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Advanced Low NO_x Ribbon Burner Combustion System

Development and Demonstration in California

Gavin Newsom, Governor

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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division manages the Natural Gas Research and Development program, which supports energy-related research, development, and demonstration (RD&D) not adequately provided by competitive and regulated markets. These natural gas research investments spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution, and transportation.

The Energy Research and Development Division conducts this public interest natural gas-related energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public and private research institutions. This program promotes greater natural gas reliability and lower costs, increases safety for Californians, and is focused in these areas:

- Buildings End-Use Energy Efficiency
- Industrial, Agricultural, and Water Efficiency
- Renewable Energy and Advanced Generation
- Natural Gas Infrastructure Safety and Integrity
- Energy-Related Environmental Research
- Natural Gas-Related Transportation

Advanced Low NO_X Ribbon Burner Combustion System is the final report for the Low NO_X Ribbon Burner Combustion System Demonstration in California project (Contract #PIR-14-017) conducted by Gas Technology Institute. The information from this project contributes to the Energy Research and Development Division's Natural Gas Research and Development Program.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the CEC at 916-327-1551.

ABSTRACT

According to the American Bakers Association, there are more than 1,000 wholesale baking facilities and baking suppliers nationwide. A typical mid-size bakery has three production lines and consumes about 7 to 8 million cubic feet of natural gas per month. The United States baking industry consumes approximately 0.8 trillion cubic feet of natural gas annually and produces more than 3 million tons of carbon dioxide. Flue gas recirculation—an approach where a portion of exhaust gas (which is laden with carbon dioxide) is mixed with the combustion air—can be used to reduce the nitrogen oxide (NO_X) emissions produced by industrial ribbon burners or other burners with partially premixed flames. This was demonstrated in a full-scale wholesale bakery, confirming that the technology can meet new, stricter regulations limiting NO_X emissions without expensive modifications to the burner systems. The demonstrated advanced low NO_X ribbon burner combustion system achieved greater than 50 percent reduction in NO_X production in laboratory and pilot-scale testing, and 25 percent reduction in full-scale technology demonstration, with potential for greater reductions with further burner tuning. Additionally, there is potential for fuel savings of 5 percent or more through preheating of combustion air inherent in the system or other heating services at the bakery site. Adoption of this technology could lead to significant annual reduction of pollutant emissions from the ribbon burner installed base, retaining and increasing demand for natural gas-fired ribbon burner systems and technologies in the baking oven, flame treatment, gas-fired drying, and process heating industries while meeting strict air quality regulations.

Keywords: Low NO_X burner, ribbon burner, flue gas recirculation, combustion system, NO_X formation

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EXECUTIVE SUMMARY

Introduction

The heating and baking of food products in California is accomplished almost exclusively by conventional ribbon burners that use corrugated stainless steel lengths of different patterns for improved flame retention and uniform heat distribution. Ribbon burners are also used in many other industrial cooking and drying applications, particularly heat-treatment. These natural gas burners/systems are coming under stricter emissions regulations in many regions of the United States, especially in California. According to the 2018 California Gas Report, the California baking industry alone uses an estimated 4,116,000 million cubic feet per year of natural gas or about 0.2 percent of the state's demand. Emissions are estimated at 65,655 tons per year of carbon dioxide (CO_2) carbon equivalent and 481 tons per year of nitrogen oxides (NO_X). Reducing NO_X emissions is critical for the continued use of ribbon burners for food preparation, and for other existing combustion equipment. There are 170 wholesale bakeries with regulated ribbon burners across the State of California according to the Sosland 2019 Red Book (http://digital.bakemag.com/sosland/bake/2019_08_01/index.php#/0).

Project Purpose

There is a significant need for a cost-effective, low emission solution to traditional ribbon burners in California. Economic and regulatory pressures have necessitated either converting existing ribbon burners to other technologies, or modifying existing ribbon burners to improve efficiency and reduce emissions. Both options can be complicated and expensive, with the former likely requiring new and more complex heating and control systems with high capital and operating costs.

The Gas Technology Institute has developed an advanced low NO_X ribbon burner combustion system applicable to the business and environmental concerns of the California bakery industry. Considering the broad application of ribbon burners, the advanced low NO_X combustion system has the potential to support the wholesale baking industry in meeting and exceeding more stringent emission requirements while increasing efficiency and maintaining product quality.

This project focused on the development and field demonstration of an advanced low NO_X ribbon burner combustion system. The advanced low NO_X ribbon burner provides an option for the modification of traditional direct-fired ribbon burners widely employed across a variety of industries, including food processing, surface treating, drying, material thermoforming, and others.

Project Process

To demonstrate the energy (fuel) saving technology and the potential for drastic reductions in NO_X emissions, the project was conducted in three phases:

- Phase I included advanced low NO_X concept and laboratory-scale evaluation in a controlled environment at Gas Technology Institute applied research facilities (supported by Utilization Technology Development, a nonprofit company).

- Phase II included pilot-scale testing of the advanced low NO_X system on a baking oven with no active production. Testing took place at an industrial baking oven original equipment manufacturer pilot-scale facility (supported by Utilization Technology Development).
- Phase III included full-scale wholesale bakery ALN technology demonstration in a production setting at Western Bagel Baking Corporation jointly supported by the California Energy Commission, Southern California Gas Company, and Utilization Technology Development.

Project Results and Conclusions

The advanced low NO_X ribbon burner showed 50 percent NO_X reductions in laboratory and pilot tests and 25 percent NO_X reductions in full technology demonstration, with potential for even greater reductions. This brings emission levels well below the stringent new air quality regulation emissions in southern California. Flue gas recirculation—an approach where a portion of exhaust gas (which is laden with CO_2) is mixed with the combustion air—can be used to reduce NO_X emissions produced by industrial ribbon burners or other burners with partially premixed flames. This approach was demonstrated in a full-scale wholesale bakery, confirming that it can meet new stricter regulations limiting NO_X emissions without the need for expensive modification to the burner systems. For situations when the NO_X reduction is critical and replacing the conventional ribbon burner is not possible or is cost-prohibitive, the demonstrated approach can become a viable option, especially in light of the strengthening of Federal and State environmental regulations. Results of conducted experiments and computational fluid dynamics modeling demonstrated that the dilution of the combustion air with CO_2 can result in significant reductions in NO_X formation.

Preliminary discussions on the licensing of this promising technology have been initiated with the participating industrial partners and baking ovens manufacturers. Quantifiable fuel savings compared to the baseline run were demonstrated during the project, and bagel production was successfully accomplished with the modified system with no loss of production.

Technology Transfer

The development and demonstration of the energy-saving and emission-reduction technology have been distributed among the targeted audience including the thermal-fluid scientists, researchers, and engineers as well as promoted to the manufacturing companies and end users via presenting and publishing the most promising results:

- Combustion Science and Technology (2019), DOI: 10.1080/00102202.2019.1622532- American Baking Association Technical Conference (2018), Indianapolis, IN, October 28-30
- International Mechanical Engineering Congress (2014), Montreal, Canada, November 14-20

The project team has also made several presentations to the leading wholesale bakeries in California including Western Bagel (Van Nuys), Kroger (La Habra), J&J Snacks (Colton), Bimbo Group (Placentia), Puritan Bakery (Carson) and others. The major combustion system suppliers were also contacted to initiate commercialization discussions.

The technology transfer activities in progress include a plan to expand commercialization discussions to industrial baking oven manufacturers such as C.H. BABB Gemini, Despatch, FMC and others at the 2019 International Baking Industry Expo (Las Vegas, NV) and 2020 Baking Industry Manufactures Association Conference (Chicago, IL).

Benefits to California

New California limits on NO_X and CO_2 emissions (SCAQMD Rule 1153-1, adopted November 7, 2014) require further improvements to ribbon burner performance to ensure continued use of this reliable and effective technology. The advanced ribbon burners demonstrated reduced NO_X emissions of up to 50 percent. At the same time, internal recuperation gives these new ribbon burners the potential to increase natural gas use efficiency by up to 5 percent. Emission reductions will prevent the need for natural gas-fired ribbon burners to be replaced with more costly electric systems.

Some companies might be expected to voluntarily adopt this technology, due to the 3.5 year payback from fuel savings. Assuming a 30 percent market penetration in the baking and heat-treating industries, California-wide emissions reductions are estimated as:

- Natural gas reductions of 1.3 million to 1.5 million therms per year
- Carbon dioxide emission reductions of 7,500 to 10,000 tons per year
- NO_X emission reductions of 200 to 300 tons per year

California ratepayers will benefit from a ribbon burner system that:

- Provides higher natural gas use efficiencies, conserving natural gas resources and enhancing use of California's gas distribution system.
- Reduces greenhouse gas emissions.
- Reduces harmful NO_X emissions.
- Supports local jobs and the local economy.
- Reduces the need for manufacturers to pass along higher production costs to consumers.

CHAPTER 1: Introduction

1.1 Current State of Ribbon Burner Technology

The ribbon burner is a mature low-cost technology that has found widespread application in industrial baking, drying, and surface treatment applications and is due to high heat release firing where a linear even flame is essential. Ribbon burners employ stainless steel ribbons of different patterns for excellent flame retention and uniform heat distribution. Thousands of burners are installed on food processing lines, particularly in baking industry operations. Figure 1 illustrates examples of ribbon burners that are available off-the-shelf. State-of-the-art ribbon burners typically have emission production of 25-30 parts per million, volume (ppmv) of nitrogen oxides (NO_X) and < 15 ppmv of carbon dioxide (CO), both corrected to 3 percent oxygen (O_2).

Figure 1: Conventional Ribbon Burners

Source: Maxoncorp (left) and Burner Depot (right)

1.1.1 Motivation

The California bakery industry uses an estimated 4,116,000 million cubic feet per year of natural gas. Emissions are estimated as 65,655 tons per year of CO_2 equivalent; and 481 tons per year of NO_X. The heating and baking of food products in California is accomplished almost exclusively by conventional ribbon burners, which are also widely used in other industrial cooking and drying applications. The wholesale bakery industry is highly competitive and financial resources are constantly reassessed and prioritized on short- and long-term planning horizons.. Burners and systems fueled with natural gas are under strict regulations in many regions of the United States, especially in California. South Coast Air Quality Management District (SCAQMD) Rule 1153-1, adopted November 7, 2014, limits NO_X emissions for industrial baking equipment to 40 parts per million (ppm) (0.042 lb/million British Thermal Units [MMBtu]) for processes ≤ 500 degrees Fahrenheit (°F) and to 60 ppm (0.073 lb/MMBtu) for processes > 500°F, corrected to 3 percent O_2, dry[1]. The estimated costs to operators for complying with proposed environmental rules could reduce competitiveness with other regions

1 Rule 1153.1 Emissions of Oxides of Nitrogen from Commercial Food Ovens. Adopted November 7, 2014.

in the United States and overseas, driving this industry to seek low-cost solutions in order to remain in business. Reducing NO_X emissions is critical for the continued use of ribbon burners and the continued use of existing combustion equipment in California.

Without an improved ribbon burner combustion system, environmental regulatory pressures soon could lead to the need for the industry to either:

- Convert from ribbon burners to other burner technologies requiring new and more complex heating and control systems with high capital and operating costs, or
- Modify existing ribbon burner systems to improve efficiency and reduce emissions at a lower cost.

1.2 Project Description

The Gas Technology Institute (GTI) developed an advanced low NO_X (ALN) ribbon burner combustion system that is directly applicable to the California bakery industry's business and environmental concerns. The major improvement includes significant reduction of NO_X emissions without substantial redesign of the combustion system. Considering the broad application of ribbon burners for industrial processes, the ALN combustion system has the potential to support the wholesale baking industry in meeting and exceeding more stringent emission requirements while increasing efficiency and maintaining product quality without sacrificing process control.

1.2.1 Background

In 2012-2013, a GTI project team performed an exploratory research and development (R&D) effort to validate potential strategies for NO_X reduction while maintaining stable operation of the conventional pipe ribbon burner that is widely employed in industrial bakeries. The positive findings served as a basis for the design of a follow-on laboratory-scale test rig for the proof-of-concept evaluation.

In 2013-2014, the follow-on laboratory-scale evaluation was performed at the firing range of 15,000-25,000 Btu/hour (hr or h) that corresponds to the wholesale bread baking operations (600-1,200 Btu/h/linear inch). The results served as a basis for the design of the pilot-scale system for performance assessment in a near-production environment.

In the follow-on effort in 2014-2015, the GTI team, along with the ribbon burner's original equipment manufacturer (OEM), Flynn Burner Corporation, designed and evaluated the performance of the ALN ribbon burner combustion system at pilot-scale in the industrial settings at the oven manufacturer test facility, and obtained encouraging results.

In June 2015, the California Energy Commission (CEC) funded a project to perform a field-demonstration of the ALN ribbon burner combustion system in a full-scale production environment at a wholesale bakery, Western Bagel Baking Corporation (Western Bagel), in California. This report relates the results from this demonstration.

1.2.2 Objectives

The goals of this effort were (1) to demonstrate that the developed direct natural gas-fired ALN ribbon burner combustion system provided cost and environmental benefits in a broad range of agricultural and industrial applications, and (2) to take the first steps to bring the technology to the California market by its demonstration in a full wholesale baking facility. There was specific interest in determining whether the ALN technology applied in a commercial setting would be able to reduce ribbon burner NO_X production by 50 percent from current state-of-the-art burners that produce 30 parts per million by volume (ppmv) NO_X at 3 percent O_2, as demonstrated at the laboratory and pilot scale. The project also sought to determine the potential for reducing energy (fuel) consumption through partial energy recovery from the gas-fired exhaust (specifically for preheating of combustion air).

