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IMPLICATIONS OF NATURAL GAS INTERCHANGEABILITY FOR CALIFORNIA CUSTOMERS

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PREFACE

The California Energy Commission Energy Research and Development Division supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

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Implications of Natural Gas Interchangeability for California Customers is the summary final report for the Implications of Natural Gas Interchangeability for California Customers project (CEC-500-05-026) conducted by Gas Technology Institute and Lawrence Berkeley National Laboratory. The information from this project contributes to Energy Research and Development Division's Energy-Related Environmental Research Program.

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ABSTRACT

This study provided guidance on fuel interchangeability and the potential environmental impacts – with a focus on emissions and exposures to air pollutants – of increased variability in California's natural gas supply, specifically related to the use of imported liquefied natural gas.

Industrial and commercial burners were examined with their combustion control systems, commercial foodservice equipment, and residential furnaces, water heaters, and cooking burners. Air quality and exposure impacts were evaluated for outdoor and indoor air. Interchangeability considerations included performance and safety, in addition to the environmental impacts of liquefied natural gas and other substitute gases relative to traditional natural gas formulations.

Laboratory and field tests identified classes of industrial burners most sensitive to changes in natural gas composition. Various gas compositions that provided acceptable interchangeability for specific burners were identified, and protocols were developed to adapt them to a wider range of natural gas compositions. Adjustments that allow substituting different gas compositions for industrial burners were found to vary from none to numerous adjustments in operating and control protocols.

Appliance tests in the laboratory and in homes measured performance and emissions of various gas compositions and all appliances and industrial burners operated safely over the range of natural gas compositions tested. Appliance impacts on indoor air quality were measured and modeled. Impacts to outdoor air quality were modeled based on potential changes to emissions. Commercial cooking appliances were tested in the laboratory, and divided into those requiring no, minor, or significant adjustments to address interchangeability with varying gas compositions. The performance of multiple range hoods was measured, with performance found to vary significantly.

Keywords: interchangeability, natural gas, LNG, industrial burners, appliances, air quality, emissions

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EXECUTIVE SUMMARY

Introduction

Natural gas consumption in California and the United States is anticipated to rise, largely from growth in gas-based power generation and transportation. Growing natural gas demand will be partly met with new gas supplies including unconventional gas, gas from renewable sources, and liquified natural gas (LNG). These new gas supplies provide challenges in processing, delivery, and interchangeability. Natural gas interchangeability is defined by the NGC+ Interchability Work Group as "the ability to substitute one gaseous fuel for another gaseous fuel in a combustion application without materially changing operational safety or performance and without materially increasing air pollutant emissions."

The varying compositions of LNG relative to traditional gas raise questions regarding fuel gas interchangeability. Variations in composition and heating value must be defined so that performance and emissions of end-use equipment are not significantly affected. Project work focused on the interchangeability of Pacific Basin LNGs with domestic natural gas; however, projections to import LNG into California have dropped significantly since the start of the project. Project results remain relevant because the compositions of other new gas supplies, such as shale gas and gas from renewable sources, also differ from traditional natural gas compositions. The effects of these other gas supplies on interchangeability can be determined from the project results as long as the gas composition of those new supplies are within the ranges evaluated for LNGs.

To address anticipated natural gas interchangeability issues in California, the project team conducted a comprehensive, multi-year project that included laboratory and field investigations of the performance of industrial burners, home appliances, and commercial foodservice equipment with changing natural gas composition. The ability of range hoods to remove air pollutants from residential cook tops was also evaluated. Other work included determining interchangeability impacts on indoor and outdoor air quality and developing protocols to address interchangeability issues for industrial burners. This work has been presented in a series of reports on various aspects of interchangeability. This Summary Final Report is a compilation of key findings presented in preceding reports.

Purpose and Objectives

The overall goal of this study effort was to provide guidance on interchangeability and potential environmental impacts – with a focus on emissions and exposures to air pollutants – from the potential variability in California's natural gas supply, specifically from using imported LNG. The study examined classes of industrial and commercial burners along with their combustion control systems, residential appliances, range hoods, and commercial foodservice equipment. Air quality and exposure impacts were evaluated for indoor and outdoor air. Interchangeability considerations included performance safety, and environmental impacts of LNG and other substitute gases, relative to traditional natural gas formulations. Substitute gases are any fuel gas such as natural gas, regassified LNG or alternative fuel gas that is delivered to end users as a replacement, or 'substitute' for a common or historic fuel gas such as natural gas. Testing

identified the impacts of gas composition changes on operation of combustion systems and emissions generated while operating. Results can be used to develop optimization protocols that serve as guides when gas composition changes occur. Results can also inform system operators and regulators regarding the impacts of changing gas composition on overall emissions while providing information on which combustion systems are most sensitive to changes in gas composition. This interchangeability information will provide means to operate the most flexible and safest natural gas system with the widest gas supply options for California customers.

Background

Natural gas is a mixture of methane with a number of other gases. Under common market practice, natural gas composition is held relatively constant, with variations in the gas heating value and Wobbe number limited to less than two percent. Wobbe number is commonly used as a measure of combustion system performance and is considered the best, yet incomplete, index for determining interchangeability. Wobbe number is defined as the gas heating value divided by the square root of specific gravity. Two fuel gas mixtures with the same Wobbe number may have different heating values and specific gravities but will deliver the same heat flux through an orifice (as in a burner nozzle).

Industrial combustion equipment (burners, boilers, engines, turbines, and related devices) is designed and tuned to provide peak efficiency and minimum carbon monoxide (CO) and nitrogen oxides (NOx) emissions when operated with the locally available natural gas. Home appliances and foodservice equipment are designed to be sold into a broad national market. In some locations, non-traditional gas supplies such as LNG are being introduced into the market, leading to a wider natural gas composition range at the burner tip. California is a large state that produces and imports natural gas. Traditionally, California regions have seen a consistent but fairly large range of natural gas compositions. Introducing non-traditional gas supplies, could cause some regions of California to see wider ranges of gas composition.

Measuring and evaluating impacts on burner performance and emissions from different compositions of natural gas is known as interchangeability. An interchangeability analysis has two broad goals. The first determines if the expanded gas composition presents any operational or safety problems (such as poor ignition, overheating, and undesirable flame shape). The second examines the change in air pollutant emissions with increasing changes in the gas composition. Comparisons are made between emissions when firing a range of gases and a baseline gas. Interchangeability emission analyses are comparisons expressed in either relative or absolute values.

Methodology

This study examined the interchangeability of LNG for a variety of natural gas burners common in California and evaluated the outdoor and residential indoor air quality impacts of changes to air pollutant emissions. The most sensitive industrial combustion systems were laboratory tested with a wide range of gas compositions, and three industrial burners were tested in place during plant operation. A group of the most common commercial foodservice equipment was tested in the laboratory using a wide range of gas compositions. Residential appliances were

tested in the laboratory and as installed in homes. The impact of fuel composition was studied using simulation modeling of combustion for a typical residential burner. Residential indoor and regional outdoor air quality impacts were studied with simulation models of these environments, using the emissions determined from experiments, the literature and emissions inventories. And the potential of range hoods to mitigate residential air quality impacts was assessed by studying in-situ performance of a variety of hoods installed in homes.

Testing of industrial and commercial burners including commercial foodservice equipment was completed using three baseline gases representing the current range of California natural gases. Two substitute gases with high Wobbe numbers were defined as representative Pacific Basin LNGs. Both substitute gases were diluted with nitrogen to create gases with lower Wobbe numbers covering the range all the way down to the lowest Wobbe baseline gas. Residential appliances and indoor and outdoor air quality modeling examined the impacts of one or more substitute gases in relation to natural gas with a Wobbe number of 1335, which was representative of fuels distributed throughout Southern and Northern California at the time of this study. Although the California Rule 30 includes a limit of 1385 Wobbe, testing and modeling was carried out with gases having Wobbe values up to 1425. Experiments and analyses were completed with gases exceeding 1385 so trends could be better understood.

Conclusions and Recommendations

Conclusions and recommendations from the project's studies are summarized.

Industrial Burners

Interchangeability tests were carried out in the laboratory with seven industrial combustion systems and as many as 13 gas compositions ranging from 1310 to 1425 Wobbe. Two combustion systems were operated in industrial settings in California over ten gas compositions ranging from 1310 to 1385 Wobbe. Blending station limitations prevented all compositions from being tested with all burners. The specific gas compositions tested with each burner are listed in the detailed testing results for each burner.

This study examined the industrial burner types of most concern regarding interchangeability. Scope limitations prevented evaluating all common burner types or the study of burners produced by different manufacturers using different burner geometries. Although incomplete, this study was broad enough that general conclusions can be drawn for industrial burners operating on a range of natural gas of 1310 to 1425 Wobbe:

- No industrial burners were found to have ignition or light-off issues. The project team believes this conclusion can be extended to industrial burners not tested in this program.
- Industrial burners can be operated over the full gas composition range with no operational or safety concerns.
- The CO and NOx emissions from industrial burners varied differently with changing gas composition for different burners.

- For all burners, the relationship between CO and Wobbe Number depended on excess air level (where incomplete combustion produces excessive levels of CO) and on tuning burners to different adjust gases. Adjust gases are fuel gases such as natural gas in common and historic use that have been used to tune and 'adjust' burners to optimum performance by equipment manufacturers.
- NOx emissions varied widely among burners and burner tunings to different adjust gases. NOx varied from 2 to 180 ppm when adjusted to 3 percent excess air (excluding the oxygen burner where concentrations are on a different scale).
- Operating protocols can be established for all industrial burners to minimize any increases in CO and NOx with changing gas composition. In most cases, emissions can be kept to the same level experienced when the burner was operated with conventional natural gas.
- Some industrial burners require no operational changes.
- Some industrial burners can be tuned to operate with no increases in emissions when fired with LNGs.
- Some industrial burners can be operated with no increase in emissions with LNGs by defining an operational and tuning protocol based on gas composition.

Recommendations

- Identify locations where gas composition changes are expected and develop protocols to communicate with industrial burner operators how best to optimize industrial burner performance and minimize emissions. Emphasis could target facilities that operate burners with major concerns about emissions interchangeability.
- Use project's test results to address specific operating goals. Industrial burners are generally operated with integrated control systems and can be tuned in the field. Recommended adjustments can be made by operators on site or by manufacturer service technicians
- Devise and evaluate a simple emissions monitoring test to screen industrial burners. In this test, the burner could be operated with an adjust gas and a substitute gas with the highest anticipated Wobbe number (such as the Rule 30 limit of 1385 Wobbe). Evaluation would include CO and NOx emissions levels with both gas compositions. Burner adjustments could be listed that are designed to prevent unwanted emissions increases with higher Wobbe gas.
- Release a list of burners with no interchangeability concerns, and extend the list with future evaluations. This list would encourage operators and regulators to focus on burners with specific interchangeability concerns.
- Prepare properly designed and practiced protocols that allow some burners to produce lower emissions than when tuned to a single gas composition.

- Optimize performance, efficiency, and emissions of industrial burners by encouraging proper, routine tuning.

Commercial Foodservice Equipment

Interchangeability tests were performed with ten commercial foodservice equipment over 11 gas compositions ranging from 1310 to 1425 Wobbe (3 adjust gases, 2 substitute gases, and each substitute gas diluted with nitrogen to Wobben 1385 and the Wobbe of adjust gas 1 and adust gas 2). These appliance types represented the largest consumption of natural gas for commercial cooking and the most common appliance brands used in California.

Studies did not attempt to provide a comprehensive evaluation of all types of cooking equipment, burner types, or brands, but were broad enough that the following general conclusions and recommendations for future actions can be made:

- No foodservice equipment was found to have ignition or light-off issues over the range of 1310 to 1425 Wobbe. The project team believes this conclusion can be extended to appliances not tested in this program.
- Some appliances exceeded their nameplate firing capacity when fired with high Wobbe gas. Appliances that are expected to operate with high Wobbe gas for extended periods of time should be replaced or modified by trained technicians.
- Some appliances show small increases in CO, NOx, or both when natural gas is switched from a lower Wobbe number supply to a higher Wobbe number supply. Many of the foodservice equipment cannot be adjusted in the field.
- Some appliances show large increases, particularly in CO, when substitute gas with a high Wobbe number is fired. These appliances are typically operated with low excess air. This is the small group of foodservice equipment that should receive the most attention because they are of the most concern from an interchangeability perspective.
- One group of appliances that was identified as needing attention are those with changes in flame shape and surface impingement leading to increased CO emissions when higher Wobbe gas is substituted for other natural gas supplies. These appliances, particularly ovens, should be modified by manufacturers when the equipment is located where natural gas with a wide range of Wobbe values is anticipated.

Residential Appliances

The effect of LNG on pollutant emissions was evaluated experimentally with used and new appliances in the laboratory and with appliances installed in residences, targeting information gaps from previous studies. Burner selection targeted available technologies that are projected to comprise the majority of installed appliances over the next decade. Experiments were conducted on 13 cooktop sets, 12 ovens, five broiler burners, five storage water heaters, four forced air furnaces, one wall furnace, and six tankless water heaters. Measurements of pollutant concentrations, carbon dioxide, and oxygen levels in exhaust streams were used to calculate air-free concentrations. Fuel properties were also used to calculate emission factors related to fuel

energy consumption (for example, in units of nanogram of pollutant emitted per Joule of fuel energy).

Results were obtained for CO, NOx, nitric oxide, nitrogen dioxide (NO_2), and the number of particles over individual burns, and for formaldehyde over multi-burn cycles. Size-resolved measurements (counting particles in discrete size ranges) showed the majority of particles were less than 100 nanometers in aerodynamic diameter; that is, they were ultrafine particles. The baseline fuel was Northern California line gas with Wobbe number of 1320–1340; test fuels had Wobbe numbers of about 1390 and 1420, with some at 1360.

No ignition or operational problems were observed during test fuel use. Baseline emissions varied widely across and within burner groups and with burner operational mode. Statistically significant emissions changes were observed for some pollutants on some burners.

Pollutant emissions varied widely across and within burner groups. Baseline emissions of CO, NOx, NO_2, and particle number varied with operating mode for oven-bottom and tankless water heater burners. In many cases, the number of particles emitted was observed to be elevated in the first and sometimes the second experiment of the day.

Bivariate (assuming one variable depends on only one other variable) and multivariate (assuming one variable depends on multiple other variables) linear models were used to estimate the magnitude and statistical significance of fuel Wobbe number effects on emission rates independent of these factors. Formal statistical analyses were conducted to estimate the effect of fuel Wobbe number on each pollutant emission factor. The dependence of emissions on fuel Wobbe number was assumed to be linear and was calculated per 50 Wobbe number increase. These results can be scaled to estimate impacts for any level of Wobbe number increase up to the bounds of the experimental assessment; that is, to fuels with a Wobbe number of roughly 1420.

Among cooking burners with substantial baseline CO emissions (taken here as ≥ 100 nanograms per Joule), almost all had CO increase at rates of 5–40 percent per 50 Wobbe number fuel change. An increment of 50 Wobbe number increase represents the shift from fuels currently distributed in much of Northern and Southern California (with typical Wobbe number of roughly 1335) to the current regulated limit of 1385. For cooking burners having substantial baseline NO_2 emissions (taken here as ≥ 5 nanograms per Joule), roughly half had NO_2 emissions increase; the increase was in most cases on the order of 20 percent or less for a 50 Wobbe number increase in fuel. Only one of the cooking burners with the highest emissions of formaldehyde (≥ 1 nanograms per Joule) had emissions increase with fuel Wobbe number. Particle number emission rates from cooking burners varied much more with operating conditions (including recent use history) than with fuel Wobbe number.

Among the vented burners, primary pollutant emissions from tankless water heaters appear to be the most sensitive to fuel Wobbe number. Two of the six tankless water heaters – including the one with highest baseline CO – had CO increase by about 110 percent, and a third had CO increase by 22 percent per 50 Wobbe number fuel increase. Nitrogen dioxide was found to increase by 3–19 percent per 50 Wobbe number increase in five of six tankless water heaters and

decrease by 3 percent in the sixth. Formaldehyde was estimated to decrease by 5–22 percent for a 50 Wobbe number change in five of six tankless water heaters. Two of the four central furnaces had CO emissions decrease by 26 percent for a 50 Wobbe number fuel increase.

As a complement to the experimental evaluation, the project team conducted a computer modeling study of a partially premixed flame issuing from a single cooktop burner port. The model consisted of a reactive computational fluid dynamics three-dimensional spatial grid and a 71-species chemical mechanism with propane combustion capability. Simulations were conducted with a simplified fuel mixture containing methane, ethane, and propane in proportions that yield properties similar to fuels distributed throughout much of California now and in recent years (baseline fuel), as well as with two variations of simulated LNG blends. A variety of simulations were conducted with baseline fuel to explore the effect of several key parameters on pollutant formation and other flame characteristics. Simulations started with fuel and air issuing through the burner port, igniting, and continuing until the flame was steady with time. Conditions at this point were analyzed to understand fuel, secondary air and reaction product flows, regions of pollutant formation, and exhaust concentrations of CO, nitric oxide, and formaldehyde.

A sensitivity study was conducted, varying the inflow parameters of this baseline gas centered around real-world operating conditions. Flame properties responded as expected from reactive flow theory. In the simulation, CO levels were influenced more by the mixture's inflow velocity than by the gas-to-air ratio in the mixture issuing from the inflow port.

Additional simulations were executed at two inflow conditions – high heat release and medium heat release – to examine the impact of replacing the baseline gas with two mixtures representative of liquefied natural gas. Flame properties and pollutant generation rates were very similar among the three fuel mixtures.

Details about the experimental study of interchangeability for residential appliances are provided in Singer et al. 2009 report (CEC-500-2009-099). Details about the combustion modeling study are provided in the Tonse and Singer 2011 report cited in Appendix E.

Residential Indoor Air Quality

Using LNG for residential cooking burners can increase air pollutant emission rates relative to operation with conventional natural gas blends distributed in California. This study quantified the impacts of using LNG on pollutant concentrations and exposures in California homes. A physics-based mass balance model was applied to calculate time-dependent concentrations of CO, NO_2, and formaldehyde resulting from cooking burner use in homes. The model simulated pollutant emissions from cooking, pollutant entry from outdoors, dilution throughout the home, removal by ventilation, and other processes that affect exposure for one week each in summer and winter for a representative sample of homes in Southern California. Residence characteristics – including building age; floor area; number of children, adults, and seniors; and cooking frequency – were obtained from the 2003 Residential Appliance Saturation Survey database. Ventilation rates, occupancy patterns, and the extent of burner use per meal were inferred from household characteristics. The researchers measured emission factors for natural

gas and LNG in controlled experiments. The model tracked pollutant emissions from cooking burners, entry of CO and NO_2 from outdoors, indoor dilution, removal by surface deposition (NO_2 only), and removal by ventilation. Impacts were quantified per 1,000 homes, to allow scaling to any LNG distribution.

Model results indicate that cooking with conventional natural gas and without regular use of a kitchen exhaust fan can cause pollutant concentrations in homes that exceed health-based standards. For winter conditions in homes that cook with gas and do not use exhaust, the model estimates that 40—45 percent of residents are exposed to NO_2 at levels exceeding the federal 1-hour outdoor standard, 4—6 percent are exposed to CO in excess of the 8-hour outdoor standard, and 20—25 percent exceed the federal guideline level for acute formaldehyde exposure. With LNG, these rates increase by about 3.5 percent for NO_2, 1 percent for CO, and 1—2 percent for formaldehyde.

