demonstration were sufficiently low to always meet emission regulations.

Update to CO/O_2 trim technology would require setup of a PPC4000 controller and servomechanisms. However, the oxygen measurement probe would be replaced by a multi-sensor box that includes O_2 as well as CO concentration measurement. Tuning and commissioning of the system would require additional control parameters (see Final Report). Education and training would be necessary for adoption and to ensure efficiency gains.

8.1 ADAPTATION TO SITE

WVA is a well-operated facility and incorporation of a new controller proved seamless. The GUI for the controller was readily installed in available space on the control panel. Changes to the boiler involved mounting the servomotors and careful alignment with the linkage rod for the air valve. Problems were not encountered during the installation and startup of the PPC4000. When applied to other sites, system installation activities would have to adapt to specific configurations, depending on the type of boiler, space available, and requirements of the boiler operator. The introduction of the CO/O_2 trim technology would not create additional adaptation needs other than those encountered for the PPC4000 today. Ease of configuration through the user interface panel and the ability to upload profiles via SD card would lessen installation time.

8.2 ACCURATE TUNING

The commissioning process was straightforward and performed by Joe Firlet of Steam Plant Systems and Barry Neill of Fireye. A handheld gas analyzer was used in conjunction with temperature, pressure, fuel, and steam flow readings to set a 12 point air to fuel ratio profile for operation of the boiler from low to high fire, for each fuel use. Different profiles can be set to adapt to different operation conditions. The O_2 trim system will also have an O_2 set point associated with each point in the profile and the controller will close the loop on this value.

Tuning of the CO/O_2 trim controller requires particular attention and care during the commissioning phase, as it introduces new parameters and requires precision in setting the traditional O_2 trim parameters. More details are found in the Final Report.

8.3 APPLICABLE REGULATIONS

Boilers are regulated under the new U.S. Environmental Protection Agency (USEPA) rule, National Emission Standards for Hazardous Air Pollutants for Industrial/Commercial/ Institutional Boilers and Process Heaters. A "no action assurance" for boiler operators is currently in effect through October 2012. The boilers under consideration require compliance of the Area Source Rule, for existing sources larger than 10 MMBtu/hr. For this category of boilers, emission limits under the rule do not apply, but a yearly tuning of the boiler system must be performed. The rule does not discuss the use of using digital controls. The use of electronic controls in lieu of mechanical ones would provide immediate measurement of emissions and greatly simplify recommissioning procedures.

Boiler control technology in DoD facilities is regulated under the Unified Facility Criteria (UFC) 3-430-11 Boiler Control Systems issued on February 14, 2001. Boiler operation is discussed in Section 5.2-13.3.1 of the UFC. It reads, "CO analyzers used in a boiler plant may utilize a catalytic element, wet electrochemical cell, or non-dispersive infrared absorption. Install the CO analyzer in a clean gas stream that is downstream of the particulate removal system. A CO analyzer permits firing at lower oxygen levels than without it. A minimum air requirement is established by decreasing oxygen in the stack gas until a large increase in the CO reading occurs. A CO analyzer is also useful in boiler startup. During start-up monitor the CO analyzer closely for unsafe firing conditions. High CO readings indicate incomplete combustion, which implies potentially unsafe conditions in the furnace."

Further, application guidelines for maintenance and upkeep of CO/O_2 trim technology could be included in UFC 3-430-07 Operations and Maintenance: Inspection and Certification of Boilers and Unfired Pressure Vessels, particularly relative to changes with inspection requirements that the new technology would require.

Finally, the creation of technical notes such as those issued by the U.S. Army Corps of Engineers (USACE) could be used to facilitate adoption and inform boiler operators and installation energy managers of the availability of a new technology.

While electronic boiler control has been available for more than two decades and is used broadly in Europe and the rest of the world, adoption in the United States (and DoD) has been slow.

Emphasizing and following the guidelines indicated in the UFC when boiler plant overhaul or maintenance occur would be a first good practice to ensure broader adoption. Championing at the Facility Command level for the three main DoD services would help to diffuse knowledge to all installations. For example, NAVFAC has created the Navy Technology Demonstration and Validation (TECHVAL) with the purpose of demonstrating new technology to augment and diffuse knowledge. TECHVAL could be used to demonstrate advanced boiler control. Venues such as GovEnergy should be used to increase awareness and educate boiler operators.

8.4 PATH TO IMPLEMENTATION AS PRODUCT AND ADOPTION

The CO/O_2 trim technology was demonstrated at TRL6 as a prototype operating in a real environment. Additional operational savings to those achievable with O_2 trim only were demonstrated, with a potential of additional 1% savings on boilers similar to that used for demonstration. It was considered that results obtained in demonstration should be a lower attainable limit, given that the boiler and burner are well maintained and were already operated quite efficiently. At current natural gas fuel prices, payback of about 2% to 2½ years is possible at an attractive NPV. When operated with oil, O_2 trim technology enabled 7% savings.

To achieve TRL8 (fully qualified, approved, commercially released product) with the CO/O_2 trim system, the following steps will need to be pursued by Fireye:

- System and software optimization will be required to make the system conform to a commercially viable product release and obtain safety certification by UL and FM Global;
- Additional testing of the prototype on several additional boilers to ensure adaptation to multiple sites. The dual CO sensor system implemented at WVA worked flawlessly during a 2 month test period. However, the system is considered a prototype and is not UL certified.

United Technologies Corporation (UTC) companies have a proven process for product engineering and commercialization.

The technology demonstrated with this project will be suitable for acquisition and adoption by installations that manage and operate their boilers directly by means of the ECIP. Where operation of equipment is managed via Energy Service Companies (ESCO) or Utility Energy Service Contracts (UESC), adoption will have to occur as part of a portfolio of energy improvements selected by the private companies. The installation will pay a rate for generation of hot water or steam. In this case, the value of the investment in new technology will be captured by the service company who will transfer part of the benefit to the installation in terms of a rate discount.

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APPENDIX A

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