1.3 Market Impact

According to the *Research and Markets 2012 Bakery Product Manufacturing* report, there are approximately 2,800 industrial and commercial bakeries nationwide[2]. A typical mid-size bakery might have three production lines and would consume about 7,000,000 cubic feet (cf) of natural gas per month. As such, the United States baking industry consumes approximately 0.8 trillion cubic feet (TcF) of natural gas annually and produces over 3 million tons of CO_2. Ribbon burner-based combustion systems are also becoming popular in more industrial applications, like gas-fired drying and process heating, due to increased interest in natural gas-fired systems. The savings and reductions with 30 percent market penetration in the California baking and heat-treating industries are estimated to be:

- Natural gas reductions of 1.3 million to 1.5 million therms per year.
- Carbon emissions reductions of 7,500 to 10,000 tons per year.
- NO_X reductions of 200 to 300 tons per year

[2] *US Commercial Bakery Sector Pulls in $30bn a Year.* 8 Nov 2012. Accessed 27 Aug 2018. https://www.bakeryandsnacks.com/Article/2012/11/08/US-bakery-sector

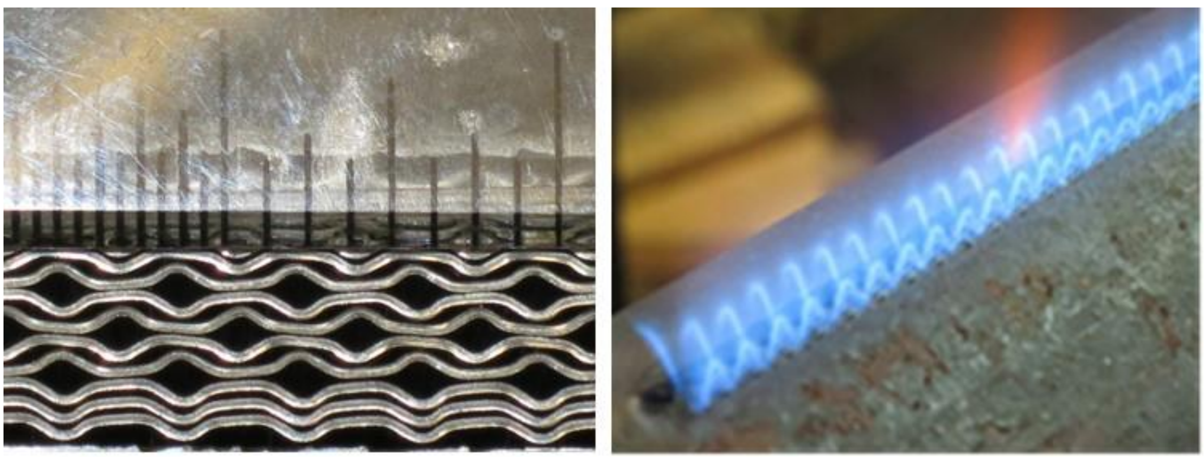
CHAPTER 2:
Ribbon Burners and NO_X Formation

2.1 Ribbon Burners

2.1.1 Design

The conventional ribbon burner is made of steel pipe that uses a long, thin slot filled with corrugated metal strips to create a narrow array of short, interconnected flames. Different ribbon designs are installed to ensure various heat outputs and flame patterns. Figure 2 illustrates Flynn Burner Corporation's ribbon and the flame pattern of the conventional ribbon burner for industrial baking applications. These burners ignite easily and the flame travels to all ports instantaneously, simplifying the ignition and safety systems.

Figure 2: Pipe-Type Ribbon Burner by Flynn Burner Corporation



Flynn Burner's ribbon burner (left) and flame pattern of the burner at the average firing rate (right).

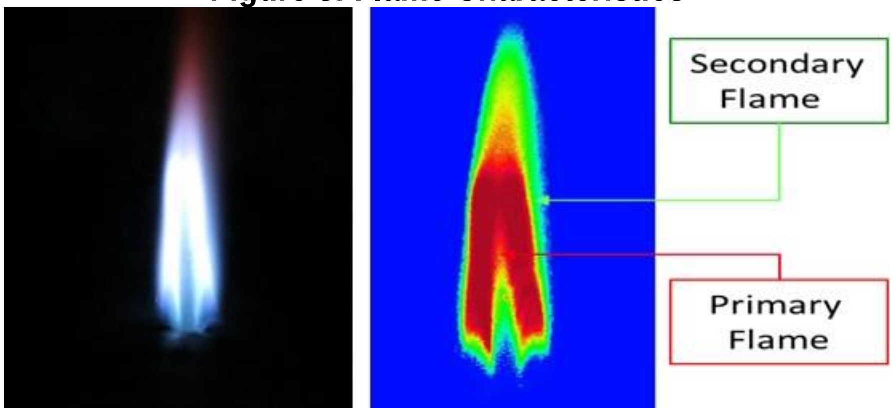
Source: GTI

2.1.2 Operation

Burners are typically operated either fully aerated (fully premixed oxidizer and fuel) or partially aerated (partially premixed oxidizer and fuel). In practice, the typical or common oxidizer media used with conventional burners is air. In such operation, the portion of air used for (partial) combustion that is mixed with the fuel is commonly called "primary air;" the remaining portion of air is commonly called "secondary air." Fully aerated burners only use primary air; partially aerated burners use primary air and secondary air.

The typical ribbon burner flame has a high temperature core and low temperature periphery, as shown in Figure 3. NO_X is mostly produced at the high temperature core, or primary flame.

Figure 3: Flame Characteristics



Ribbon burner flame characteristics showing high temperature primary flame and lower temperature secondary flame (left), with flame imagery taken at GTI lab (right).

Source: GTI

2.2 NO_X Formation

Most industrial operations are under strict environmental regulations. Although reduction of NO_X emissions is critical for continued use of ribbon burners, many common NO_X reduction techniques are not practical for smaller-sized premixed flames such as those found in bakery operations. NO_X formation includes both nitric oxide (NO) (~90 percent) and nitrogen dioxide (NO_2) (~10 percent). The three main ways NO_X forms in burners are described.

2.2.1.1 Thermal NO_X

Thermal NO_X is formed by the reaction of atmospheric oxygen and nitrogen at elevated temperatures. In the classical mechanism by Y. Zeldovich, the amount of NO_X formation increases with temperature and/or higher oxygen and atmospheric nitrogen concentration.

N2 + O → NO + N (nitrogen dissociates at high temperature > 2,900°F)
N + O2 → NO + O
N + OH → NO + H (extended mechanism)

This formation accounts for the majority of NO_X emissions in natural gas burners.

2.2.1.2 Prompt NO_X

Prompt NO_X, in the form of NO, is formed by the reaction of hydrocarbon radicals with atmospheric nitrogen to produce NO_X. This formation mechanism contributes to about 5 percent of the total NO_X.

2.2.1.3 Fuel NO_X

Fuel NO_X is formed by the reaction of the organically bound nitrogen in the fuel with oxygen. For natural gas burners, the contribution is negligible.

2.3 Mitigation Techniques

Developing a lower NO_X emission ribbon burner combustion system that does not jeopardize the simplicity, reliability, and the low-cost advantages normally associated with the use of ribbon burners has presented a significant challenge. Some mitigation techniques employed to reduce NO_X formation are described in the following sections.

2.3.1 Efficiency Improvement

Efficiency improvements are one way to realize NO_X emission reductions. These improvements are accomplished both by reducing overall fuel consumption with associated NO_X emissions, and by optimizing combustion to reduce the emissions per unit of fuel consumed. Both waste-heat recovery and a well-tuned combustion system with optimized air/fuel ratio control will result in lower emissions. This will limit the excess air in flue gases, reducing NO_X formation.

2.3.2 Flame Temperature Reduction

The general goal of techniques falling under this category is to reduce flame temperature and thereby suppress the formation of thermal NO_X. Some examples of these techniques include flame staging, flue gas recirculation, and burner design.

2.3.2.1 Flame Staging

In this approach, the proportions of fuel and/or air are staged across the burner. Flame staging can use various techniques, but the general goal is to reduce the flame temperature and/or oxygen concentration in the primary flame, thereby reducing NO_X formation[3].

2.3.2.2 Flue Gas Recirculation (FGR)

The flue gas recirculation (FGR) technique involves mixing a portion of the flue gas combustion products to at least one of either the primary and/or the secondary oxidizer supply to the burner. FGR is designed to reduce NO_X emissions by lowering both peak flame temperature and the available concentration of oxygen for reaction with elemental nitrogen. This technique is commonly applied to large boilers and heat-treating furnaces.

2.3.2.3 Burner Design

Flame temperature can also be lowered by altering the physical design of the burner. For ribbon burners and other types of partially premixed burners, one approach for reducing NO_X has been with porous or mesh materials rather than corrugated metal strips in the burner. This technique allows an increase in heat transfer from the combustion process via the radiation mode of operation while also reducing the flame temperature. This approach, however, has power output limitations as well as lower reliability and durability.

2.3.3 Post-Combustion Treatment

Post-combustion treatments such as selective catalytic reduction (SCR), selective non-catalytic reduction (SNCR), and catalytic oxidation to reduce NO_X emissions involve the introduction of

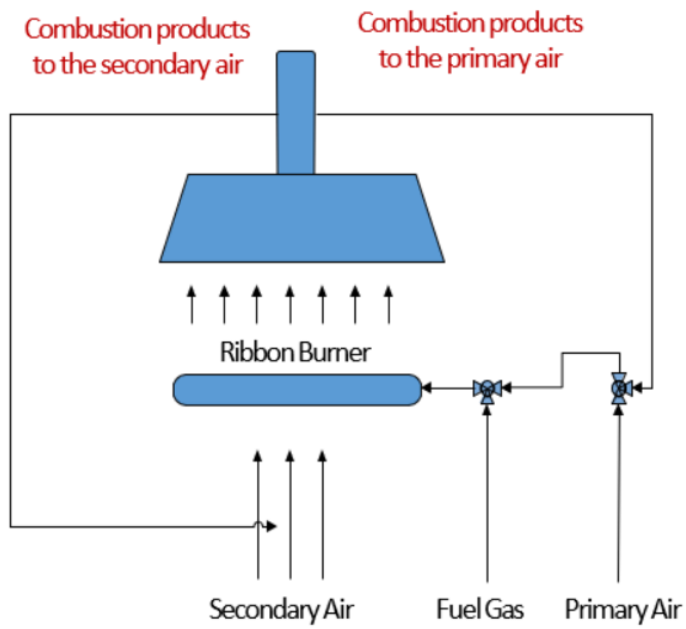
[3] Bell, Ron D., Buckingham, Fred. An overview of technologies for reduction of oxides of nitrogen from combustion furnaces. MPR Associates. https://www.mpr.com/uploads/news/nox-reduction-coal-fired.pdf

outside reagents and/or catalysts to convert NO_X in the exhaust to elemental nitrogen. These methods are typically limited to large industrial applications.

2.4 Technical Concept

As described, one of the promising approaches to reducing NO_X emissions from partially aerated burners is FGR, which involves modifying primary and/or secondary air composition through recirculation of combustion products from an exhaust stream. The oxygen concentration in the combustion air is diluted to below ambient (20.9 percent). Premixed combustion of natural gas and air with lower oxygen content occurs at significantly lower temperatures in the primary flame zone (Figure 3) than with conventional burner operations, thereby producing lower thermal NO_X. This approach is illustrated in Figure 4. Using FGR is especially promising for ribbon burners, as it enables significantly improved NO_X emissions without sacrificing the simplicity, low cost, reliability, and safety of ribbon burner operations. Another benefit is that no significant burner redesign is required.

Figure 4: Technical Concept for NO_X Mitigation



Simplified schematic of a system for reducing nitrogen oxide emissions from a ribbon burner by admixing flue gas combustion products with primary and secondary air.

Source: GTI

Implementing this goal requires an appropriate technique or system for admixing a portion of the flue gases from the ribbon burner into the primary and/or secondary air stream(s). For industrial and commercial baking and drying applications, flue gases are typically already gathered into a common flue duct or ducts (flue stacks). A blower can draw a portion of the flue gases out of the stack through the addition of a branch line and push the flue gases into the primary and/or secondary air stream(s). As described later in this report, this process was first demonstrated at laboratory-scale in ribbon burners through the dilution of the combustion air with CO_2, resulting in significant reduction of NO_X. Since the exhaust gas is laden with CO2, this created an expectation that FGR, which mixes exhaust gas with combustion gas, could reduce the NOx emissions from industrial processes. FGR can allow industrial companies to meet new stricter regulations limiting NO_X emissions without the need for expensive modification of the burner systems. For situations when the NO_X reduction is critical and replacing the conventional ribbon burner is not possible or is cost-prohibitive, this approach can be a viable option. Early testing and full-scale demonstration also showed this could be accomplished with no loss of burner efficiency and with the potential for fuel savings with well-tuned burners.

CHAPTER 3: Host Site Evaluation

3.1 Background

In June 2015, the Energy Commission awarded a project for the field demonstration of the ALN ribbon burner combustion system in a full-scale production environment at a participating wholesale bakery in California. Through several site evaluations, the project team selected a wholesale bagel bakery in Van Nuys, California, Western Bagel Baking Corporation, as the qualified site for the full-scale technology demonstration (Appendix A presents photographs illustrating this full-scale technology demonstration). Equipment installation for the demonstration was initiated in 2016 and was completed in 2017, working around oven maintenance outages. Several other sites were evaluated initially but were unable to participate for economic, technical, or administrative reasons.

3.2 Western Bagel Baking Corporation

Western Bagel is a wholesale bakery (established 1947) that has two baking ovens in operation in its Van Nuys facility. The oven identified for the study is a 74.0′ long x 12.0′ wide x 4.0′ high tunnel-type oven equipped with 60 ribbon burners. The heat input for the oven is rated at 2.94 MMBtu/hr. There are two exhaust stacks located on the oven. The first exhaust stack is located at the east end of the oven, where the bagels are loaded. The second exhaust stack is located at the west end of the process, where the bagels are sorted and packaged. The baking process, which operates on a conveyor system with the ribbon burners both above the bagels in the oven cavity and below the oven floor, takes approximately eight minutes but can be longer depending on bagel type and topping application. The Van Nuys facility can process 22,800 bagels per hour. Figure 5 shows the exterior and interior of the demonstration oven. Following extensive oven evaluations, as well as technical and legal discussions, Western Bagel was selected as a qualified host site for the GTI technology demonstration.

3.3 Oven Operation

The Direct Gas-Fired (DGF) oven consists of a number of heating zones. The heat is generated within each zone using direct gas-fired pipe or profile ribbon burners. Combustion air is provided by a blower delivering air at the required volume and pressure. The combustion air induces the fuel flow from the gas line fitted with a zero-gas pressure regulator by means of a venturi effect through an air/gas mixer. The oven is fitted with one blower that feeds a main air header across the entire length of the oven. Taps from the main header are fed to the individual zones, each with a direct-acting motorized valve. The air/gas mixture is ignited at the burner by the ignition electrode. A flame safety relay initiates the spark and subsequently senses the flame. The ribbon assembly is designed to provide stable flames throughout the power range of the burners. The DGF oven uses automation software to maintain a specified temperature or heat profile and adjust according to oven contents.[4] The heat input for the

[4] Flynn Combustion Automation. *DGF Oven Operational Manual.* 2018

oven is rated at 2.94 MMBtu/hr. The oven is within SCAQMD jurisdiction. A copy of the DGF Oven Manual is provided in Appendix B.

Figure 5: Baking Oven at Western Bagel

Overview of the full-scale technology demonstration baking oven at Western Bagel.