The installed performance of cooking exhaust fans was evaluated through residential field experiments conducted on a sample of 15 devices varying in design and other characteristics. The sample included 2 rear downdraft systems, 2 under-cabinet microwave over range units, 3 different installations of an under-cabinet model with grease screens across the bottom and no capture hood, 2 devices with grease screens covering the bottom of a large capture hood (1 under-cabinet, 1 wall-mount chimney), 4 under-cabinet open hoods, and 2 open hoods with chimney mounts over islands. Performance assessment included measurement of airflow and sound levels across fan settings and experiments to quantify the contemporaneous capture efficiency for the exhaust generated by natural gas cooking burners. Capture efficiency is defined as the fraction of generated pollutants that are removed through the exhaust and thus not available for inhalation of household occupants. Capture efficiency was assessed for various configurations of burner use (e.g., single front, single back, combination of 1 front and 1 back, oven) and fan speed setting. Measured airflow rates were substantially lower than the levels noted in product literature for many of the units. This shortfall was observed for several units costing more than $1,000. Capture efficiency varied widely (from < 5 percent to roughly 100 percent) across devices and across conditions for some devices. As expected, higher capture efficiencies were achieved with higher fan settings and the associated higher air flow rates. In most cases, capture efficiencies were substantially higher for rear burners than for front burners. The best and most consistent performance was observed for open hoods that covered all cooktop burners and operated at higher airflow rates. The lowest capture efficiencies were measured when a front burner was used with a rear backdraft system or with lowest fan setting for above-the-range systems that do not cover the front burners. Overall, these results indicate that range hoods have the potential to serve as an effective mitigation for gas quality related increases in pollutant emissions from natural gas cooking burners.

Outdoor Air Quality in the South Coast Air Basin

The effects of LNG on pollutant emission inventories and air quality in California's South Coast Air Basin were evaluated using the emission impact measurements from the previously described experiments on industrial, commercial, and residential gas burners together with a state-of-the-art regional photochemical air quality model applied to the South Coast Air Basin.

The analysis used LNG distribution scenarios developed by modeling Southern California gas flows, including supplies from the LNG receiving terminal in Baja California, Mexico. Based on these scenarios, the projected penetration of LNG in the South Coast Air Basin was expected to be limited. In addition, the increased Wobbe index of delivered gas (resulting from mixtures of LNG and conventional gas supplies) was expected to cause less than 0.05 percent increase in overall (area-wide) NOx emissions. Based on the photochemical state of the South Coast Air Basin, any increase in NOx is expected to cause an increase in the highest local ozone concentrations, and this was reflected in model results. However, the magnitude of the increase was well below the generally accepted accuracy of the model and would not be discernible with the existing monitoring network. Modeling hypothetical scenarios indicated that discernible changes to ambient ozone and particulate matter concentrations would occur only at LNG distribution rates that are not achievable with current or planned infrastructure, and with Wobbe index values that exceed current gas quality tariffs. Results of these hypothetical scenarios are presented for consideration of any proposed substantial expansion of LNG supply infrastructure in Southern California.

Details about the ambient air quality modeling study are provided in the Sospedra et al. 2011 report cited in Appendix C (CEC-500-2011-041).

Limitations

Additional interchangeability (including emissions of air pollutants) studies of a number of end-use areas are still needed. Power systems need more studies. This work needs to be carried out with full-scale turbines and in cooperation with turbine makers and their engineering teams. Engines have been studied for performance and knock, but this data must be reviewed and supplemented to thoroughly understand interchangeability limits for engines. Non-combustion uses of natural gas are dependent on specific compositions, and users must be surveyed to learn the acceptable composition limits for their processes.

Benefits

This interchangeability information provides ways to operate the most flexible and safest NG system with the widest gas supply options for California customers. The research addressed the likelihood of greater fuel diversity in California by evaluating the safety and air quality implications of using LNG. This program also improves information on potential indoor and regional air quality impacts and safety and operability implications from burning more natural gas and LNG in California. These results help guide actions to reduce or eliminate potential negative impacts, and help increase awareness of potential health and safety risks and identify appropriate measures for reducing those risks. This knowledge is useful for determining compatibility, or interchangeability, of natural gas and LNG with existing combustion systems. Information developed will be helpful in developing guidelines, regulations, and designing natural gas devices to ensure that new natural gas supplies can be used in California in a safe, energy efficient, and environmentally sound manner benefitting ratepayers while allowing for a wider range of gas formulations. This information will also be useful for developing operational guidelines.

CHAPTER 1: Introduction

The Gas Technology Institute (GTI) and Lawrence Berkeley National Laboratory (LBNL) conducted an interchangeability study of potential performance and operational issues associated with using imported liquefied natural gas (LNG) and other high Wobbe gases. An interchangeability study first adjusts combustion equipment for optimum performance with a baseline fuel gas, and then runs the adjusted equipment with a substitute gas. The equipment's performance determines whether the "substitute gas" is acceptable for use in place of the "adjust gas," and can also investigate what must happen to make a substitute gas acceptable.

In 2005, the U.S. Energy Information Administration forecasted that domestic production of natural gas and Canadian imports would not keep pace with the growth of demand through 2023. Numerous proposed LNG receiving terminals along the United States' west coast were being considered to accommodate this demand. These new terminals could have lead to large-scale use of vaporized LNG as a fuel in California, with the San Diego area receiving the largest impacts. While the scale of LNG importation is now expected to be much smaller, LNG importation could still be a factor in the gas supplied to Southern California. Because the available LNG differs in composition from California's historical fuel gas compositions, equipment adjusted to the local gas quality could respond differently when firing the imported fuel, possibly affecting emissions, the manufacturing equipment, or product quality.

The NGC+ Interchangeability Working Group defines natural gas interchangeability as "The ability to substitute one gaseous fuel for another gaseous fuel in a combustion application without materially changing operational safety or performance and without materially increasing air pollutant emissions."(NCG+, 2005)

Consumption of natural gas in California and the United States is anticipated to increase mostly from growth in gas-based power generation and transportation. New supplies will be required to meet growing demand and to maintain price stability. At the beginning of this project, it was expected that LNG would be imported to meet state demand. Although it is not expected that this will happen in the near future due to increased use of shale gas, the infrastructure is in place if the need and economics change.

LNG imports from suppliers in Asia and the Pacific Rim were expected to supplement a portion of California's natural gas supply. Because the available LNG differs in composition from California's historical fuel gas composition range, equipment adjusted to the local gas quality could respond differently when firing the imported fuel, possibly affecting emissions, the manufacturing equipment, or product quality.

Imported LNG gas supplies provide challenges in processing, delivery, and interchangeability. The varying compositions of new gas supplies relative to traditional gas raise questions regarding fuel gas interchangeability. Variations in composition and heating value must be defined so that performance and emissions of end-use equipment are not significantly affected.

For interchangeability purposes, end-use equipment can be divided into several broad categories:

- Appliances, primarily residential scale
- Commercial foodservice equipment
- Industrial and commercial burners
- Turbines, micro-turbines, and power boilers
- Stationary and vehicle engines
- Non-combustion and feedstock applications

Natural gas interchangeability studies have been conducted by groups including the American Gas Association (AGA), GTI, and the Southern California Gas Company (SoCal Gas), and work has been funded by a variety of clients in many countries. Historical work has focused on residential appliances, and much of the reported data must be assessed from the limited framework of the studies. This project has addressed many of the research gaps needed to better understand natural gas and LNG interchangeability.

This project was structured to provide crucial data and analysis regarding LNG interchangeability, including emissions of air pollutants for industrial and commercial burners. This is the end-use area in which the least data was publicly available. Few studies have been published, burners and control systems have become more complex and sensitive to changes in recent decades, and many of these combustion systems are tightly regulated for emissions. Appliances as a class of combustion equipment have been the most extensively studied for interchangeability, but studies were needed for new, high-efficiency appliances, maladjusted appliances, and older appliances still in use in large numbers. Little information has been published regarding the interchangeability behavior of commercial foodservice equipment.

1.1 Objectives

The goal of this research was to develop good scientific data that can be used by regulators, policy makers and industry to develop standards (e.g., fuel specifications), guidelines (e.g., for indoor air quality), regulations. This data will help in the designing of natural gas devices, ensuring that new natural gas supplies can be used in California in a safe and environmentally sound manner while allowing for a wider range of gases. The research focused on increased variability in the California natural gas (NG) supply, specifically related to using LNG. The study examined classes of industrial and commercial burners along with their combustion control systems, residential appliances, range hoods, and commercial foodservice equipment. Air quality and exposure impacts were evaluated for indoor and outdoor air. Interchangeability considerations included performance and safety, in addition to the environmental impacts of LNG and other high Wobbe gases relative to traditional natural gas formulations. This interchangeability information will provide means to operate the most flexible and safest natural gas system with the widest gas supply options for California customers.

1.1.1 Project Description

This program identified and evaluated safety and emissions performance of LNG use in various industrial/commercial with control systems, residential and commercial foodservice cooking burners and identified preliminary approaches to mitigating negative impacts. Tests were conducted using multiple natural gas and LNG compositions:

- Laboratory tests on seven industrial/ commercial burners representing a range of the most sensitive burner types and two field tests to validate that laboratory tests represent normal industrial operations – infrared, two radiant tube, ribbon, high velocity, oxyfuel, two boilers and one low NOx boiler burners.
- Laboratory and field experiments on residential appliance - 13 cooktop sets, 12 ovens, five broiler burners, five storage water heaters, four forced air furnaces, one wall furnace, and six tankless water heaters.
- Laboratory experiments on ten commercial foodservice equipment– two fryers, griddle, steam, braising pan, range top, oven, convection oven and two combi ovens.

Also, because more efficient range-hoods may reduce pollutant concentrations and exposures, as-installed effectiveness and efficiency of residential range-hoods was tested. In addition, the indoor and regional air quality implications of using LNG were evaluated.

Test gases were selected based on existing supplies of natural gas in California. Gases were blended to represent common composition of Asian basin LNG and diluted with nitrogen to meet California gas requirements.

The objectives of this study were to:

- Develop and provide data associated with use of potential alternative fuels that can be used by policymakers and regulators to evaluate implications of the wider range of fuel quality.
- Develop and provide data associated with potential alternative fuels that can be used by Original Equipments Manufacturers (OEMs) and utilities to establish technology requirements for systems designed for such fuels.
- Develop design tools for OEMs to use in evaluating fuel flexibility of their current and future products.
- Develop guidelines for OEMs to use in evaluating fuel flexibility of their current and future products.

The approach used in this study to address these objectives was to:

- Establish testing needs by burner class and evaluate potential impact on California energy use and air quality goals.
- Define performance variables for analyzing combustion system performance based on changing fuel composition. These include burner ignition, flame stability, flame length, and emissions including CO and NOx.

- Develop test protocols by which classes of burners can be evaluated for robustness in meeting California performance and emission requirements.
- Test sensitive classes of burners and typical combustion control systems under defined boundaries of natural gas and LNG supply options to determine changes in performance and emissions.
- Analyze the results of testing with selected classes of commercial and industrial burners and review the implications relative to California energy efficiency and emissions objectives and on performance.
- Analyze the results of testing with selected commercial foodservice equipment and review the implications relative to California energy efficiency and emissions objectives and on performance.
- Quantify emissions and performance of in-use home appliances and burners, using currently delivered natural gas and selected LNG formulations.
- Use photochemical and transport models to evaluate the effect of variable NG and LNG supplies on ozone and other air quality parameters in the South Coast Air Basin of Southern California.
- Evaluate the effect of variable NG and LNG supplies on indoor and neighborhood scale human exposure to pollutants emitted from natural gas burners and appliances.

1.2 Report Organization

This comprehensive Summary Final Report provides an overview and summary of results from the component project studies. The report is divided into chapters summarizing the key findings of the interchangeability studies conducted for each burner class.

Detailed descriptions of the methods, results, and conclusions of the component studies described above are available in independent reports; Appendix A provides a list of these reports. Appendix B describes the major classes of industrial burners investigated during the study project and provides product details. Appendix C discusses the specification of adjust and substitute gases. Industrial commercial burner reports are in Appendix D. The commercial foodservice report is in Appendix E and the estimates of indoor exposures to pollutants from natural gas cooking burners are in Appendix F.

CHAPTER 2:
Industrial Burners: Summary of Interchangeability Test Results

2.1 Overview

This section of the interchangeability project study examined classes of industrial and commercial burners along with their combustion control systems. Possible interchangeability concerns for industrial users of natural gas-fired equipment are changes in emissions, the lifetime of their manufacturing equipment, or the quality of their product.

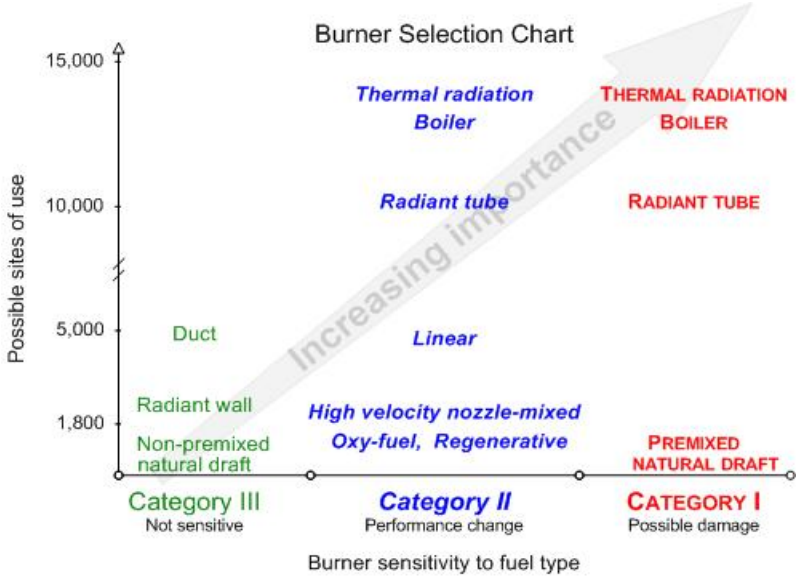
2.2 Selection of Industrial Burners for Testing

Selection of industrial burners for testing was based on the report, *Natural Gas in California: Environmental Impacts and Device Performance: Literature Review and Industrial Burner Evaluation* (Rue, D. 2006). The study included industrial burner evaluations identifying which burners are both prevalent in California and sensitive to changes in fuel gas composition.

Two methods were used to characterize industrial burners. Burner operating mode characterization grouped burners by fuel type, oxidizer type, draft type, mixing type, heating type, and control type. Burner application characterization sorted burners into the broad categories of radiant, nozzle mixed, regenerative, natural draft, boiler, linear grid-in duct, oxygen, and flare burners.

To identify burners that could be adversely impacted by varying the fuel input composition, the most commonly used burner types were classified into three categories. The first category contains the types of burners that are most likely to experience physical damage to the burner or other associated equipment or hardware. The second category contains the types of burners that are likely to be affected in terms of major combustion characteristics such as emissions, flame geometry/shape, safety, and noise. The third category includes the types of burners that are unlikely to be affected. Figure 2-1 summarizes the three categories and assigns color codes to aid recognition of each category.

Figure 2-1. Ranking Burner Classes by Population and Sensitivity to Fuel Type



The two methods of characterizing industrial burners served as guides in selecting the burners tested in this project. Since there are many types, sizes, and applications of industrial burners, the project team selected examples of burners that were anticipated to be most sensitive to changes when the fuel gas composition is changed, and burners that are most common in California industry. All selected burners were from manufacturers that rank either first or second in a particular industrial market segment. A more detailed description of each of the major industrial burner types is presented in Appendix B.

Table 2-1 expands on Figure 2-1 and summarizes the anticipated sensitivity of burners in different industries to changes in fuel gas composition.

Table 2-1. Anticipated Sensitivity of Burners in Different California Industries to Changes in Fuel Gas Composition

CATEGORY I: possible damage Category II: possible performance change Category III: change unlikely

Industry	Sites in CA	Relative Gas Use, % of all industrial	Category	Burners Used
Petroleum	218	34.8%	I or III III III	NATURAL DRAFT BURNER Radiant wall burner Flare burner
Oil and Gas Extraction	232	13.1%	I and II III	BOILER BURNER (PRESSURE) Flare burner
Food and Beverage	4,544	10.2%	I and II I and II II II III	BOILER BURNER (HEAT) RADIANT TUBE BURNER Thermal radiation burner Line burner In-duct burner
Cement, Mineral and Glass	1,524	7.3%	II II II	Oxy-fuel burner Regenerative burner High-velocity burner
Sugar and Frozen Food	114	6.8%	I and II III	BOILER BURNER (HEAT) In-duct burner
Textile, Paper, Apparel, Publishing	11,506	4.7%	I and II II	BOILER BURNER (HEAT) Thermal radiation burner
Chemical	1,615	4.1%	I and II I and II II III	BOILER BURNER (HEAT) RADIANT TUBE BURNER Thermal radiation burner Radiant wall burner
Primary Metal	510	3.9%	I and II I and II II II II	BOILER BURNER (PRESSURE) RADIANT TUBE BURNER Oxy-fuel burner Regenerative burner High-velocity burner

Industry	Sites in CA	Relative Gas Use, % of all industrial	Category	Burners Used
Fabricated Metal	7,931	3.4%	I and II I and II	BOILER BURNER (PRESSURE) RADIANT TUBE BURNER
Pulp	1	2.7%	I and II	BOILER BURNER (HEAT)
Semiconductor	1,500	1.9%	I and II	RADIANT TUBE BURNER
Construction	69,023	0.6%	II	High-velocity burner

2.3 Test Gas Compositions

Substitute gas compositions for the industrial burner interchangeability study needed to reflect the range of LNG compositions potentially available for import into California. It is nonetheless important to start with the fuel gases available for California to import and those that California currently uses. These fuels are detailed below. Measures of interchangeability vary between burner sectors. For industrial burners that can be tuned, performance variables to measure include burner ignition, stable operation, flame length, and emissions of CO and NOx. Performance variables important to other burners such as knock (engines) and flame lifting (appliances) are not relevant to industrial burners and were not observed, calculated, or reported.

A total of 11 gases were tested on the commercial burners. Three adjust gases were selected as representative of typical California natural gas compositions in both the southern and northern parts of the state. The adjust gases covered 95 percent of the Wobbe number range of California natural gas. Two substitute gases with compositions matching Pacific Basin LNGs were selected. Note that LNG compositions from a single source can vary with time, so the selected gas compositions should be considered as representative of LNGs but not exactly equal to any one LNG at any specific time. Additional substitute gases were created by blending nitrogen with the selected substitute gas compositions. This produced gases with declining heating value and Wobbe number as nitrogen content was increased. Sufficient nitrogen was blended into the two substitute gases to produce other substitute gases with Wobbe numbers equal to the adjust gas Wobbe numbers. Nitrogen was blended into the high-Wobbe number substitute gases because this is the approach most likely to be used at the LNG import facility to bring LNG into Wobbe range compliance with California regulations. The heating value vs. Wobbe number relationships for the adjust gases, substitute gases, and nitrogen blended substitute gas are shown below in Figure 2-2, followed by the compositions of the three adjust gases and two substitute gases, presented in Table 2-2.

