Market Assessment of Emerging Ultra Low NOx Burner Technologies

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GAS EMERGING TECHOLOGIES PROGRAM (GET)

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Disclaimer

Abbreviations and Acronyms

Abbreviation	Description
BARCT	Best Available Retrofit Control Technology
CEC	California Energy Commission
CO	Carbon Monoxide
FGR	Flue Gas Recirculation
LBNL	Lawrence Berkeley National Laboratory
SCAQMD	South Coast Air Quality Management District
SCR	Selective Catalytic Reduction
SJVAPCD	San Joaquin Valley Air Pollution Control District
SME	Subject Matter Expert
ULN	Ultra-Low NOx

Executive Summary

The goal of this study was to gather updated market data on emerging Ultra-Low NOx (ULN) burner technologies to provide recommendations of technologies for customers and address gaps that can be further explored by energy efficiency programs. Generally, ULN is defined as <9 ppm NOx; however, exact numbers are determined by the Air Quality Management Districts depending on the application and the rated heat input.

The first step of the study was to conduct a literature review on ULN burners to develop an understanding of the technology and its applications. The literature review along with additional research efforts were used to develop a list of manufacturers and research institutes to obtain more information on the latest ULN burner offerings. A total of 17 organizations were contacted and a 35% response rate was achieved. We also had conversations with ULN burner manufacturers in a more casual setting at the AHR Expo in Atlanta on Feb. 7-9, 2023.

From the literature review, in addition to the interviews, a total of 25 different ULN burner models were identified from this market study, two of which are expected to hit the market toward the end of 2023. Each model had a unique configuration; however, the most common ULN burner design uses some form of air and fuel premixing technology that allows for flame control and optimal heat transfer, resulting in ULN emissions and more efficient combustion than older generation burners.

There is a wide array of applications that these burners could be optimized for in order to fit the needs of the California marketplace. Boilers and furnaces are the most common application; however, certain burners have been developed for specific applications such as greenhouses, digestors, residential and commercial cooking equipment, water treatment plants, outdoor IR heating, and oil refineries.

This study also investigated the hydrogen blending limits of ULN burners and identified 11 burner models that are suitable for hydrogen blends ranging from 20% to 100%. In theory, hydrogen is a lighter fuel and less energy dense than natural gas; therefore, a burner needs to burn more fuel, which can result in an increase in NOx that occurs when excess oxygen is heated during combustion. However, literature indicates inconsistencies in NOx formation associated with hydrogen fuel mix, but generally older equipment performs the worst with respect to hydrogen blends and NOx emissions. The burners identified in this study have successfully maintained ULN levels, some even at 100% hydrogen fuel, which suggests that these technologies can be used to retrofit older burners as hydrogen fuel availability becomes increasingly available.

Several barriers have been cited by burner manufacturers for various reasons including difficulty keeping up with regulatory changes, brand recognition for newer ULN models, and difficulty getting permits and local representation.

Finally, to address gaps identified in this market study, we recommend additional cost analysis studies to quantify the benefits and fuel savings of ULN burner retrofits. This study also recommends further testing of hydrogen blends with ULN burners in various retrofit equipment to further demonstrate how newer ULN burners perform in older retrofitted equipment in real-life settings.

Introduction

Global emissions of Nitrogen Oxides (NOx) are projected to fall by 10% over the period from 2022 to 2040. Both a significant reduction in emissions and high efficiency are crucial to meet market demands in terms of tightly connected cost and sustainability [1]. Ultra-Low NOx (ULN) burners with NOx emissions typically less than 9 ppm from commercial burners with thermal inputs of 2 MBTUH, are required in many areas of California and are regulated by the Air Quality Management District (AQMD).

California has 35 AQMDs, which are responsible for addressing emissions from stationary sources through permits and local rules. The South Coast Air Quality Management District (SCAQMD) and San Joaquin Valley Air Pollution Control District (SJVAPCD) have some of the strictest NOx and greenhouse gas emissions standards in the nation.

SCAQMD Rule 1146.2 limits the manufacturing and use of appliances with NOx emissions greater than 14 ng/J or 20 ppm NOx at 3% volumetric O_2 on a dry basis. The appliances include large water heaters, process heaters, and boilers. SCAQMD rule 1146.2 also limits NOx emissions in different metal heating and furnace to 15 ppm NOx for units greater than 40MMBtu/hr and 40 ppm NOx for units sized less than 40 MMBtu/hr. Additional requirements are listed in Appendix 1, with the strictest requirements being <5 ppm NOx for certain applications [2].

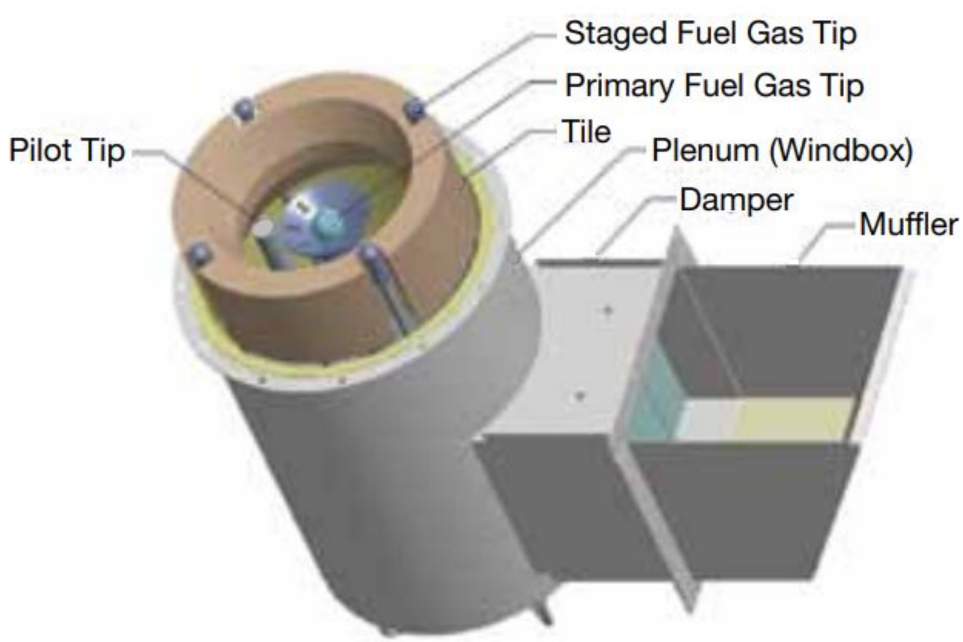
SJVAPCD Rules 4305–4308, 4320, and 4351 establish NOx emissions limits for process heaters, boilers, and steam generators listed in Appendix 1.2 [3]. The SJVAPCD has also adopted the Best Available Retrofit Control Technology (BARCT) rule. BARCT states that if businesses achieve lower NOx emissions than originally mandated by SJVAPCD, then all new permits must meet this achieved-in-practice limit. This rule establishes a moving target of NOx emissions for businesses since they cannot receive new permits unless they meet the lowest industry standards.

To meet these standards, new and emerging ULN burner technologies have been fabricated and tested in recent years. This study will explore the background of ULN burners, as well as identify promising ULN technologies including applications, retrofit opportunities, and hydrogen readiness.

Background

Burners are devices that provide fuel to burn fully under control by mixing it with air. They play an important part for heating technologies and have applications in many industries. While most burners have common operating characteristics, they can be characterized in different ways based on their flame shape, emissions, and fuel type [4]. Many process burners have a similar design (Figure 1) where air enters the burner through the muffler and is then distributed into the burner throat via the plenum, also known as the windbox. The fuel gas tips inject fuel into the air stream and the pilot tip ignites the burner.

Figure 1. Typical Process Burner Design and Components [4]



Burners are often classified based on their NOx emissions as either conventional, low-NOx, ULN, or next-generation ULN [4]. Nitrogen Oxides (NOx) which refers to both nitric oxide (NO) and nitrogen dioxide (NO_2) are dangerous pollutants that create a wide range of environmental concerns. NOx is a main component in the formation of ground-level ozone which is linked to severe respiratory illness. NOx along with sulfur oxides (SOx) contribute to the phenomenon known as acid rain, and NOx can react to form nitrous oxide (N_2O), which is a greenhouse gas that contributes to global warming [5].

Conventional burners are the oldest technology, and their design only focuses on the flame shape and stability of combustion without giving any consideration to NOx limits. Low-NOx burners, which emerged in the mid-1980’s, were developed to focus on lowering NOx, CO, and other greenhouse gas emissions. Low-NOx burners delay combustion by staging the air or fuel in multiple zones so that the initial fuel-air mixture is made either very rich or lean, thus slowing the combustion process and reducing the peak flame temperatures and NOx production. In ULN burners systems, more advanced techniques such as internal flue gas recirculation (FGR), combustion at high excess air, or the use of a stack cleanup system such as selective catalytic recirculation (SCR) and lean premixing of the air and fuel are utilized to reduce NOx emissions to near zero levels [6]. Another method of removing greenhouse gases from combustion processes is Acid Gas Removal (AGR), which mainly removes products including hydrogen sulfide (H_2S), carbonyl sulfide (COS), and carbon dioxide (CO_2) depending on the application. This market study will identify and summarize emerging ULN burner technologies.

Assessment Objectives

The main objective of this project is to collect market data and evaluate emerging ULN burner technologies. To accomplish this task, an initial literature review was conducted to identify and summarize new and emerging ULN burners. To build on this information, a list of subject matter experts (SMEs) including technology developers and manufacturers was developed along with a survey to gather updated market data on their ULN burner offerings. Interviews and site visits were conducted to gather additional data on various ULN technologies.

Survey Questions

A list of questions was prepared for use during the interview or site visits to collect more information on the ULN burners are listed below:

<u>List of Questions for SMEs</u>

1. Describe your ULN Burners technology?
2. How do your burners compare to other ULN burners on the market?
3. What are some applications that your burners can be used for?
4. What are some market challenges preventing the adoption of your ULN burner?
5. Are there any market opportunities for these technologies that you can think of, that don't currently exist?
6. Retrofit applications/new applications that your ULN burners could be used for?
7. Interested in broader product integration?

<u>List of Burner Specification Data to be gathered:</u>

1. Ultra Low NOx Burner Make Details
2. Burner Model
3. Flue Gas Recirculation (FGR) present
4. NOx (ppm)
5. CO (ppm)
6. SOx (ppm)
7. O2 trim (for boiler/process burners)
8. Linkageless control (for boiler/process burners)
9. Turndown Ratio
10. Furnace Pressure Capability (for boilers/process burners)
11. Fuel type (premixed, hydrogen, etc.)
12. BTU range

13. Maintenance needs
14. Burner Geometry
15. Operating Cost
16. Hydrogen blend % compatibility (if any)

SME Interviews

The interviews and site visits took place from April to May 2023, and brief conversations with burner manufacturers took place during the AHR expo from February 6-9th 2023 in Atlanta, Georgia. Organizations we spoke to along with the context of where they took place are organized below in Table 1:

Table 1. Customer Interviews

Interview/Site Visit	AHR Expo
Lawrence Berkeley National Lab (LBNL)	CIB Unigas
ClearSign	Cleaver Brooks
Rogue Burner	Honeywell
Powerflame Inc.	Industrial Combustion
Vitotherm	Powerflame Inc
Gas Technology Institute (GTI)	Vitotherm
	Micron Fiber Tech

At the AHR Expo, the conversations lasted anywhere between 5-30 minutes, while interviews conducted during Milestone 4 lasted anywhere between 30 minutes to 1+ hours. Note that some burner manufacturers spoken to at the AHR expo also agreed to a longer, more in-depth interview on their ULN burner offerings, while some did not respond to our emails or calls. In addition to the AHR expo, multiple efforts were made to reach other burner manufacturers and R&D organizations for a longer interview or site visit. The response rate is summarized in Table 2.