Source: GTI

CHAPTER 4: Laboratory-Scale Testing

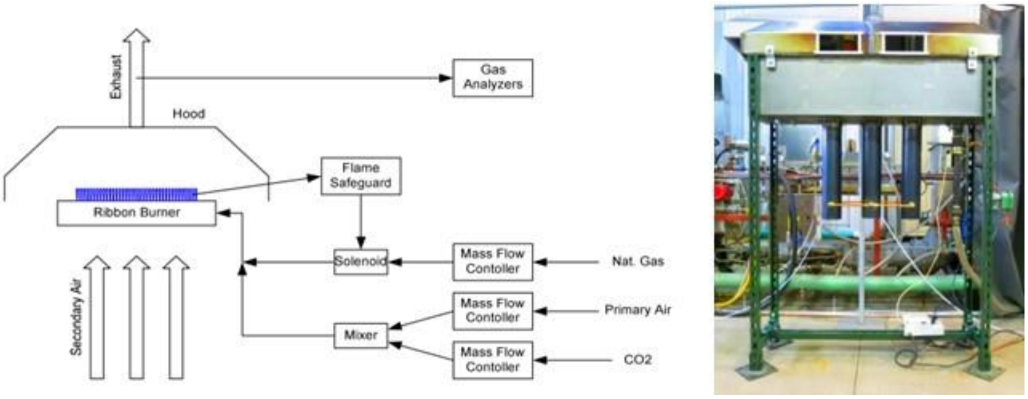
4.1 Background and Experimental Setup

In 2012-2013, the GTI project team performed an exploratory R&D effort to validate potential ways of achieving NO_X reduction while maintaining stable operation of conventional pipe ribbon burners. The findings served as a basis for the design of a follow-on laboratory-scale test rig for the proof-of-concept evaluation.

In 2013-2014, the laboratory-scale evaluation was performed at a firing range (15,000-25,000 Btu/hr) corresponding to wholesale bread baking operations (600-1200 Btu/h/linear inch). The experimental setup consisted of a ribbon burner, a blending station for fueling the burner, a hood for collecting the exhaust gases, and a combustion gas analyzer. The ribbon burner was made from a 1¼" (nominal diameter) Schedule 80 (wall thickness) pipe with an overall length of 32" and a slot length of 24". The slot was 11/64"-wide and contained 4 ribbons. The nominal capacity of the burner was 17,000 Btu/h at 0.5" Water Column (WC) supply pressure, with normal operation at 24,000 Btu/h. Figure 6 shows the schematic of the experimental setup.

The blending station is an in-house designed-and-built apparatus that provides custom gas blends to burners to study the effects of fuel interchangeability and the combustion of syngas. It contains two mass flow meters, four mass flow controllers, pressure regulators, a static mixer, and a data acquisition system. In its normal mode of operation, it can blend up to four different gas components into one of two main flow streams at up to 21 different programmable ratios. In this study, it was used to provide the combustion air, carbon dioxide, and natural gas to the burner. A stream of carbon dioxide was blended into the primary combustion air that directly fed into the burner along with natural gas.

Figure 6: Schematic and Overview of the Experimental Setup

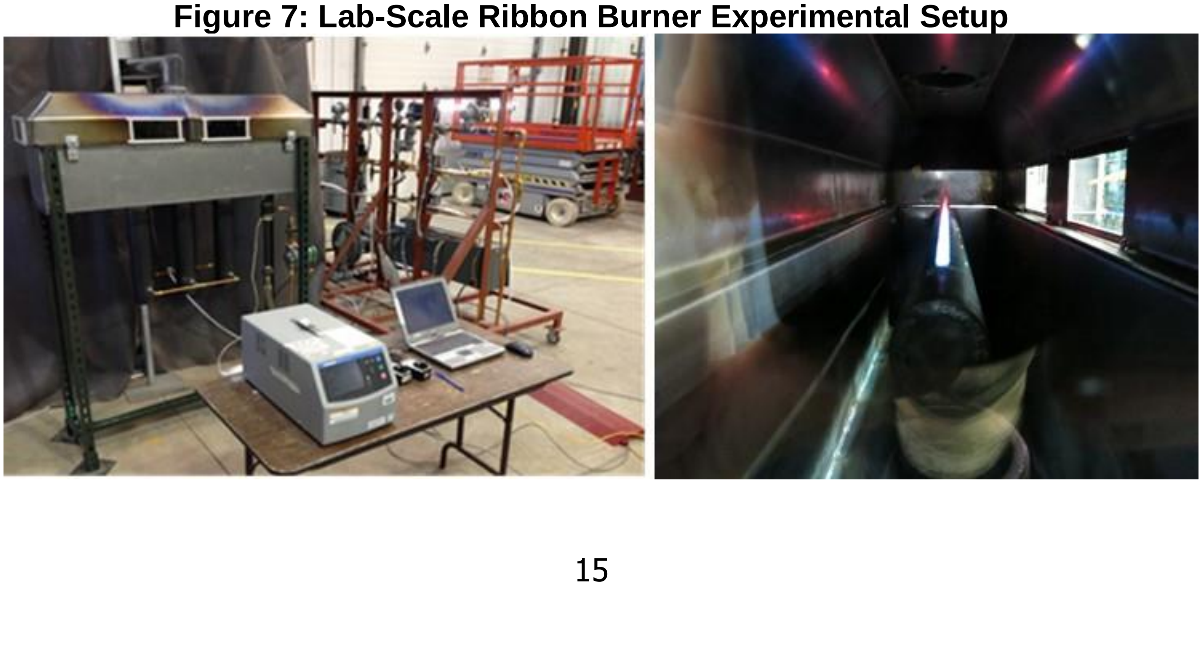


Experimental setup containing the ribbon burner, a blending station for fueling the burner, a hood for collecting the exhaust gases, and a combustion analyzer.

Source: GTI

The basic test procedure was to start up the ribbon burner on air and natural gas and allow the burner and hood to warm up while calibrating the combustion gas analyzer. The primary air and natural gas flow rates were then set for the day's first firing rate and Primary Equivalence Ratio (PER), which is the primary fuel/air ratio divided by the stoichiometric fuel/air ratio. The stoichiometric fuel/air ratio is the theoretical ratio of fuel to air resulting in all fuel burned without leftover fuel or oxygen; the PER therefore measures the extent of excess fuel or excess air in the burner. The emissions readings were allowed to stabilize, and then baseline NO_X, CO, CO_2, and O_2 concentration levels in the exhaust duct were recorded. CO_2 was then added to the primary air, which reduced the oxygen concentration in the primary air from 20.9 percent to 20.0 percent. The emissions readings were recorded once they stabilized. Additional CO_2 was added in steps that further reduced the oxygen concentration in the primary air by about 0.4 percent per step, with emissions readings recorded at each step. This methodology continued until the flame became unstable (high CO emissions) or the flame extinguished ("blew off"). Figure 7 is a photograph of the experimental setup layout.

Figure 7: Lab-Scale Ribbon Burner Experimental Setup



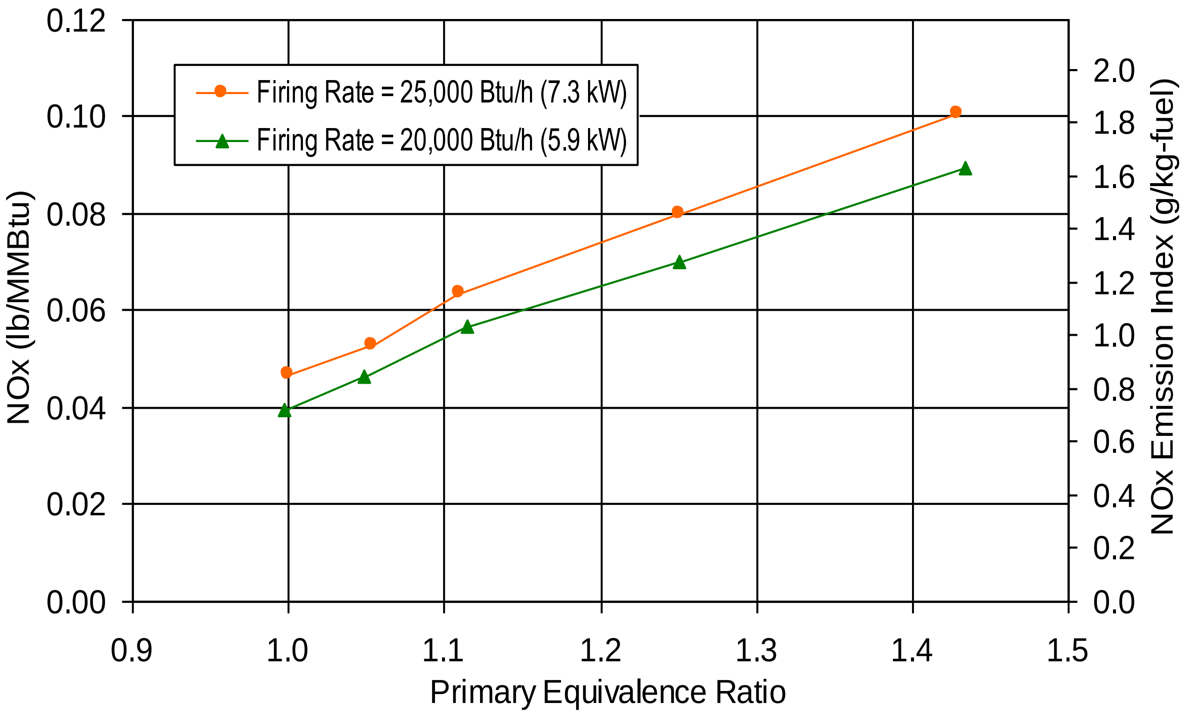
External (left) and internal (right) views of the experimental setup for testing NO_X emissions from a ribbon burner.

Source: GTI

4.2 Results

In ribbon burners, a large amount of air is premixed with fuel to achieve stable and easily controlled operation. A degree of partial aeration strongly affects NO_X emissions. As shown in Figure 8, NO_X formation is lowest at PER around 1. A lower PER results in a larger portion of the fuel being consumed in the primary combustion zone of the ribbon burner's partially premixed flame. At PER >1, combustion in the primary zone (or primary flame) occurs under fuel-rich conditions while the combustion in the secondary combustion zone (or secondary flame) is controlled by the diffusion of the surrounding air[5,6]. The increase of NO_X emissions with PER (at 1 < PER < 1.5) is usually due to prompt mechanism of NO formation[6]. These results informed the decision of the target PER for further tests with partially premixed air diluted with CO_2.

Figure 8: Effect of Primary Equivalence Ratio on NO_X Emissions



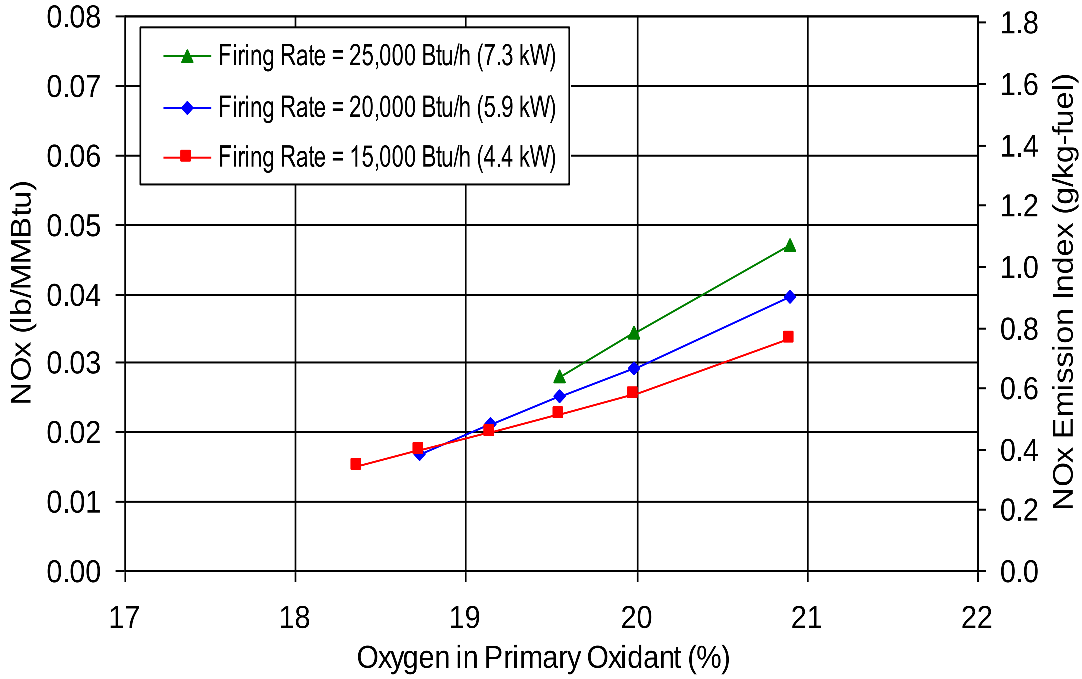
Source: GTI

[5] J. P. Gore, Structure and NOx emission properties of partially premixed flames. In Advances in Chemical Propulsion: Science and Technology. G. Roy Ed., CRC Press, Hoboken. NJ, 2001.

[6] Kim, T. K., B. J. Alder, N. M. Laurendeau, J.P. Gore. 1995. Exhaust and in situ measurements of nitric oxides for laminar partially premixed C2H6–air flames: Effect of premixing level at constant fuel flow rate. Combustion Science Technology 110–111:361–78.

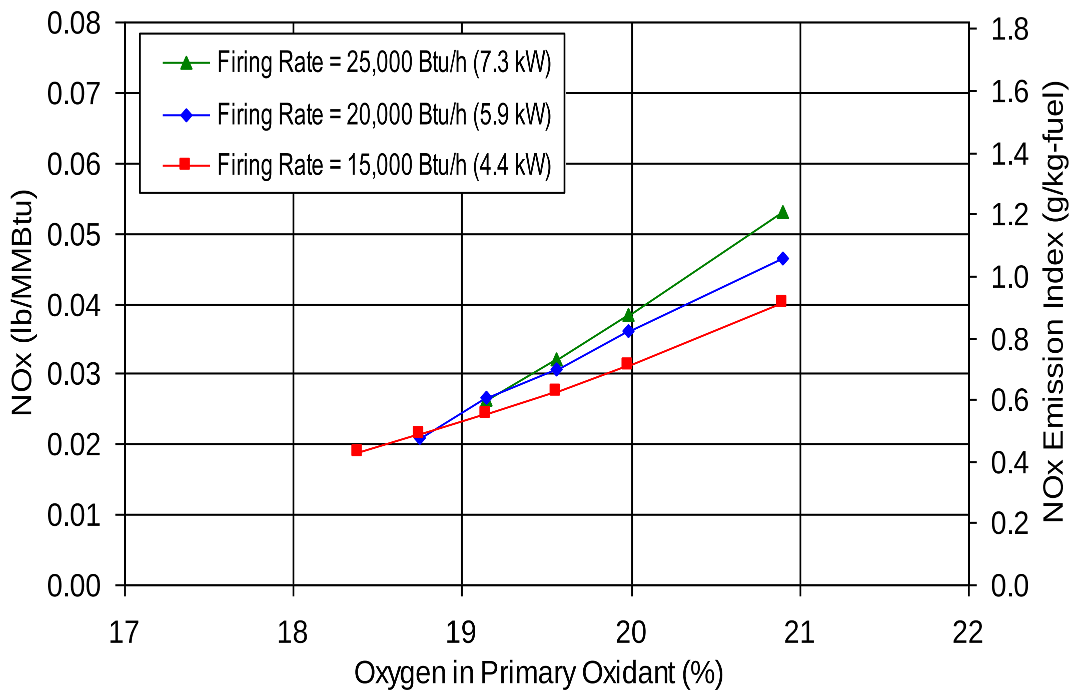
Figure 9 depicts reductions of NO_X formation in ribbon burner flame with dilution of the primary oxidant supplied to the burner with CO_2. The overall oxygen-to-fuel ratio was not changed to maintain complete combustion, but the result of the dilution was that the effective concentration of oxygen in the primary oxidant stream (mixture of air and CO_2) was decreased to as low as 18.4 percent. The maximum level of dilution for each combination of firing rate and PER depended on maintaining low levels of CO emissions. The combustion of natural gas mixed with oxidant containing concentrations of oxygen lower than 21 percent resulted in a significant decrease in the NO_X formation. The NO_X reduction is likely attributed to lower flame temperatures and suppression of thermal NO_X mechanism. The curves for different firing rates merge at the lower limit of oxygen contents. Figure 10 presents similar trends for a PER of 1.053. A NO_X emission index below 0.6 grams per kilogram (g/kg) was achieved at 19 percent of oxygen content in the primary oxidizer stream for all the firing rates studied.