Figure 2-2. Relationship Between Higher Heating Value and Wobbe Number for Natural Gases

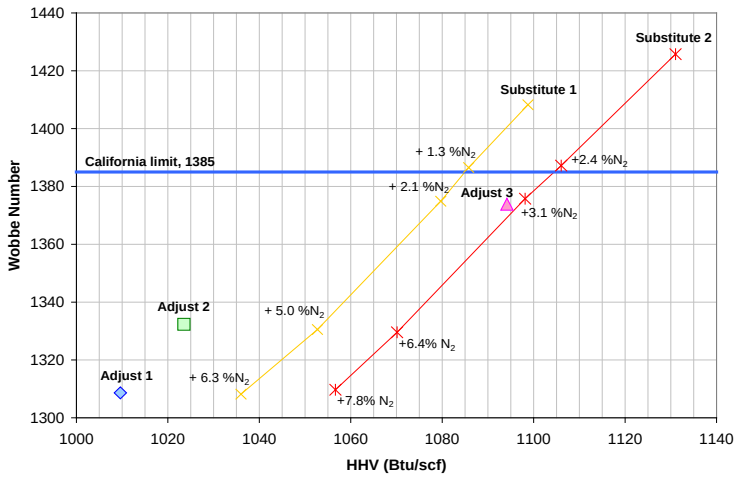


Table 2-2. Adjust and Substitute Gases Selected for Industrial Combustion System Interchangeability Tests

	Composition, %							HHV	Wobbe
	C1	C2	C3	C4	C5+	N2	CO2	Btu/SCF	Number
Adjust Gas 1 (A1)	93.2	2.52	0.41	0.16	0.08	2,69	0.92	1010	1308
Adjust Gas 2 (A2)	94.5	2.55	0.42	0.14	0.10	1.36	0.93	1024	1332
Adjust Gas 3 (A3)	90.5	2.45	3.40	1.38	0.10	1.30	0.89	1097	1375
Substitute Gas 1 (S1)	92.4	4.90	1.90	0.79	0.00	0.00	0.00	1099	1408
Substitute Gas 2 (S2)	89.4	7.10	2.50	1.04	0.00	0.00	0.00	1130	1425

Each industrial combustion system was first tuned to optimum performance with one of the adjust gases. Burner performance was recorded under these operating conditions. The fuel gas was subsequently changed to each of the substitute gases and nitrogen-blended substitute gases by using a blending station. Performance data including firing rate, flame condition, and emissions was collected during operation at each of these fuel gas compositions. The process was then repeated for each of the other two adjust gases. Results of this testing constitute the bulk of the data collected during industrial combustion system testing in this project. Specification of adjust and substitute gases is given in Appendix B.

2.4 Industrial Burner Systems Descriptions

A total of nine industrial combustion systems were tested. The group included seven burners tested over a wide range of conditions under tight laboratory conditions. The other two tests were field tests conducted in California with burners that were considered sensitive to changing

gas composition. The field tests covered a narrower range of test gas compositions (and Wobbe numbers), but the ranges were wide enough to allow comparison between laboratory and field test results with similar burners at similar operating conditions and changes.

Burners were set up following manufacturer instructions. Laboratory conditions cannot perfectly match industrial conditions, but burners were tested on furnace chambers that most closely resembled industrial conditions. Selected burner models had firing rates within common industrial operating ranges. These firing ranges were well matched to the capacities of the test furnace chambers. Two different sizes of blending stations were assembled and used for testing. The details of the blending stations for smaller and larger volume blending are provided in the burner testing reports in Appendix D. All gases for testing were prepared by blending GTI house natural gas with nitrogen, methane, ethane, propane, and butane. A gas chromatograph was used together with mass flow meters to obtain each desired gas blend with target composition.

The burners tested in the laboratory are listed along with manufacturer, model, and firing rate range information in Table 2-3. All burners were either already available in the GTI Industrial Combustion Laboratory or borrowed from the manufacturers. All burners were checked for optimal operation and were matched with recommended controls. Burner emissions were measured in real time with dedicated instruments. Standard, calibrated combustion emission monitors were used and operated per manufacturer specifications. Calibrations were carried out daily to assure accuracy. Details of the instrumentation are provided in the separate reports for each burner in Appendix D. Flue gas components monitored were oxygen, carbon dioxide, carbon monoxide, and total nitrogen oxides and unburned HC.

Table 2-3. Industrial Burners Tested Under Laboratory Conditions

Manufacturer	Model Name	Comment	Control	Capacity, MMBtu/hr
Radiant Burners				
North American	Evenglow	Radiant Tube	Modulating + Pressure Balance	0.02 – 0.5
Maxon	Radmax	Radiant Panel	On/Off + Venturi Mixer	0.025 per head
Boiler Burners				
Powerflame	Type C	Packaged System	Modulating + Cam Linkage	2 – 14.7
Cleaver-Brooks	SB-200-080-150	Packaged System	Modulating + Parallel Positioning	15 – 100 HP
Linear/Grid/Duct Burners				
Flynn Burner	Pipe Burner	Linear Burner (baking)	Modulating + Venturi Mixer	0.04 per inch
Oxygen Enhanced Combustion				
Eclipse	PrimeFire 300	High Luminosity	On/Off + Pressure Balance	0.5 – 8.0
Nozzle Mixed Burners				
Eclipse Combustion	ThermJet	High Velocity	Modulating + Pressure Balance	0.15 – 20

The field tests were included to address several questions. Field tests provided the opportunity to collect additional interchangeability data on the two most sensitive industrial combustion systems identified in laboratory testing, the radiant tube and boiler burners. At the same time, field testing enabled the assessment of differences in performance between well-tuned

equipment in the laboratory and equipment operating for long periods of time in industrial settings. Both field tests were carried out in Southern California. The industrial combustion systems tested in place were:

- Bloom model 2320 radiant tube burner with spark ignited pilot. The combustion system consisted of a W-shaped radiant tube with a dedicated burner, recuperator, and cooling section.
- Parker model 48L Low-NOx (30 parts per million by volume [ppmv]) 48 horsepower (hp), 2 MMBtu/h, 100 pound-force per square inch gauge (psig), horizontal drum sectional water-tube boiler with modulating control based on steam pressure and premixed gas and air metal fiber burners

Detailed descriptions of all industrial combustion systems are provided in separate burner reports in Appendix D. These reports also include information on gas compositions, blending protocols, burner setup and calibration, test procedures, and flue gas analysis instrumentation. All industrial combustion systems were calibrated per manufacturer procedures. They were operated using the most common specified control systems.

2.5 Laboratory Testing and Field Testing Results

Complete results of laboratory testing of seven industrial combustion systems and field testing of two industrial combustion systems are presented in separate burner reports in Appendix D. All burners operated stably over the full range of interchangeability testing conditions. Ignition tests found no problems with lighting burners or with burners staying lit when changing fuel gas compositions over the full range studied from 1317 to 1425 Wobbe. No significant changes in flame shape or flame length were observed over the range of fuel gases tested. The most measureable differences observed with changing fuel composition were emissions of NOx and CO. Unburned hydrocarbon emissions were also monitored and were found to be low, with little change (under 5% of value) over the full Wobbe range of gases. Changes in hydrocarbon emissions are presented in the separate burner reports (Appendix D). They are not shown in the main body of this report because hydrocarbon concentration levels are low, there is significant scatter in the data, and there are few clear trends. All burners were found to generate hydrocarbon emissions well below regulatory limits over the full range of fuel gas compositions tested.

Industrial burners in the laboratory were tested in both continuous and modulated firing mode. In continuous firing, burners were fired at a constant fuel rate (or constant Btus per hour). In modulating mode, burners were modulated by their control systems so that a constant process temperature could be maintained. Results of all tests are presented in the burner reports, but only the modulated firing data is presented here since burners are most commonly operated in modulating mode in industrial furnaces. Field testing was not conducted in both continuous and modulating firing modes. Field burners were operated per typical industrial practice, and those results are included in the summary below.

The largest variations in industrial burner performance relative to changing fuel gas composition were found to be NOx and CO emissions. Carbon monoxide is a product of incomplete combustion, and increases reflect either a lack of sufficient oxygen for complete combustion or poor mixing in the flame zone. NOx, on the other hand, is formed by multiple mechanisms and has a more complex relationship to air to fuel ratio, flame speed, flame mixing, temperature, and burner geometry. In general, the highest NOx level from a specific burner is reached at ideal stoichiometry (or zero excess air level). Burners are commonly operated under slightly oxidizing conditions so that little CO forms and NOx production is below the peak value. All testing began with burners tuned to the excess air level specified by the manufacturer for one of the three adjust gases (see Table 2-2). The air to fuel ratio was not changed as all of the substitute gases and substitute gas-nitrogen blends were subsequently fired in the tuned burner. This leads to changes in air to fuel ratio based on the energy content of the substitute gases. The procedure was then repeated for each burner when the burner was tuned for the second, and then the third, adjust gas.

The NOx and CO data from modulated firing of the infrared, linear, high velocity, and oxy-gas burners are presented in Figures 2-3 and 2-4. Emissions data is shown corrected to 3 percent oxygen in order to compare all burners on the same basis. The plots show changing NOx and CO emission levels when each burner is first tuned to each of the three adjust gases and then fired with the two substitute gases and all of the substitute gas-nitrogen blends. There are no standards for defining interchangeability in terms of changes in emissions. Emissions can increase or decrease with changes in fuel gas composition and air to fuel ratio. Testing reveals emission changes in absolute or relative terms and reveals which burners and which operating changes lead to significant changes in emissions. Observations for each of these four burners are summarized below and are presented in more detail in the individual burner reports in Appendix D.

Infrared burner – Extremely low NOx, under 5 ppmv, was measured for all firing conditions with no effect of adjust gas tuning or fuel gas composition on NOx emissions. CO for this burner was between 20 and 60 ppmv. When tuned to adjust1, the low Wobbe fuel gas, CO increased from 20 to 35 ppmv when the burner was fired with substitute gases as Wobbe Numbers were increased to as high as 1385 (the California Rule 30 limit for maximum Wobbe). This is likely a result of operation in a low excess air condition. When the burner was tuned to adjust2 and adjust3, this increase in CO with increased Wobbe disappeared and reversed, likely because sufficient air was present for complete combustion. The infrared burner was found to be fully interchangeable over the full range of adjust and substitute gases tested. This burner can be tuned to any fuel gas in this range and will produce similar, low NOx emissions, and optimum tuning can therefore be used to minimize CO emissions. Tuning to a fuel gas in the center of the range (such as Adj 2 at 1335 Wobbe) provides moderate, stable CO emissions over the full range of fuel gases tested.

Linear burner – This burner generated 20—40 ppmv of NOx over the range of fuel gases tested. The NOx level increased as the Wobbe gas number increased when tuned to each of the three adjust gases. NOx values were somewhat lower (although the trend was the same) when the burner was tuned to the high Wobbe Adjust gases (Adj 3). CO varied over a narrow range of 12-

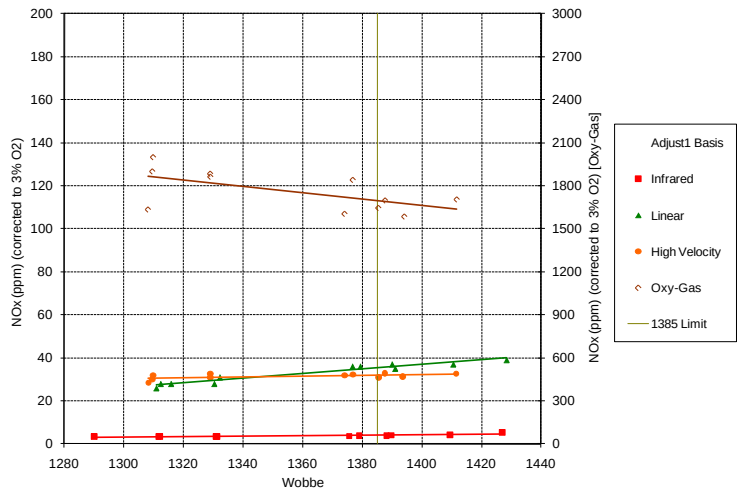
22 ppmv and decreased with increasing Wobbe fuel gas for all burner adjust gas tunings. The lowest CO emissions were measured when the burner was tuned to the medium adjust2 and high Wobbe fuel gases adjust3. These tests led to the conclusion that the linear burner is fully interchangeable over the full range of fuel gases. However, NOx is always lower when operating with a low Wobbe fuel gas (in the range of 1310 to 1335 Wobbe) no matter to what adjust gas the burner is tuned. Lowest NOx and CO emissions over the full Wobbe range are achieved by tuning the burner to a gas with Wobbe number near the high end of the range of expected fuel gases.

High velocity burner – This common industrial burner generated NOx of 30—35 ppmv over the range of fuel gases tested. This narrow NOx range, seen when the burner was tuned independently to each of the three adjust gases, demonstrates the stability of this class of burners. Tuning the burner to different adjust gases showed no trend, with the lowest NOx for the full Wobbe range found when the burner was tuned to the middle adjust gas, Adj 2. CO production was high from this burner and decreased with increasing Wobbe number. This indicates insufficient time for complete combustion with the low Wobbe gases anda tendency toward more complete combustion with high Wobbe number fuel gases. The quantity of CO generated and trend toward lower production with higher Wobbe number fuel gases was independent of initial adjust gas tuning. These tests led to the conclusion that the high velocity burner is stable over the full range of adjust and substitute gases tested when tuned to any of the adjust gases. Overall emissions are lowest for this burner when operated with the middle Wobbe number fuel gas (Adj 2 at 1335 Wobbe).

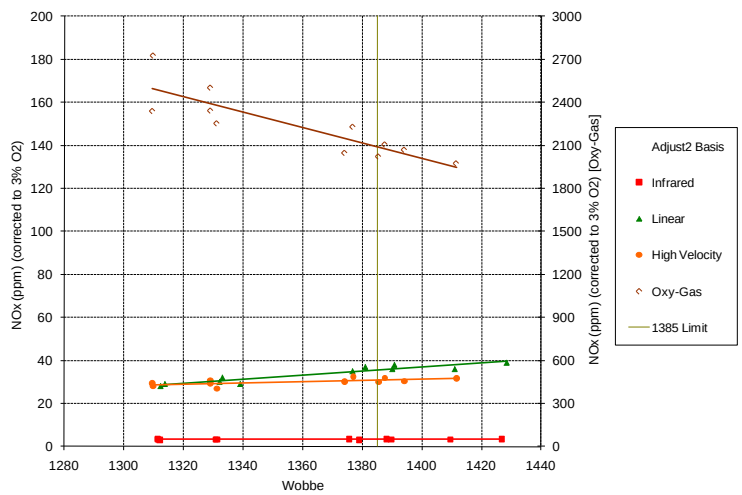
Oxy-gas burner – NOx generation levels from oxy-gas burners cannot be directly compared with other burners because levels of this emission depend on the nitrogen content of the fuel gas, purity of the oxygen, and leakage of the furnace. The laboratory furnace was sealed to prevented nitrogen infiltration. This is the same practice as followed in industry, but industrial furnaces are more difficult to seal tightly. Since the laboratory furnace and industrial furnaces cannot be sealed to the exact same extent, care must be taken to analyze the trends for the oxy-gas burner rather that the absolute values of emissions. Simulation was, however, close enough to determine interchangeability effects to be expected on an industrial furnace. Trends from the interchangeability testing, however, are considered reliable. NOx decreased with increasing Wobbe for all tested fuel gases for all three adjust gas tunings. The best way to minimize NOx production is by minimizing furnace air infiltration and by using fuel gas and oxygen with the lowest possible nitrogen content. Oxy-gas burners are operated with the lowest practical excess oxygen level to minimize oxygen cost. Testing found that when the oxy-gas burner was tuned to the lowest Wobbe adjust gas, large amounts of CO were generated as test fuel gas Wobbe number increased. The rate of increase with increasing fuel gas Wobbe number was lower when the burner was tuned to the medium Wobbe adjust gas (adjust2) and disappeared when the burner was tuned to the high Wobbe adjust gas (adjust3). CO emissions were minimized with increment Wobbe gases when the burner was tuned to the high Wobbe fuel gas. These tests led to the conclusion that the lowest NOx is achieved by tuning the burner to a low Wobbe gas such as Adj 1. This will lead to excessive CO production if the burner is then fired, without adjustment, with a high Wobbe gas of 1360 to 1385. To mitigate this high CO level, the oxygen

should be increased to avoid problems with incomplete combustion, or the burner should be tuned to a moderate gas such as Adj 2 (1335 Wobbe) to prevent excessive CO production while accepting some increase in NOx.

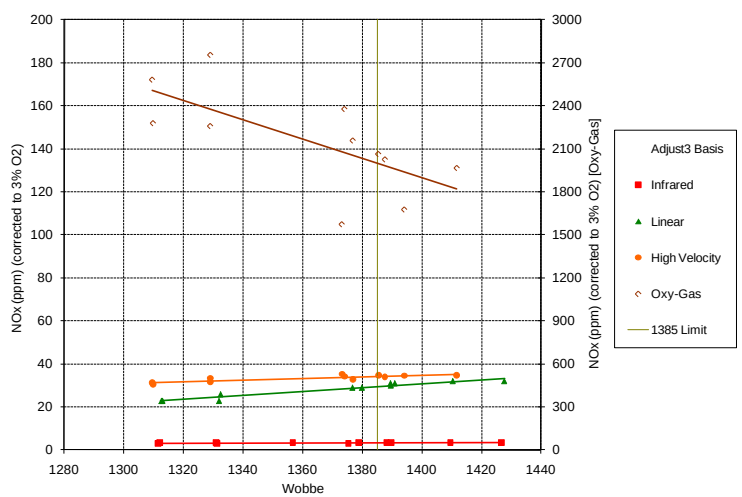
Figure 2-3. NOx Emissions for Infrared (IR), Linear (L), High Velocity (HV), and Oxy-Gas (OG) Burners



a. Burners tuned to Adjust 1



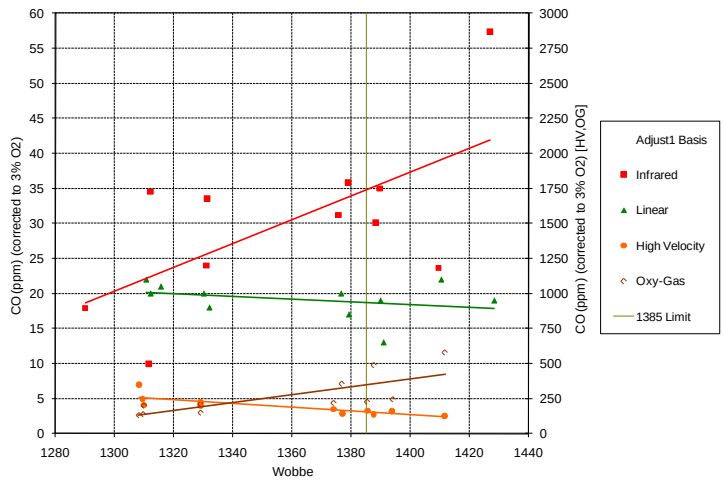
b. Burners tuned to Adjust 2



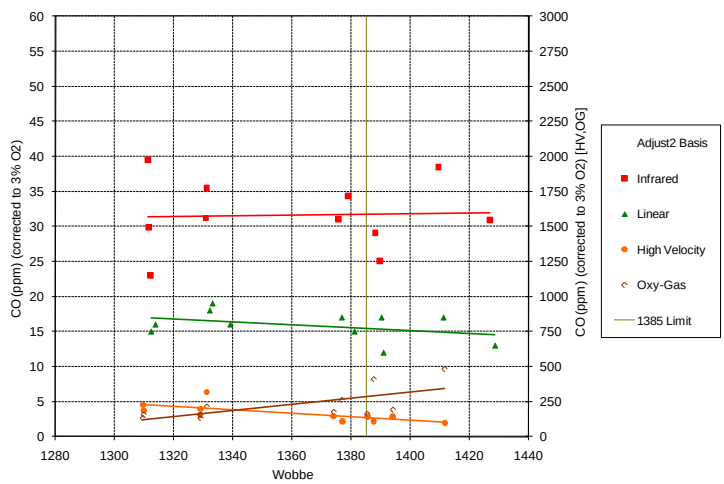
c. Burners tuned to Adjust 3

Scale on right for oxy-gas burners

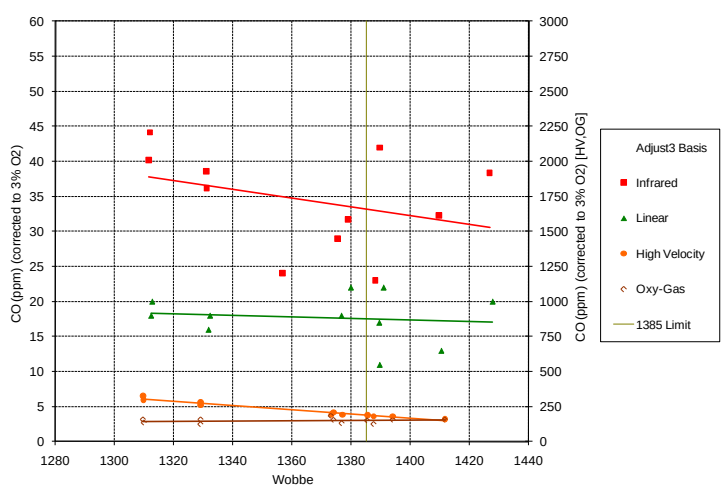
Figure 2-4. CO Emissions for Infrared, Linear, High Velocity, and Oxy-Gas Burners



a. Burners tuned to Adjust 1



b. Burners tuned to Adjust 2



c. Burners tuned to Adjust 3

Scale on right for high velocity and oxy-gas burners

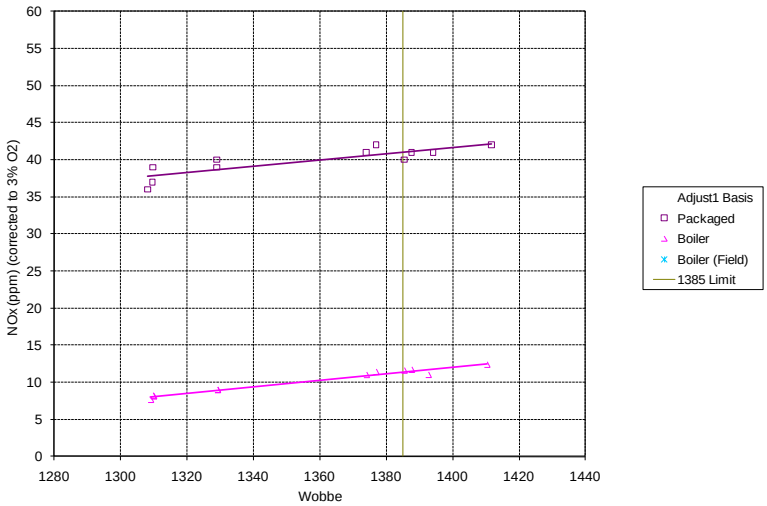
Three boilers were tested for interchangeability, two (a packaged boiler and a low NOx boiler) in the laboratory and one in the field. Emissions measured under all test conditions are presented in Figures 2-5 and 2-6. Adj 1 gas was not used for the field test because it was not available. Burner type and boiler configuration led to significant differences in NOx and CO generated, but the emissions trends as a function of fuel gas Wobbe number were similar for all three boilers.