Table 2. Organization Response Rate

# of Organization's Contacted	# of Organizations that Responded	Actual Participation	Response Rate
18	9	6	33%

As indicated in Table 2, a 35% response rate was recorded. Outside the AHR expo, a total of 17 organizations were contacted. Organizations were contacted based on initial research conducted during the literature review phase of the study, and some conversations took place at the AHR expo. A total of 9 organizations initially responded and agreed to an interview, however some backed out or stopped responding due to reasons beyond our control. Most organizations are US based companies, and a few are European companies with a smaller market in California and other parts of the US. The comprehensive list of all organizations contacted for this market study is shown below:

1. Industrial Combustion
2. Powerflame Incorporated
3. CIB Unigas
4. Vitotherm
5. Micron Fiber-Tech Corporation
6. Honeywell
7. Lawrence Berkeley National Laboratory (LBNL)
8. ALZETA Corporation
9. Altex Technologies Corporation
10. Linde Technologies
11. GTI
12. Swiss Federal Laboratory for Materials Science and Technology
13. Cleaver Brooks
14. John Zink Hamsworthy Combustion
15. Polidoro
16. Rogue Burner
17. ClearSign
18. Fives Group

Technology Findings

This section will summarize the key findings from conversations with ULN burner manufacturers and research scientists. Longer summaries from interviews can be found in Appendix 2.0. Table 3 summarizes all the burners, applications, and general technology which are explained in more detail in the following sections.

Table 3. Ultra Low NOx Burner Technology Findings

Burner Name	Organization	NOx	CO	BTU Firing Range	FGR Present	Technology Description	Applications
Catalytic Hydrogen Burner	Swiss Federal Laboratory for Materials Science and Technology	<9.49 ppm <0.38 ppm at 33% H_2	0 ppm	n/a	No	Catalytic oxidation process involving Pt coated porous SiC foams with non-premixing hydrogen and air	Residential and commercial cooking appliances
ClearSign Core™ Boiler Burners	ClearSign[1]	<2.5 ppm	<50 ppm	4-100 MMBtu/hr	Internal FGR	Combination of air fuel premixing, internal FGR, patented distil flame holder technology	Firetube boilers
ClearSign Core™ Flare Burner	ClearSign	<15 ppm	<15 ppm	1-30 MMBtu/hr	Internal FGR	Combination of air fuel premixing, internal FGR, patented distil flame holder technology	Digestor gas, landfill gas, thermal oxidizers, vapor combustors, water treatment plants, coker heaters
ClearSign Core™ Process Burner	ClearSign	<5 ppm	<50 ppm	20 MMBtu/hr (Natural Draft Operation)	Internal FGR	Combination of air fuel premixing, internal FGR, patented distil flame holder technology	Vertical cylindrical canned heaters, cabin heaters, steam generators, steam methane reformer heaters, ethylene cracking furnaces

Burner Name	Organization	NOx	CO	BTU Firing Range	FGR Present	Technology Description	Applications
COOLstar®	John Zink Hamworthy Combustion®	<15 ppm	n/a	1.7-20 MMBtu/hr	Yes	Proprietary flue-gas entrainment and mixing technology	Large industrial processes such as coker heaters, horizontally fired platformers, crude and vacuum heaters, down fired methanol, ammonia, hydrogen reformers, ethylene cracking furnaces, hot oil heaters, charge heaters, and reboilers
CSB™	ALZETA®	<7 ppm	n/a	2 – 65 MMBtu/hr firetube boiler Up to 125 MMBtu/hr watertube boiler	FGR optional	metal-fiber burner, patented premixed surface-stabilized combustion process	Commercial and industrial boilers and process heaters
Duratherm™	ALZETA®	<7 ppm	n/a	16 MMBtu/hr	n/a	Ceramic-fiber burner, premixed surface-stabilized combustion process using patented PYROCORE® technology	Residential and commercial heaters and boiler applications. Air heaters, furnaces, commercial cooking equipment

Burner Name	Organization	NOx	CO	BTU Firing Range	FGR Present	Technology Description	Applications
Firetube Boiler Burner	Rogue Combustion[1]	<2.5 ppm	<50 ppm	4-100 MMBtu/hr	Internal FGR	Combination of air fuel premixing, internal FGR, patented distil flame holder technology	Firetube boilers
Flameless Oxyfuel Combustion Burner	Linde Technologies	<9 ppm	n/a	n/a	FGR present	Flameless oxyfuel technology which replaces nitrogen in air with pure oxygen to boost efficiency	most types of furnace applications, but most notably steel reheating furnaces
IWFC Low NOx burners	Micron Fiber-Tech	<9 ppm (standard) <5 ppm options available for certain applications	Near zero	16 MMBtu/hr	n/a	Proprietary metal fiber technology. Compact flame with stainless steel shell	Immersion Tube heating, direct air heaters, steam boiler heating, water heating
Low Swirl Burner	LBNL	<9 ppm	<50 ppm	4-60 MMBTu/hr	No FGR	Air swirler, premixed fuel	Boilers for wastewater treatment, IR heating, on-demand water heaters
nanoSTAR™	ALZETA®	<3 ppm	n/a	60 MMBtu/hr	n/a	Premixed, surface-stabilized combustion process	Industrial gas turbines for mechanical drive and power generation applications

Burner Name	Organization	NOx	CO	BTU Firing Range	FGR Present	Technology Description	Applications
NP2 burner	Powerflame Incorporated	<9 ppm	Low CO	700-6,100 MBtu/hr	No FGR	A patented premixed surface stabilized combustion all-metal firing head technology	Process heating in hospitals, furnaces, boilers, ovens, bath vaporizers for LNG conversion, autoclave ovens, distillery/brewery
NVC Burner	Powerflame Incorporated	<9 ppm	<50 ppm	2-64 MBtu/hr	No FGR	A patented premixed surface stabilized combustion all-metal firing head technology	Wide variety of commercial, industrial, process applications
NZNB Burner	Altex Technologies Corporation	<5.7 ppm	<50ppm	3.1-6.9 MMBtu/hr	FGR present	Patented multi flame zone technology with post-combustion Nox reduction process	Firetube boilers, commercial boilers, water heaters, process heaters
Oxy-Therm® burner	Honeywell	<9 ppm	n/a	1-24 MBtu/hr	No FGR	Patented staged oxygen design. No excess O_2 required for complete combustion	High temperature applications like furnaces, glass furnaces, day tanks, incinerators, metal-heating furnaces, linear and rotary hearth furnaces, reheat furnaces

Burner Name	Organization	NOx	CO	BTU Firing Range	FGR Present	Technology Description	Applications
Pillard NANOxFLAM®	Fives Group	<9 ppm	<10 ppm	5-60 MW (17 MBtu/ hr -54 MBtu/hr)	FGR Present	Patented premix technology	Firetube boilers and water tube boilers, as well as single burner and multi-burner applications.
Ring Stabilizer Burner	LBNL	<9 ppm	n/a	scalable	No FGR	Premixed air and fuel at low velocities, natural draft	Residential and commercial cooking equipment
RMB™	John Zink Hamworthy Combustion®	<9 ppm	<25 ppm	Up to 300 MMBtu/hr	FGR Present	Rapid premixing system of air and fuel with proprietary burner geometry	Boilers, retrofits, refractory-lined furnaces for dryers, or fluid bed boiler-warm up applications
SBR-5 ULN burner	Cleaver Brooks	<5 ppm	n/a	10.5-42 MMBtu/hr	FGR present	Unique firing head to achieve controlled combustion	Firetube and water tube boilers, Process steam heating, industrial process heating, waste heat recovery, hospital space heating, laundry and dry cleaning, refinery, petrochemical applications
SOLEX™	John Zink Hamworthy Combustion®	<5 ppm	Near zero	1 MMBtu/hr-20 MMBtu/hr	No FGR	Patent pending AIRmix™ technology and COOLmix™ technology	Variety of applications including upfired down fired, or horizontally fired applications

Burner Name	Organization	NOx	CO	BTU Firing Range	FGR Present	Technology Description	Applications
Super Low NOx Series (10 MW N1060V)	CIB Unigas	<9 ppm Still undergoing testing	n/a	n/a	FGR Present	Staged combustion and FGR technology	boilers
Tube Burners	Micron Fiber-Tech	<9 ppm	n/a	100 MMBtu/hr	n/a	Proprietary metal fiber technology	Dryers, coffee roasters, Food service, ovens, industrial furnaces, paint (powder) curing, sugar condenser, outdoor IR heating
Ultra CMAX Ultra-Low NOx burner	Powerflame Incorporated	<9 ppm	<50 ppm	700-6,100 MBtu/hr	Yes	Premixed firing head and reduced blower power	Firetube boilers, Process heating in hospitals, furnaces, boilers, ovens, bath vaporizers for LNG conversion, autoclave ovens, distillery/brewery
Unreleased model (as of July 2023)	Vitotherm	<5 ppm	0 ppm	2-34 MMBtu/hr	n/a	n/a	Greenhouse applications, indoor applications

*Note that N/A means that no specific value was found, or information was not publicly available

LBNL ULN Burners

This market study involved two interactions with scientists from LBNL. The first was a general conversation on their current research with ULN burners and the second included a site visit to LBNL. LBNL has developed two ULN burner technologies listed below:

- Low-Swirl Burner
- Ring Stabilizer Burner

Low-Swirl Burner (LSB)

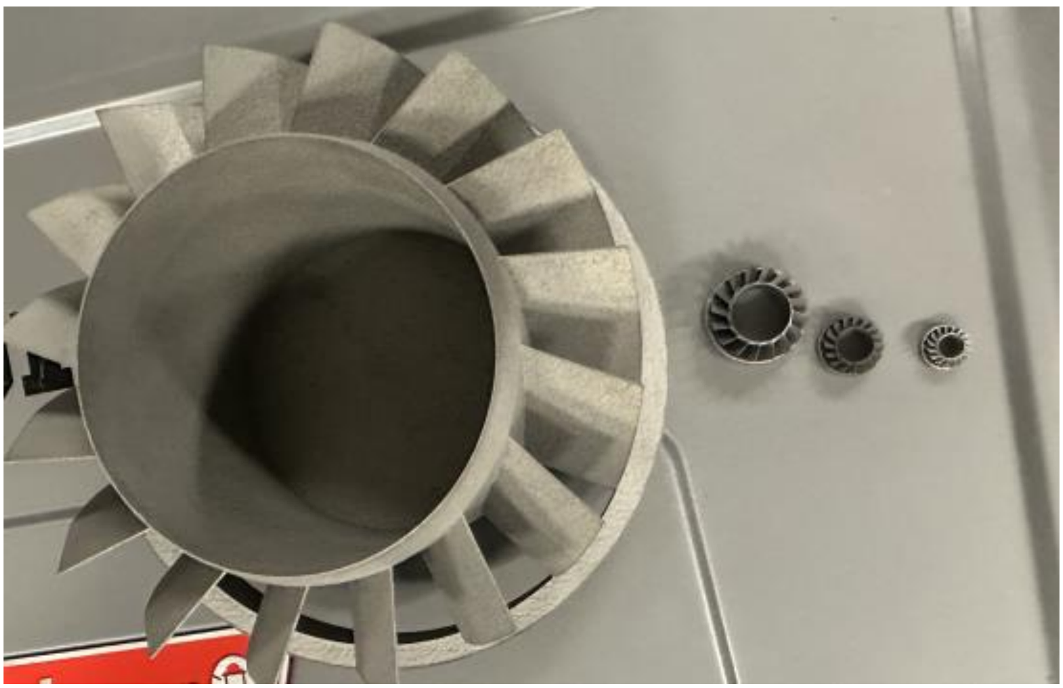
The low swirl burner consists of an open tube fitted with an air swirler. The LSB offers high-performance with ultra-low emissions while requiring less hardware control due to its flame stabilization features. An important feature of this technology is the flame stabilization, in which the mean velocity of the flame decreases linearly down the stream of the burner throat. The velocity “down ramp” provides the flame stabilization mechanism [7]. Overall, the LSB is a simple, low-cost technology with ULN and sub 50 ppm CO emissions. The low flame temperatures generated by the premixed fuel for combustion eliminate the need for catalysts, fuel-air staging, or flue gas recirculation [8].