Figure 9: Effect of Oxygen Content in Primary Oxidant on NO_X Emissions at a PER of 1



Source: GTI

Figure 10: Effect of Oxygen Content in Primary Oxidant on NO_X Emissions at a PER of 1.053

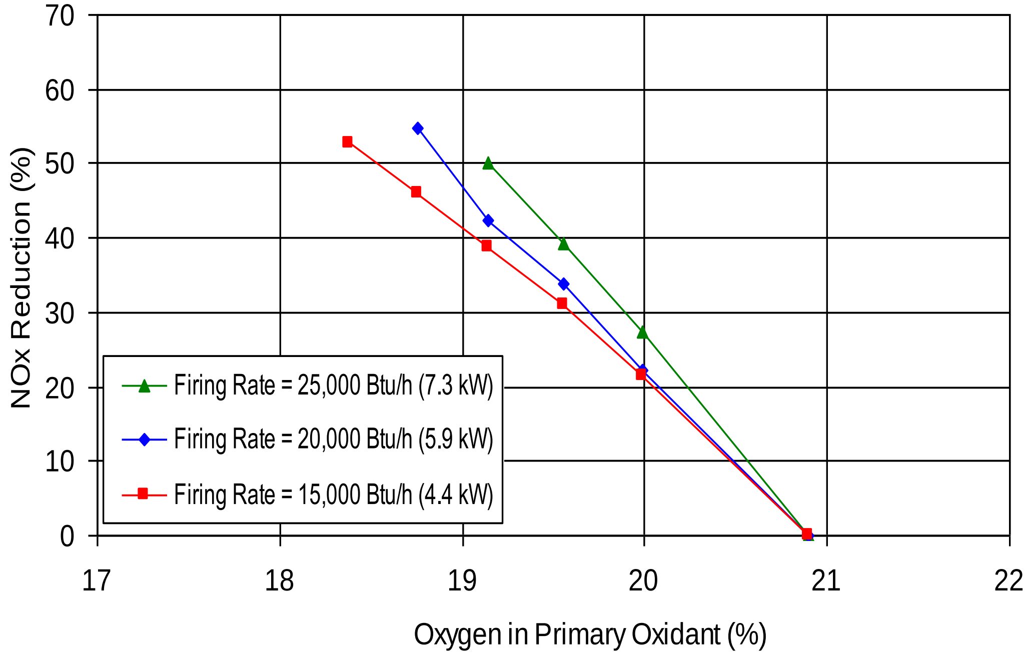


Source: GTI

Figure 11 shows the effect of the primary oxygen content on NO_X reduction at a primary stoichiometric ratio of 0.95 (PER = 1.053). The reduction of NO_X is close to 50 percent for

25,000 BTU/h (7.3 kW) firing rate and exceeds 50 percent for the firing rates of 15,000 Btu/h (4.4 kilowatts [kW]) and 20,000 BTU/h (5.9 kW).

Figure 11: Effect of Primary O_2 Content on NO_X Emissions Reduction at PER = 1.053



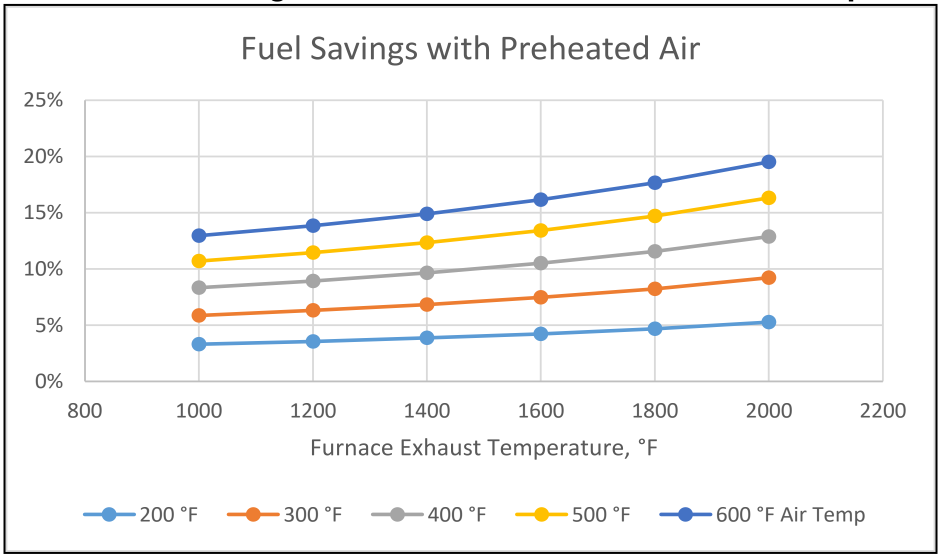
Source: GTI

The major results for the laboratory tests, as illustrated in Figure 11, show that reduced firing rates result in an associated slight reduction of NO_X. However, lower primary oxygen content plays the critical role in maintaining a ~50 percent NO_X reduction. These laboratory results served as a basis for the design of the pilot-scale system for the performance assessment in near-production environment, as discussed in Chapter 5.

4.2.1 Fuel Savings

The team also initiated an assessment of the fuel efficiency improvements enabled by this approach, as part of the laboratory demonstration in the fourth quarter of 2014 and the first quarter of 2015. Preheating the combustion air can lead to fuel savings even with low temperature processes. When the air is preheated, the flame becomes hotter and thus the fuel flow rate must be reduced to maintain the same furnace temperature. Figure 12 illustrates the amount of fuel savings that can be expected for various oven exhaust temperatures with various moderate levels of air preheating.

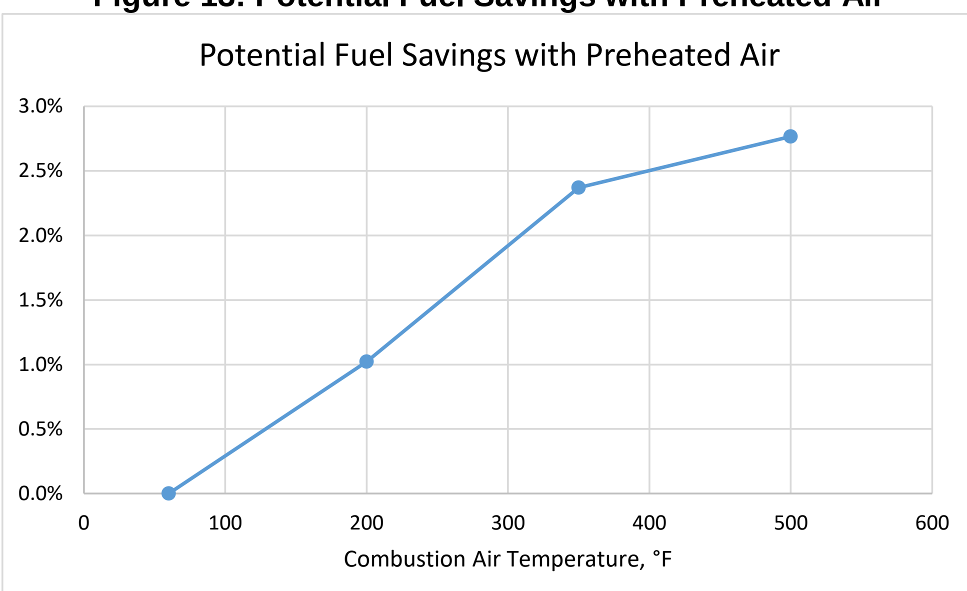
Figure 12: Fuel Savings with Preheated Air at Different Temperatures



Source: GTI

The preliminary calculations indicated that preheating the combustion mixture to relatively low temperatures could result in 5–10 percent fuel savings. The project team modified the ALN experimental setup to enable simulation of the combustion mixture preheating by FGR. Experiments were conducted at GTI with a ribbon burner that measured the furnace exhaust temperature with different levels of air preheated for the same fuel flow rate. Calculations were then made to estimate the amount that the fuel flow rate would have to be reduced to obtain the same furnace exhaust temperature as with the non-preheated air. Figure 13 illustrates the amount of fuel savings that can be expected for various combustion air temperatures with this type of burner.

Figure 13: Potential Fuel Savings with Preheated Air



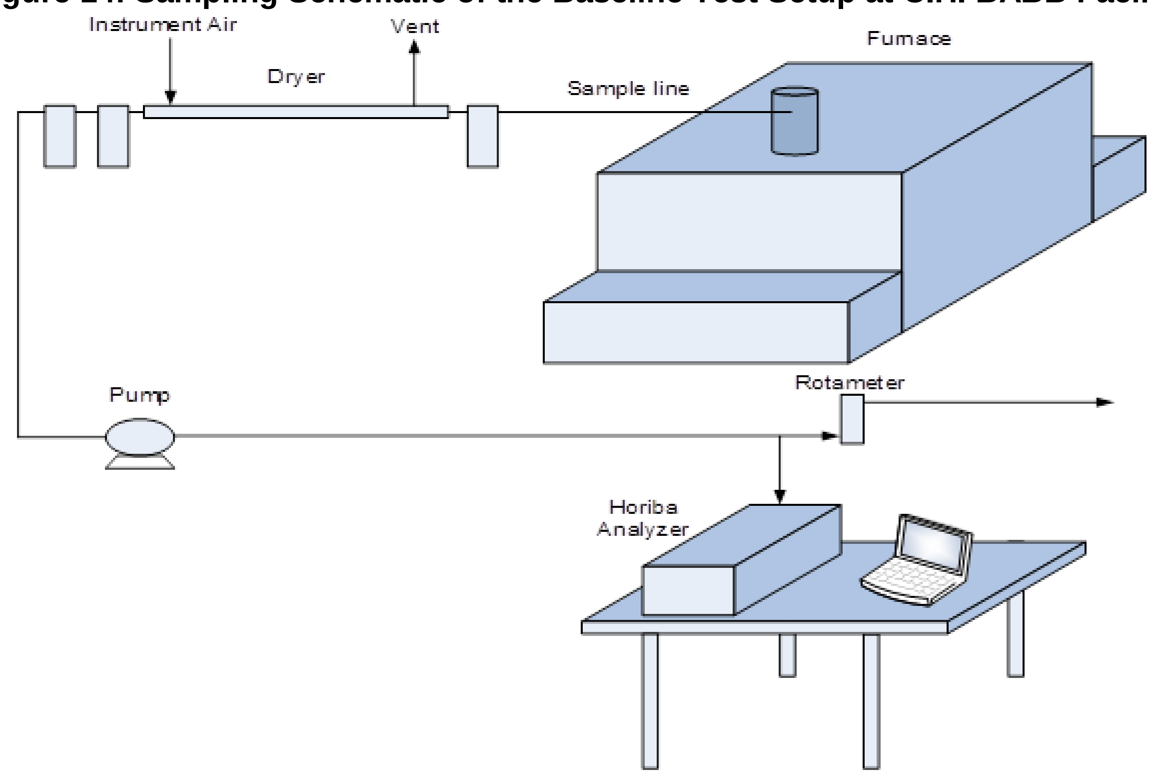
Source: GTI

CHAPTER 5: Pilot-Scale Testing at C.H. BABB

5.1 Background and Experimental Setup

Following successful laboratory-scale testing, GTI and Flynn Burner Corporation (FBC) conducted baseline testing at the C.H. BABB Company (baking oven manufacturer). The pilot-scale oven is a semi-commercial system used mostly by food processors, such as commercial and industrial bakeries, for the evaluation of new recipes and baking processes. The oven is equipped with 16 ribbon burners manufactured by FBC. The nominal firing rate of each burner is approximately 125,000 Btu/h. The goal of the testing was to assess the NO_X level produced by a typical commercial oven equipped with a typical ribbon burner combustion system. A schematic of the test sampling and a photograph of the test setup overview are shown in Figure 14, and Figure 15.

Figure 14: Sampling Schematic of the Baseline Test Setup at C.H. BABB Facility



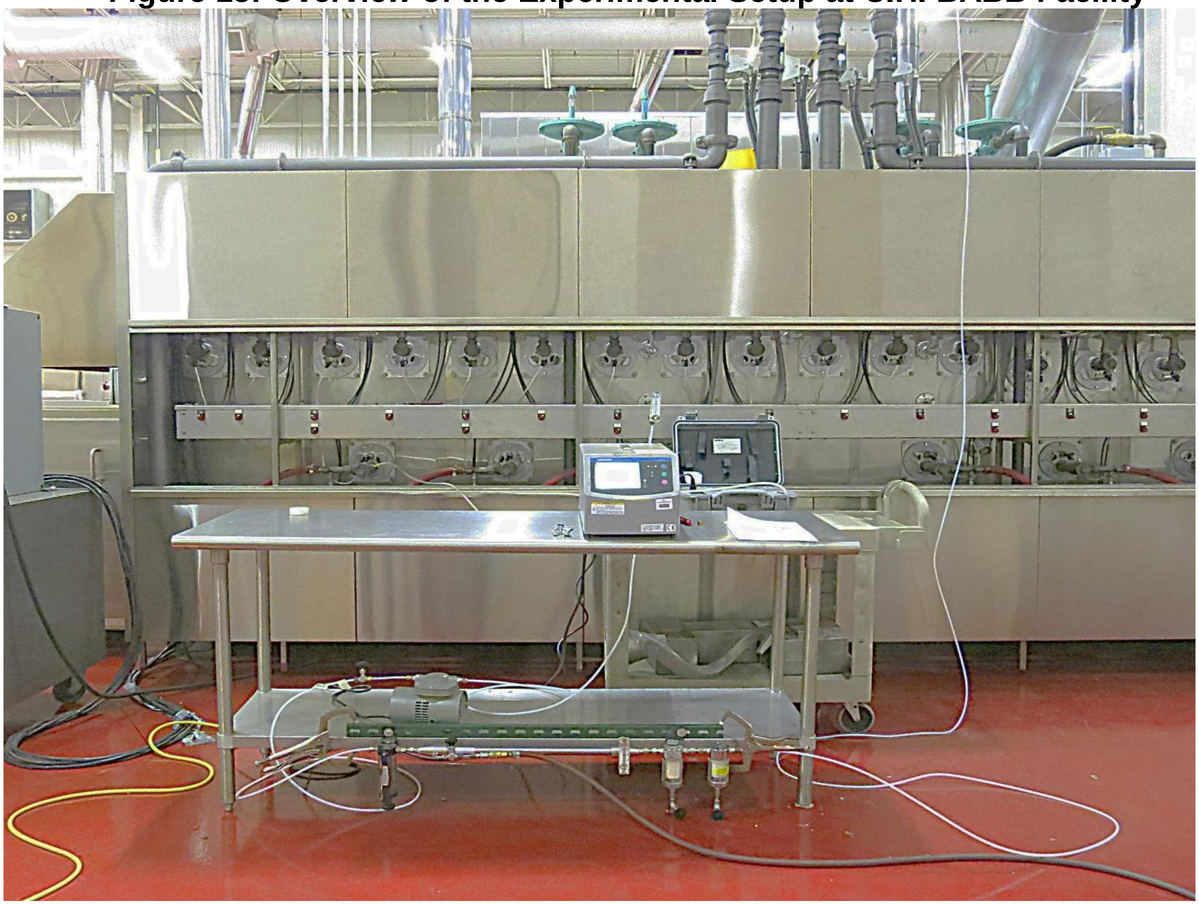
Schematic showing test setup at pilot-scale test facility.