All three boilers showed increased NOx generation as Wobbe number of the test fuel gas was increased. This trend was observed when each boiler was tuned to each of the three adjust gases. There is no clear evidence that tuning to any specific adjust gas leads to lower NOx than any other adjust gas. The lowest NOx is achieved by operating the boiler with the lowest Wobbe number fuel gas possible, no matter what adjust gas the boiler is tuned to.

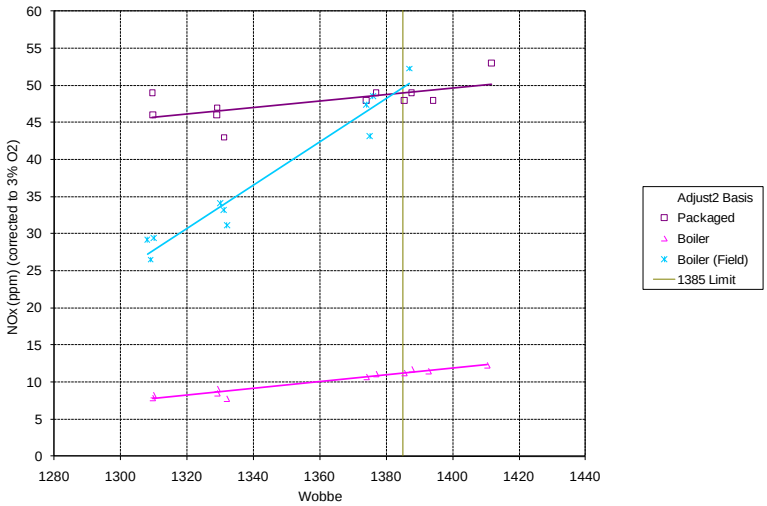
CO yields were found to decrease with increasing Wobbe number of the fuel gas for all three boilers. Although the trend was clear, there was a significant amount of unexplained scatter in the field. The CO yield was similar when boilers were tuned to the low and medium Wobbe fuel gases (Adj1 and Adj 2) and higher when tuned to the higher Wobbe number fuel gas (adjust3).

CO decreased with increasing Wobbe number and NOx increased with increasing Wobbe number for all three boilers when the boilers were tuned to each of the three Adjust gases. There is no way to simultaneously minimize both CO and NOx emissions. If NOx is to be minimized, the boilers should be tuned to a lower Wobbe number adjust gas. If CO is to be minimized, the boilers should be tuned to a medium Wobbe number adjust gas.

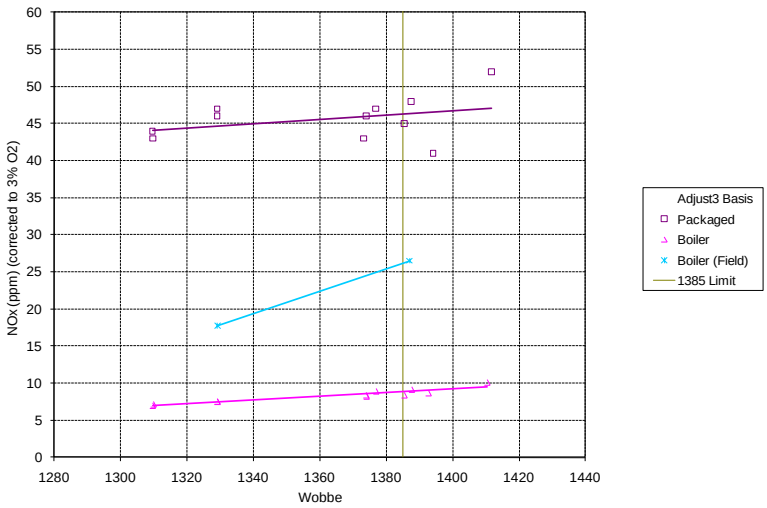
Figure 2-5. NOx Emissions for Boiler Burners



a. Burners tuned to Adjust 1

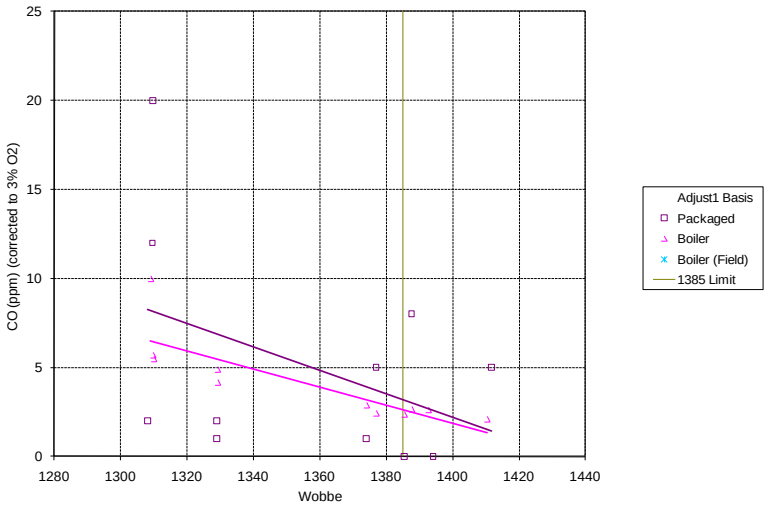


b. Burners tuned to Adjust 2

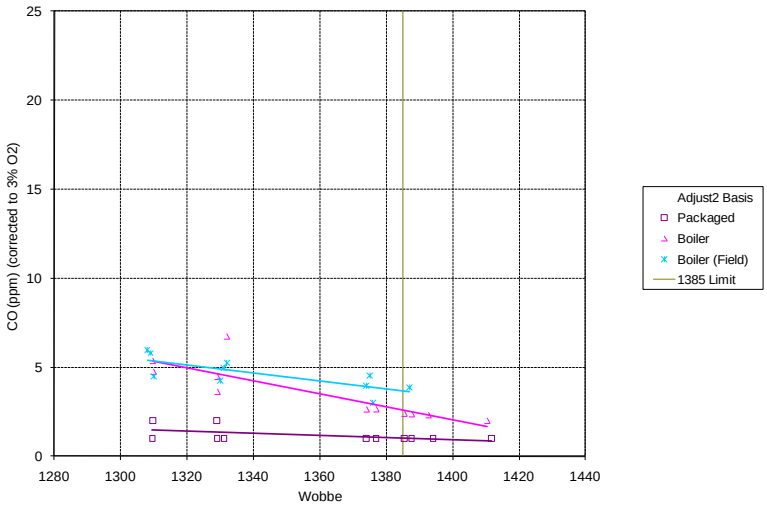


c. Burners tuned to Adjust 3

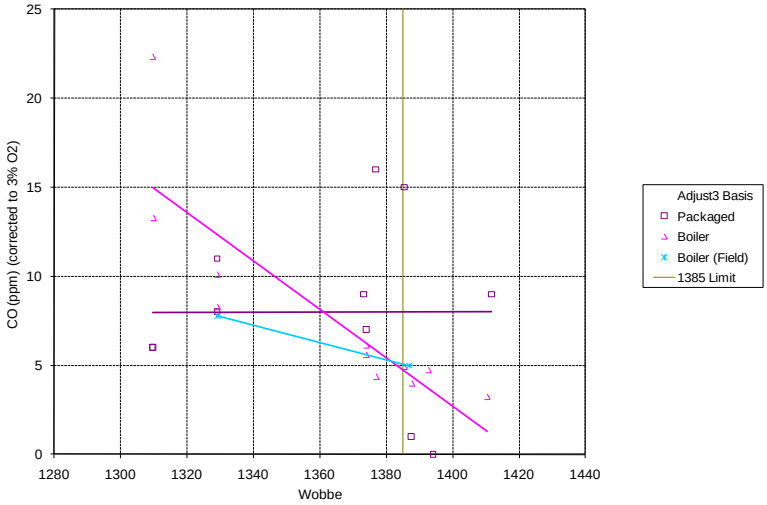
Figure 2-6. CO Emissions for Boiler Burners



a. Burners tuned to Adjust 1



b. Burners tuned to Adjust 2



c. Burners tuned to Adjust 3

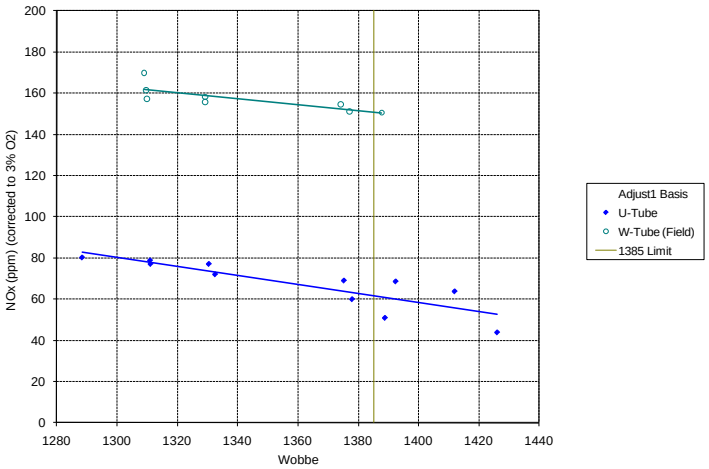
The radiant tube tested in the laboratory was a 'U' tube, shaped like a U. In the field, one 'W' tube was tested. Emissions of NOx and CO measured from radiant tube burners in the laboratory and in the field are presented in Figures 2-7 and 2-8. NOx yields were relatively high for these burners at 40 to 180 ppmv. The trends in NOx generation were consistent. For the U-tube burner, NOx levels decreased with increasing natural gas Wobbe number and were similar with tuning the U-tube burner to different adjust gases, with the lowest NOx obtained when tuned to Adjust2. The lowest NOx levels for the U-rube burner for all adjust gas tunings was realized when firing the fuel gas with the highest Wobbe number. W tube NOx levels also decreased with increasing Wobbe for all adjust gas tunings, and the NOx levels were unchanged when the W tube was tuned to different adjust gases.

In the laboratory the U-tube burner was tuned per manufacturer instructions to a low air to fuel ratio. When tuned to the two lower Wobbe adjust gases (Adjust1 and Adjust2) and then fired with a substitute gas with higher Wobbe number, the burner generated very high levels of CO. This was a result of insufficient oxygen for complete combustion under these tuning and subsequent operating conditions. When the laboratory U-tube was tuned to the high Wobbe number adjust gas (Adjust3), CO production did not rise exponentially as a function of substitute gas Wobbe number.

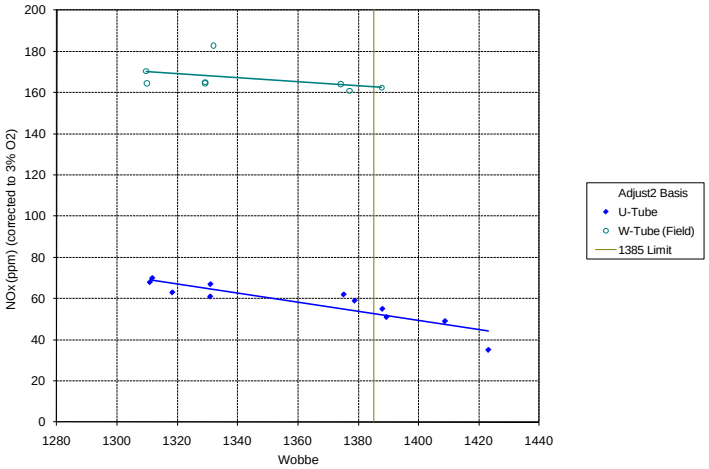
The W-tube tested in the field did not demonstrate the same behavior. For all adjust gas tunings, the CO generated either stayed the same or changed very little (decreased or increased) as the substitute fuel gas Wobbe number was increased. This reflects the tuning of the field W-tube burner to a higher air to fuel ratio.

These tests led to the conclusion that in order to minimize CO emissions, U-tube and W-tube burners should either be tuned to a fuel gas at the high end of the Wobbe number range of interest, or tuned to a higher air to fuel ratio than recommended by some manufacturers. This protocol will prevent excessive levels of CO from being produced while NOx emissions will not be significantly changed.

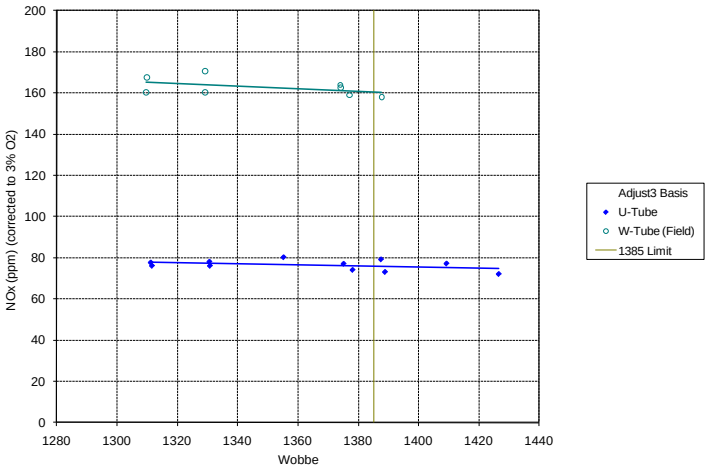
Figure 2-7. NOx Emissions for Radiant Tube Burners



a. Burners tuned to Adjust 1

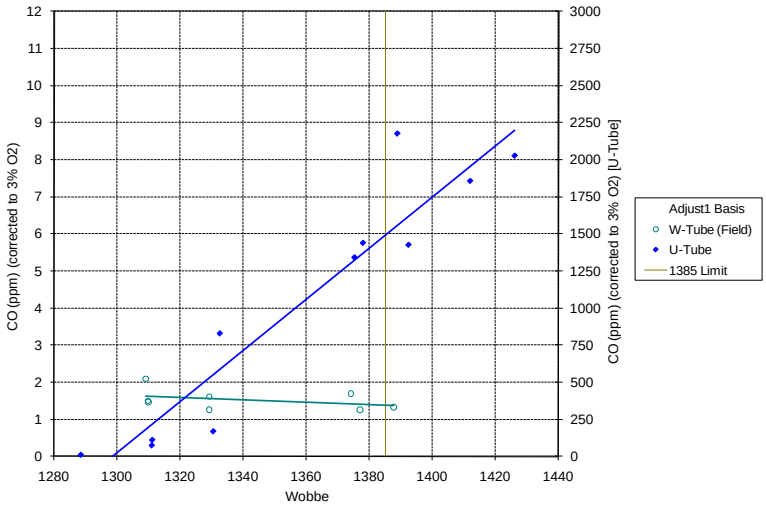


b. Burners tuned to Adjust 2

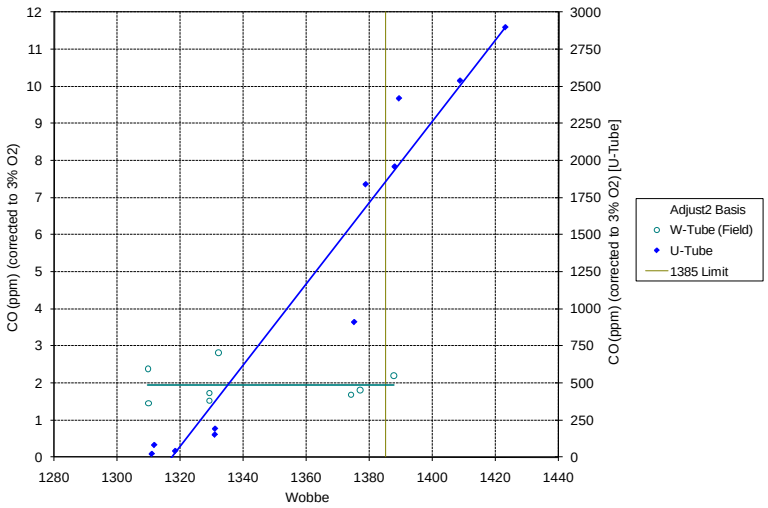


c. Burners tuned to Adjust 3

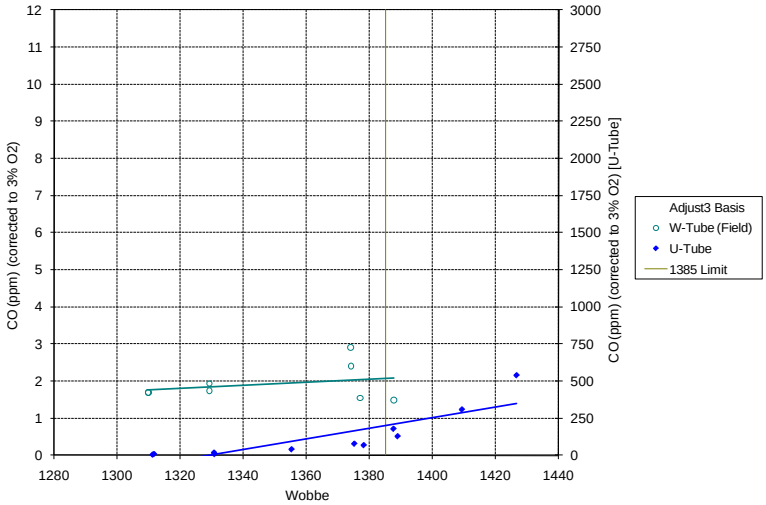
Figure 2-8. CO Emissions for Radiant Tube Burners



a. Burners tuned to Adjust 1



b. Burners tuned to Adjust 2



c. Burners tuned to Adjust 3

Scale on right for radiant U-tube

2.6 Summary and Conclusions

Data collected under laboratory conditions and field testing provides guidelines for tuning different types of combustion systems so that emissions are minimized when operating under steady and varied natural gas Wobbe number situations. Guidelines developed based on the testing in this project are presented in this section.