Figure 2. Low Swirl Burner prototype

Low Swirl Burner Applications

LBNL collaborated with the California Energy Commission (CEC) on a project to study real time fuel flexing between biogas and natural gas in a wastewater treatment plant for a boiler application. Figure 2. shows the swirler that has been developed for use in a boiler for the wastewater treatment plant. This burner also has a hydrogen blend capability anywhere between 0-100% hydrogen while maintaining NOx below 9 PPM. The Low-swirl burner technology has been commercialized in Maxon and Honeywell burners for use with boilers but is not widely spread in other applications as the focus is just on boilers. LBNL has also integrated this burner into a central furnace and proved its technology, however this application is not yet commercially available. LBNL has adapted and tested the low-swirl burner technology for other commercial applications including outdoor radiant heaters and tankless (on-demand) water heaters, the latter of which has been tested.

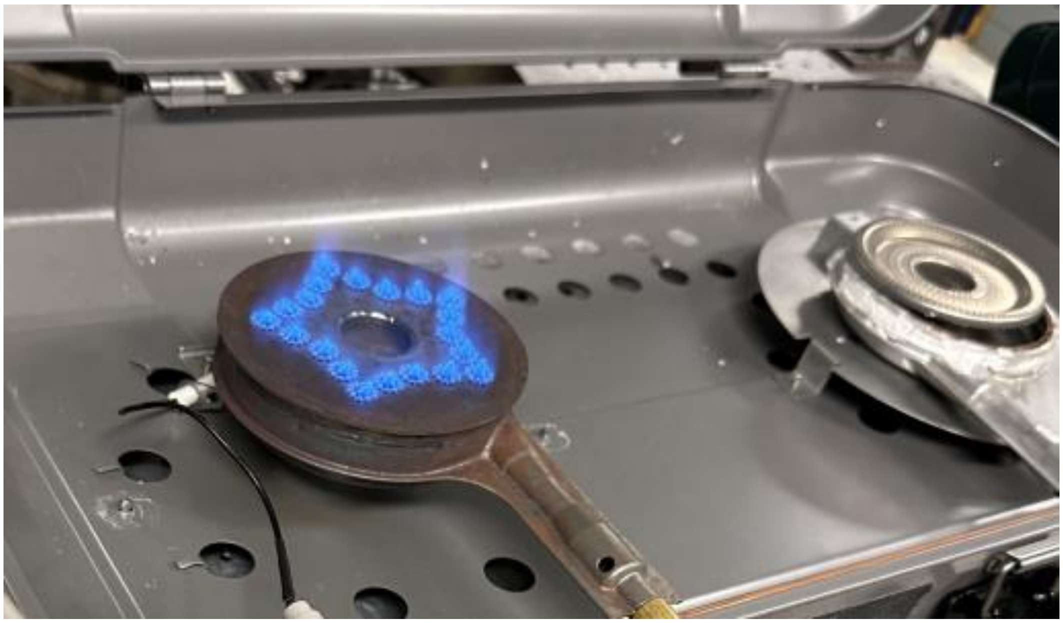
Figure 3. Different sizes of the swirler for the Low swirl burner.



Ring Stabilizer Burner

The ring stabilizer burner combustion technology was initially developed by LBNL for a NASA funded microgravity experiment. In a project with the CEC, LBNL adapted the ring-stabilizer burner to develop a simple ULN natural draft gas burner. This burner is a scalable burner that is designed to maximize the heat transfer on the flame's surfaces, which allows for efficient combustion. This burner technology achieves its low NOx emissions by stabilizing premixed air and fuel at low velocities. Unlike other premixed burner technologies, the natural draft burner does not require air blowers and can operate without electricity or fans which make it ideal for improving energy efficiency and curtailing emissions for residential and commercial cooking operations. For the ring stabilizer burner, the reason it increased efficiency for cooking was because it decreased boiling time by roughly 25% compared to a conventional burner. The way that the flames were designed according to researchers is "flat," which means that there is a lot of contact between the flame and the pan which results in better heat transfer. Figure 3 shows the geometry of the ring stabilizer burner compared to a traditional burner. The shape of the flame essentially will have better contact with whatever item trying to be heated in the kitchen, thus optimizing the energy efficiency.

Figure 4. Ring burner (left), next to a conventional burner (right)



Applications of Ring Stabilizer/Natural Draft Burner

The ring stabilizer burner can be retrofitted into a variety of other appliances and can be applied to furnaces, ovens, heaters, water heaters, and even industrial heating. LBNL conducted analyses on integrating it into cooktops, however projected revenue margins were not good. From earlier analysis, it was revealed that there were two main burner manufactures for cooking appliances and the cost to retrofit their burner into the cooktop would be too expensive. LBNL decided to explore other applications, such as storage water heaters and ovens. Prior to the pandemic, the focus was on optimizing the burner for water heaters, however that development has been halted due to the pandemic.

<u>Barriers</u>

During conversations with scientists from LBNL it was revealed that the pandemic paused or stopped some projects they had with customers.

Market Opportunities for LBNL ULN burners

The LBNL burners are all highly scalable, especially the low swirl burner which can be scaled to millions of BTUs, and can be used for many applications, even industrial process heating. Both burner types are fuel flexible. The burners would need to be optimized for the specific application.

ClearSign Burners

ClearSign is a burner R&D company that develops burners for most generic commercial and industrial markets. They use their ClearSign Core^{Tm} technology in their burners which consist of air fuel premixing, internal Flue Gas Recirculation (FGR), and their patented distil flame holder technology. They are the only burner company that has that unique combination of those three combustion elements in a fuel burner. Unlike other burner manufacturers who have tweaked a regular burner to get to ULN levels, ClearSign's burner has been purposely developed to be ULN from the beginning and therefore has tremendous operational flexibility. The design of the ClearSign burner is unlike any other since it operates more like a turbine than a burner, with a very high velocity. They offer three main ULN burner products:

- Process Burner
- Boiler Burner
- Flare Burner

ClearSign Process Burner

The process burner developed by ClearSign can use heavy refinery fuels with varying fuel composition and has been tested with up to 80% hydrogen gas. ClearSign has partnered with Zeeco Inc, in an agreement to jointly develop, sell, and supply ClearSign process burners.

Boiler Burner

Rogue burner is the exclusive partner for selling the ClearSign boiler burner, and California Boiler acts as the exclusive installer in California, Oregon, and Nevada. All of ClearSigns boiler burners are retrofit into a variety of legacy boiler brands.

Flare Burner

The flare burner using ClearSign Core^{Tm} technology is a niche product since not many places require ultra-low NOx flares. Flares are a high-temperature oxidation process to burn waste gases and are used for burning waste gases in applications like sewage digestors, and water treatment plants. Generally, most flares are known as "stick flares," which consists of a pipe full of fuel and the burner is located at the tip of the pipe, with the flame exposed at the top of the burner. With a stick flare, there is no stack to contain the flue gases, so there is no way to measure the NOx emissions. To combat this, California is the only state that has a requirement for enclosed flare burners with a ULN capability for feasible applications. Enclosed flares have a much bigger diameter stack, and the flame is inside the stack which means there is no visible flame. As a result, NOx measurements are put in place for these enclosed flame burners. ClearSign has supplied seven flare burner retrofits in the central valley region that operate on a <15 ppm NOx for oil production facilities. Compared to other flare burners which operate on a 95% destruction efficiency, the ClearSign burner has a very high 99% destruction efficiency. Note that the destruction efficiency is the percentage of a specific pollutant like CO_2 in the flare flue gas that is converted to different product.

ClearSign Burner Applications

There are a variety of applications that could benefit from ClearSign's burners. For process burners, this technology can be used in vertical cylindrical, canned heaters, cabin heaters, and steam generators. In the future, ClearSign is interested in expanding the capability to other process heaters such as furnaces, including delayed coker heaters. They are looking to develop and test an installed delayed Coker heater burner. There are around 20 such coker heaters in Los Angeles and a few in the bay area, so it is a very niche market. Other process burner applications that ClearSign is interested in including the steam methane reformer heater, and ethylene cracking furnaces which are used to produce raw materials in the petrochemical industry.

Beyond the firetube boiler burner, ClearSign is interested in watertube boiler applications. They are currently still testing their burner in a water tube boiler and have found that they would need to shorten the length of the burner and increase heat release to suit the watertube boiler market.

For flare burner applications, ClearSign representatives have stated that they can be used for digestor gas, landfill gas, thermal oxidizers, vapor combustors, and water treatment plants. They are also interested in developing their product for delayed Coker heater applications. Coker heaters can be used for instances when dealing with heavy crude oil. Since California local crude oil is very heavy, special heaters like Coker heaters are useful. ClearSign is interested further research for this application.

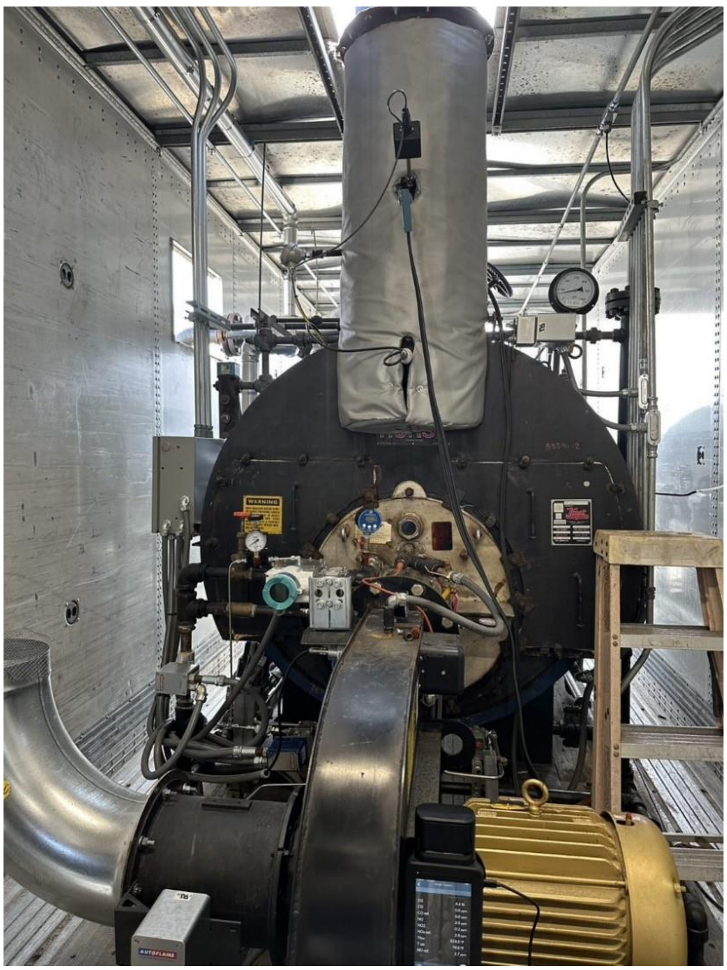
Market Barriers

From conversations with ClearSign representatives, a major challenge was that any type of regulatory compliance project has little return on investment for the operator of the facility. The ClearSign burner has some return on investment, since their process burner has operability advantages, and the boiler burner is more efficient than other boiler burners on the market due to its ability to achieve NOx levels without the use of any reagents, catalysis, or high excess air conditions commonly seen in other burners. Another barrier mentioned was brand recognition.