Source: GTI

5.2 Results

The results of the baseline testing confirmed that slightly-tuned lean ribbon burners produce an average of 30-40 ppmv of NO_X (corrected at 3 percent O_2). However, the tests also showed that adjusting to fuel-rich conditions to increase heat input or obtain more luminous and longer flames produced significantly higher NO_X. NO_X levels as high as 120–130 ppmv were observed while the burners were operating under fuel-rich conditions, well above NO_X emission limits. The oven temperature and the level of internal recirculation in the oven chamber were also varied to assess the influence of these parameters on NO_X formation. The project team did not see any significant changes from the oven temperature (450°F -750°F) or from the "turbulizer" fan speed variations on the NO_X formation in the oven. Experiments were conducted with a ribbon burner that measured the furnace exhaust temperature with different levels of air preheated for the same fuel flow rate. Calculations were then made to estimate the fuel flow rate needed to obtain the same furnace exhaust temperature as the non-preheated air.

Figure 15: Overview of the Experimental Setup at C.H. BABB Facility



Experimental setup at pilot-scale test facility, depicting ribbon burners and gas analyzer

Source: GTI

A portable combustion analyzer (Horiba PG-250), shown in Figure 16, was used to monitor the flue gas composition (nitrogen oxides, carbon monoxide, carbon dioxide, and oxygen) produced by the test oven.

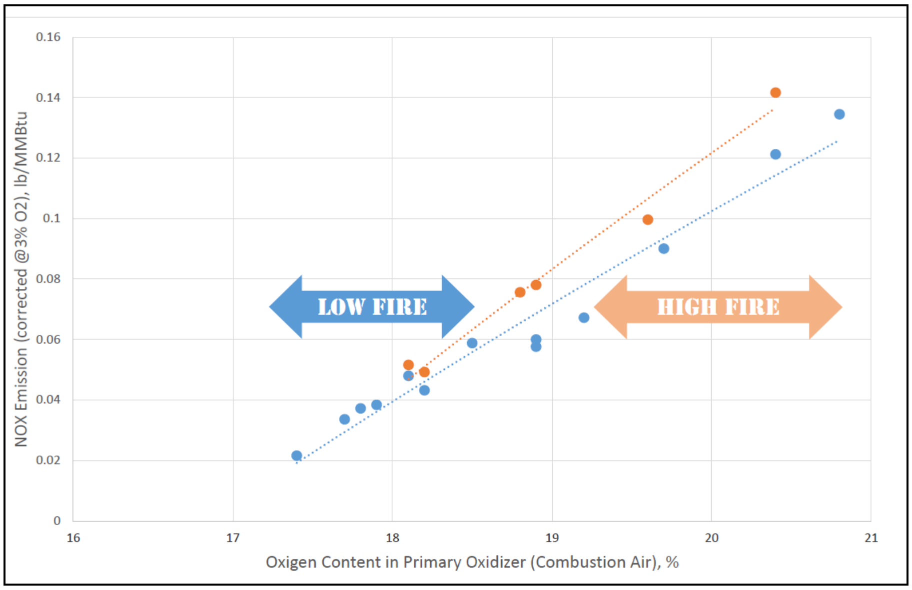
Figure 16: Ribbon Burner and Baseline Data

Ribbon burner (left) and Horiba PG-250 gas analyzer baseline data (right).

Source: GTI

During pilot-scale testing, the air/exhaust mixing ratios were set to gradually reduce oxygen content of the combustion air to less than 18 percent. Figure 17 illustrates NO_X reduction of up to 50 percent during the pilot-scale operation of the industrial-grade baking oven at high and low firing rates when changing the O_2 content in the primary air supply.

Figure 17: Pilot-scale NO_X Data as Function of O_2 Content



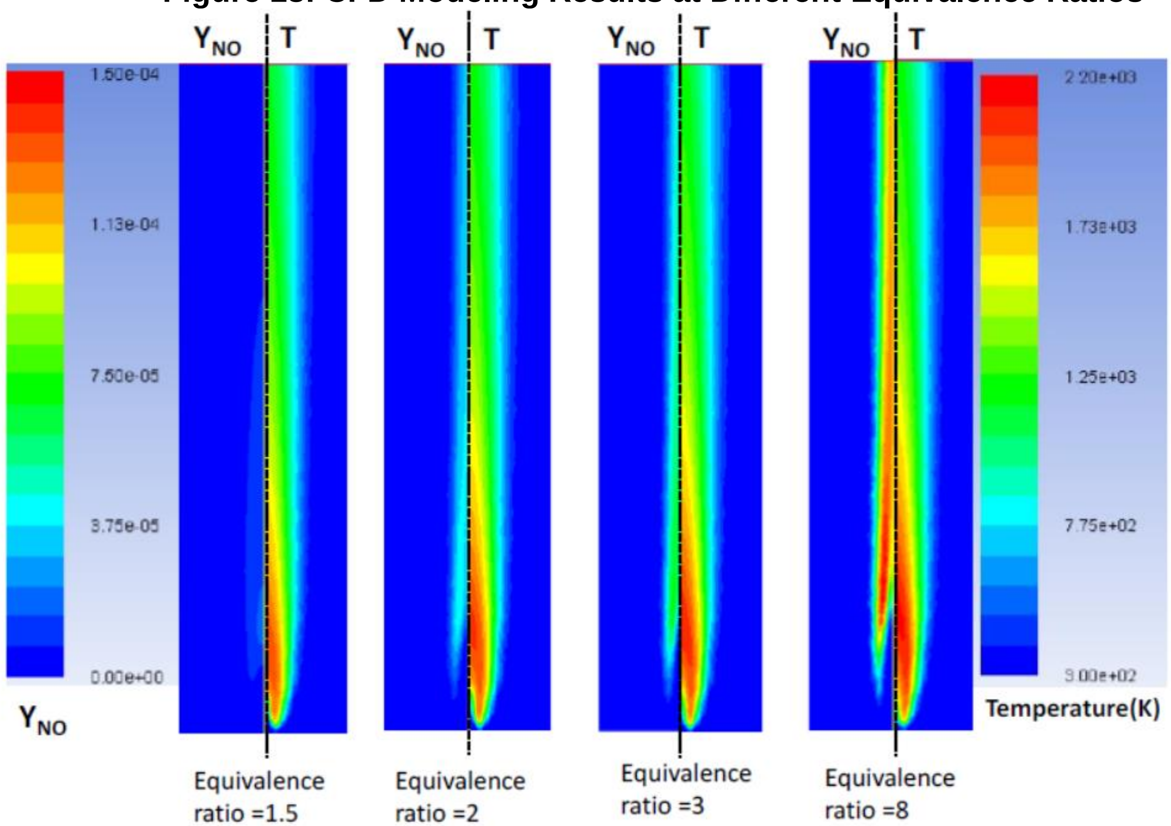
Results showing the correlation between NO_X emission and O_2 content. Blue (low fire): <900 Btu/in.; Orange (high fire): >2000 Btu/in.

Source: GTI

5.3 Computational Fluid Dynamics Modeling

Concurrent to the ongoing demonstration testing, North Carolina State University (NCSU) conducted numerical studies on NO_X formation in ribbon burners to refine the approach for minimizing NO_X formation levels using recirculation of combustion products to the partially premixed zone of the flame. This effort helped to refine the strategy for NO_X minimization without reducing burner efficiencies and other performance characteristics. Figure 18 shows qualitatively how the flame temperature (T) and therefore the NO_X formation (Y_{NO}) is reduced at lower equivalence ratios using only air as the premix medium. The experiment was repeated at varying equivalence ratios using air diluted by CO_2 such that the O_2 concentration in the air stream was 18 percent (by volume). The results showed a sharp decrease in the emission index of NO_X compared to the premix flames with primary air at 20.9 percent (by volume). This reduction compared to partially premixed flames without CO_2 dilution was observed to be higher for low equivalence ratios. At higher equivalence ratios, the percentage of air reduces and, as a result, the amount of dilution by CO_2 also reduces. Appendix C presents the NCSU report.

Figure 18: CFD Modeling Results at Different Equivalence Ratios



Contour plots showing comparison of temperature and NO_X for different levels of premixing with CO_2 diluted air.

Source: NCSU

CHAPTER 6: Full-Scale Testing at Western Bagel Baking Corporation

Demonstration at a full-scale wholesale baking facility was the concluding portion of the multi-phase ALN ribbon burner combustion system development effort. The successful laboratory- and pilot-scale tests provided the foundation for performing a full-scale commercial test of the advanced low-NO_X ribbon burner system. The project team was led by GTI, with Flynn Burner Corporation fabricating the ALN combustion system. Long-term data collection was performed by GTI and the independent measurement and verification (M&V) contractor TetraTech Inc. Western Bagel agreed to serve as the test hosting facility for the full-scale demonstration.

6.1 Scope

This phase of the project was a full-scale ALN technology demonstration at a wholesale bakery in full production settings. This effort involved the following steps:

- Survey of the test baking oven and facility resources
- Baseline data collection
- System engineering
- Combustion system assembly, installation, and tuning
- Technology demonstration and data collection
- Post-demonstration monitoring and tuning
- Final performance verification and data collection

6.2 Demonstration Layout

6.2.1 ALN Technology

The ALN technology for reducing emissions and increasing combustion efficiency was installed at Western Bagel in Van Nuys, California. It was designed by GTI and manufactured by FBC. The installation included 90 new pipe-type ribbon burners with individual flame control units for each burner, and an oven control unit that modulates the oven temperature based on demand. A controlled portion of the exhaust stream was collected and routed back to the primary combustion air source. This required the installation of a high-temperature combustion blower, along with upgrades to the induced draft fans due to the large volume of exhaust. A new control panel was installed to accommodate the upgrades.

6.2.2 Piping and Installation Diagram (P&ID) and Burner Layout

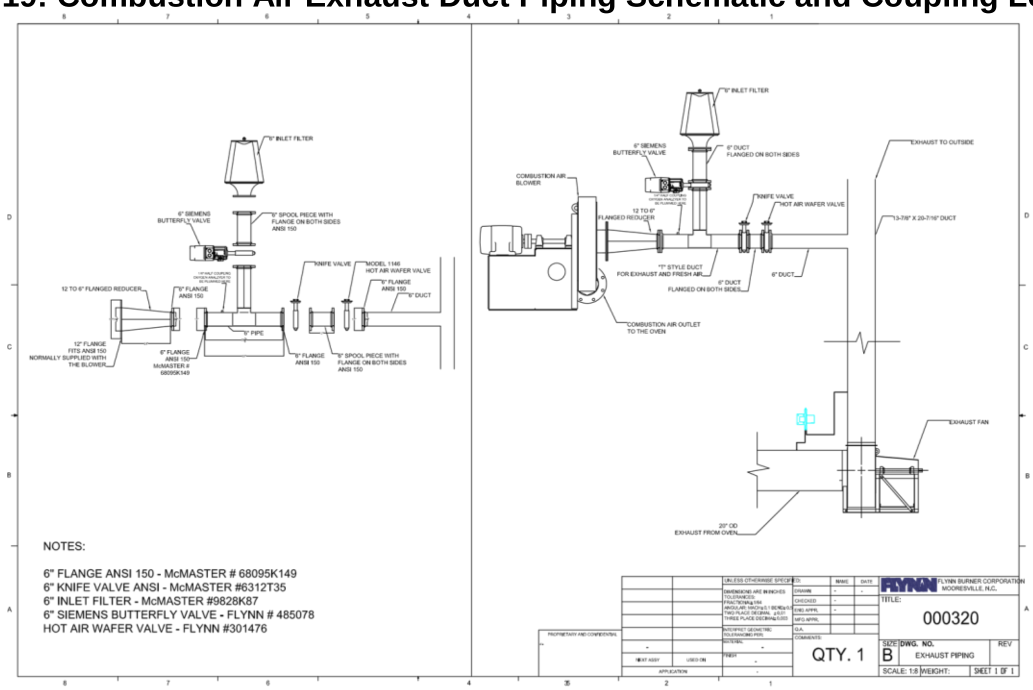
Equipment installed to upgrade the existing oven to the ALN system included:

- Low NO_X flame manager duct work
- New combustion blower

- New higher capacity induced draft (ID) fan
- Low NO_X burners
- FBC Low NO_X control panel
- Electrical wiring

Figure 19 is the P&ID for the flue gas recirculation, showing the new ductwork, combustion blower, and ID fan. The take-off for flue gas was added downstream of the ID exhaust fan. This flue gas was mixed with fresh combustion air going to the combustion blower, which provided the primary air for the ribbon burners. Figure 20 shows the oxygen analyzer positions, and Figure 21 shows the burner and trough layout for the upgraded ALN ribbon burner system with 90 burners.