Emissions were measured over a wide Wobbe range for seven types of combustion systems in the laboratory and the field, including three distinct boiler combustion systems. Table 2-4 shows the emission behavior of the different burners as a function of Wobbe Number of the natural gas. The observed CO and NOx trends confirm that several of the burners behave in a similar manner (radiant U tube and oxy-gas burners in one group and linear, high velocity, and boiler burners in a second group). The radiant W tube and infrared burners behaved differently from the other burners. While developing burner optimization protocols is beyond the scope of this project, the emission production patterns for the different burners strongly suggest that protocols can be developed to classify industrial burners into groups and to then specify methodologies to minimize NOx and CO under various conditions of natural gas variability.

Table 2-4. Trends in Industrial Burner Emissions With Increasing Natural Gas Wobbe Number

Industrial Burner Type	Change in NOx With Increasing Wobbe Number	Change in CO With Increasing Wobbe Number
Infrared Burners	Very Low (<5 ppmv)	Variable – depending on Wobbe Number gas to which burner is tuned (15-45 ppm)
Radiant Burner – U Tube – tuned tightly to low air/fuel ratio	Decreasing (50-80 ppm)	Increasing (50-1800 ppm)
Radiant Burner – W Tube – tuned above the manufacturer's recommended tight air/fuel ratio	Decreasing (150-180 ppm)	Level – very small changes (1-2 ppm)
Linear Burners	Increasing (25-35 ppm)	Decreasing (15-25 ppm)
High Velocity Burners	Increasing (30-35 ppm)	Decreasing (3-10 ppm)
Oxy-Gas Burners	Decreasing (1600-2500 ppm)	Increasing (100-400 ppm)
Boiler Burners	Decreasing (8-50 ppm)	Decreasing (2-20 ppm)

Levels of NOx and CO emissions from combustion systems have been shown to vary with the tuning of the burners as well as with the composition and Wobbe number of the natural gas fired in the burner. Burner modeling and emissions predictions have commonly been carried out assuming a known, unchanging natural gas composition. Work in this project has shown that allowance of natural gas having a range of Wobbe numbers need to expand the approaches employed to minimize emissions.

To illustrate this point, three practical scenarios are projected that match most of the possible variations in gas supply. To represent the majority of real world situations, idealized scenarios have been specified in which the natural gas supply has (1) a relatively constant composition and Wobbe number over time, (2) a bimodal distribution representing two gas supplies that are delivered at different times, or (3) a gas supply that varies randomly and unpredictably over a range of Wobbe numbers but is still in compliance with regulatory limits. Table 2-5, summarizes how each of the combustion systems tested should be tuned to minimize emissions based on each of the three possible gas supply scenarios. In situations in which either NOx or CO can be minimized, but both cannot, the decision was made to favor minimization of NOx production. The exception to this decision was situations in which very large quantities of CO were generated. This was true for several of the radiant burners and the oxy-gas burner, all because low air to fuel ratios produced conditions for incomplete combustion.

Interchangeability testing was carried out with natural gas compositions commonly distributed in California or anticipated as LNG becomes more common. Therefore, the conclusions derived from the combustion system testing must be assumed valid only for natural gas with Wobbe numbers from 1310 to 1385, with 1385 being the present California Rule 30 limit. Testing was carried out by burning natural gas with a Wobbe number as high as 1425 because this was the highest-Wobbe LNG considered for importation at the time of testing. Undiluted LNG or LNG diluted to a Wobbe between 1385 and 1425 could be available at some future point. The testing team felt this range should be covered for this potentiality and should be covered to provide a wider Wobbe range to confirm emissions trends as a function of Wobbe number. The same conclusions apply between 1385 and 1425 Wobbe as apply below 1385 Wobbe. For practical reasons, the project team recognizes that the Rule 30 limit of 1385 Wobbe is in force, and all conclusions are drawn only up to that value.

The combustion systems all exhibited stable operation and reliable ignition over the full range of tunings and gas compositions tested. The emissions generated by the different combustion systems varied significantly. Some burners showed almost no variation in NOx or CO (either one or the other or both) with changes in tuning or changes in natural gas composition, while other burners showed increasing or decreasing relationships between the Wobbe number of the natural gas and emissions of NOx and CO. Variations in emissions based on tuning over the range from adjust 1 gas to adjust 3 gas could be as large as 25 percent, which suggests that proper burner tuning can be used as one method for maintaining low emissions and that regular tuning of certain burner types is needed to maintain low emission levels. This conclusion holds whether the natural gas supply is steady or variable.

The combustion systems that showed only small changes (<10 ppm change) in emissions with changes in tuning or changes in gas composition were:

- Infrared burner – noting the large scatter on CO emission readings
- Linear burner
- W-tube radiant burner (field test with higher than recommended air to fuel ratio) – both NOx and CO

- High velocity burner

Small, but minor, improvements in emissions levels can be achieved with these burners. But proper operation following original equipment manufacturer (OEM) tuning specifications should keep emissions at near the minimum for both burners over the full range of gas compositions of interest.

All other industrial combustion systems tested showed significant changes (well in excess of 5% in relative change) in NOx or CO emissions, or both, based on tuning and on gas composition changes. A number of burners, including the high velocity burner, the oxygen-gas burner, and the radiant U tube burner, generated large amounts of CO. The oxy-gas and radiant U-tube burners generated high CO when tuned to a low Wobbe gas Adj 1 or Adj 2and then fired with a high test Wobbe gas. This occurred because these burners are tuned to a tight air-fuel ratio, leading to low excess oxygen in the exhaust gas and consequently too little oxygen when tuned to low Wobbe gas and fired with high Wobbe gas. The high-velocity burner produced high CO when fired with low-Wobbe gas when tuned to each of the three Adjust gases. This represents insufficient air-gas mixing causing incomplete combustion for the low-Wobbe gases.

The radiant W tube tested in the field was not tuned to as low an air-fuel ratio and did not exhibit the same exponential increase in CO under low Wobbe tuning with high Wobbe firing. This example illustrates the need to understand burner operating conditions before determining the preferred approach to minimize emissions relative to the interchangeability of the natural gas supply.

Table 2-5. Guidelines for Industrial Combustion System Tuning to Minimize NOx and CO Emissions with Natural Gas Ranging from 1310 to 1385 Wobbe

Combustion System	Narrow Wobbe Range	Bi-Modal Wobbe Range[1]	Broad Wobbe Range[2]
Infrared Burners	Tune burner for 1332 Wobbe gas (similar to Adj 2). NOx is unaffected by Wobbe. This tuning keeps CO low over full 1310-1385 Wobbe range.	Tune to the higher Wobbe value. NOx is unchanged with Wobbe and this will minimize CO.	Tune to high end of the Wobbe range. NOx is unchanged with Wobbe and CO will be kept low
Radiant Burner – U Tube – tuned tightly to low air/fuel ratio	Either 1) tune to 1385 Wobbe (or upper limit of allowed Wobbe). NOx is 0-20 ppm above the minimum. CO is at a minimum over the full range of possible Wobbe values, or 2) tune to 1335 Wobbe and add a small amount to excess air, This keeps NOx at a minimum and prevents exponential increase in CO due to low oxygen to gas ratio.	Tune to the higher Wobbe value. NOx will be no more than 0-20 ppm above the minimum. CO will be low for both Wobbe values.	Tune to the high end of the range. NOx is 0-20 ppm above the minimum. CO is kept from increasing exponentially when too little oxygen is available.
Radiant Burner – W Tube – tuned above the manufacturer's recommended tight air/fuel ratio	Tune to a Wobbe of 1310 such as Adj 1. NOx is a minimum over the full Wobbe range. CO is also a minimum over the full Wobbe range.	Tune to the lower Wobbe value. NOx will be minimized. CO is lower or unchanged over the full Wobbe range.	Tune to the low end f the expected Wobbe range. NOx is minimized at the low end of the Wobbe range. CO is lower or unchanged over the full Wobbe range.
Linear Burners	Tune to Wobbe 30 points above the expected range. NOx decreases. CO is below the highest level at 1310 Wobbe .	Tune to the higher Wobbe value. NOx is lower. CO is either at minimum or only slightly above minimum values.	Tune to high end of Wobbe range or even a little above the Wobbe range. NOx is minimized and CO is either minimized or increases only slightly.
High Velocity Burners	Tune to 1332 Wobbe similar to Adj 2. NOx varies less than 5 ppm (under 20% of the low NOx level) over full 1310-1385 Wobbe range. CO levels are lowest at 1385 Wobbe firing.	Tune to the lower Wobbe value. NOx is slightly lower with lower Wobbe. CO could be either slightly lower or higher depending on the two gases.	Tune to the low end of the Wobbe range. NOx will be at or near a minimum over the Wobbe range. CO will either be unchanged or higher or lower near the high end of the Wobbe range.

Combustion System	Narrow Wobbe Range	Bi-Modal Wobbe Range[1]	Broad Wobbe Range[2]
Oxy-Gas Burners	Tune to a low Wobbe gas (1310 Wobbe) similar to Adj 1.CO is increased for gas above 1360 Wobbe but not for lower Wobbe gas. NOx is at a minimum for all gases from 1310 to 1385 Wobbe. Some additional oxygen could be added if gases with Wobbe above 1360 are fired so CO emissions do not increase excessively.	ITune to the lower Wobbe gas. NOx is minimized for both gases. CO is the same for the lower Wobbe gas and slightly higher for the higher Wobbe gas.	Tune to a low Wobbe gas (1310 Wobbe) similar to Adj 1.. CO is increased only for gas above 1360 Wobbe, but NOx is at a minimum for all gases from 1310 to 1385 Wobbe.
Boiler Burners	Tune to a low Wobbe such at 1310 like Adj 1. There is variability among the boilers, but this tuning provides the lowest NOx for all boilers over the full 1310-1385 Wobbe range. CO is not minimized under these conditions for all boilers or all Wobbe gases, but CO sonly shows a small increase relative to tuning for minimum CO production.	Tune to the lower Wobbe value. NOx is minimized. CO is higher at the lower Wobbe value, but CO is low over the full range of Wobbe values.	Tune to the low end of the Wobbe range. NOx is kept to a minimum. CO is above the minimum, but CO is under 15 ppmv for all Wobbe values.

[1] Two gas supplies that are delivered at different times

[2] Gas supply varies randomly and unpredictably

Further testing, beyond the scope of this project, is needed to fully characterize the classes of industrial combustion systems tested and to provide more complete emissions data for the burners tested. All data points reported were averages over an operating period. Despite limited testing in this program, the industrial burners believed to be most sensitive to changes in natural gas combustion were tested, and other burners are expected to be less sensitive to changes in natural gas composition. Spot tests of other burners would determine if this analysis is correct, and new burners entering the market should be evaluated on an as-needed basis.

CHAPTER 3:
Commercial Foodservice Equipment: Summary of Interchangeability Test Results

3.1 Overview

As a general rule, commercial kitchens consume five times more energy per square foot than other types of commercial spaces. Natural gas consumption in commercial kitchens is dominated by the cook line. Of the 1 million commercial foodservice equipment installed and operating in California, roughly 80 percent are powered by natural gas, with an estimated 480 million therms of natural gas consumed annually. A PIER project on the energy efficiency potential of commercial cooking is nearing completion by the Foodservice Technology Center (FSTC). Based on study results, the FSTC estimates commercial cooking in California consumes 480 million therms of natural gas annually.

With more than 90,000 eating and drinking establishments currently operating in California, an estimated $54 billion in food and drink sales in 2007, and the generation of $4.5 billion in California sales tax per year, restaurants are indisputably a driving force in both the state employment and revenue sectors. Over 1.4 million people are currently employed in food industry jobs in California.

Shown here are the performance summaries to highlight the interchangeability performance of the foodservice equipment. This highlights the appliances most sensitive to gas quality. The detailed results of testing are presented in Appendix E.

The FSTC estimates that the total gas load for commercial kitchens approaches half the overall commercial gas consumption in the state. Of the many types of commercial foodservice equipment, the four most common and their California populations are listed below in Table 3-1.

Table 3-1. Commercial Cooking Appliance Population in California (Year 2007)

Appliance	California Population (units)	Baseline Efficiency, %	Annual Energy Use per Unit, therms	Total Annual Energy, million therms
Convection Oven	65,000	30	860	56
Deep Fat Fryers	110,000	30	1,390	153
Griddles – standard	41,000	30	810	33
Steamers - pressureless	29,000	15	2,190	63
Total				305

Natural gas usage in California by convection ovens, fryers, griddles, and steamers combined is over 305 million therms per year. The four appliance types represent about 64 percent of commercial cooking usage. Understanding the impact of changing gas composition on the performance of these appliances and on their emissions is important in generating a full understanding of the impacts of LNG use in California.

3.2 Selection of Commercial Foodservice Equipment for Testing

GTI conducted a series of interchangeability tests on 10 appliances. The appliances were chosen based on existing population, gas load, and burner designs. The specific types of appliances tested include the appliances listed in Table 3-1 along with several additional appliances of concern. They were:

- Fryer (two)
- Griddle
- Convection Oven
- Steamer
- Braising Pan
- Combi Oven (steamer and oven modes)
- Range Top
- Oven

The appliances for testing were supplied by commercial foodservice manufacturers that have previously worked with GTI, and with assistance from the North American Association of Foodservice Equipment Manufacturers (NAFEM)-member companies.

3.3 Test Gas Compositions

To evaluate interchangeability performance, each cooking appliance was operated with a range of gas compositions matching the compositions and ranges of adjust and substitute gases used in the industrial burner tests. These pieces of equipment are not built for field adjustment, so no adjustments were made to shutters, baffles, air to fuel ratios, or other combustion controls when switching between gases.

The interchangeability tests were completed using American National Standards Institute (ANSI)-defined methodologies to measure performance and emissions changes with changing gas (natural gas to LNG) compositions. Each appliance is addressed by a different ANSI protocol, and the protocols for each cooking appliance are described in the detailed testing report. The fuels chosen for testing represent natural gas and LNG compositions over a range of 1310-1425 Wobbe numbers. For each appliance, the flue gas (oxygen, CO2, NOx, CO, and hydrocarbons), burner firing rate, and critical temperatures were measured for each test gas composition. For each appliance, 20 minutes of reading were collected by the data acquisition

system at 5 second intervals. Duplicate tests were run on separate days for each fuel for each appliance.

Table 3-2 provides analyses of the gas compositions used for testing. Three adjust gases were selected as representative of the range of natural gas in California. Adj2 is the average gas composition in the Southern California Gas Company gas territory and is also similar to the gas available from the local utility to the GTI laboratory. For these reasons, Adj2 was selected as the baseline gas.

Two substitute gases (Sub1 and Sub2) were selected as having similar compositions to Pacific basin LNGs. Both Sub1 and Sub2 have higher Wobbe numbers than allowed in California, so each was diluted with nitrogen to match the Wobbe numbers of the three selected adjust gases. While Wobbe numbers of the substitute and adjust gases are matched, compositions are different, and heating values of the nitrogen-diluted substitute gases do not exactly match the adjust gases with the same Wobbe Number. The Wobbe number of gases fired in the interchangeability tests ranged from 1309 (Adj1) to 1426 (Sub 2). Gases with Wobbe above the California Rule 30 limit of 1385 were tested so trends in equipment performance and emissions could be confirmed and not because these higher Wobbe gases are expected to be delivered to customers in California. Table 3-2 shows the heating values and Wobbe numbers of:

- Adjust gases (Adj1, Adj2, Adj3)
- Substitute gas 1 (Sub1)
- Sub1 with varying nitrogen levels to match Wobbe numbers of the adjust gases (Sub1-Adj1, Sub1-Adj2, Sub1-Adj3)
- Substitute gas 2 (Sub2)
- Sub2 with varying nitrogen levels to match Wobbe numbers of the adjust gases (Sub2-Adj1, Sub2-Adj2, Sub2-Adj3)

Table 3-2. Composition of Test Natural Gases

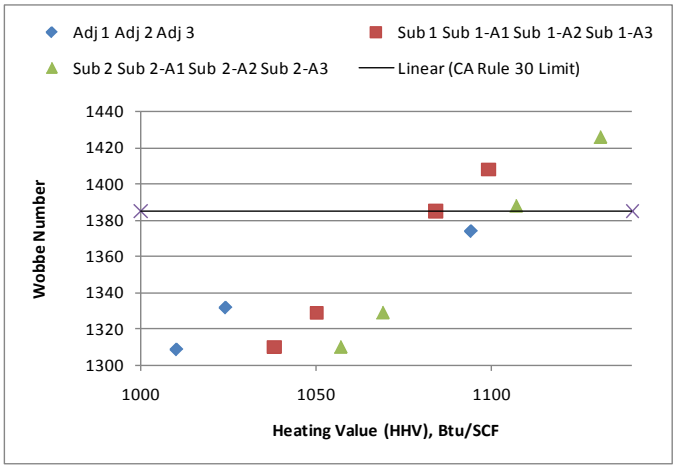
	Adj1H mol%	Adj2H mol%	Adj3H mol%	Sub1 mol %	Sub1-Hi mol%	Sub1-A2 mol%	Sub1-A1 mol%	Sub2 mol %	Sub2-Hi mol%	Sub2-A2 mol %	Sub2-A1 mol%
Methane	0.92	0.94	0.89	0.92	0.91	0.88	0.87	0.89	0.87	0.85	0.84
Ethane	0.02	0.03	0.04	0.05	0.05	0.05	0.05	0.07	0.07	0.07	0.07
Propane	0.01	0.01	0.03	0.02	0.02	0.02	0.02	0.03	0.02	0.02	0.02
n-Butane	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Nitrogen	0.04	0.03	0.03	0.00	0.01	0.04	0.06	0.00	0.02	0.05	0.07
HHV	1010.04	1024.05	1094.00	1098.85	1084.97	1050.37	1038.25	1130.58	1106.77	1069.35	1056.88
Wobbe Index	1308.97	1331.97	1373.98	1408.42	1385.49	1329.16	1309.70	1425.57	1387.73	1329.20	1309.93

Gas heating value and Wobbe number data from Table 3-2 is presented in graphical form in Figure 3-1. The plot shows the range of natural gas heating value and Wobbe Number covered and includes the 1385 Wobbe limit currently mandated in Southern California as an upper limit on gas. Points for each gas show how nitrogen dilution decreases both Wobbe number and heating value. After dilution with nitrogen, neither the heating value nor the Wobbe number matches for any gases. For that reason, the investigators elected to match Wobbe number because Wobbe is generally accepted as a better predictor of interchangeability than heating value alone.

On the left side of Figure 3-1 is a table repeating the heating values and Wobbe numbers for all of the test gases. The table provides a ratio of the Wobbe number of each gas to the Wobbe of Adj2. Adj2 was selected as the baseline gas, so this ratio provides a ready indication of the variation of the Wobbe of each test gas relative to the baseline gas. Test data on emissions (Figs 3-2 and 3-4) for the commercial foodservice equipment is plotted as emissions on the y-axis and the Wobbe number ratio on the x-axis. The same results would be observed if Wobbe number was plotted on the x-axis. But the data presentation method utilized enables the reader to quickly see the relationship of emissions as a function of the fractional variation in Wobbe number.