Rogue Burner

Rogue Combustion, LLC partnered with ClearSign which resulted in the Rogue Burner. Rogue specializes in fire tube boiler burners, which can be supplied for new boilers or retrofitted into existing boiler equipment. The complete boiler system includes the burner, blower, fuel gas train, combustion controls, and installation. Compared to other boiler burners, this boiler burner system has no need for costly catalysts, chemicals, or extra ducts or controls. Figure 4. shows the firetube boiler with the burner located in the middle.

Figure 5. Rogue Boiler Burner



This boiler burner using the ClearSign Core technology has exceptional flexibility for controlling NOx emissions. During the site visit, we were able to tweak the burner to operate close to sub 1 ppm NOx. From conversations with representatives, they claimed that they have not yet even come close to “optimizing” the burner.

Powerflame Incorporated Burners

Powerflame Inc. offers three types of ULN burners:

- Ultra Cmax burner
- NP2 burner
- NVC burner

The key features of Powerflame's ULN burner technology include premixed firing head featured in their Ultra CMAX burner and a metallic firing head in the NP2 burner. Powerflame offers state-of-the-art electronic linkageless controls to accurately maintain fuel air ratios throughout the firing range for optimum performance. They have successfully tested their burners with up to a 30% hydrogen blend.

Figure 6. Ultra CMAX Ultra-Low NOx burner

Applications

Powerflame claims to retrofit boilers with their ULN burners fairly often. Other applications include process heating in hospitals, furnaces, ovens, bath vaporizers for Liquid Natural Gas (LNG) conversion, autoclave ovens, and distillery/brewery operations in <9 ppm NOx requirement regions in California.

Barriers

From conversations with Powerflame Inc. representatives, one barrier they have faced with respect to hydrogen blending is the increase in NOx output because of the required additional hydrogen flow required to maintain the same heat output. Since hydrogen is a lighter fuel and less energy dense than natural gas and therefore a burner needs to burn more fuel which can result in an increase in NOx that occurs when excess oxygen is heated during combustion.

Another barrier discussed was that laws and regulations in California don't take all the possible burner applications into consideration when establishing NOx requirements. An example brought up was that applications requiring higher pressure such as those in the canning industry which operate at around 200 psi at high pressure steam. It requires more heat to create that pressure which works against the burner company from a NOx standpoint as well. The Powerflame representative pointed out that from a regulatory standpoint if officials "see a boiler running under 5 ppm NOx in CA they will just assume that all boilers can do that regardless of the application."

Powerflame has also expressed that it seems like the NOx limit seems to a moving target for CA and has caused them to scramble to figure out how to make their technology work for specific applications, and often losing money at certain jobs due to new regulatory setbacks.

Vitotherm Burners

Vitotherm is a burner R&D company based in the Netherlands. Vitotherm burners are designed to last for a long time and are designed for easy operation and maintenance. Vitotherm has a new ULN burner line to be released at the end of 2023 but has not yet been commercialized as of June 2023. This will be their first ULN burner model offering. A unique characteristic regarding their ULN burner line is that it has 0 ppm CO emissions in addition to <5 ppm NOx since they have focused on greenhouse applications. Since their main customer is the greenhouse market in California, they are looking for other partners and applications to expand their burner offerings. The 0 ppm CO emissions combined with the ULN burner make their burners a good solution for indoor applications.

Barriers

Some barriers that Vitotherm has faced is getting permits for their burners at greenhouses. They also lack local representation in California to help them expand their offerings. They are having trouble finding a partner for selling in the industrial market in the United States.

GTI

We contacted GTI to learn about any ULN burner offerings being developed. However, the interview with GTI ended up being more of a general overview of ULN burners. When asked about specific technologies like the CSB burner, which is featured on their webpage, the researchers did not have much information to offer. However, GTI seems open to collaborating on burner combustion technologies.

ULN Burner Findings - AHR expo

The following burner companies did not respond to a longer interview or site visit; however we had brief interactions with them at the AHR expo. Further research was conducted to fill in the gaps and collect more information on these technologies.

Honeywell Burners

Honeywell has designed a next-generation Oxy-Therm® burner that is capable of significantly reducing NOx emissions. The Oxy-Therm® FHR uses a patented staged oxygen design which improves radiant heat transfer and thus significantly reduces NOx emissions which Honeywell claims has the lowest NOx emissions in industry.

The Oxy Therm® Burners are uniquely designed to run with close to pure oxygen instead of traditional burners that run only on air, which is only made up of approximately 21% Oxygen. By using almost pure oxygen, the burner does not lose as much heat to flue gases and the products of combustion. Traditional burners that use air end up wasting a significant amount of heat input by heating the inert Nitrogen (~79%) in the air. Thus, the next generation Oxy-Therm® Burner claims to offer fuel savings of as much as 25% gas or 40% oil compared to air-fuel burners [9]. However, unlike air which is free, producing oxygen with higher purity levels comes at a cost which can fluctuate based on market demand. Oxygen is manufactured using processes like electrohydrodimerization, electrolysis (which may be driven by green or non-green power sources), and cyrogenic separation, the latter two also coproduce hydrogen and nitrogen [21]. Oxygen can be stored in liquid or compressed form, and for larger scale needs cryogenic tank trailers are used for transportation and storage purposes [21]. It is unclear to what extent the sourcing and storage of pure Oxygen will have an impact on the overall cost savings of the burner system. Honeywell has not quantified this in any of its technical documents pertaining to this burner.

The Oxy-Therm® Burner was designed with operational flexibility in mind. Some advantages include its capability of firing with up to a 20% Hydrogen and natural gas fuel blend by simply changing a nozzle to change the fuel type. The burner offers a patented adjustable oxygen staging to vary flame length and comes in four block sizes with different custom oil and gas nozzles for the burner location. Additionally, the fuel type or burner capacity can easily be changed without replacing the housing assembly which can be beneficial for a wide range of industrial applications.

<u>Applications</u>

The Oxy-Therm® FHR burner is suitable for high temperature applications like furnaces. The Oxy-Therm® burners have been successfully applied to glass furnaces, day tanks, incinerators, metal melting furnaces, linear and rotary hearth furnaces, reheat furnaces, and many other high temperature (>1400 °F) applications [9].

Micron Fiber-tech

Micron Fiber-tech offers a variety of burner and heating solutions. Two ULN burners were discussed at the AHR expo:

- Tube Burners
- IWFC Low NOx burners

Both burner offerings offered <9 ppm NOx and near CO emissions.

Applications

The applications for these burners are as follows:

- Dryers
- Coffee roasters
- Food cooking
- Bakery ovens
- Industrial furnaces
- Paint (powder) curing
- Sugar condenser
- Outdoor IR heating

Cleaver Brooks

Cleaver brooks offers Ultra-Low NOx burners, achieving <5 ppm NOX with FGR. The SBR-5 model of burners offers natural gas fuel options from 10.5 to 42 MMBTU/hr. The forced-draft design controls the air and fuel mixture, resulting in complete combustion with low CO emissions without a fragile surface combustion burner head. The burner offers higher efficiency as a result of its parallel positioning and O2 trim controls, which allow the burner to optimize its fuel-to-air ratio. The premixed fuel also allows for equal heat transfer due to a uniform flame.

Figure 7. Cleaver Brooks SBR-5 ULN burner

Applications of the SBR-5 burner include:

- Process Steam
- Industrial Process
- Waste Heat Recovery
- Hospital and Healthcare
- Laundry and Dry Cleaning
- Refinery and Petrochemical uses

CIB Unigas

CIB Unigas is an Italian burner R&D company that offers ULN burners in parts of Europe. They have recently installed their first burner in California; however, it was not clear if this was a Low-NOx or ULN burner. From a conversation with their representative, their burners are suitable to run on up to 75% blend of Hydrogen and natural gas while maintaining ULN emissions. They have tested 100% hydrogen on their burners in a laboratory setting.

Further, their burners can all fire with hydrogen gas with some changes needed based on the hydrogen blending levels. They have concluded that only minor changes to the burner are required up to around 55% hydrogen. CIB Unigas is currently working to test hydrogen with their ULN burner heads, which use a mix of staged combustion and FGR to achieve ULN levels. As of July 2023, they are still working on the new ULN burner designs.

Additional ULN Burner Technologies

This section will summarize the various ULN burner technologies identified from a literature review conducted earlier in this study in addition to ongoing research. Note that this will include technologies from burner manufacturers who were contacted during the interview phase of this study, however, they did not respond to our request for further data. This section also includes burner manufacturers who were also not present at the AHR conference.

ALZETA® Ultra-Low NOx Burners

ALZETA® Corporation offers a few ULN Burners that deliver less than 7 ppm NOx in most applications. Their burners utilize a premixed, surface-stabilized combustion process that offers uniform heating to operate at minimum combustion temperatures. Different ALZETA® ULN burners are summarized below:

1. The ALZETA® CSB™ is a metal-fiber burner that is used for ULN applications.

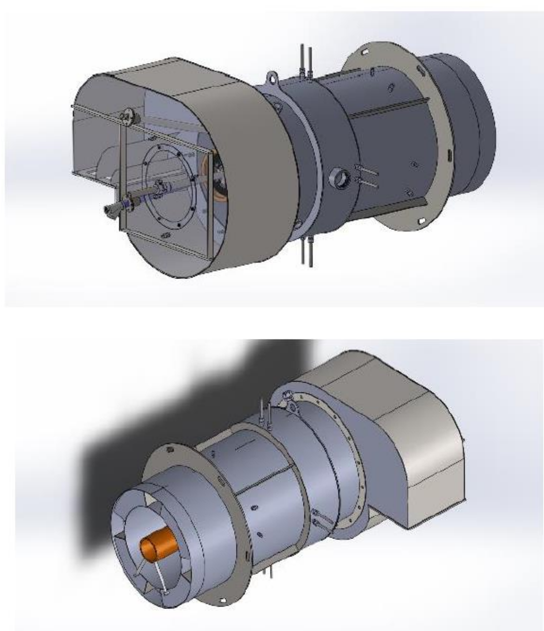
2. The Duratherm™ is a ceramic-fiber burner which is used for ULN applications where a low heat flux and uniform heating are required.
3. The ALZETA® nanoSTAR™ burner offers a 3 ppm NOx solution for industrial gas turbines [10].

Altex Technologies Corporation Near-Zero NOx Burner

Altex Technologies Corporation is an R&D company that focuses on combustion systems. In the past, they have previously demonstrated low NOx performance with their Ultra Reduced NOx Burners (URNB) technology, which uses a patented multi-flame zone technology [11]. This burner was previously able to demonstrate <9 ppm NOx, with the lowest recorded being 3.5 ppm, however CO emissions were around 400-500 ppm, which does not comply with current air quality regulations in certain California districts. Thus, Altex decided to develop a next generation ULN burner to meet current regulations.

Researchers at Altex Technologies Corporation, along with support from the CEC have fabricated and tested a commercial-scale, near-zero NOx Burner (NZNB). This is a multi-flame zone burner that integrates a post-combustion NOx reduction (PCNR) process to reliably achieve emissions of under 5 ppm NOx and 50 ppm CO. Some key features include the PCNR's in-furnace NOx reduction which eliminates the bulky and expensive after treatment of selective catalytic reduction (SCR) which is used in some burners and is often too large and expensive for smaller commercial systems [11]. The final fabricated model of the Altex NZNB burner is shown in Figure 4.