Figure 19: Combustion Air Exhaust Duct Piping Schematic and Coupling Location

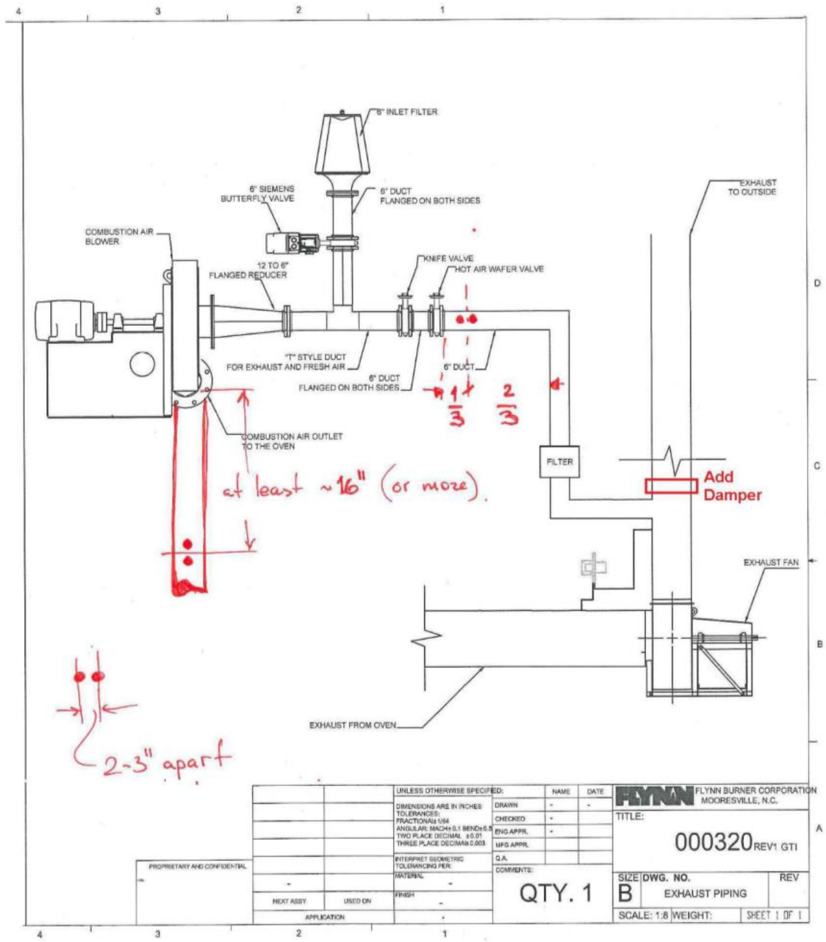


The ¼" half-coupling needs for the oxygen analyzer is located on the T section after the mixture of fresh and recirculated air. The oxygen analyzer positions were chosen to provide the oxygen value of the recirculated exhaust air alone, and also the oxygen value after the mixture of the fresh air and exhaust air in the blower line. The exhaust gas pull-off was located after the exhaust fan. Putting the sample location downstream of the blower ensured adequate mixture of the air before a sample was taken. Figure 20, following, shows the final positions for exhaust gas take-off locations and analyzer locations, with the positions of damper additions.

Source: GTI

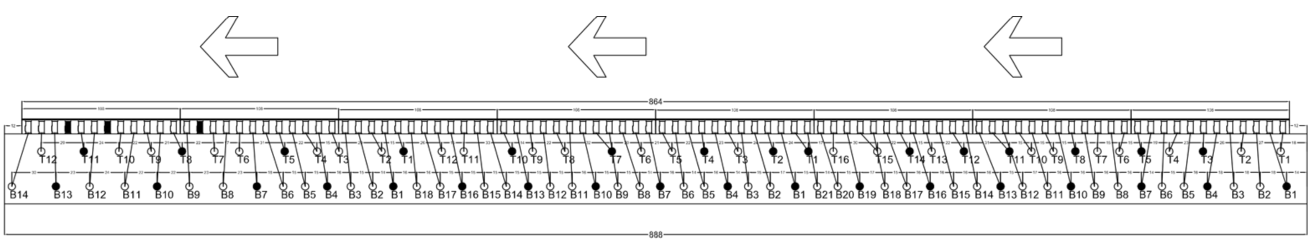
There were numerous challenges to installation. The installation timeline was dependent on Western Bagel providing downtime on the equipment, which was difficult in a high capacity facility on a tight production schedule. Additionally, the existing 1984 tunnel oven had structural deficiencies that required additional engineering effort, including building structural supports for the new blower and the low NO_X ductwork.

Figure 20: Oxygen Analyzer Positions



Source: GTI

Figure 21: Western Bagel Burner and Trough Layout



Source: GTI

6.2.3 Measurement and Verification (M&V)

TetraTech was the measurement and verification lead for the technology demonstration. The M&V plan, outlined below, documented steps taken to determine the performance of the FBC technology. While operating at Western Bagel, emissions testing was performed by Almega Environmental Services.

Table 1 outlines the quantitative performance metrics used to verify the baseline and the redesigned emission and combustion efficiency performance of the system. Table 2 lists the specific monitoring details used to verify the performance metrics. The monitoring points were identified prior to baseline testing and used for baseline testing, demonstration testing, and performance verification.

Table 1: Program Quantitative Performance Metrics

Performance Objective	Metric	Data Requirements
Emission	NO_X, CO, O_2, and GHG	Emission measurement under baseline and flue gas recirculation conditions
Fuel Use	Percent decrease in fuel usage and/or fuel use per ton product using the gas	Fuel rate per ton product during baseline and flue gas recirculation conditions

Source: M&V Plan for PIR-14-017

Table 2: Data Point, Measurement Parameter, Sampling Location

Data Point	Sampling Location	Measurement Parameter and Device	Engineering Units
Fuel	Fuel supply line to oven	Dresser Roots Fuel Meter with Dresser Roots Micro Corrector (IMC) Continuous measurement pulse output with data logging system	Standard cubic feet per minute (scf/min), temperature and pressure corrected. Accumulated scf using an integrated meter control data logging unit (hr/day/yr). Units set to imperial. IMC equipped.
Stack Gas parameters	Performance during sampling per SCAQMD Methods 1-4 on the East and West Stack	Barometric pressure Temperature Moisture content Sample volume Stack gas flow rate	in. Hg °F % dry standard cubic feet (dscf) actual cubic feet per minute (acfm) & dry standard cubic feet per minute (dscfm)
Diluent gases	Stack gas exit point(s) on oven – in accordance per SCAQMD Method 100 on the East and West Stack	O_2 & CO_2 – paramagnetic analyzer	% volume
Flue gas composition	Stack gas exit point(s) on oven – in accordance per SCAQMD Method 100 on the East and West Stack	NO_x – chemiluminescent analyzer	Concentration measured (parts per million volume, dry [ppmvd]) Emission rate (pounds per hour [lb/hr])
Flue gas composition	Stack gas exit point(s) on oven – in accordance per SCAQMD Method 100 on the East and West Stack	CO – Non-Dispersive Infra-Red (NDIR) analyzer	Concentration measured (ppmvd) Emission rate (lb/hr)

Source: M&V Plan for PIR-14-017

6.3 Testing Phases

6.3.1 Baseline

The baseline testing, performed on September 13, 2016, established the burner operation for the existing ribbon burners at normal load. Three 40-minute test runs were conducted, with the oven operating under normal production conditions (fully filled with bagels) at each stack location (east and west). The fuel use was recorded for each test period. The baseline emission test did not utilize a flue gas recirculation system and were performed during a typical baking and production schedule.

6.3.2 Performance Demonstration: Flue Gas Recirculation

After baseline testing was completed, the project team installed the ALN combustion system. By July 2017, the ribbon burner combustion system was installed and calibrated, and the demonstration oven was brought to full production capacity. Appendix A presents photographs of the installation.

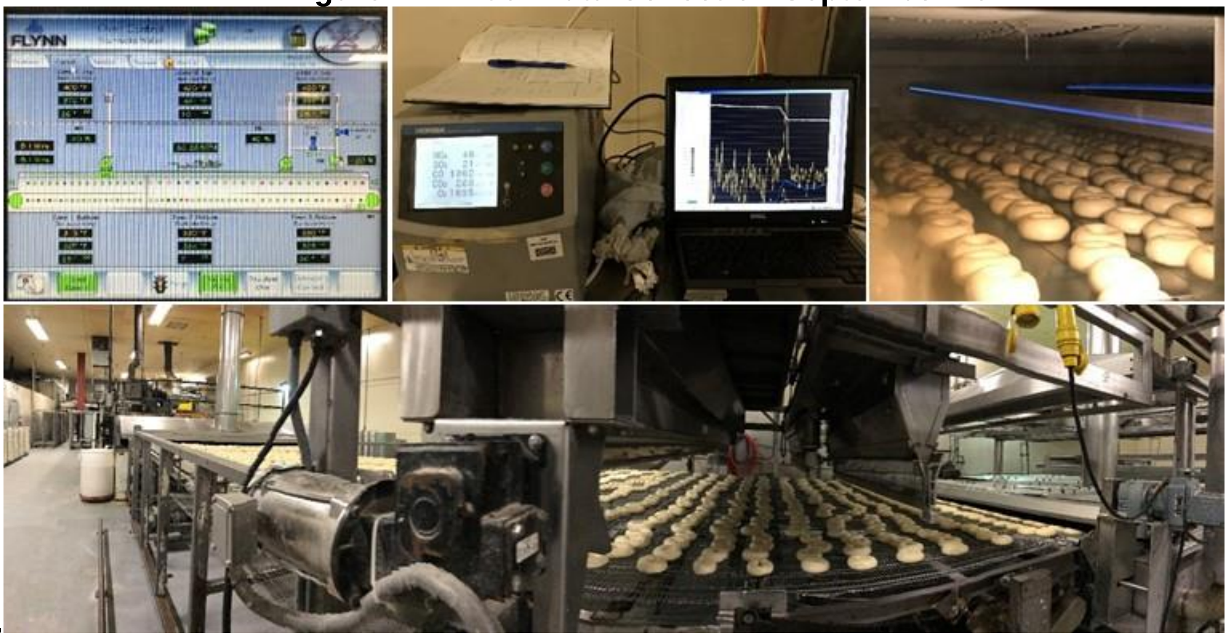
Single point emission testing was performed on September 6, 2017. Seven 10-minute test runs were conducted, operating under normal production conditions (fully charged with bagel production) at each stack location (east and west). Each of the seven test runs was conducted at a different set point of the combustion air oxygen (O_2) concentration. The analysis took place after the combustion air O_2 concentration was stabilized at each desired set point. The combustion air O_2 concentration ranged from 20.9 to 18.0 percent and was determined from previous studies performed by GTI[7]. Figure 22 shows the oven setup and data collection and Table 3 lists the percent recirculation air and makeup air to achieve the target O_2 level in the combustion chamber.

The final test run with flue gas recirculation was discarded because the bagels did not pass quality control and the flames were beginning to show instabilities. Given further opportunities for extended testing, these instabilities could be addressed by tuning the burners to a lower oxygen content in the combustion air.

The production data collected for each test day included the bagel type, bake time, and pounds of bagels baked during the set production evaluation period. This data allowed for normalization of the inconsistencies inherent in production (i.e., varying start and end times). Production downtime was considered as a constant since employee break and lunchtime operations, including shutdown parameters, are consistent during the production day.

7 NOx Reduction in Partially Premixed Flames by Flue Gas Recirculation. IMECE2014-39367

Figure 22: Initial Data Collection September 2017



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Clockwise from top left: Control screen; GTI analytical setup; Demonstration oven interior; panoramic overview of the demonstration baking line.

Source: GTI

Table 3: Percent Recirculation Air and Makeup Air

Test Number	Combustion Air (% O_2)	Recirculation Gas (%)	Makeup Air (%)
1	20.90	0	100
2	20.15	20	80
3	19.37	40	60
4	18.80	55	45
5	18.38	70	25
6	18.00	N/A	N/A
7	20.90	0	100

Source: GTI

6.3.3 Post-Demonstration Monitoring

Seven months of post-demonstration monitoring took place, allowing system adjustments to keep the technology in good operational state and maintain efficient performance. During this time, the gas analytical and data logging systems for final performance verification of stack emissions and oven temperature profile were prepared and calibrated.

6.3.4 Performance Verification

After the performance demonstration, monitoring of the burner performance continued through March 2018, with adjustments made to optimize the burner operation. The final performance verification was performed on March 27, 2018. The stack gas analysis was collected at several oxygen-deficient conditions along with the temperature profile and the oven, using data-logging systems. The demonstration setup can be seen in Figure 23. *The Performance Verification Summary Report* is presented in Appendix D.

Figure 23: Technology Performance Post-Demo Verification, March 2018

Photos taken during the technology performance post-demonstration verification.

Source: GTI

6.4 Results

6.4.1 Emission Test Data

Table 4 and Table 5 summarize the emission test data collected by Almega Environmental during the baseline test period. The baseline data established the NO_X and CO emissions for the oven without modifications. As observed during previous testing of ribbon burners, the NO_X levels were slightly above 30 ppmv corrected to 3 percent O_2.

Table 4: Baseline Emission Test Data – East Stack

Test	Moisture (%)	O_2 (%)	NO_X (ppmvd)	NO_X (ppm @3% O_2)	CO (ppmvd)	CO (ppm @3% O_2)
1	12.94	16.28	8.32	32.24	93.2	361.10
2	12.9	16.31	8.18	31.9	71.4	278.44
3	13.77	16.37	7.97	31.49	65.7	259.61

Source: GTI

Table 5: Baseline Emission Test Data – West Stack

Test	Moisture (%)	O_2 (%)	NO_X (ppmvd)	NO_X (ppm @3% O_2)	CO (ppmvd)	CO (ppm @3% O_2)
1	11.1	17.69	5.42	30.22	80.1	446.66
2	10.2	17.84	5.61	32.82	76.2	445.75
3	9.86	17.96	5.62	34.22	72.8	443.24

Source: GTI

The stack emissions were also measured during the FGR test. There were seven distinct test periods, each at a different level of flue gas recirculation. The first and last test had no FGR. Table 6 and Table 7 present data collected by Almega Environmental from the FGR test. An additional O_2 concentration was taken at the combustion air going to the burner. This allowed the team to monitor the reduction of O_2 in the primary combustion air to the burner. This data, along with the stack flow rate, was used to calculate the pounds per hour of NO_X produced during each run. The results of data collected during the test and evaluation period demonstrated that using recirculated flue gas to lower the average oxygen concentration in the combustion air reduced NO_X formation, as shown in Figure 24.