Figure 3-1. Range of Test Gas Higher Heating Value (HHV) and Wobbe Number

Gas	HHV	Wobbe	W(Gas) / W(A2)
Adj 1	1010	1309	0.983
Adj 2	1024	1332	1.000
Adj 3	1094	1374	1.032
Sub 1	1099	1408	1.057
Sub 1-A1	1038	1310	0.983
Sub 1-A2	1050	1329	0.998
Sub 1-A3	1084	1385	1.040
Sub 2	1131	1426	1.071
Sub 2-A1	1057	1310	0.983
Sub 2-A2	1069	1329	0.998
Sub 2-A3	1107	1388	1.042

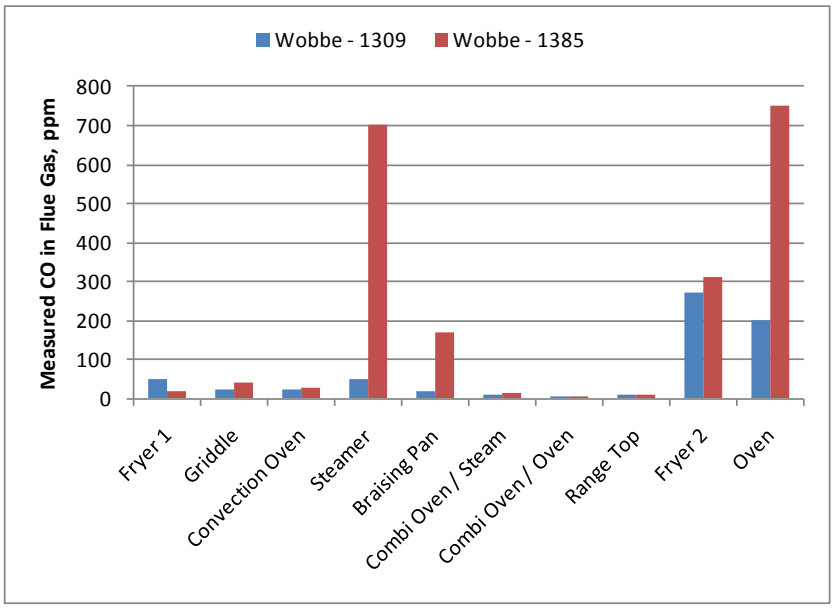


The results for the different commercial foodservice equipment showed that changing the composition of the fuel led to a range of changes in terms of burner performance. For all of the appliances, the firing rate proportionally increased with the increase in the heating value. In some cases, the firing rate exceeded the recommended limit of more than 10 percent of the faceplate rating, but strategic temperature readings on the appliances did not suggest excessive overheating for short term appliance operation. Studying the long-term effects of the higher firing rate and resulting temperatures was beyond the scope of this project. No appliance experienced ignition or operational difficulties over the full range of gas compositions tested.

Determination of changes in appliance performance and emissions are of primary importance in this interchangeability study, but appliance performance is also regulated by ANSI standard Z83. ANSI Z83 stipulates for the gas-fired commercial foodservice equipment tested in this program that CO emissions are not to exceed 800 parts per million (ppm) corrected to 0 percent O2 (oxygen) for steady state burner operation and/or before burner cycling. Interchangeability goes beyond ANSI requirements by evaluating changes in emissions as the composition of the gas changes. Therefore, an appliance can be well within the 800 ppm ANSI requirement but still be of concern because (1) appliances are not built to be adjusted, and (2) increases in other air pollutant emissions are undesirable.

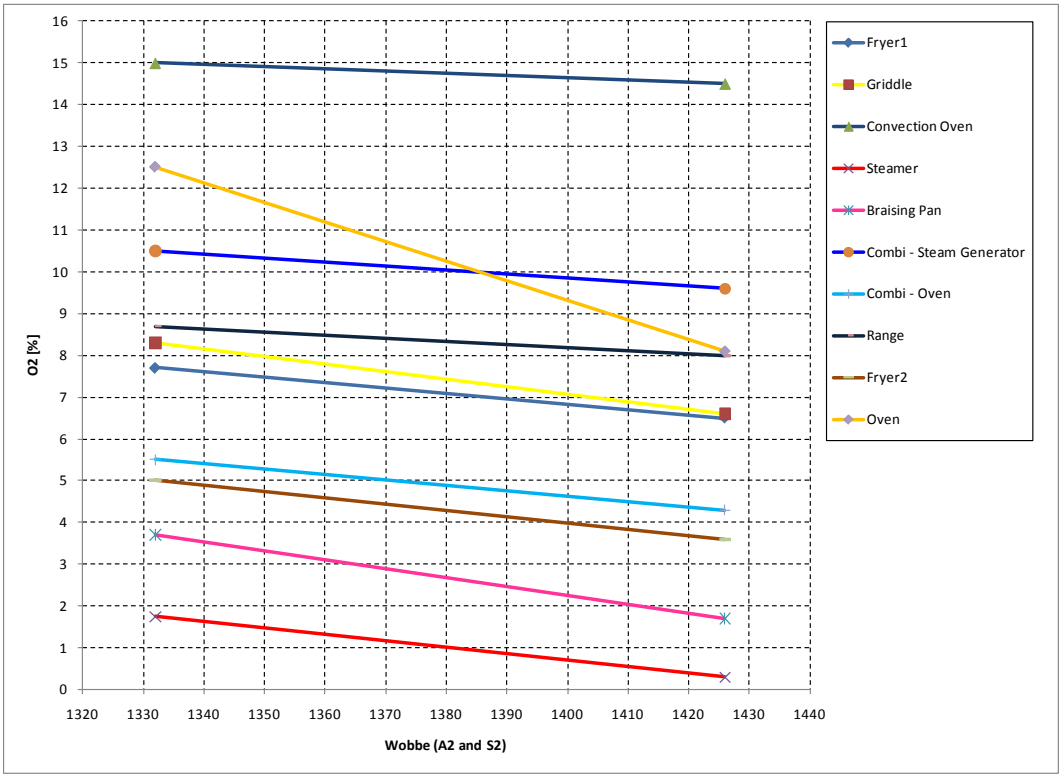
Figure 3-2 shows a summary of the CO emissions from the foodservice equipment tested. CO emissions are shown when firing with the lowest Wobbe gas tested (1309 for Adj 1) and with gas at the California Rule 30 limit of 1385. Four appliances showed a significant increase in CO emissions with increase in Wobbe number. The steamer and the oven are of concern because they showed CO levels near the 800 ppm limit when fired with 1385 Wobbe gas. The griddle is of concern because CO increased from 25 ppm to 40 ppm when increasing Wobbe from 1309 to 1385. The braising pan is of concern because CO increased from 10 ppm to 175 ppm over the 1309 to 1385 Wobbe range. This presents no issues relative to the ANSI limit but does indicate a large percentage increase in CO emissions.

Figure 3-2. Range of CO in Flue Over Wobbe Range of Gases



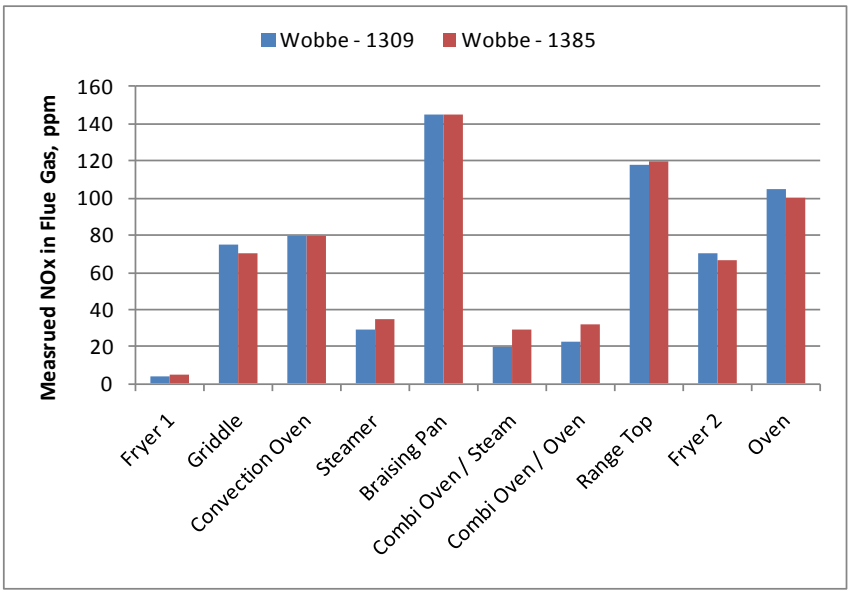
High levels of CO in the exhaust gas usually are produced by burners operated with low excess air. Figure 3-3 shows the measured flue gas oxygen concentration as a function of fuel gas Wobbe number for all of the foodservice equipment tested. Three of the four appliances with CO concentrations above 50 ppmv (steamer, braising pan, and fryer 2) are the three appliances with the lowest exhaust gas oxygen concentrations. The oven also had CO concentrations in the exhaust gas well above 50 ppmv but had high exhaust gas oxygen content. The oven's exhaust gas CO content was high because the higher Wobbe fuel gases increased flame length and caused flame-surface impingement. Flame impingement on a surface is a second combustion operating mode that produces elevated CO impingement.

Figure 3-3. Commercial Foodservice Equipment Exhaust Gas Oxygen Content as a Function of Flue Gas Wobbe Number



Emissions of NOx are also of concern in interchangeability analyses. Figure 3-4 shows the NOx emissions of the foodservice equipment for gases with Wobbe of 1309 and 1385. Unlike CO emissions, the NOx emissions did not vary much with changing fuel gas. However, the NOx did increase for the steamer, the combi oven in steam generation mode, and the combi oven in oven mode. While the increases were modest, any increase for an appliance that cannot be adjusted in the field is of concern in a tight regulatory environment.

Figure 3-4. Range of NOx in Flue over Wobbe Range of Gases



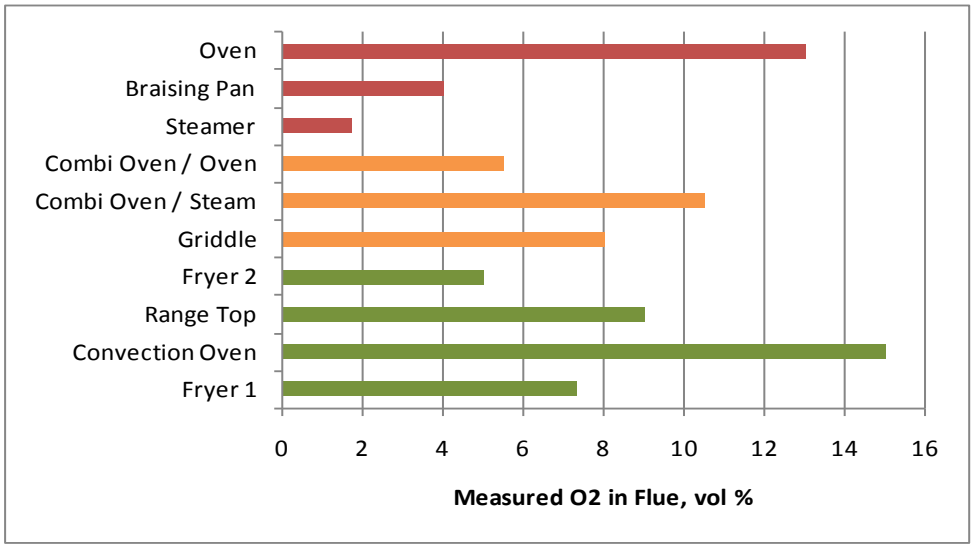
3.4 Summary and Conclusions

Data on both CO and NOx emissions are combined in Figure 3-5 to illustrate which foodservice equipment is of concern for interchangeability. None of the appliances has operational or ignition issues. Short-term temperatures were higher than recommended in some circumstances (particularly the oven), but long-term testing was beyond the scope of this project. Flame lengthening was a concern with high Wobbe gases in the oven.

Emissions concerns can be divided into three groups. Fryer 1, the convection oven, the range top, and fryer 2 did not show any emissions increases (see Figures 3-2 and 3-4). The griddle and the combi oven (although the NOx emission are still within expected range, the increase is of concern) in both steam generation and oven modes showed some increases in emissions and are therefore of mild concern for interchangeability emissions. The steamer, the braising pan, and the oven showed large emissions increases, particularly in CO (with increases of a factor of 3 to 10, and increases of more than 150 ppm CO at 1385 Wobbe vs. 1309 Wobbe), and are therefore of strong concern regarding interchangeability emissions.

Figure 3-5. Summary of CO and NOx Emissions and O2 from Commercial Foodservice Equipment

Appliance		CO at W - 1309	CO at W - 1385	NOx at W - 1309	NOx at W - 1385	CO Concern	NOx Concern
1	Fryer 1	50	20	4.5	5		
2	Griddle	25	40	75	70	x	
3	Convection Oven	25	30	80	80		
4	Steamer	50	700	29	35	x	x
5	Braising Pan	20	170	145	145	x	
6	Combi Oven / Steam	12	15	20	29		x
7	Combi Oven / Oven	7	8	23	32		x
8	Range Top	9	9	118	120		
9	Fryer 2	270	310	70	67		
10	Oven	200	750	105	100	x	



All of the gas-fired commercial foodservice equipment was able to operate for the range of test gases at the Adj2 Wobbe of 1335 without exceeding CO emissions limits to be out of compliance with the standards set in ANSI Z83. However, for the test gases with Wobbe greater than 1350 (see Appendix X), the CO emissions increased to levels that present significant issues with the performance of the burner system for the steamer and braising pan that eventually performed to levels that would not be in compliance with standards established by ANSI. The griddle, fryer2 and oven did not exceed 800 ppm of CO, but exhibited behavior suggesting emissions were tending toward levels of concern. The results show that within the population of commercial foodservice equipment, there is a significant population that could have interchangeability and safety issues with higher Wobbe number natural gases near the 1385 limit.

Foodservice equipment is not designed to be field adjusted. So, unlike industrial combustion systems, the operator has fewer options for dealing with increased emissions from burning natural gas with a higher Wobbe value. Table 3-3 summarizes optimum operating procedures up to 1385 Wobbe for the 10 appliances tested. Trends above 1385 are the same and are shown in the testing report provided in the Appendix. A number of the appliances are fully interchangeable over the full range of gases tested. In cases where a wide range of fuel gases is anticipated, appliance manufacturers should be consulted so their equipment can be adjusted, either before installation or on site to minimize increases in CO and NOx emissions. New appliances are being designed to operate with higher efficiency, but these designs could be prone to higher emissions if improperly adjusted for the fuel gas range fired by the appliance. A more complete study of foodservice equipment examining specific burner designs and focusing in particular on newer appliances operating with low excess air is recommended. These appliances currently are not market leaders and do not make up a large fraction of the in-place equipment, but they are of concern and are expected to grow to a larger fraction of in-place appliances in the future.

Table 3-3. Guidelines for Commercial Foodservice Appliance Operation to Minimize Emissions with Natural Gas Ranging from 1310 to 1385 Wobbe

Foodservice Appliance	Narrow Wobbe Range	Bi-Modal Wobbe Range[1]	Broad Wobbe Range[2]
Fryer 1	Fully interchangeable over the tested range of 1309-1385 Wobbe		
Griddle	Specify Wobbe range to the manufacturer or have tuned to the narrow Wobbe range	Have unit tuned to the higher Wobbe value to prevent higher NOx at the higher Wobbe value	Have unit tuned to the high end of the Wobbe range to prevent any increase of CO for higher Wobbe gases
Convection Oven	Fully interchangeable over the tested range of 1309-1385 Wobbe		
Steamer	Specify Wobbe range to the manufacturer or have tuned to the narrow Wobbe range. Sufficient air must be available to avoid excess CO formation	Have manufacturer increase air to fuel ratio to increase available air and prevent formation of excess CO	Have manufacturer increase air to fuel ratio to increase available air and prevent formation of excess CO. Tune to the upper end of the Wobbe range
Braising Pan	Specify Wobbe range to the manufacturer or have tuned to the narrow Wobbe range. Sufficient air must be available to avoid excess CO formation	Have manufacturer increase air to fuel ratio to increase available air and prevent formation of excess CO	Have manufacturer increase air to fuel ratio to increase available air and prevent formation of excess CO. Tune to the upper end of the Wobbe range
Combi Oven – Steam Generator	Specify Wobbe range to the manufacturer or have tuned to the narrow Wobbe range	Specify for the manufacturer to tune to the higher Wobbe value	Have manufacturer tune to the upper half of the expected Wobbe range
Combi Oven – Oven	Specify Wobbe range to the manufacturer or have tuned to the narrow Wobbe range	Specify for the manufacturer to tune to the higher Wobbe value	Have manufacturer tune to the upper half of the expected Wobbe range
Range Top	Fully interchangeable over the tested range of 1309-1385 Wobbe		
Fryer 2	Fully interchangeable over the tested range of 1309-1385 Wobbe. CO level is high at all Wobbe values. Modification of burner could be carried out to lower the CO emissions.		
Oven	Specify Wobbe range to the manufacturer or have tuned to the narrow Wobbe range	Have manufacturer tune to the higher Wobbe value or increase the air to fuel ratio to decrease CO emissions	Have manufacturer tune to the high end of the Wobbe range or increase the air to fuel ratio to decrease CO emissions

[1] Two gas supplies that are delivered at different times

[2] Gas supply varies randomly and unpredictably

Manufacturer tuning or field tuning of a number of foodservice equipment is needed to avoid increased CO and NOx emissions. Tuning can include changing orifices, adjustment of air ratios, modifying dampers, and changing burners. These are common methods used with appliance combustion systems to maintain the performance of lower Wobbe gases with higher Wobbe gases.

Highly efficient, newer appliances are of particular interest because air-to-fuel ratios are lower. These appliances (not tested in this program because of their low current population) may need adjustment of the burner and combustion systems to maintain low emissions over a wide Wobbe range. Attention must also be paid when operating with high Wobbe gases that the nameplate energy input is not exceeded. A final consideration for some appliances such as the oven is that flame lengthening can lead to increased emissions with higher Wobbe gas. These appliances must be tuned to accept higher Wobbe gas without surface impingement or flame quenching that can increase CO emissions.

CHAPTER 4: Residential Appliances: Summary of Interchangeability Test Results

4.1 Overview

The goal of this component study was to experimentally evaluate the effect of gas quality on residential appliance performance and pollutant emissions. The following specific objectives and focus areas were selected to address gaps in the existing knowledge base:

- Quantify baseline emission rates of ultrafine particles (as indicated by particle number) and formaldehyde from common domestic appliances using natural gas currently distributed by Pacific Gas and Electric Company (PG&E) in Northern California
- Measure the effect of gas quality variability on pollutant emissions from used appliances during operating cycles that start with ignition and include transient periods when the burner is not fully warmed
- Measure emissions of CO, NOx, nitrogen dioxide, particle number, and formaldehyde
- Investigate the effect of gas quality variability on performance and pollutant emission rates for emerging technology devices that have not been adequately examined in past studies
- Investigate and quantify the effect of gas quality variability on performance and pollutant emission rates for common installed appliances

Experiments were conducted on used appliances currently installed in residences and on used and new appliances in the laboratory. Appliances were operated through test cycles designed to capture key variations and transient features of actual use patterns.