Figure 8. Final Solidworks Model of Altex NZNB burner [11]



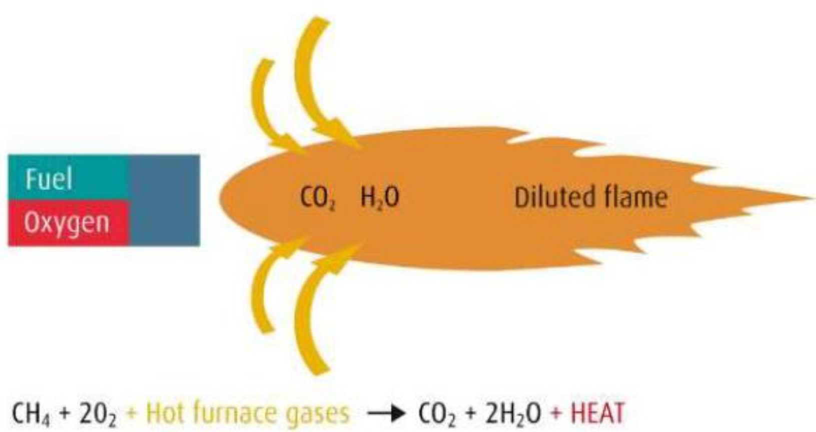
Altex has tested this burner in a firetube boiler setting, where NOx levels of 5.7 ppm were achieved, and corrected CO emissions were under 10 ppm. The successful operation of this burner led to the conclusion that the NZNB burner can be commercialized to meet stricter air quality regulations in California for boilers, water and process heaters.

Linde Technologies Flameless Oxyfuel Combustion Burner

Linde Technologies has successfully developed and demonstrated its Flameless Oxyfuel (FO) burner since 2003 and has installed over 400 different units of the FO burner in all kinds of furnace and heating applications. To meet stricter NOx emission demands, Linde has developed solutions to improve upon the oxyfuel combustion process that increases the flame temperature while also minimize emissions and maintaining energy efficiency heating.

Flameless combustion refers to the visual aspect of the combustion type in which the flame is no longer seen or easily detectable by the human eye. In the flameless oxyfuel process, shown in Figure 5, the mixture of the fuel and oxidant reacts uniformly through the flame volume and the combustion gases are effectively dispersed throughout the furnace or vessel which ensures more efficient and uniform heating of materials [12].

Figure 9. Flameless Oxyfuel combustion showing the diluted flame [12].



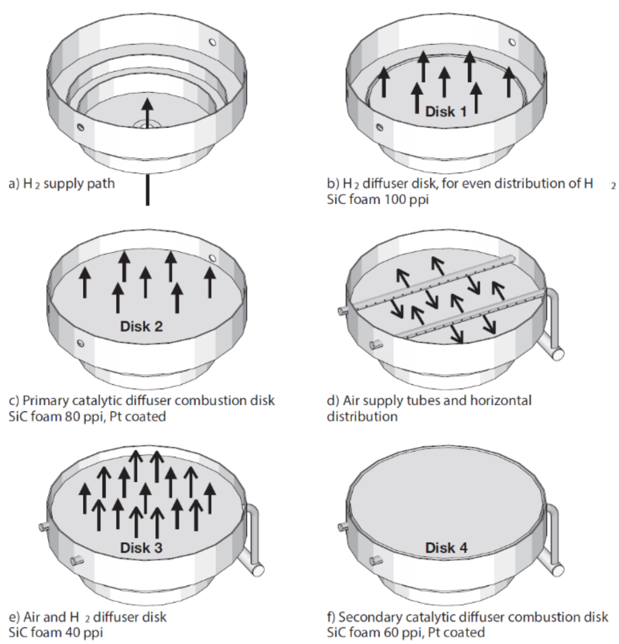
The flameless oxyfuel burner is highly efficient since there is no presence of nitrogen in the combustion. Since nitrogen is not combustible, replacing the nitrogen in air with 100% oxygen allows for more efficient combustion, higher thermal efficiency, and lower volumes of exhaust gases and emissions. The recirculation of hot flue-gases ensures that the heat input from the flameless oxyfuel burner will only cover the needed heat to the steel and losses through the outer walls. Another operational benefit of the flameless oxyfuel burner is that it offers fuel flexibility and is characterized as hydrogen ready, meaning that it can partly or fully use hydrogen as a fuel. Thus, this burner system has the potential to bring

CO_2 emissions to zero if using renewable hydrogen as fuel. This technology has successfully been tested with 100% hydrogen in a steel producing furnace, with a permanent field demonstration planned in 2023 [12].

Swiss Federal Laboratory for Materials Science and Technology-Catalytic Hydrogen Combustion Burner

Open flame hydrogen burners without catalytic combustion produce more NOx than natural gas burners. To minimize NOx emissions on hydrogen-fueled burners, scientists at the Swiss Federal Laboratory for Materials Science and Technology have researched the NOx emission in the flue gas of a catalytic hydrogen combustion process, operating without premixed hydrogen and air supply. The study was conducted on a novel designed gas under glass stove top burner, for domestic kitchen applications using hydrogen as the main fuel source. The study used a new approach to catalytic oxidation involving Pt coated porous SiC foams with non-premixing hydrogen and air shown in Figure 10.

Figure 10. Catalytic Hydrogen Burner design with Pt coated combustion disk, the H2 and air supply system and the different porous SiC disks for homogeneous distribution of hydrogen and air [13].



The basic catalytic burner assembly consists of two platinum coated silicon carbide (SiC) foam disks that are stacked with a 10 mm space between them for uniform air supply and distribution. Hydrogen is supplied from below the assembly and air is blown in between the two Pt coated catalytic SiC disks, leading to a homogeneous air distribution and thus a uniform catalytic reaction of hydrogen and air. Tests were performed at various hydrogen flow rates and NOx emissions of 0.09 ppm to 9.49 ppm were achieved using this novel developed catalytic combustion design [13]. The test results show a safe approach for catalytic H_2 oxidation with ULN formation.

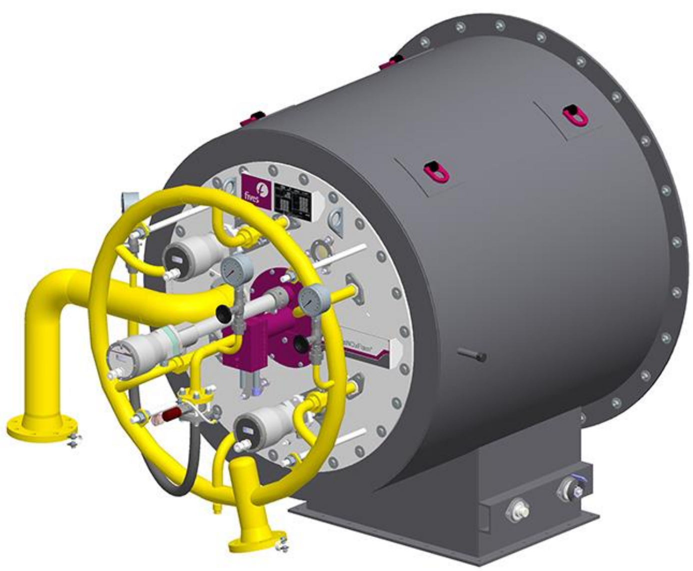
Applications

The catalytic hydrogen combustion burner has been applied to cooking appliances that operate between 100-700 °C. The first unit of this was operated in residential areas and further development towards industrial manufacturing for stoves and commercial applications is in progress.   The catalytic oxidation reaction that takes places occurs below room temperature, which is an added safety feature for cooking appliances.

Pillard NANOxFLAM® Burner

The Pillard NANOxFLAM® burner was designed and manufactured by the Fives Group, a European company that specializes in machinery and processing equipment. This burner unit is available in two versions: a duoblock and monoblock burner. The Pillard NANOxFLAM® duoblock burner, shown in Figure 11, uses a unique patented premix technology, in which fuel gas and air are mixed before entering the combustion zone, which results in low-temperature flames. This technology was recognized by the European Union as a Best Available Technique (BAT) for preventing or minimizing emissions.

Figure 11. Pillard NANOxFLAM® Duoblock ULN burner [14]



The duoblock burner can reach <9 ppm NOX emissions at 3% excess O_2 with FGR [14]. This burner has been installed over 110 times around the world, with its key markets in China and Korea.

Applications

The Pillard NANOxFLAM® duoblock burner is suitable for both firetube boilers and water tube boilers, as well as single burner and multi-burner applications. The monoblock burner offers a compact solution for smaller boilers and furnaces.

John Zink Hamworthy Combustion® ULN Burners

John Zink Hamworthy Combustion® (JZHC) has developed and manufactured a variety of burner solutions. The COOLstar® burner offers <15 ppm NOX emissions for large process applications. This burner technology applies JZHC's proprietary flue-gas entrainment and mixing technology which uses the energy of incoming fuel and air streams, which results in stable flames and low emissions [15]. The compact nature of the flames also maximizes thermal efficiency. The burner design is flexible and has design options to reduce NOx emissions even further for certain applications.

The SOLEX™ Burner is capable of achieving 5 ppm NOx emissions, and near-zero CO emissions without the assistance of SCR or other NOx reducing technology like FGR. The SOLEX™ Burner consists of JZHC's patent pending AIRmix ™ technology and their COOLmix™ technology which result in a short, compact flame length [16].

The Rapid Mix Burner (RMB™) by JZHC offers another burner solution that can operate at <9 ppm NOX and <25 ppm CO emissions. The technology offers a different gaseous injection and mixing system resulting in rapid mixing of combustion air and fuel gas prior to ignition. The RMB™ burner geometry works to produce a stable flame and FGR is used to reduce peak flame temperatures to maximize thermal efficiency.

Applications

The COOLstar® burner is designed for both new builds and retrofit applications. This burner is typically used in larger industrial processes. Some applications include coker heaters, horizontally fired platformers, crude and vacuum heaters, downfired methanol, ammonia, and hydrogen reformers, ethylene cracking furnaces, hot oil heaters, charge heaters, and reboilers [15].

The SOLEX™ Burner is also suitable for retrofit applications and fits traditional ULN burner footprints. This burner can be upfired, downfired, or horizontally fired to fit different applications.

The RMB™ burner system is suitable for use on both new boilers and retrofits of existing units. Other applications include water tube boilers, refractory-lined furnaces for dryers or fluid bed boiler warm-up [17].

Hydrogen Blending and ULN Burners

A number of burner manufacturers have begun to research and test hydrogen gas as an alternative, clean fuel for burners. Blending natural gas and hydrogen has become increasingly popular over the past years due to its ability to curb carbon dioxide emissions. Researchers have found that even blending up to 20% hydrogen and natural gas in UK households can eliminate 6 million tons of CO_2 emissions every year, which is roughly equivalent of removing 2.5 million cars off the roads [18].