Table 6: Flue Gas Recirculation Emission Test Data – East Stack

Test	Combustion Air (% O_2)[8]	Moisture (%)	O_2 (%)	NO_X (ppmvd)	NO_X (ppm @3% O_2)	CO (ppmvd)	CO (ppm @3% O_2)
1	20.9	12.02	15.96	6.74	24.42	46.5	168.49
2	20.15	12.02	15.96	6.30	22.83	39.4	142.77
3	19.37	12.01	16.09	6.52	24.26	64.1	238.54
4	18.8	11.28	16.23	5.82	22.31	90.3	346.12
5	18.38	11.25	16.44	5.70	22.88	87.2	349.97
6	18	11.25	17.34	4.50	22.63	50.2	252.41
7	20.9	11.27	16.31	6.70	26.13	37.2	145.07

Source: GTI

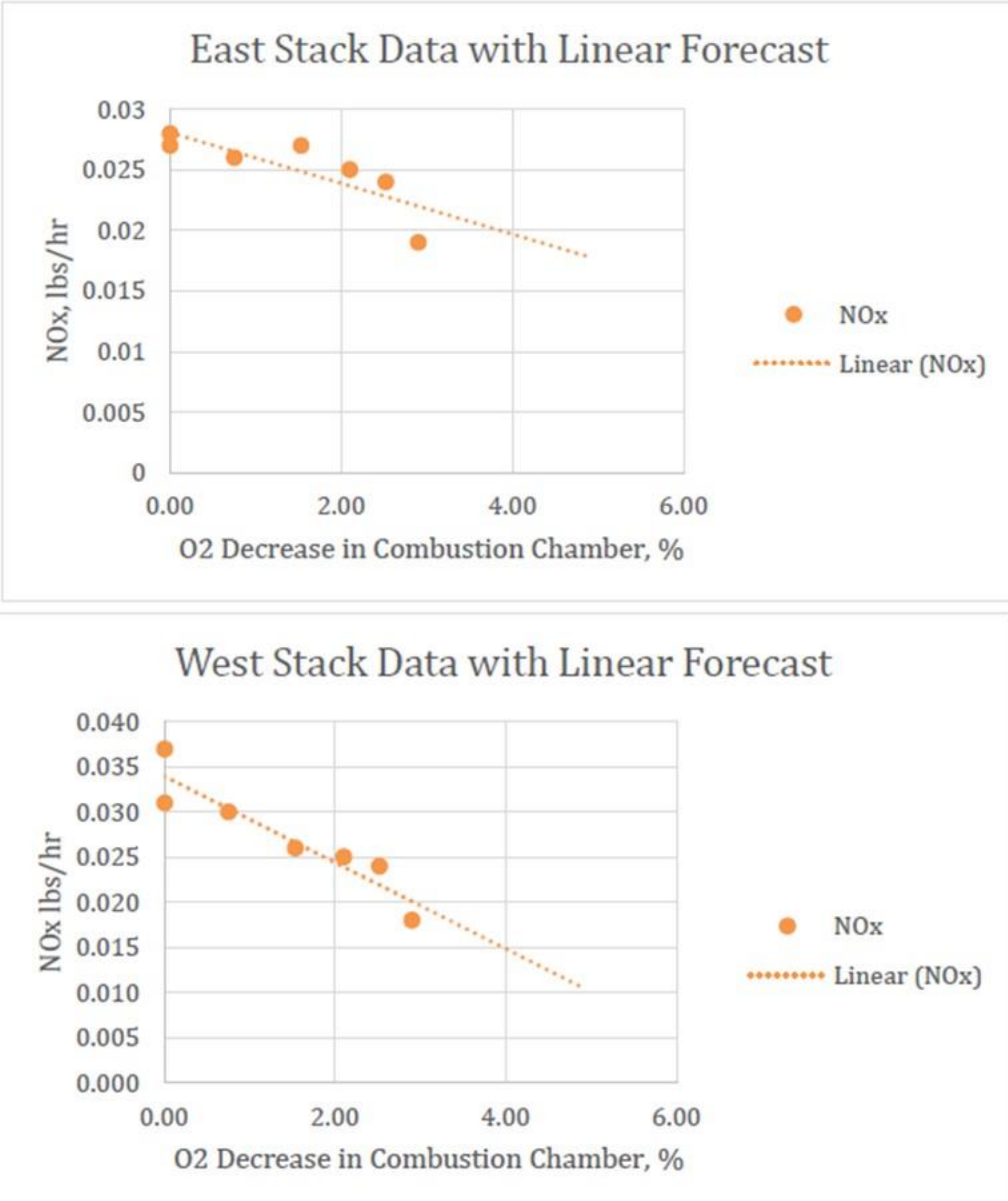
Table 7: Flue Gas Recirculation Emission Test Data – West Stack

Test	Combustion Air (% O_2)[8]	Moisture (%)	O_2 (%)	NO_X (ppmvd)	NO_X (ppm @3% O_2)	CO (ppmvd)	CO (ppm @3% O_2)
1	20.9	11.08	16.94	7.19	32.5	113.5	513.04
2	20.15	11.08	16.89	6.77	30.22	55.2	246.4
3	19.37	11.07	17.41	5.90	30.26	98.1	503.15
4	18.8	10.76	17.24	5.71	27.93	102	498.85
5	18.38	10.73	17.28	5.32	26.31	71.5	353.55
6	18	10.73	18.26	4.20	28.48	49.4	334.95
7	20.9	9.93	16.97	8.44	38.44	92.6	421.77

Source: GTI

[8] Combustion air measured by GTI. Single point reference made by Tetra Tech and represents an average O_2 percent in the combustion chamber.

Figure 24: Performance Demonstration NO_X Results



Linear forecast of NO_X based on monitoring of the east and west exhaust stacks during technology performance demonstration on September 6, 2017.

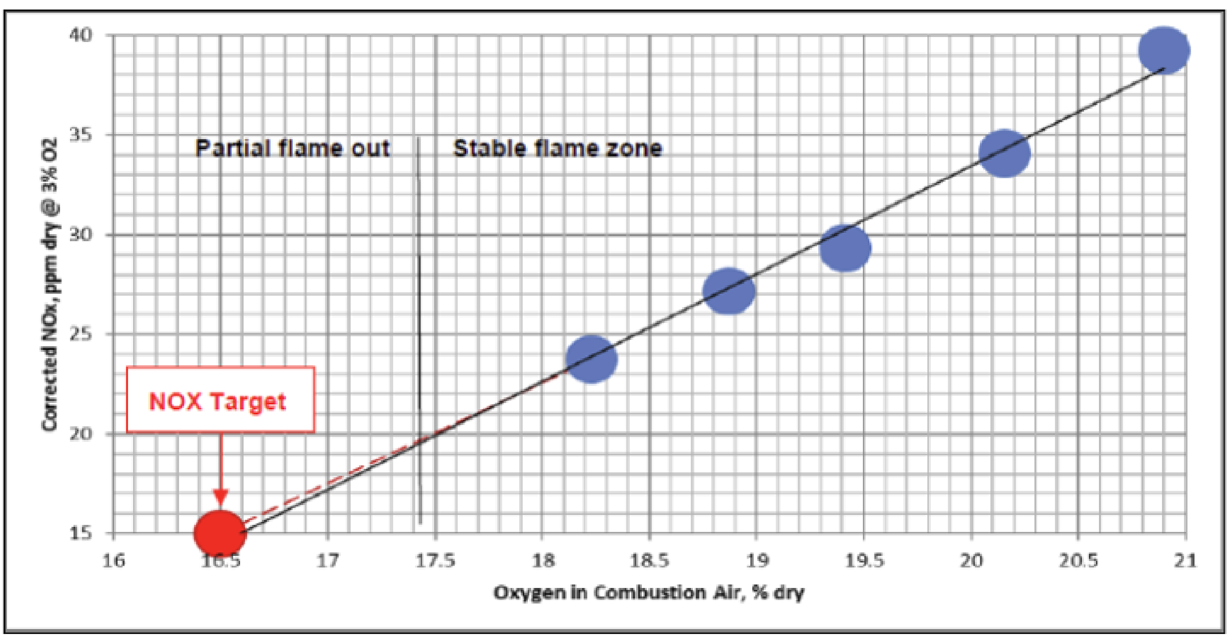
Source: TetraTech and GTI

The compliance limit for in-use ovens, as identified by SCAQMD in Rule 1153.1. Emissions of Oxides of Nitrogen from Commercial Food Ovens, is 40 ppm NO_X and 800 ppm CO. There are some increases of CO as the concentration of oxygen in the combustion gas is decreased; however, these increases are still well below the SCAQMD limits.

The data collected during the technology demonstration tests confirmed that the ALN technology lowers the NO_X concentration in the oven relative to the baseline oven operation with no modifications. The average emission rate during the three baseline runs was 0.040 lb NO_X/MMBtu of burner output. In contrast, during the technology demonstration, the lowest NO_X emission achieved during Test 5, with 18.38 percent O_2 in the combustion air, was 0.030 lb NO_X/MMBtu of burner output, a 25 percent reduction in NO_X.

The technology demonstration test also confirmed that with further burner tuning to enable higher FGR, even greater NO_X reductions could be achieved. The first technology demonstration test was done at normal operation at 20.9 percent oxygen in the combustion air with no flue gas recirculation. The burners were calibrated for 20.9 percent O_2, so as the oxygen content in the combustion gas approached 18 percent, the flame stability decreased and bagel quality began to suffer. The recirculation of flue gases could not be increased any further and burner operation was returned to 20.9 percent O_2 for the final test. Results showed about 35–40 ppmv NO_X corrected to 3 percent O_2 with no flue gas recirculation. Figure 25 shows how reduction of oxygen in the primary combustion air decreases the NO_X production. These results were from the GTI measurements using a Horiba gas analyzer taken in parallel with environmental testing by Almega. With tuning of the burners to a lower oxygen content in the combustion gas, even lower NO_X concentrations to the target of 15 ppm could be achieved.

Figure 25: NO_X Production at Decreasing Percentages of O_2 in the Combustion Air



In Table 8, the percent decrease of NO_X and CO is calculated relative to Tests 1 and 7 of the ALN demonstration, during which there was no recirculation of exhaust. The total oven emissions are calculated from the east and west stacks, and the trend clearly demonstrates lower NO_X as the oxygen content in the combustion air is reduced. The demonstrated emission reduction potential showcases the possibilities available with even further tuning of the oven.

While achieving significant NO_X reductions, the data from Test 6 was disregarded since the quality of bagels produced did not pass quality control. The bagels produced during Tests 3, 4, and 5 did pass quality control, with the resulting data showing an average NO_X reduction of 18.16 percent.

Table 8: Oven Emission Rate and Reduction Potential

Test	NOX Emission Rate (ppmv corrected to 3% O2)	NOX Emission Rate (lb/MMBtu)	NOX Emission Rate (lb/hr)	NOX Reduction, ppmv or lb/MMBtu, Compared to no FGR (%)	NOX Reduction, lb/hr, Compared to no FGR (%)
1	28.08	0.035	0.059	N/A	N/A
2	26.25	0.032	0.056	12.70	8.94
3	26.87	0.033	0.053	10.64	13.82
4	24.83	0.031	0.050	17.43	18.70
5	24.45	0.030	0.048	18.68	21.95
6	25.18	0.031	0.037	16.25	39.84
7	32.05	0.040	0.064	N/A	N/A

Source: GTI

Overall, full-scale results confirm that significant reductions in NOx are achieved with this ALN technology.

6.4.2 Fuel Use Test Data

The results of the fuel use monitored during the tests is presented in Table 9. The data collected indicates that there is potential for fuel savings, and associated greenhouse gas reductions, by using the ALN ribbon burner combustion system. However, these results will be strengthened by future opportunities to (1) optimize the production of bagels to the conditions established during flue gas recirculation, and (2) tune the burner to hold the optimized position for longer than ten minutes of production.

The production data in pounds of bagels produced was provided by the facility for the hours of 09:00–15:00. The production rate was calculated from the average heat input for the oven during the aforementioned 6-hour period, with times when production was halted removed from the calculation. When normalized by the production of bagels, the ALN burner system demonstrated ~5 percent fuel savings compared to the baseline run. If these same average production rates are assumed, but the average fuel use is investigated from only the 4-hour period during which FGR was utilized, the fuel savings rise above 8 percent.

Table 9: Production Data

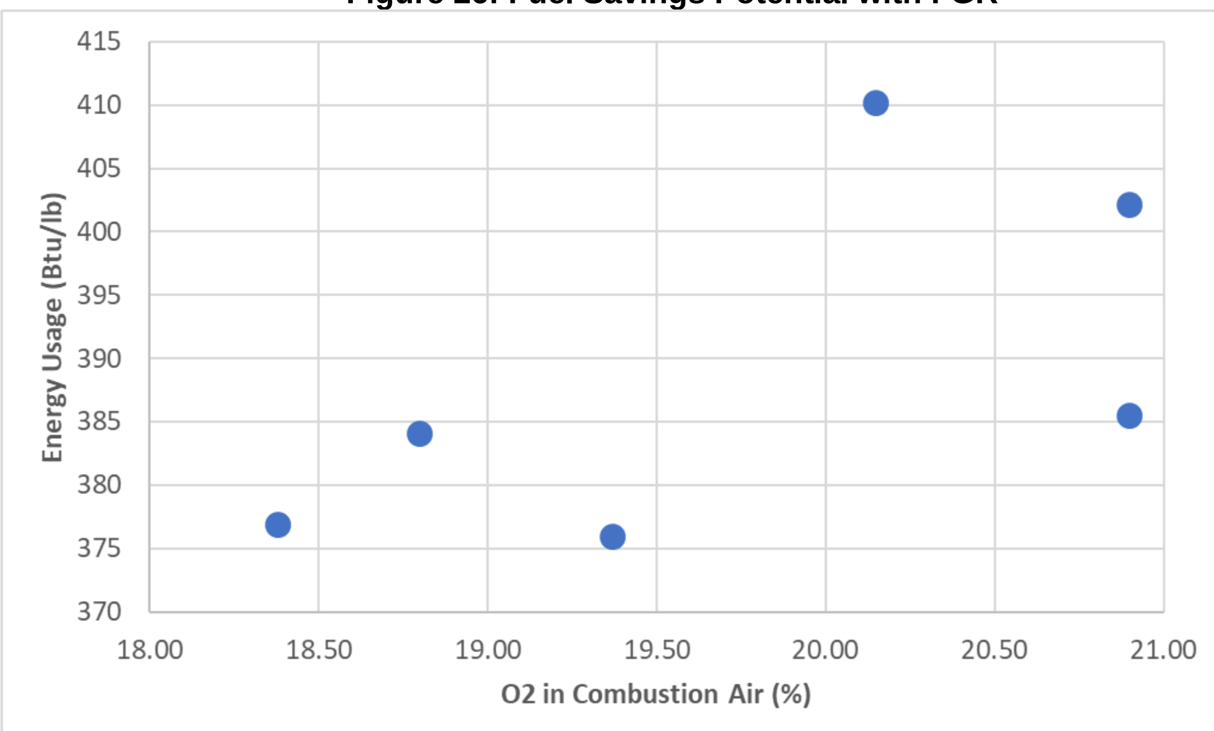
Test	Production Rate (lbs/6 hr)	Production Rate (lbs/hr)	Average Heat Input (MMBtu/hr)	Energy usage rate (Btu/lb)
Baseline – 13 Sep 2016	23,469	3911.5	1.86	476

Test	Production Rate (lbs/6 hr)	Production Rate (lbs/hr)	Average Heat Input (MMBtu/hr)	Energy usage rate (Btu/lb)
Tech Demo – 6 Sep 2017	25,234	4205.6	1.91	454

Source: GTI

Fuel savings increase with higher flue gas recirculation rates, due to better waste heat recovery with recirculation. Figure 26 shows the relationship between energy usage rate and oxygen in the combustion air during the technology demonstration testing. The calculation of energy usage rate for each test assumes a constant production rate throughout all test periods. The oven fuel and firing rate was calculated using the methodology described in Appendix E, *M&V Report for PIR-14-017*.