4.2 Test Gas Compositions

Appliances were operated with line-supplied natural gas from PG&E as a baseline fuel and with simulated LNG blends. Blends were formulated to achieve Wobbe numbers (a measure of energy delivery rate through a fixed orifice) of roughly 1420, 1390, and in later experiments, 1360 (as calculated from fuel heating value in Btu per standard cubic foot). Compositions of the fuels in the appliance experiments are summarized in Table 4-1. PG&E line gas used in experiments typically was in the range of 1320–1340 Wobbe numbers. (Table 4-1 provides statistics on PG&E blends that were analyzed by gas chromatography during the early phase of the experiments. During later phases of experiments, physical properties of PG&E gas blends were recorded from online data that PG&E provides to customers about fuel being distributed throughout its system.) Two variations each of the 1420 and 1390 Wobbe number fuels were used, as shown in Table 4-1. Early laboratory experiments used site-mixed blends, whereas all field and many laboratory experiments used premixed cylinders.

Table 4-1. Properties of fuels used for appliance experiments

Location:	**Lab/Field**	**Lab**			**Field, Lab[2]**	
Fuel ID:	PG&E	3A	3A + N_2	3C	1C	2C
Valid samples: [(1)]	16	19	12	6 [(3)]	5 [(3)]	5 [(3)]
Methane (%)	95.1 ± 1.5	90.2 ± 0.3	88.6 ± 0.2	86.5 ± 0.2	92.0 ± 0.1	90.4
Ethane (%)	2.65 ± 1.02	5.77 ± 0.13	5.62 ± 0.19	12.0 ± 0.2	8.04 ± 0.08	7.90
Propane (%)	0.44 ± 0.42	2.96 ± 0.10	2.87 ± 0.09	1.57 ± 0.02	-	-
Butanes & C5+ (%)	0.13 ± 0.11	1.09 ± 0.04	1.06 ± 0.03	-	-	-
Nitrogen (%)	0.85 ± 0.21	0.04 ± 0.09	1.80 ± 0.09	-	-	1.70
Carbon dioxide (%)	0.89 ± 0.18	-	-	-	-	-
Heating value (Btu/scf)	1023 ± 17	1123 ± 3	1102 ± 3	1125 ± 2	1071 ± 1	1053
Wobbe number (Btu/scf)	1336 ± 10	1417 ± 2	1385 ± 3	1419 ± 1	1390 ± 1	1359

Data for PG&E and fuels 3A, 3A+N2, 3C and 1C are based on gas chromatographic chemical analysis at LBNL and PG&E. Characteristics of 2C provided by fuel supplier

[(1)] One or two samples were collected per experiment, but often only one was analyzed. Contamination (typically air leakage into bag) was determined by the presence of O_2 or excessive N_2. For example, N_2 was observed at levels of 0.25–0.28% in 3 of 22 samples for fuel 3A; these are excluded from the table.

[(2)] Fuels 1C and 3C were used in lab experiments starting in February 2008. Use of fuel 2C started in January, 2009.

[(3)] Roughly one-third of the fuel samples from the November 2007 field sampling effort were analyzed at PG&E several weeks after collection, and this group had a higher incidence of contamination.

Experiments were conducted on thirteen sets of cooktop burners, twelve oven bottom burners, five dedicated "waist-high" broilers, five storage water heaters, four central forced air furnaces, one wall furnace, and six tankless (on-demand) water heaters. In all but one case, burners were evaluated with PG&E line gas and blends at 1390 and 1420 Wobbe number; many were additionally evaluated with the 1360 Wobbe number blend. Including method development and preliminary evaluations, over 250 experiments were conducted. Measurements of pollutant concentrations, CO2, and oxygen levels in exhaust streams were used to calculate air-free concentrations; fuel properties were used to also calculate emission factors related to fuel energy consumption (for example, in units of nanogram of pollutant emitted per Joule of fuel energy). Results were obtained for CO, NOx, nitric oxide, nitrogen dioxide, and the number of particles over individual burns, and for formaldehyde over multi-burn cycles. Size-resolved measurements showed that the vast majority of particles were < 100 nanometers in aerodynamic diameter; that is, they were ultrafine particles. Cooktops were operated with four burners at maximum firing rate. Broilers and storage water heaters were operated at a single setting and

firing rate. Ovens were operated at three temperature settings and tankless water heaters were operated at three water flow rates. Two of the furnaces were operated at low and high firing rates; the other two were operated at the single firing rate that was available.

4.3 Summary and Conclusions

In no case was basic burner operation (ignition and flame stability) observed to be compromised by use of the higher Wobbe number fuels.

Emissions of all pollutants varied widely across and within burner groups. Baseline emissions of CO, NOx, nitrogen dioxide, and particle number varied with operating mode for oven-bottom and tankless water heater burners. The number of particles emitted was observed to be elevated in the first and sometimes the second experiment of the day in many cases. Bivariate (assuming one variable depends on only one other variable) and multivariate (assuming one variable depends on multiple other variables) linear models were employed to estimate the magnitude and statistical significance of fuel Wobbe number effects on emission rates independent of these factors. Formal statistical analyses were conducted to estimate the effect of fuel Wobbe number on each pollutant emission factor. The dependence of emissions on fuel Wobbe number was assumed to be linear and was calculated per 50 Wobbe number increase. These results can be scaled to estimate impacts for any level of Wobbe number increase up to the bounds of the experimental assessment; that is, to fuels with a Wobbe number of roughly 1420.

The tables provided at the end of this section provide information about the burners evaluated and the number of experiments conducted at each fuel Wobbe level, as well as the measured pollutant emission rates with PG&E line gas, and the estimated percent change in emissions for a 50-unit increase in fuel Wobbe number. This increment represents the shift from fuels currently distributed in much of Northern and Southern California (with typical Wobbe number of roughly 1335) to the current regulated limit of 1385 Wobbe number. In the tables, the abbreviation “ns” indicates that no statistically significant trend was observed for a given pollutant on a given burner; lack of a discernible trend is independent of the magnitude of Wobbe number change.

These results should be considered in the context of potential impacts on air quality and human health. Since cooking appliances typically emit pollutants directly to indoor air, the focus is on pollutants which directly impact health (such as CO, NOx, formaldehyde, and particle number concentration) and a hazard can result from any individual burner with high emissions that increase with an increase in fuel Wobbe number. Emissions of primary pollutants from all groups of burners present a potential ambient air quality concern to the extent that they contribute to overall levels of an area’s pollutants. Nitrogen oxides contribute to air-basin wide ozone and secondary aerosol formation. Since water heating and space heating comprise the majority of residential natural gas use and since emissions of NOx do not vary widely by burner group, the impact of fuel changes on total ambient NOx from residential appliances will depend mostly on water heaters and furnaces.

Among cooking burners with substantial baseline CO emissions (taken here as ≥ 100 nanograms per Joule), almost all had CO increase at rates of 5–40 percent per 50 Wobbe number fuel change. For cooking burners having substantial baseline nitrogen dioxide emissions (taken here as ≥ 5 nanograms per Joule), roughly half had nitrogen dioxide emissions increase; the increase was in most cases on the order of 20 percent or less for a 50 Wobbe number increase in fuel. Only one of the cooking burners with the highest emissions of formaldehyde (⩾ 1 nanograms per Joule) had emissions increase with fuel Wobbe number. Particle number emission rates from cooking burners varied much more with operating conditions (including recent use history) than with fuel Wobbe number. The impacts of cooking burner pollutant emission changes on pollutant exposures in California homes were assessed in the Singer et al. interim project report, Simulation-Based Estimates of Indoor Exposures to Pollutants from Natural Gas Cooking Burners (Appendix F).

Among the vented burners, primary pollutant emissions from tankless water heaters appear to be the most sensitive to fuel Wobbe number. Two of the six tankless water heaters – including the one with highest baseline CO – had CO increase by about 110 percent, and a third had CO increase by 22 percent per 50 Wobbe number fuel increase. Nitrogen dioxide was found to increase by 3–19 percent per 50 Wobbe number increase in five of six tankless water heaters and decrease by 3 percent in the sixth. Formaldehyde was estimated to decrease by 5–22 percent for a 50 Wobbe number change in five of six tankless water heaters. Two of the four central furnaces had CO emissions decrease by 26 percent for a 50 Wobbe number fuel increase.

Consistent with past studies, NOx emissions for most appliances were found to be marginally sensitive to changes in fuel Wobbe number. Mean NOx was estimated to increase by 3–7 percent per 50 Wobbe number increase in three furnaces. The effect was even smaller for the storage water heaters tested. Tankless water heaters had lower NOx on average relative to storage water heaters, but NOx in these burners was much more sensitive to fuel Wobbe number. The outdoor air quality impacts of potential changes to fuel Wobbe number are assessed in Sospedra et al. (2011).

One prominent finding that was not a focus of this study was the starkly different pollutant emissions of tankless and storage water heaters. Tankless units had emissions of CO and formaldehyde that were orders of magnitude higher on average compared with storage water heaters. This finding suggests that a large shift to tankless technology (in the absence of controls on these emissions) could dramatically impact the baseline emission inventory for CO and formaldehyde from natural gas water heating. A major increase in the population of tankless water heaters (with burner technology similar to that evaluated in this study) would also make the CO and NOx inventories for residential gas water heating much more sensitive to changes in gas quality.

Tables 4-2 through 4-7 list and summarize all of the appliance interchangeability tests. Detailed descriptions of equipment set up, test protocols, analytical equipment, and results are presented in Singer et al. (2009).

Table 4-2. Summary of Experiments and Results(1) for Cooktop Burners

ID Site[2]	Burner description and ratings[3] (kBtu/h)	Age	Fuels WN (n)[4]	NO_X (ng/J)	CO (ng/J)	NO_2 (ng/J)	HCHO (ng/J)	PN (10^4/J)
CT01 Lab	sealed; cast Al burner w/slots; cast iron cap; 9.1 (x3), 7	12	PG&E (2) 1390 (3) 1420 (5)	*31.5* *+3.2%*	**11** **+27%**	**6.7** **+14%**	**0.31** **+35%**	11 (1-490)
CT02 Lab	open; stamped Al w/slots; 9 (x4)	9	PG&E (4) 1390 (3) 1420 (3)	37.3 (ns)	*29* *+10%*	**8.5** **+5.7%**	0.55 (ns)	117 (29-460)
CT03 Lab	sealed; cast steel punched ports; 12 (x2), 9.2 (x2)	6	PG&E (2) 1390 (3) 1420 (2)	34.9 (ns)	**231** **+30%**	**12.1** **+20%**	**1.00** **+62%**	265 (90-570)
CT04 Res4	sealed; cast Al burner w/slots; cast iron cap; 16, 12, 9.5, 5	2	PG&E 1420	47.3 (ns)	42 (ns)	10 (ns)	no data	310, 430[5]
CT05 Lab	open; stamped Al w/slots; 9 (x4)	5	PG&E 1390 1420	**41.9** **+4.5%**	87 (ns)	11.2 (ns)	0.67 (ns)	1270 (610-9200)
CT06 Lab	sealed; cast Al burner w/slots; cast iron cap; 12, 9.5 (x2), 5	11	PG&E 1390 1420	*38.5* *+1.7%*	**13** **+93%**	5 (ns)	0.12 (ns)	320 (191-1080)
CT07 Lab	open; stamped Al w/slots; 9 (x4)	13	PG&E 1390 1420	34.2 (ns)	**59** **+16%**	**7.3** **+12%**	**0.44** **+37%**	550 (380-2250)
CT08 Lab	sealed; cast iron, drilled ports; cast iron cap; 10 (x2), 6 (x2)	16	PG&E (2) 1390 1420	33.5 (ns)	**7** **+14%**	6.7 (ns)	0.09 (ns)	305 (129-1640)
CT09 Lab	sealed; cast Al burner w/slots; cast iron cap; 9 (x4)	2	PG&E (2) 1390 1420	25 (ns)	**823** **+5.9%**	17.7 (ns)	4.7 (ns)	197 (101-1110)
CT10 Lab	open; stamped Al w/slots; 9.5 (x4)	12	PG&E 1360, 1390 1420	36.2 (ns)	**57** **+26%**	9.6 (ns)	*1.15* *-28%*	34 (8-183)
CT11	sealed; cast Al burner w/slots; cast iron cap;	8	PG&E	*29.6* *+2.5%*	**107** **+23%**	*7.6* *+4.9%*	0.31 (ns)	168 (68-1100)

Lab	12, 9.5 (x2), 5		1360, 1390 1420					
CT12 Lab	Same as CT03; sealed; cast steel punched ports; 12 (x2), 9.2 (x2)	17	PG&E (2) 1360, 1390 1420	34.3 (ns)	**123** **+40%**	**10.2** **+11%**	0.81 (ns)	1380 (1100-5400)
CT13 Lab	sealed; cast Al burner w/slots; cast iron cap; 12, 9.5 (x3)	6	PG&E (2) 1360, 1390 1420	**34.9** **+1.5%**	**48** **+54%**	**7.1** **+11%**	0.10 (ns)	205 (43-1180)

WN = Wobbe number, NOx = nitrogen oxide, CO = carbon monoxide, NO_2 = nitrogen dioxide, HCHO = formaldehyde, PN = particle number, ng/J = nanogram per Joule, ns = not significant.

(1) For NO_X, CO, NO_2 and HCHO, first value in each cell is full burn emission rate with PG&E line gas. Percent change is for 50 Btu/scf increase in fuel WN adjusted for effect of burner temperature; changes for p-values ≤ 0.15; p ≤ 0.05 in bold (broader limits for HCHO, see text of report), indicating statistically significant results. Values shown for PN are the median and range of particle number counts for individual burns across all fuels.

(2) Res = residence, identified by number.

(3) Rating for each burner. Number of tests in parenthesis if greater than 1.

(4) Number of gases blends tested for that WN fuel in parenthesis if greater than 1.

(5) Only two tests were run.

Table 4-3. Summary of Experiments and Results(1) for Oven Bottom Burners, Adjusted for Effect of Oven Temperature

ID Site	Burner description and rating	Age	Fuels WN (n)(2)	NO_X (ng/J)	CO (ng/J)	NO_2 (ng/J)	HCHO (ng/J)	PN (10^4/J)
OV01 Lab	tube burner under bottom plate; hot surface ignition; 15.5 kBtu/h	12	PG&E (2) 1390 (2) 1420 (4)	35.9 (ns)	**16** **+37%**	3.8 (ns)	0.49 (ns)	27-335 3-48
OV02 Lab	tube burner under bottom plate; pilot ignition; 18 kBtu/h	9	PG&E (3) 1390 (2) 1420 (2)	34.4 (ns)	*99* *+34%*	**7.5** **+18%**	*0.38* *+11%*	75-191 395-6300
OV03 Lab	tube burner under raised bottom; hot surface ignition; 18 kBtu/h	6	PG&E (4) 1390 (2) 1420 (2)	36.3 (ns)	**61** **+93%**	**5.1** **+17%**	0.46 (ns)	18-530 11-122
OV05 Lab	tube burner under bottom plate; hot surface ignition; 18 kBtu/h	5	PG&E 1390 (2) 1420	**31.4** **-2.8%**	**163** **+24%**	13.9 (ns)	*0.43* *+23%*	-4 to 25 81-285
OV06 Lab	tube burner under raised bottom; hot surface ignition; 16 kBtu/h	11	PG&E (2) 1390 (2) 1420	33.0 (ns)	**124** **+5%**	8.1 (ns)	1.01 (ns)	13-144 12-145
OV07 Lab	tube burner under bottom plate; hot surface ignition; 18 kBtu/h	13	PG&E 1390 (2) 1420	**31.8** **-2.4%**	**156** **+5.9%**	**6.1** **+8.5%**	0.57 (ns)	24-76 180-790
OV08 Lab	tube burner under raised bottom; hot surface ignition; 18 kBtu/h	16	PG&E 1360, 1390 1420	**33.3** **-3.9%**	**108** **+30%**	**5.5** **+11%**	*3.0* *-21%*	17-61 18-31
OV09 Lab	tube burner under bottom plate; hot surface ignition; 18 kBtu/h	2	PG&E 1360, 1390 1420	**27.4** **-7.3%**	**174** **+19%**	11.3 (ns)	0.6 (ns)	0-10 -1 to 275
OV10 Lab	tube burner under bottom plate; hot surface ignition; 18 kBtu/h	12	PG&E (2) 1360, 1390 1420	32.9 (ns)	**58** **+26%**	**4.4** **+24%**	0.32 (ns)	11-29 310-890
OV11 Lab	tube burner under bottom plate; hot surface ignition; 16 kBtu/h	8	PG&E 1360, 1390 1420	*40.5* *+2.3%*	**528** **-14%**	13.2 (ns)	5.5 (ns)	89–137 240-2750
OV12 Lab	tube burner under bottom plate; hot surface ignition; 16 kBtu/h	17	PG&E 1360, 1390 1420	**34.5** **-2.2%**	**36** **+15%**	**5.6** **+10%**	0.25 (ns)	101-132 71-89

OV13 Lab	tube burner under bottom plate; hot surface ignition; 18 kBtu/h	6	PG&E (2) 1390 1420	*39.7* *-1.6%*	**70** **+47%**	**6.3** **+38%**	**0.33** **+20%**	0-107 -3 to 36

WN = Wobbe number, NOx = nitrogen oxide, CO = carbon monoxide, NO_2 = nitrogen dioxide, HCHO = formaldehyde, PN = particle number, ng/J = nanogram per Joule, ns = not significant.

(1) For NO_X, CO, NO_2 and HCHO, first value in each cell is mean of full burn emission rates with PG&E line gas measured at 350°F, 425°F, and 500°F. Percent change is for 50 Btu/scf increase in fuel WN adjusted for effect of oven temperature; changes for p-values ≤ 0.15; p ≤ 0.05 in bold (broader limits for HCHO, see text of report), indicating statistically significant results. Values shown for PN are the ranges of particle number counts across all fuels for burns at 350°F and 500°F.

(2) Number of gases blends tested for that WN fuel in parenthesis if greater than 1.

Table 4-4. Summary of Experiments and Results(1) for Broiler Burners

ID Site	Burner description and rating	Age	Fuels WN (n)(2)	NO_X (ng/J)	CO (ng/J)	NO_2 (ng/J)	HCHO (ng/J)	PN (10^4/J)
BR01 Lab	tube burner with spreader; hot surface ignition; 11 kBtu/h	12	PG&E 1390 1420 (4)	**30.8** **+7.6%**	**44** **+45%**	**2.8** **+47%**	no data	44 (26-169)
BR02 Lab	same burner as OV02; 18 kBtu/h	9	PG&E (2) 1390 (2) 1420	30.3 (ns)	**145** **+17%**	11.2 (ns)	no data	2550 (950-2650)
BR03 Lab	tube burner with spreader; hot surface ignition; 13 kBtu/h	6	PG&E (2) 1390 1420	31.7 (ns)	124 (ns)	*13.0* *-7.2%*	no data	245 (138-590)
BR06 Lab	tube burner with spreader; hot surface ignition; 16 kBtu/h	11	PG&E 1390 1420 (2)	**17.1** **-1.4%**	**120** **-5.1%**	7.8 (ns)	*0.93* *+7.5%*	67 (63-107)
BR12 Lab	tube burner with spreader; hot surface ignition; 13 kBtu/h	17	PG&E 1360, 1390 1420	**36.8** **+5.5%**	**29** **+32%**	**5.7** **+13%**	*0.13* *+15%*	295 (69-570)
BR13 Lab	tube burner with spreader; hot surface ignition; 14 kBtu/h	6	PG&E 1360, 1390 1420	*30.1* *-4.0%*	*178* *+14%*	12.6 (ns)	*0.79* *+20%*	410 (245-1070)

WN = Wobbe number, NOx = nitrogen oxide, CO = carbon monoxide, NO_2 = nitrogen dioxide, HCHO = formaldehyde, PN = particle number, ng/J = nanogram per Joule, ns = not significant.