One challenge in combustion processes is that higher concentrations of hydrogen gas could affect the NOx emissions. The molecular weight of hydrogen is about 2.0 g/mol compared to natural gas which is around 17 g/mol. Because hydrogen is a lighter fuel, and less energy dense, it requires about 3.4x the volumetric flow rate of natural gas to achieve the same heat input. Literature reports for hydrogen and natural gas compositions have yielded highly variable data, where NOx emissions range from −12% to +39% at a 5% hydrogen blend and −50% to +154% for a 20% hydrogen blend [19]. In a study analyzing boilers specifically, the large variability of NOx emissions because of hydrogen blending is attributed to different burner flame designs, the experimental conditions used, as well as type of boiler used. The study found that older, conventional NOx equipment generally performs poorly with Hydrogen and natural gas blends with respect to NOx, and thus investing in newer combustion equipment or burner retrofits would help decrease NOx and Carbon emissions [19]. A different study by the University of California, Irvine (UCI) found that NOx decreases when hydrogen is added to natural gas in water heaters [20]. The same study also indicated that low NOx devices were able to tolerate greater blends of hydrogen compared to conventional NOx devices. Researchers at UCI also found that reporting NOx emissions on a mass basis per unit fuel energy input should be the best practice going forward as opposed to the typical dry concentration basis. The latter is misleading since the greater amount of water produced by hydrogen results in a perceived increase in NOx as hydrogen blends are added, which isn't the case [20]. Experts have called for further testing to include NOx in field trials where Hydrogen and natural gas blends are being deployed to better understand the true range of NOx outcomes in higher hydrogen blends.

This market study has identified a number of next generation burners that have been tested with hydrogen and natural gas blends. Once hydrogen blends become increasingly available in the commercial and industrial markets, these burners could be a key retrofit for existing equipment to help them maintain ULN concentrations at higher hydrogen levels.

Table 4. ULN Burners and Hydrogen Blending Compatibility

Burner Name	Organization	Hydrogen Blends tested	NOx
Low Swirl Burner	LBNL	100%	<9 ppm
ClearSign Core™ Boiler Burners	ClearSign[1]	80%	<2.5 ppm
Firetube Boiler Burner	Rogue Combustion[1]	80%	<2.5 ppm
ClearSign Core™ Process Burner	ClearSign	100%	<5 ppm
Ultra CMAX Ultra-Low NOx burner	Powerflame Incorporated	30%	<9 ppm
ULN burner pending release by the end of 2023	Vitotherm	25%	<5 ppm
Super Low NOx Series (10 MW N1060V)	CIB Unigas	75% (field) 100% (lab)	The exact number is unclear due to ongoing testing; however, representatives claim ULN levels.
Oxy-Therm FHR Burner	Honeywell	20%	<9 ppm
COOLstar® burner	John Zink Hamworthy Combustion	100%	<15 ppm
Flameless Oxyfuel Combustion Burner	Linde Technologies	100%	<9 ppm
Catalytic Hydrogen Burner	Swiss Federal Laboratory for Materials Science and Technology	66% H2 *This is a H2-O2 ratio, this burner does not use natural gas.	<9.49 ppm at 66% H2 <0.38 ppm at 33%H2

Note that the Rogue Combustion burner and ClearSign are the same burner technology.

Conclusions

A total of 25 ULN burner models were identified from this market study and are summarized in Table 3. Of the burners listed, a majority are commercially available, and some ULN burners identified are expected to hit the market later this year. Most of the ULN burner manufacturers identified from this study are based in the US, however several European ULN burner manufacturers have slowly begun to enter the California marketplace.

Based on the study conducted and the various conversations with ULN burner manufacturers, most ULN burner developers employ some form of proprietary air fuel premixing technology, and burner head design to achieve desirable emissions and optimize efficiency.

The burners identified in this study can fit a variety of applications with varying BTU ranges, from small boilers and furnaces up to large industrial processes like oil refineries. This study concluded that most ULN burners are easily able to be retrofitted into current heating systems such as boilers and furnaces without having to replace the entire unit. Since most ULN burners are smaller and compact, without the need for expensive add-ons like SCR which occupy additional space, manufacturers claim that operating costs are less compared to older low NOx burners, and size isn't usually concern for retrofits given its smaller size.

Hydrogen fuel is of interest to many burner manufacturers based on a number of conversations taken place throughout the duration of this market study. Hydrogen and natural gas blends ranging from 20-100% have been successfully tested with several burners while still achieving ULN levels.

Finally, a variety of burner manufacturers have cited regulatory challenges, such as the BARCT rule, as a barrier to implementing their ULN technology. The moving NOx target has resulted in a loss of income for some manufacturers at times. Other barriers include brand recognition for those who are newer to the market, in addition to getting permits and local representation which is the case of foreign burner manufacturers.

Recommendations

The next generation ULN burners are ready to be adopted in California. These burners can provide cost benefits to customers across California's investor-owned utility territory because of the newer, more fuel-efficient technologies and lower emissions. Further cost analysis to quantify the benefits of ULN burner retrofits is recommended to further encourage its adoption. It is recommended that energy efficiency programs require ULN technologies going forward.

It is recommended that decision makers such as product representatives and engineers who are responsible for buying combustion equipment to meet process needs are informed of the updated ULN burner offerings so that they may be able to provide up-to-date information and recommendations to their customers.

The study also recommends further testing of hydrogen blends with ULN burners in various retrofit equipment to further demonstrate how newer ULN burners perform in older retrofitted equipment in real-life settings.

Appendix 1.0: Air Quality District NOx Regulations

Appendix 1.1: SCAQMD Rule 1146 NOx Emission Limits [2]

Table 1146-1 – NOx Emission Limits and Compliance Schedule

Rule Reference	Category	Limit[1]	Compliance Schedule for Non-RECLAIM Facilities	Compliance Schedule for RECLAIM and Former RECLAIM Facilities
(c)(1)(A)	All Units Fired on Gaseous Fuels	30 ppm or for natural gas fired units 0.036 lbs/10^6 Btu	September 5, 2008	See Rule 1100 – Implementation Schedule for NOx Facilities
(c)(1)(B)	Any Units Fired on Non-gaseous Fuels	40 ppm	September 5, 2008	
(c)(1)(C)	Any Units Fired on Landfill Gas	25 ppm	January 1, 2015	
(c)(1)(D)	Any Units Fired on Digester Gas	15 ppm	January 1, 2015	
(c)(1)(E)	Atmospheric Units	12 ppm or 0.015 lbs/10^6 Btu	January 1, 2014	
(c)(1)(F)	Group I Units	5 ppm or 0.0062 lbs/10^6 Btu	January 1, 2013	
(c)(1)(G)	Group II Units (Fire-tube boilers with a previous NOx limit less than or equal to 9 ppm and greater than 5 ppm prior to December 7, 2018)	7 ppm or 0.0085 lbs/10^6 Btu	See (c)(6)(A)	
(c)(1)(H)	Group II Units (All others with a previous NOx limit less than or equal to12 ppm and greater than 5 ppm prior to December 7, 2018)	9 ppm or 0.011 lbs/10^6 Btu	January 1, 2014	
(c)(1)(I)	Group II Units (All others)	5 ppm or 0.0062 lbs/10^6 Btu	December 7, 2018	
(c)(1)(J)	Group III Units (Fire-tube boilers, excluding units with a previous NOx limit less than or equal to 12 ppm and greater than 9 ppm prior to December 7, 2018)	7 ppm or 0.0085 lbs/10^6 Btu	December 7, 2018 or See (c)(6)(B) for units with a previous NOx limit less than or equal to 9 ppm prior to December 7, 2018	
(c)(1)(K)	Group III Units (All others)	9 ppm or 0.011 lbs/10^6 Btu	January 1, 2015 or See (c)(7) for units with a previous NOx limit less than or equal to 12 ppm prior to September 5, 2008	
(c)(1)(L)	Thermal Fluid Heaters	12 ppm or 0.015 lbs/10^6 Btu	December 7, 2018 or See (c)(6)(C) for units with a previous NOx limit less than or equal to 20 ppm prior to December 7, 2018 or See (e)(2) for units with a previous NOx limit greater than 20 ppm prior to December 7, 2018	

[1]All parts per million (ppm) emission limits are referenced at 3 percent volume stack gas oxygen (O_2) on a dry basis averaged over a period of 15 consecutive minutes or pounds per million Btu (lbs/10^6 Btu).

Appendix 1.2: SJVAPCD Rule 4306 [3]

Table 1: Tier 1 NOx and CO Limits

Category	Operated on Gaseous Fuel			Operated on Liquid Fuel	
	NOx Limit		CO Limit (ppmv)	NOx Limit	CO Limit (ppmv)
	Standard Option	Enhanced Option			
A. Units with a rated heat input equal to or less than 20.0 MMBtu/hour, except for Categories C, D, E, F, G, H, and I units	15 ppmv or 0.018 lb/MMBtu	9 ppmv or 0.011 lb/MMBtu	400	40 ppmv or 0.052 lb/MMBtu	400
B. Units with a rated heat input greater than 20.0 MMBtu/hour, except for Categories C, D, E, F, G, H, and I units	9 ppmv or 0.011 lb/MMBtu	6 ppmv or 0.007 lb/MMBtu	400	40 ppmv or 0.052 lb/MMBtu	400
C. Oilfield Steam Generators	15 ppmv or 0.018 lb/MMBtu	No option	400	40 ppmv or 0.052 lb/MMBtu	400
D. Refinery units with a rated heat input greater than 5 MMBtu/hr up to 65 MMBtu/hr	30 ppmv or 0.036 lb/MMBtu	No option	400	40 ppmv or 0.052 lb/MMBtu	400
E. Refinery units with a rated heat input greater than 65 MMBtu/hr up to 110 MMBtu/hr	25 ppmv or 0.031 lb/MMBtu	No option	400	40 ppmv or 0.052 lb/MMBtu	400
F. Refinery units with a rated heat input greater than 110 MMBtu/hr	5 ppmv or 0.0062 lb/MMBtu	No option	400	40 ppmv or 0.052 lb/MMBtu	400
G. Load-following units	15 ppmv or 0.018 lb/MMBtu	9 ppmv or 0.011 lb/MMbtu	400	40 ppmv or 0.052 lb/MMBtu	400
H. Units limited by a Permit to Operate to an annual heat input of 9 billion Btu/year to 30 billion Btu/year	30 ppmv or 0.036 lb/MMBtu	No option	400	40 ppmv or 0.052 lb/MMBtu	400
I. Units in which the rated heat input of each burner is less than or equal to 5 MMBtu/hr but the total rated heat input of all the burners in a unit is greater than 5 MMBtu/hr, as specified in the Permit to Operate, and in which the products of combustion do not come in contact with the products of combustion of any other burner.	30 ppmv or 0.036 lb/MMBtu	No option	400	40 ppmv or 0.052 lb/MMBtu	400

Table 2: Tier 2 NOx and CO Limits

Category	Operated on Gaseous Fuel		Operated on Liquid Fuel	
	NOx Limit	CO Limit (ppmv)	NOx Limit	CO Limit (ppmv)
A. Units with a total rated heat input > 5.0 MMBtu/hr to ≤ 20.0 MMBtu/hr, except for Categories C through E unit				
1. Fire Tube Boilers	7 ppmv or 0.0085 lb/MMBtu	400	40 ppmv or 0.052 lb/MMBtu	400
2. Units at Schools	9 ppmv or 0.011 lb/MMBtu	400	40 ppmv or 0.052 lb/MMBtu	400
3. Units fired on Digester Gas	9 ppmv or 0.011 lb/MMBtu	400	40 ppmv or 0.052 lb/MMBtu	400
4. Thermal Fluid Heaters	9 ppmv or 0.011 lb/MMBtu	400	40 ppmv or 0.052 lb/MMBtu	400
5. All other units	9 ppmv or 0.011 lb/MMBtu	400	40 ppmv or 0.052 lb/MMBtu	400
B. Units with a total rated heat input > 20.0 MMBtu/hr, except for Categories C through E units				
1. Fire Tube Boilers with a total rated heat input > 20.0 MMBtu/hour and ≤ 75 MMBtu/hour	7 ppmv or 0.0085 lb/MMBtu	400	40 ppmv or 0.052 lb/MMBtu	400

Appendix 1.2: SJVAPCD Rule 4306 Continued. [3]