Figure 26: Fuel Savings Potential with FGR



Source: GTI

CHAPTER 7:
Findings and Recommendations

7.1 Results Summary

The results of modeling and conducted experiments (laboratory, pilot- and full-scale testing) demonstrated that the dilution of combustion air with CO_2 has a strong potential for significantly reducing NO_X formation and decreasing fuel use at the same time. Therefore, FGR—an approach where a portion of exhaust gas (which is laden with CO_2) is mixed with the combustion air—can be used to reduce NO_X emissions produced by industrial processes that utilize ribbon burners or other burners with partially premixed flames. This approach can allow industrial companies to meet recent stricter regulations limiting NO_X emissions without the need for expensive modifications. For situations when NO_X reduction is critical and replacing the conventional ribbon burner is not possible or is cost-prohibitive, this approach can be a viable option for maintaining, and potentially improving, efficiency. This may be necessary with increasingly stringent federal and state environmental regulations.

7.2 Emission Reduction Takeaways

According to the Research and Markets 2012 Bakery Product Manufacturing report[9], there are approximately 2,800 industrial and commercial bakeries nationwide and over 6,000 retail bakeries and suppliers. A typical mid-size industrial bakery has three production lines and consumes about seven million cubic feet of natural gas per month, resulting in approximately 0.8 Tcf of annual natural gas consumption by the United States baking industry, with annual CO_2 production of over three million tons.

Reaching the target of 50 percent reduction in NO_X production (<15 ppmv at 3 percent O_2) could lead to significant reductions of pollutant emissions from the ribbon burner installations and achieve compliance with current and future SCAQMD rules and regulations.

Based on a potential of 5 percent reduction in fuel consumption through preheating of combustion air using FGR, estimated savings and reductions in the California baking industry from this technology are:

- Natural gas use reductions of 1.3 million to 1.5 million therms per year
- Carbon emissions reductions of 7,500 to 10,000 tons per year
- NO_X emissions reductions of 200 to 300 tons per year

These numbers may vary depending on the percentage of California bakeries that convert to the ALN ribbon burner system.

[9] *US Commercial Bakery Sector Pulls in $30bn a Year.* 8 Nov 2012. Accessed 27 Aug 2018. https://www.bakeryandsnacks.com/Article/2012/11/08/US-bakery-sector

7.3 Impacts and Benefits to California Ratepayers

7.3.1 Quantitative and Qualitative Benefits

Ribbon burners are a reliable, cost-effective type of natural gas combustion equipment widely used throughout two key California industrial markets, baking and heat-treating and several smaller markets. The California baking and heat-treating markets consume about 88 million therms of natural gas annually (38 million therms in bakeries and 50 million therms in heat-treating furnaces).

New California limits on NO_X and CO_2 emissions require further improvement to ribbon burners; specifically, emissions will have to be lowered to ensure continued use of ribbon burners and to avoid their costly replacement with electric-powered systems. The ALN burner technology developed by GTI and demonstrated in this project lowered NOx emissions by 50 percent and improved the energy efficiency by reducing fuel consumption up to 5 percent. Although these benefits will accrue to owners, there are also benefits to California ratepayers at large:

- By providing higher natural gas efficiencies, ALN burner systems will conserve natural gas resources for other uses by ratepayers.
- The risk of higher-priced industrial baking products will be reduced if baking facilities do not need to pass along to consumers the expense of converting existing baking ovens from natural gas-fired to electric-powered systems.
- Greenhouse gas emissions will be reduced.
- The manufacturing and installation of ALN burner systems will support local jobs and the economy.

Although all market segments are important, Table 10 shows the potential energy, emissions, and cost savings to be realized through adoption of the new high efficiency ribbon burner technology in the two largest California markets. A market penetration rate of 30 percent was deemed reasonable by FBC, a project partner and major supplier of ribbon burners to California industrial customers. Based on ribbon burner lifetimes, market forces driving higher efficiency and lower emissions, and business growth, FBC believes a 30 percent market penetration in 10 years to be conservatively low.

Table 10: Annual Emissions and Energy Savings With 30% Market Penetration

California ribbon burner market size, total	88 million therms/yr
California ribbon burner market size, baking industry	38 million therms/yr
California ribbon burner market size, heat-treating, drying, etc.	50 million therms/yr
Assumed advanced ribbon burner market penetration	30%
Technology adoption rate	10 years
CO_2 production from combustion of natural gas	11.7 lb./therm
Current NO_X production by ribbon burners at 30 ppm	0.366 lb./therm
CO_2 reduction after 30% market penetration	7,700 ton/yr
NO_X reduction after 30% market penetration	4.8 million lb/yr
Natural gas price	$0.50/therm
Natural gas energy savings after 30% market penetration for total ribbon burner market	1.3 million therm/yr
Natural gas energy savings after 30% market penetration for baking industry ribbon burner market	0.57 million therms/yr
Natural gas energy savings after 30% market penetration for heat-treating, drying, etc. ribbon burner market	0.77 million therms/yr
Natural gas cost savings after 30% market penetration	$660,000

Source: GTI

The low NO_X, higher efficiency ribbon burner system also provides qualitative benefits. Adoption of the new ribbon burner will lead to cleaner and more efficient baking, which has the potential to improve product quality and tighten process control. By meeting California's emissions requirements, the technology will allow for continued utilization of natural gas-fired ovens in baking facilities. As a result, existing jobs will be preserved and product variety can be maintained or even expanded. Advanced ribbon burner combustion system adoption will also prevent an increase in electricity consumption in California, which will enhance electric grid stability by reducing demand.

7.3.2 Benefit-Cost Analysis

To consider the cost benefits of adopting the new ribbon burner technology, a simple case study is provided. This scenario assumes that a representative-size bakery consumes approximately 600,000 therms/year of natural gas at a price of $0.50/therm. With a 5 percent improvement in fuel efficiency due to the ALN burner system, the fuel cost savings can be calculated to be 600,000 x 0.05 x 0.50 = $15,000 per year. The ALN burner system does not require any burner or baking oven redesign, but rather modification of the oven's flue gas exhaust and air supply arrangements to allow flue gas recirculation. The cost of such a retrofit after the modification procedure is optimized is not expected to exceed $50,000 per bakery. In the above scenario, the ALN burner system will fully pay back in less than 3.5 years. However, the actual payback time is expected to be considerably shorter, since the lower NO_X emissions will eliminate any direct or indirect costs needed to comply with California's future NO_X requirements. Furthermore, additional cost savings may be captured if air emissions treatment systems can be reduced in size.

7.4 California Industrial Baking Market

California's baking industry has a total economic impact of approximately $59 billion annually, directly supporting over 100,000 jobs[10]. These statistics represent the full complement of establishments in the baking industry. To drill down to the types of industrial bakeries that are more likely to take advantage of the ALN burner combustion system, the United States Census Bureau noted that as of 2012, there were 1,598 bread, cookie, cracker, and bakery product manufacturing establishments in California. These industrial bakeries employed approximately 32,000 people. Given the economic recovery in the intervening years, it is reasonable to assume that the market has only grown larger.

7.5 Market Readiness

There are two approaches to assessing the market readiness of an emerging technology: "push"-based, in which the effectiveness and manufacturability of the technology is primarily assessed; and "pull"-based, in which customer needs and commercial barriers are a more central focus. A common "push"-based assessment is the Technology Readiness Level (TRL), a nine-stage approach estimating the technological maturity of critical components. This technology, having successfully deployed a prototype in a relevant existing environment, is at a TRL of 5 or 6. However, important commercial barriers exist in the competitive industrial world of bakeries and heat-treatment facilities.

One of the primary means of assessing market readiness is interviewing key market players on the leading edge of the technology's development. Within the industrial ribbon burner market there are two dominant companies, Selas Heat Technology (formerly Ensign Ribbon Burner) and Flynn Burner Corporation. GTI held discussions with both manufacturers to solicit their experience, perspective, and feedback on the technology and its market in California and beyond. Selas Heat Technology noted that while California may be leading the market on ultra-low NO_x regulations, there are several other states and countries that are also moving in this direction, notably Oregon and Washington states within the United States, and Australia, New Zealand, and Europe. Technology developments that take hold in California are likely to spread to these other markets.

FBC is an experienced player in the natural gas combustion equipment and controls market, with clients among both the industrial baking sector and industrial baking equipment manufacturers. FBC is active in California as well as in the rest of the United States and internationally. FBC has developed the necessary skill set for making the ALN ribbon burner combustion system modifications, which include proper engineering design and software changes. At this stage, it is estimated that start-up, commissioning, and re-setting oven

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profiles to fully implement the modifications would typically take one to two weeks, with potentially an additional week for larger, more complex sites.

The modifications necessary for the ALN combustion system to be implemented at a bakery site are still in the relatively early stages of demonstration. The primary factors limiting near-term, widespread adoption include:

- Cost
- Risk acceptance
- Openness to change

FBC has a dominant market share of industrial baking equipment, which represents the majority of FBC's business. Based on FBC's expertise and experience with ALN system modifications, it is estimated that while engineering design, software adjustments, and labor are relatively fixed costs of the system, equipment costs could represent a sizable sum, particularly for larger sites with several ovens, which would multiply the equipment costs on a per-oven basis. As noted above, the cost for the ALN ribbon burner combustion system modifications could average about $50,000 per bakery, or more for operations with more equipment. This cost is significant for any site to consider and overcome, particularly as there are other commercially available and potentially more affordable options for meeting California's low NOx requirements.

The adoption of emerging technologies is always associated with some degree of risk. Thorough research and extensive demonstration are critical to gaining market acceptance. Although this project successfully demonstrated large emissions reductions in full-scale testing, the limited runtime is likely insufficient to convince industrial bakeries to immediately adopt a new technology, particularly when more well-known, mature technologies exist to meet California's NO_x requirements. Beyond demonstrations to show the performance and reliability of the technology, bakeries will also need to be reassured the technology does not negatively impact the baking quality and throughput. Until then, companies active in this market segment will be reluctant to push innovative technological solutions if they feel there are more reliable/known options for complying with California emission regulations. The desire of these companies to provide customers with proven solutions while maintaining a positive business relationship would likely caution them from offering an emerging technology.

Finally, at an industrial bakery—as with most competitive, high volume businesses—openness to technological change is usually limited. Profit margins are tight, operating hours are long, and equipment is expensive. Convincing these sites to change the status quo, even with the temptation of energy savings, will be a challenge. The SCAQMD NO_X requirements will almost certainly be the primary driver, but as long as the reduced emissions threshold is met, the sites will likely be looking for the most affordable and least disruptive route to compliance. In some cases, the modified ALN ribbon burner combustion system may be that solution, based on this successful demonstration. However, engineering optimization of the ALN system design and specification (based on the project findings and operating experience during the performance data collection and post-trial monitoring), followed by additional demonstration work with significantly more runtime hours, will likely be needed for near-term market readiness and adoption.

As more stringent emissions rules and regulations are adopted in the future, advanced reduced NO_X technologies will need to be readily available. These early research, development, and field-based testing efforts are a critical component to meeting future needs. Currently, existing technologies are able to meet current emissions standards. However, California frequently tightens emission requirements and it is important to continue developing this system through the remaining technological stages so that a solution is ready for the industry in the coming years. To this aim, the ALN burner system is currently pending a United States patent (publication #20160178194).

7.6 Market Penetration

Two scenarios should be considered to estimate market penetration: (1) under the adoption of a regulatory requirement, and (2) under voluntary market forces. In the former, market penetration would depend to some extent on the availability of other technologies or solutions to meet the mandated low NO_X regulations. . Since at this time there are no known commercialized options for achieving 15ppm or less of NO_X in a ribbon burner system, it can be assumed that market penetration would be very significant in California. Some sites may elect to change equipment, use a novel approach, or move their facilities elsewhere, but market penetration could reasonably be expected to be very high within the state.

The latter scenario would be confronted with all the limiting factors noted above (cost, risk acceptance, openness to change). These could be overcome with additional demonstration efforts, including longer operating times, robust datasets available for sharing, bakery operator endorsement and support, and evidence of negligible to no impact on throughput and baking quality. The primary driver for a bakery to adopt this technology in the absence of a regulatory requirement would likely be environmental stewardship. There are some wholesale bakeries, such as Bimbo Bakeries USA one of the largest wholesale bakeries in the world, that have expressed genuine concern about sustainability. In the long run, such companies acknowledge the cost efficiencies of these types of improvements and may be willing to adopt them voluntarily to support their bottom line as well as the environment. If large players adopt these improvements, they will likely implement them throughout their portfolio, not just in an isolated region. Such economies of scale could yield cost and system improvements, potentially spurring other companies to pursue the ALN system.

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LIST OF ACRONYMS

Term	Definition
acfm	Actual cubic feet per minute
ALN	Advanced Low NO_X
Btu	British Thermal Unit
CEC	California Energy Commission
cf	Cubic feet
CFD	Computational fluid dynamics
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DGF	Direct Gas Fired
dscfm	Dry standard cubic feet per minute
^oF	Degrees Fahrenheit
FBC	Flynn Burner Corporation
FGR	Flue gas recirculation
g/kg	Grams per kilogram
GTI	Gas Technology Institute
GHG	Greenhouse gases
h	Hour
hr	Hour
ID	Induced draft
in. Hg	Inches of mercury
kW	kilowatt
MMBtu/hr	Million British Thermal Units per hour
M&V	Measurement and verification
NCSU	North Carolina State University
NDIR	Non-Dispersive Infra-Red
NO	Nitric oxide
NO_2	Nitrogen dioxide

Term	Definition
NO_x	NO_x is a shorthand for one or more of the nitrogen oxides NO, NO_2, and N_3O, all of which are heavily regulated hazardous air pollutants formed during combustion.
O_2	Oxygen
OEM	Original Equipment Manufacturer
PER	Primary Equivalence Ratio, defined as the actual primary fuel/air ratio divided by the stoichiometric fuel/air ratio. The stoichiometric fuel/air ratio is the theoretical ratio of fuel to oxidizer or air that results in complete combustion with no remaining or leftover fuel and no leftover oxidizer or air.
P&ID	Piping and installation diagram
ppm	Parts per million
ppmv	Parts per million by volume
ppmvd	Parts per million, volume dry
R&D	Research and development
RD&D	Research, development, and demonstration
SCAQMD	South Coast Air Quality Management District
Scf	Standard cubic feet
scfm	Standard cubic feet per minute
SCR	Selective catalytic reduction
SNCR	Selective non-catalytic reduction
T	Flame temperature
TcF	Trillion cubic feet
TRL	Technology Readiness Level
UTD	Utilization Technology Development NFP
WC	Water Column
Western Bagel	Western Bagel Corporation
Y_{NO}	Formation rate of NO_x

APPENDICES

Appendices A-E are available in a separate volume (Publication Number CEC-500-2020-016-APA-E) upon request: Please contact Rajesh Kapoor at rajesh.kapoor@energy.ca.gov.