Table 2: Tier 2 NOx and CO Limits				
Category	Operated on Gaseous Fuel		Operated on Liquid Fuel	
	NOx Limit	CO Limit (ppmv)	NOx Limit	CO Limit (ppmv)
2. All other units with a total rated heat input > 20.0 MMBtu/hour and ≤ 75 MMBtu/hour	7 ppmv or 0.0085 lb/MMBtu	400	40 ppmv or 0.052 lb/MMBtu	400
3. Units with a rated heat input > 75 MMBtu/hour	5 ppmv or 0.0061 lb/MMBtu	400	40 ppmv or 0.052 lb/MMBtu	400
C. Oilfield Steam Generators				
1. Units with a total rated heat input > 5.0 MMBtu/hr and ≤ 20.0 MMBtu/hr	9 ppmv or 0.011 lb/MMBtu	400	40 ppmv or 0.052 lb/MMBtu	400
2. Units with a total rated heat input > 20.0 MMBtu/hr and ≤ 75.0 MMBtu/hr	9 ppmv or 0.011 lb/MMBtu	400	40 ppmv or 0.052 lb/MMBtu	400
3. Units with a total rated heat input > 75.0 MMBtu/hr	7 ppmv or 0.0085 lb/MMBtu	400	40 ppmv or 0.052 lb/MMBtu	400
4. Units firing on less than 50%, by volume, PUC quality gas	15 ppmv or 0.018 lb/MMBtu	400	40 ppmv or 0.052 lb/MMBtu	400
D. Refinery Units				
1. Boilers with a total rated heat input > 5.0 MMBtu/hr and ≤ 40.0 MMBtu/hr	30 ppmv or 0.036 lb/MMBtu 5 ppmv or 0.0061 lb/MMBtu for replacement units	400	40 ppmv or 0.052 lb/MMBtu	400
2. Boilers with a total rated heat input > 40.0 MMBtu/hr and ≤110 MMBtu/hr	9 ppmv or 0.011 lb/MMBtu 5 ppmv or 0.0061 lb/MMBtu for replacement units	400	40 ppmv or 0.052 lb/MMBtu	400
3. Boilers with a total rated heat input >110 MMBtu/hr	5 ppmv or 0.0061 lb/MMBtu	400	40 ppmv or 0.052 lb/MMBtu	400

Table 2: Tier 2 NOx and CO Limits				
Category	Operated on Gaseous Fuel		Operated on Liquid Fuel	
	NOx Limit	CO Limit (ppmv)	NOx Limit	CO Limit (ppmv)
4. Process Heaters with a total rated heat input > 5.0 MMBtu/hr and ≤ 40.0 MMBtu/hr	30 ppmv or 0.036 lb/MMBtu 9 ppmv or 0.011 lb/MMBtu for replacement units	400	40 ppmv or 0.052 lb/MMBtu	400
5. Process Heaters with a total rated heat input > 40.0 MMBtu/hr and ≤110 MMBtu/hr	15 ppmv or 0.018 lb/MMBtu 9 ppmv or 0.011 lb/MMBtu for replacement units	400	40 ppmv or 0.052 lb/MMBtu	400
6. Process Heaters with a total rated heat input >110 MMBtu/hr	5 ppmv or 0.0061 lb/MMBtu	400	40 ppmv or 0.052 lb/MMBtu	400
E. Units limited by a Permit to Operate to an annual heat input of 9 billion Btu/year to 30 billion Btu/year	30 ppmv or 0.036 lb/MMBtu	400	40 ppmv or 0.052 lb/MMBtu	400

Appendix 2.0: Interview and Site Visit Summaries

Appendix 2.1: Rogue Burner Interview

1. Describe your ULN Burners technology?
    a. Firetube boiler burners
    b. Rogue burner is a burner system supplier, they integrate clear sign burner, sell it and support the burner.
    c. Cleanest boiler burner in industry
2. How do your burners compare to other ULN burners on the market?
3. What are some applications that your burners can be used for?
    a. Firetube boiler applications
4. What are some market challenges preventing the adoption of your ULN burner?
5. Are there any market opportunities for these technologies that you can think of, that don't currently exist?
6. Retrofit applications/new applications that your ULN burners could be used for?
7. Interested in broader product integration?

Specification Data:

Ultra Low NOx Burner Make Details:	Firetube boiler burner
Burner Model:	n/a
Flue Gas Recirculation (FGR) present:	• Traditionally FGR is external to boiler, you would need external blower piping. • However, this will do FGR internally. Pumps FGR lowers flame temperature. • Air Fuel Premixing & internal FGR • Distil flame holder (patented technology of clearsign) moves flame certain distance away
NOx (ppm)	<2.5 ppm
CO (ppm)	<50 ppm
SOx (ppm)	n/a
O2 trim (for boiler/process burners)	n/a
Linkageless control (for boiler/process burners)	n/a
Turndown ratio	5:1
Furnace Pressure Capability	n/a
Fuel type	Natural Gas/Hydrogen

Ultra Low NOx Burner Make Details:	Firetube boiler burner
BTU range	4- 60 MMBtu/hr
Maintenance needs	Low maintenance, no special training
Burner Geometry	ClearSign Core™ technology
Operating cost	low, no costly catalysts, hazardous chemicals, extra ducts or controls
Hydrogen Blending compatibility	n/a

Appendix 2.2: Vitotherm Interview

1. Describe your ULN Burners technology?
    a. Burner company for 60 years making their own product.
    b. Ultra-low NOx, single digits. In a steam boiler. Got lower than 5ppm NOX. HIGH O2 Think that they can go lower, depending on the combination.
    c. The new burner line will be almost ready by the end of 2023.
    d. Supplying those burners 2 mil BTU- 34 mil BTU, higher btu range without FGR.
    e. Greenhouse market
    f. Same mesh, different design, way the air and gas mixes are different, requires
    g. Looking for a partner for selling in the industrial market. Few in British Colombia,
    h. 70 burners in USA and Cananda market.
2. How do your burners compare to other ULN burners on the market? Capable of higher BTU range without FGR, zero CO emissions, suitable for indoor applications like greenhouses.
3. What are some applications that your burners can be used for?
    a. Greenhouse market burner
    b. Dual block type 92 BTU
    c. Steam boilers, hot water, asphalt plants (process burner), dryers, direct fired water heaters.
    d. Enviroflame – is a client, especially design burners and water heaters.
4. What are some market challenges preventing the adoption of your ULN burner?
    a. Hospital once, 25 years ago.
    b. 99% greenhouses
5. Are there any market opportunities for these technologies that you can think of, that don't currently exist?
    a. Three big burners at a greenhouse, having problems with getting permits. NOx is an issue.
    b. They need 5ppm, cannot yet supply that.

    c. Need local representation with good engineers.
6. Retrofit applications/new applications that your ULN burners could be used for?
    a. Need to find something in the system.
7. Interested in broader product integration? N/A

Specification Data:

Ultra Low NOx Burner Make Details:	New burner line releasing end of 2023
Burner Model:	ULN model not yet commercially available
Flue Gas Recirculation (FGR) present:	no
NOx (ppm)	<5 ppm
CO (ppm)	0ppm with <5 ppm NOX
Sox (ppm)	n/a
O2 trim (for boiler/process burners)	n/a
Linkageless control (for boiler/process burners)	n/a
Turndown ratio	n/a
Furnace Pressure Capability	n/a
Fuel type	Natural gas, light fuel oil, light diesel, propane, natural gas with injected biogas
BTU range	2 MBTU-34 MBTU
Maintenance needs	Low maintenance
Burner Geometry	n/a
Operating cost	Similar to competitors
Hydrogen Blending compatibility	5% in holland, looking to upgrade it to 10% in the future. Have tested up to 25% with no effect on the burner. Project in Poland testing up to 100% hydrogen

Appendix 2.3: Power Flame Incorporated Interview

1. Describe your ULN Burners technology? N/A
2. How do your burners compare to other ULN burners on the market?
    a. There are only a handful of burner companies doing sub 5 ppm NOx, you really have to do a lot of leg work up front and it's challenging.
3. What are some applications that your burners can be used for?
    a. Process applications, canning 200 psi, high pressure steam. Works against you from a NOx standpoint
4. What are some market challenges preventing the adoption of your ULN burner?
    a. Engineers are concerned about adding to the NOx with hydrogen, preventing them from being adopted.
    b. Lots of variables work against companies, especially in process operations.
        i. Ex. Canning company wanted to operate at 200psi at high pressure steam. When you do a higher pressure, it takes more heat to create that pressure which works against you from a NOx standpoint as well.
        ii. Laws and Regulations in California don't take all processes into consideration. If they see a boiler running under 5ppm NOx in CA they will just assume that all boilers can do that regardless of the application.
        iii. The NOx limit number seems to be a moving number in CA, putting pressure on manufactures to figure out how to make their jobs work for specific applications. Most burner companies run into this challenge. End up getting stuck on a job and losing money because there is always a new regulation that sets them back which they did not know about.
    c. Large stack, in boiler sometimes it creates more back pressure in the burner.
    d. Economizer – more efficient, goes in stack and captures more heat and then runs it back down to the boiler, but creates more back pressure. Normally burner companies don't ask for economizers unless clients require it, this is usually another variable that makes it difficult for burner developers and manufacturers.
5. Are there any market opportunities for these technologies that you can think of, that don't currently exist?
6. Retrofit applications/new applications that your ULN burners could be used for?
    a. Retrofit boilers all the time. Boiler may see 2-3 burners in its lifetime.
    b. One of the challenges is retrofitting older boilers, boilers that aren't in business anymore or from 24/7 process boilers where you can't open up the boiler to gather information because it would interrupt the client's processes.
    c. Outside the boiler, process heating wide spectrum of hospitals.
    d. NPM burner sub 20 ppm smaller burner.

   e. Furnaces, ovens, bath vaporizers for LNG conversion.
   f. Autoclave ovens.
   g. Anheuser-Busch in Van Nuys California. <9 ppm burner for brewery applications.
   h. Distillery applications.
7. Interested in broader product integration?
   a. Client wants to Reduce NOx- create a design for a special application. I think they are looking to go Sub 20.

List of Burner Specification Data to be gathered:

1. Ultra Low NOx Burner Make Details: 3 types of ULN burners: NP2 Burner, NBC (use matrix head technology), guarantee sub 9 can push to sub 7 depending on application. Cooler the flame the lower the NOx.
   a. Ultra CMax burner (sub 5 with FGR), there is only a certain firing range 250 hp to 850 hp that they have proven technology, you can do oil backup (hospital).
2. Burner Model: NP2.
3. Flue Gas Recirculation (FGR) present: No FGR.
4. NOx (ppm): 9-20 ppm, sub 5 with UCM burner
5. CO (ppm)
6. SOx (ppm)
7. O2 trim (for boiler/process burners):
   a. Oxygen trim control system will correct the airflow so that the combustion efficiency remains as high as possible.
   b. Oxygen trim systems can improve the efficiency of a boiler by 1-2%.
   c. For best excess air control, a digital monitoring control system called O2 trim system can be installed on a boiler (PDF) Energy Savings and Emission Reductions in Industrial Boilers (researchgate.net).
8. Linkageless control (for boiler/process burners): Present
   a. Linkageless control systems on boilers and other industrial burners can reduce energy consumption and harmful emissions and assure better combustion.
   b. PowerFlame offers a variety of linkageless systems designed to control the air and fuel ratio of the burner more closely than a conventional linkage type system. Individually driven servos ensure the fuel and air are mixed more precisely over the entire operating range of the burner thus reducing the excess oxygen required to achieve complete combustion. Lower excess oxygen levels result in more efficient combustion and a significant reduction in fuel costs. Linkageless Control | Boiler Burners | Power Flame

   c. The burner shown above is fitted with the Honeywell ControLinks system designed to operate the air in parallel with the fuel. As a dual fuel system, you can program separate fuel/air ratio curves for the gaseous and liquid fuels. This burner is also designed to reduce NOx emissions by inducing a small amount of flue gas to limit the peak flame temperatures. The ControLinks system includes a separate servo to control the induced FGR in conjunction with the air and fuel. These programmable features are common with similar systems manufactured by Fireye, Auto Flame and Siemens. PowerFlame offers all of these systems on a majority of our burners.

9. Turndown Ratio: Ultra CMAX (10:1 on gas, and 8:1 on air atomized oil)
10. Furnace Pressure Capability (for boilers/process burners)
11. Fuel type (premixed, hydrogen, etc.): owned by Aztec, they fired around 23-30% on their test, working with UL, UL verified gas train, they are writing a standard.
12. BTU range: 400,000 – 8,600,000 BTU/HR
13. Maintenance needs
    a. Average maintenance needs
14. Burner Geometry
    a. The older burner technology was a lot smaller, burners have actually gotten bigger because of the blow out motor, fan, they have gotten a lot longer over the years and stick out, so from a retrofit standpoint need to be careful since 3-4 feet of clearance are needed from the end of the burner to the wall.
15. Operating Cost
    a. Pretty comparable to the market
    b. UCM is more popular since the Sub-5 and Mesh head is a little older technology (~20 years).
    c. Mesh head is a replicable part they can plug up sometimes and needs replacement.
    d. Clearsign can do sub 2.5 NOx only situations and have fired this burner in approx. 1-2 real world settings situations. (a little different burner design), a bit more expensive that power flame burners
    e. Lower NOx than the more expensive burners across the market.
16. Hydrogen blend % compatibility (if any)
    a. Owned by ASTEC, so Heat tech heaters are the sister company. They had a joint project where they tested up to 30% Hydrogen. Worked with UL. Right now, they have a UL verified gas train, not yet approved because UL does not have a standard set up to test It. They are currently working on the standard and once that is complete the burner will be hydrogen approved according to UL's gas fired standard.

Appendix 2.4: LBNL Interview

A brief description of ULN burner technology:

Ring stabilizer

Low-swirl burner:

- Has a CEC project with the Low Swirl Burner, looking at real time fuel flexing between biogas and natural gas in a wastewater treatment plant for boiler. Also has a hydrogen capability between 0-100% hydrogen and still maintain single digit NOx numbers.
- Commercialized in the Maxon/Honeywell boilers, just not widely spread, the focus is just on boilers. However, this technology does have a lot of commercial applications such as outdoor radiant heaters, on demand water heaters.
- Integrated this burner into a central furnace, and proved it, but is not commercially available.

What are some applications that your burners can be used for?

- Residential heating
- Process heating
- Gas Turbines
- Boilers
- Hot water and steam generation

What are some market challenges/barriers preventing the adoption of your ULN burner?

- The ring burner is not yet optimized; it has great potential but is not yet market ready.
- Many people are moving away from burners.
- COVID paused/stopped many projects they had with customers.
- Benefit: A positive/reason some people buy these burners is that they think they look beautiful
- LBNL has other low NOx combustion technologies for on demand water heaters, never found an industrial partner to integrate that in. Could also be used for boilers.

Are there any market opportunities for these technologies that don't currently exist?

- These burners are highly scalable and can be used for Industrial process heating.

Any Retrofit applications/new applications that your ULN burners could be used for?

- These burners cannot be used for any retrofit applications. They would have to be optimized.

NOx, SOx, CO information if known:

- NOx ppm are in the single digits (they did not specify the value, look at papers)

BTU range

- Ring burner: Tested and scalable depending on the application.
- Low-Swirl Burner: Millions of BTUs (Highly scalable)
- Fuel Type
- Both burner types are fuel flexible (can use anything)

Energy Efficiency

- Energy efficiency comes directly from how well the flame is transferring heat. For the ring burner, the reason it increased efficiency for cooking is because it decreased boiling time by like 25%. The way the flames are designed is flat, so there is a lot of contact of heat between the flame and the pan in addition to evenly distributing it. The heat is being transferred to the pot, vs standard cooktop heat is transferred around the center of the pan and a lot of the heat is lost in the kitchen.
- If the shape of the flame can have better contact with the thing you are trying to heat up, optimizes EE.

Appendix 2.5: Clearsign Burner Interview

1. Describe your ULN Burners technology?
   a. Clearsign is an R&D company that develops burners for most generic commercial and industrial markets.
   b. Beta Version Duplex Technology now called Clearsign Core technology.
   c. No catalyst or chemicals
   d. More efficient
   e. Three different products (1. Process burner using refinery fuels, varying fuel compositions, up to 80% hydrogen, partner with Zeeco Inc. They are clearsign's subcontractor, it is exclusive for the process burner. They can't sell you a clear sign burner. Sold exclusively through clearsign. 2. Boiler- Firetube and boiler burner-, haven't even come close to optimizing. Rogue Burners is the exclusive partner in the US for selling clearsign boiler burner. California boiler is the exclusive installer in CA, OR, Nevada. 3. Flare burner, niche product. There are not many places that require ultra-low NOx flares. Reason for that is Most flares are a stick flare which means that you have a pipe full of fuel and at the tip of the pipe you have a burner and the flame is exposed at the top of the burner. With a stick flare, there is no stack to contain flue gases so no way to measure the NOx. Some states like Ca, Colorado, have determined that for any application that is feasible they want to have an enclosed flare. Enclosed flare is a much bigger diameter stack and the flame is inside the stack so there is no visible flame. So, now you have a stack so you can put in an instrument and need NOx measurements and put ULN requirements for flares. California today is the only state that has a requirement for enclosed flares with a ULN capability and clear sign has supplied: (11 projects in CA) SC. 11.18.1 - <15 ppm NOx for oil production facilities, clearsign have supplied 4 flares in that region. Regulation SJV 43.11 mirrored 11.18.1 (7 projects in central valley, all retrofits, took out the original enclosed flare burner and put the clearsign product in.) Can do well head gas, below 15 ppm now, very high 99% destruction efficiency, compared to 95% destruction efficiency for most flare burners, which is ratio of CO_2 to other carbon species in flue gas).
   f. Air Fuel Pre Mixing and Internal FGR
   g. Patented Distil flame holder: [US Patent Application for BURNER SYSTEM INCLUDING A DISTAL FLAME HOLDER AND A NON-REACTIVE FLUID SOURCE Patent Application (Application #20210190310 issued June 24, 2021) - Justia Patents Search]
   h. Only company that has unique combination of those 3 combustion elements in a fuel burner- They call that the clear sign Core technology.

2. How do your burners compare to other ULN burners on the market?
    a. Developed specifically for ULN intentions.
    b. Design of burner is not like any other, operates more like a turban than a burner.
    c. High velocity
    d. Purposely designed to be ultra-low NOX, unlike some burner companies who take a regular burner and tweak it until it becomes lower NOx.
3. What are some applications that your burners can be used for?
    a. Steam generators
    b. Process burner used in two styles: (two specific styles of process heaters, vertical cylindrical or canned heaters, and also cabin heaters.) All applications to date have the burners mounted in the floor and firing upwards.
    c. In the future, would like to consider expanding the capability to other process heaters, such as the furnaces which include delayed cokers.
        i. California local crude oil is very heavy and refinery economics are benefited by having a delayed coking processing unit to deal with heavy crude. That requires a special kind of heater.
        ii. Looking to Develop test and install a delayed coker heater burner. Those burners are also typically mounted in the floor, but they fire against the wall. Behave differently than a burner mounted in the floor.
        iii. Theoretical design but not fabricated a prototype yet.
        iv. Approx. 20 such heaters in Los Angeles and a few in the bay area.
        v. Steam Methane Reformer heater. Many different physical designs, interested in developing a small upfire burner for a vertical cylindrical canned style heater.
        vi. Ethylene furnaces – very challenging due to high temperature. Would have to find alternate burners to construct the burners out of.
    d. Boiler burners- potential application is water tube boiler still testing, a bit larger in size. A little bit different ratio, need to shorten burner and increase heat release beyond what we have demonstrated to work in watertube boiler market. But that would be the next steps for the boiler burner product Right now sized for 90% of firetube boilers.
    e. Flare- digestor gas, landfill gas, development of thermal oxidizers, vapor combustors, wastewater treatment plant.
    f. Closed combustion.
    g. Blade Coker Heater (oil refinery) - 16 to 40 burners in each heater, interested in developing the product for.

4. What are some market challenges preventing the adoption of your ULN burner?
    a. Barrier is more control over the gas pressure for higher velocity applications.
    b. They want to run the burner at 5 psi so they need gas at 10psi supply from the utilities especially with hydrogen, which they do not have. For clear sign specifically, clear sign burner does need a bit of fuel pressure. Commercial scale facility- may have lower gas facility, industrial not a big problem.
    c. Most challenge: any type of regulatory compliance project has very little return on investment for the operator of the facility. It is a compliance cost with no payback, do this and stay in business or get major fines and threaten to get shut down.
    d. Clear sign has some ROI – process burner has operability advantages, boiler burner more efficient than other boiler burners on the market.
    e. Brand recognition and recognition.
5. Are there any market opportunities for these technologies that you can think of, that don't currently exist?
6. Retrofit applications/new applications that your ULN burners could be used for?
    a. All of their burners are retrofits, boiler retrofit.
    b. Also looking at ethylene and coker heater applications, want to test higher temperature applications and achieve low NOx.
7. Want to know more about energy efficiency. What makes the product more efficient. Any test data that you can share?
    a. Thermal efficiency – need less fuel to demonstrate the same amount of steam.
    b. Operational efficiency
    c. Energy efficiency- generally any technique used by a burner manufacturer to make lower NOx, "at what NOx".
        i. Often times, efficiency is out of control of burner. It could be the boiler itself, surface area, water preheater.
        ii. Any efficiency comparison needs to be on the same playing field.
        iii. Industry uses a couple of rules of thumbs for efficiency comparisons for burners – one is the operating O2 level. 5%o2 vs 3% o2 in the same boiler to hit the same NOx, the burner operating at 3%o2 is more efficient.
        iv. Every 1-1.5% extra O2, the burner will be 1% less efficient.
        v. External FGR, can be measured in % percentage- 1% less efficient.
        vi. "Clearsign product is more efficient than other burners at the same NOx level" (1-3% on the boiler burner)
        vii. Efficiency on process burner is less efficient.

Ultra Low NOx Burner Make Details:	Process burner, boiler burner, flares
Burner Model:	ClearSign Core™
Flue Gas Recirculation (FGR) present:	yes
NOx (ppm)	<2.5 ppm
CO (ppm)	<50 ppm, <15 ppm for flare
Sox (ppm)	n/a
O2 trim (for boiler/process burners)	n/a
Linkageless control (for boiler/process burners)	n/a
Turndown ratio	Up to 5:1
Furnace Pressure Capability	n/a
Fuel type	100% premixed fuel, don't use flame shape to control the NOX, H2 burns faster than hydrocarbons and flame shape can compromise the NOx
BTU range	Up to 200 million Btu
Maintenance needs	Low maintenance
Burner Geometry	Furnace geometry challenges: • Certain challenges, working on refining product • Optimize burner length, often times don't always have the room for length especially with watertube boiler • Lower excess O2 and get same NOx
Operating cost	• No running cost, mesh clogs up overtime in burner, replacement is expensive, however don't have mesh in clearsign burners • The tips are away from the flame so it doesn't get clogged up, even with refinery and digestor gas which can clog up the burner.
Hydrogen Blending compatibility	80%

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