(1) For NO_X, CO, NO_2 and HCHO, first value in each cell is full burn emission rate with PG&E line gas. Percent change is for 50 Btu/scf increase in fuel WN; changes for p-values ≤ 0.15; p ≤ 0.05 in bold (broader limits for HCHO, see text of report), indicating statistically significant results. Values shown for PN are the median and range of particle number counts for individual burns across all fuels.

(2) Number of gases blends tested for that WN fuel in parenthesis if greater than 1.

Table 4-5. Summary of Experiments and Results(1) for Central Forced Air and Wall Furnaces

ID Site[2]	Burner description and rating	Age	Fuels WN (n)[3]	NO_X (ng/J)	CO (ng/J)	NO_2 (ng/J)	HCHO (ng/J)	PN (10^4/J)
CF01 Res2 (mix)	condensing 94% eff.; induced draft; direct vent; 60 kBtu/h	5	PG&E 1390 1420	**33.6** **+7.2%**	3.8 (ns)	2.4 (ns)	no data	0.0 (-0.3 to 0.8)
CF02 Res4 (high)	non-cond. 82% eff.; induced draft; 80 kBtu/h	5	PG&E 1390 1420	27.1 (ns)	*13.0* *+21%*	5.9 (ns)	no data	3.9, 4.9, 5.5[4]
CF02 Res4 (low)	non-cond. 81% eff.; induced draft; 80 kBtu/h	5	PG&E 1390 1420	26.2 (ns)	**30.8** **-6.2%**	9.7 (ns)	no data	1.0, 1.5, 3.5[4]
CF03 Res7	non-cond. 81% eff.; induced draft; 69 kBtu/h	9	PG&E 1390 1420	**22.3** **+2.5%**	**19.4** **-26%**	5.1 (ns)	**0.38** **-34%**	27 (16-46)
CF04 Res8	condensing 93% eff.; induced draft; direct vent; 100 kBtu/h	6	PG&E(2), 1390 1420	**23.6** **+5.5%**	**17.2** **-26%**	**4.4** **-14%**	**0.16** **-24%**	no data
WF01 Res1	Pilot; gravity direct vent; 72% eff.; 14 kBtu/h	4	PG&E 1390 1420	32.7 (ns)	<1 (ns)	0.6 (ns)	no data	12 (3.9-30)

WN = Wobbe number, NOx = nitrogen oxide, CO = carbon monoxide, NO_2 = nitrogen dioxide, HCHO = formaldehyde, PN = particle number, ng/J = nanogram per Joule, ns = not significant.

(1) For NO_X, CO, NO_2 and HCHO, first value in each cell is full burn emission rate with PG&E line gas. Percent change is for 50 Btu/scf increase in fuel WN adjusted for effect of burner temperature; changes for p-values ≤ 0.15; p ≤ 0.05 in bold (broader limits for HCHO, see text of report), indicating statistically significant results. Values shown for PN are the median and range of particle number counts for individual burns across all fuels.

(2) Res = residence, identified by number. CF01 started at low then changed to high firing rate during 6 of 7 burns with valid data; full-burn rates include both types of operation. In each experiment, CF02 operated in low firing mode for first burn, high firing mode for second burn.

(3) Number of gases blends tested for that WN fuel in parenthesis if greater than 1.

(4) Only two test runs were conducted.

Table 4-6. Summary of Experiments and Results(1) for Storage Water Heaters

ID Site[2]	Description and rating	Age	Fuels WN (n)[3]	NO_X (ng/J)	CO (ng/J)	NO_2 (ng/J)	HCHO (ng/J)	PN (10^4/J)
WH01 Lab-A	40 gal FVIR; pilot; natural draft; std. burner; 40 kBtu/h	new	PG&E 1390 1420	**13.6** **-2.5%**	0.1 (ns)	**0.30** **-67%**	no data	3.2 (1.0-8.4)
WH01 Lab-B	See above	-	PG&E 1420	26.3 (ns)	*-0.7* *-0.07*	*1.55* *-1%*	0.03 (ns)	23 (15-40)
WH02 Res2	40 gal, pre-FVIR; pilot; natural draft; std. burner; 40 kBtu/h	6	PG&E 1390 1420	**31.9** **+3.7%**	*-0.4* *+0.2*	2.22 (ns)	no data	0.3 (-1.3 to 2.6)
WH03 Res4	50 gal pre-FVIR; piloted; natural draft; std. burner; 40 kBtu/h	4	PG&E 1390 1420	24.0 (ns)	**-1.0** **+0.5**	*0.37* *+65%*	no data	4.7 (2.8-8.9)
WH04 Lab	40 gal induced draft; FVIR; spark igniter (no pilot); 40 kBtu/h	new	PG&E 1390 1420	**29.0** **+2.8%**	**2.0** **-0.5**	**2.18** **-21%**	*0.05* *-14%*	8.7 (4.7-14)
WH05 Res8	42 gal pre-FVIR; pilot; natural draft; std. burner; 34 kBtu/h	17	PG&E (2) 1390 1420	28.8 (ns)	**0.4** **+2.2**	**1.67** **+24%**	0.05 (ns)	22 (11-51)

WN = Wobbe number, NOx = nitrogen oxide, CO = carbon monoxide, NO_2 = nitrogen dioxide, HCHO = formaldehyde, PN = particle number, ng/J = nanogram per Joule, ns = not significant.

(1) For NO_X, CO, NO_2 and HCHO, first value in each cell is full burn emission rate with PG&E line gas. Percent change is for 50 Btu/scf increase in fuel WN adjusted for effect of burner temperature; changes for p-values ≤ 0.15; p ≤ 0.05 in bold (broader limits for HCHO, see text of report), indicating statistically significant results. Values shown for PN are the median and range of particle number counts for individual burns across all fuels.

(2) Res = residence, identified by number. WH01 experiments repeated because of low NO_X results in first set.

(3) Number of gases blends tested for that WN fuel in parenthesis if greater than 1.

Table 4-7. Summary of Experiments and Results(1) for Tankless Water Heaters, Adjusted for Effect of Water Flow Rate

ID Site[2]	Venting and burner range (kBtu/h)[3]	Age	Fuels WN (n)[4]	NO_X (ng/J)	CO (ng/J)	NO_2 (ng/J)	HCHO (ng/J)	PN (10^4/J)
TW01 Lab	direct vent; 19-180	<1 [3]	PG&E (2) 1390, 1420	**24.0 +4.6%**	**50 -13%**	**8.9 +2.8%**	**1.5 -22%**	0.8 (0.1-6.7)
TW02 Res5	ducted; 20-185	6	PG&E 1390, 1420	**16.0 +45%**	**37 +109%**	**6.6 +19%**	*0.72 -16%*	0.1 (-0.4-0.8)
TW03 Res6	direct vent; 37-165	3	PG&E (2) 1390, 1420	**18.0 +3.0%**	87 (ns)	**6.1 +5.3%**	*2.4 -5.0%*	0.1 (-0.6-14)
TW04 Res7	direct vent; 15-199	4	PG&E (2) 1390, 1420	**9.0 +31%**	**19 +22%**	**4.0 +17%**	**0.25 -8.6%**	3.1 (0.4-16)
TW05 Lab	direct vent & ducted; 19-199	new	PG&E(2) 1390, 1420	**21.0 +7.2%**	**47 -1.3%**	**8.5 +5.8%**	2.0 (ns)	11.4 (0.9-27)
TW06 Lab	direct vent & ducted; 25-180	new	PG&E (3) 1390 1420 (2)	**31.0 +17%**	**434 +111%**	*7.9 -3.0%*	*0.24 -6.4%*	1.0 (0.0-15)

WN = Wobbe number, NOx = nitrogen oxide, CO = carbon monoxide, NO_2 = nitrogen dioxide, HCHO = formaldehyde, PN = particle number, ng/J = nanogram per Joule, ns = not significant.

(1) For NO_X, CO, NO_2 and HCHO, first value in each cell is mean full burn emission rate with PG&E line gas measured at 1, 2 and 3 or 4 gallons per minute. Percent change is for 50 Btu/scf increase in fuel WN adjusted for effect of water flow rate; changes for $p \leq 0.15$; $p \leq 0.05$ in bold (broader limits for HCHO, see text of report), indicating statistically significant results. Values shown for PN are the median and range of particle number counts for individual burns across all fuels.

(2) Res = residence, identified by number.

(3) All TWs had ribbon burners with fan-assisted combustion. All but TW01 were certified to meet 40 ng/J NO_X std. TW01 purchased in 2001 and used for approximately 6 months in portable classroom, then stored at LBNL until used in this study.

CHAPTER 5:
Combustion Modeling Study of Fuel Changes for Typical Residential Burner

5.1 Overview

This chapter provides a summary of a modeling effort that is described in detail in an interim project report (Tonse and Singer, 2011).

This modeling study's scientific goal was to increase understanding of the impacts of natural gas energy supply rate and composition on device performance and pollutant emissions. For this modeling study, gas composition was set as a mixture of methane, ethane, and propane. These mixtures are simplified, but the compositions reflect the overall physical properties representative of either current supplies from domestic sources ("baseline" natural gas) or liquefied natural gas blends.

The modeling tool used for this study is a reactive computational fluid dynamics computer program that represents the physical domain of the flame with a three-dimensional spatial grid. Due to computational constraints, only a single flame (issuing from a single port) was modeled, rather than the entire ring of flames from a real-world burner. By symmetry the expectation is that the multiple flames should be very similar, although it is acknowledged that any inter-flame interaction will not be captured. The modeling grid covers the physical extent of a single flame and its surroundings. Similar to real-world residential burners, in which a portion of the air for combustion is mixed within the burner head prior to issue from the port (primary air), the simulation includes a partially premixed gas-air mixture entering the main grid through a horizontal inflow port, resulting in a fuel-rich premixed flame. The remaining air necessary to complete combustion is obtained from the open atmosphere (secondary air), and results in a diffusion flame or non-premixed flame, just downstream of the premixed flame. These regions can be distinguished when observing a range-top residential burner in one's own kitchen. Before commencing the computer simulation, each grid cell is assigned an initial temperature, pressure, velocity, and mixture of individual gaseous chemical species.

Starting from an initial time, the state of the system is advanced in discrete time steps. At every time step the physical and chemical processes that occur within real flames are simulated by numerical equations. The simulation is considered complete when the flame attains a steady appearance. This fully developed simulated flame provides data on general properties of the flame and gas flows, and spatial distribution and production of carbon monoxide, nitric oxide, and formaldehyde.

A series of such computer simulations were conducted, varying the gas composition of the fuel and the heat-release rate of the burner between simulations. The heat-release rate was manipulated by changing the velocity though the inflow port and also by changing the relative ratios of fuel and primary air.

The specific objective and focus areas were as follows:

- Conduct simulations with a baseline gas composition to understand:
  - The internal features of the flame, including mapping of exhaust gas flow velocity and direction as well as the mixing of secondary air with partial combustion products of fuel and primary air
  - Formation, location, and overall emissions of CO, nitric oxide, and formaldehyde
- Using baseline gas, conduct a sensitivity study in which the inflowing gas parameters are set at values centered on real-world operating conditions but cover a wider than normal operating range. During this study, the port velocity and fuel air mixture were varied independently. The objective was to determine the degree to which flame properties and other outputs vary as the inputs are changed.
- Select two additional gases similar in composition to those used in the experimental sub-tasks of this study. The criteria for specifying these fuels were to introduce significant variation (1) in the relative amounts of ethane and propane, and (2) in heating value. Compare simulation results in which gases are interchanged while other parameters were held constant.

5.2 Summary and Conclusions

The flame resulting from a typical simulation had the smooth, laminar appearance characteristic observed in range-top burner flames. A portion of the combustion was premixed, using air mixed with the gas issuing from the inlet port. The remainder of combustion was completed with outside atmospheric air. The hottest region of the flame was seen to be just above the inlet port. This also was the region with the highest carbon monoxide concentrations and the highest thermal nitric oxide production.

During the sensitivity study (seven simulations with baseline gas), the inflow rate and fuel-to-air ratio were varied. Trends observed during this study included:

- Increasing inflow velocity resulted in longer flame length, longer distance from the port to the point where burning commenced, and farther flame extent in the horizontal direction.
- Increasing fuel-to-air ratio (keeping velocity constant) resulted in a larger flame, with the flame front farther from the port.

The unburned region between the inlet port and flame was angled more sharply upward, possibly because of the increased combustion rate. A single simulation conducted with a doubled heat delivery rate showed the horizontal extent of the flame larger, as expected, but flame height did not change as significantly.

In all of the simulations, the region of highest CO concentration was in the afore-mentioned region of high temperature just above the inlet port. Keeping fuel-to-air ratio constant and increasing inlet port velocity, CO was seen to come increasingly from this region.

Velocity had a stronger influence on the spatial distribution of CO than did the fuel-to-air ratio.

Nitric oxide increased with both increasing inlet velocity and increasing fuel-to-air ratio. The spatial distribution of nitric oxide showed regions of high concentration near the inlet, particularly above the flame.

In the model, formaldehyde was largely consumed within the flame and only insignificant quantities (parts-per-billion levels) exited the top of the simulation grid. Laboratory studies of formaldehyde production in Bunsen flames (at parts per million levels) conclude that formaldehyde as a pollutant results mainly from cooling of the flame by quenching near surfaces that conduct heat away, thereby suppressing reactions responsible for removing formaldehyde. To accurately reproduce this in the model would require refinements and additional simulations beyond the scope of the work.

Six simulations (three at medium and three at high heat release) were conducted to compare baseline fuel to two simulated LNG blends. The two LNGs had heating values and Wobbe numbers higher than the baseline fuel. From spatial plots of temperature, CO, and nitric oxide, some difference in spatial patterns was seen between the cases but nothing indicated that the basic flame properties were significantly different. When CO and nitric oxide pollutant concentrations at the top of the simulation space were integrated and summed, it was seen that the simulated LNG fuels had slightly higher pollutant emissions.

The computer model reproduces the general characteristics of the flame. A sensitivity study indicated that flame properties and pollutant levels changed gradually as the heat release in the model is varied, and follows trends that are intuitively expected. No sudden changes or transitions in flame behavior were observed in the sensitivity study. For the flame conditions studied, a high-temperature region located above the port was responsible for an increasing fraction of overall CO production as inflow velocity was increased. The same region is also responsible for most of the thermal nitrogen oxide production. Further study of this area with both a modeling component and an experimental component may be instructive. Formaldehyde is almost completely consumed within the flame, and concentrations leaving the simulation grid are negligible.

Differences in flame properties and pollutant levels seen when interchanging LNGs with the baseline gas appear to be primarily as a result of the higher heating value of the LNGs, and not directly as a result of the differing proportions of methane, ethane, and propane. An investigation of production, destruction, and interaction between intermediate species along the oxidation paths of methane, ethane, and propane qualitatively explains why the carbon monoxide production is so similar for all three fuel mixtures.

CHAPTER 6:
Indoor Air Quality Impacts of Changing Fuel Gas Compositions

6.1 Simulation-Based Estimates of Indoor Exposures to Pollutants from Natural Gas Cooking Burners

6.1.1 Methods

The first two sections of this chapter provide a summary of a modeling effort that is described in detail in an interim project report (Singer, Lobscheid, Klepeis, 2011).

The principal objective of this research task was to quantitatively assess the impacts of LNG on residential pollutant concentrations and exposures associated with cooking burner use in California. The selected approach was intended to allow for quantitative assessment of the distribution of exposures across the population (that is, not just average levels).

The general approach of this study began with measuring the quantity of pollutants emitted from the use of conventional natural gas in cooking burners, as well as the occupants' exposures to those emissions. Then the same analysis was conducted for LNG use. These analyses were accomplished with a physics-based, data-supported simulation model designed to allow analysis at county, region, or statewide scales. The model builds sample cohorts of homes from a database that is representative of the population of California residences. Time-resolved pollutant concentrations within each home were calculated using a physically based mass balance model that accounts for emissions, dilution, deposition to surfaces, and removal by air exchange. Parameters that affect these processes–including building characteristics and household cooking activity patterns–were drawn from several sources, including the California Residential Appliance Saturation Survey.

The study assessed the potential health impact of LNG through a set of quantitative exposure metrics. These include the distribution of concentrations in residences and among individual occupants averaged over periods of one hour to one week. These household and individual exposure concentrations were compared to acute and chronic health standards and guidelines, and the rates at which the standards were exceeded were tracked. Because there are no formal standards to assess indoor exposures, project engineers relied on ambient air quality standards set by the United States Environmental Protection Agency (U. S. EPA) and the California Environmental Protection Agency (Cal/EPA), and on guidelines established by the Agency for Toxic Substances and Disease Registry and California's Office of Environmental Health Hazard Assessment. Table 6-1 presents a summary of the standards and guidelines used as benchmarks against which calculated residential exposure concentrations are compared.

Table 6-1. Pollutant Standard and Guideline Concentrations for Various Exposure Periods

Pollutant	1-hr Average [a] (acute)	8-hr Average [a] (acute)	Annual Average [a] (chronic)	Agency [b]
CO	20 ppm (23 mg/m^3)	9 ppm (10 mg/m^3)	n/a	CAAQS (ARB)
	35 ppm (40 mg/m^3)	9 ppm (10 mg/m^3)	n/a	NAAQS (EPA)
NO_2	180 ppb (339 µg/m^3)	n/a	30 ppb (57 µg/m^3)[c]	CAAQS (ARB)
	100 ppb (188 µg/m^3) [d]	n/a	53 ppb (100 µg/m^3)	NAAQS (EPA)
Formaldehyde (HCHO)	40 ppb (49 µg/m^3)	8 ppb (9.6 µg/m^3)	8 ppb (9.6 µg/m^3)	ATSDR
	45 ppb (55 µg/m^3)	7.3 ppb (9 µg/m^3)	7.3 ppb (9 µg/m^3)	OEHHA non-cancer REL

[a] Units: ppm = parts per million; ppb = parts per billion; mg = milligrams; µg = micrograms; m^3 = cubic meter .

[b] ATSDR = Agency for Toxic Substance and Disease Registry; CAAQS = California Ambient Air Quality Standards set by the California Air Resources Board (ARB), listed in the Table of Standards in Section 70200 of Title 17 of the California Code of Regulations; NAAQS = National Ambient Air Quality Standards set by the U.S. EPA (U.S. EPA, 1990); OEHHA = Office of Environmental Health Hazard Assessment; REL = Reference exposure level.

[c] The California ambient air quality standard was enacted March 20, 2008.

[d] The U.S. EPA NO_2 1-hr NAAQS was enacted February 9, 2010, and effective as of April 12, 2010.

The model was configured to simulate one week of activity in the summer or winter using seasonally appropriate, county-resolved ambient air quality data. Both summer and winter scenarios used air exchange or ventilation rates assigned from building-age dependent and seasonally specified empirical distributions. These distributions were derived from available measurements that have been made in California homes and are identified in results tables as "Empirical." The winter scenario was additionally simulated to consider air exchange solely by infiltration, which corresponds to minimal or no window opening or use of other mechanical exhaust fans. These scenarios are identified in results tables as "Infiltration." The rate of air infiltration depends on the difference between outdoor and indoor temperature, winds, and the tightness or leakiness of the building. A value for building tightness was assigned to each simulated residence based on building age and type, with different values for single detached homes and apartments.

The modeled residential exposure concentrations were linked with archetypal time-activity patterns of time spent at home for each individual in a given household. Simulations separately tracked pollutants emitted from the gas cooking burners and pollutants coming from outdoors. This separation allowed for an assessment of exposure concentrations resulting only from cooking burner emissions and also for the combined effects of cooking burner emissions and pollutants entering from outdoors.

The model also takes into account near-source, or proximity effects, on the exposures to the household member that is doing the cooking (the "cook"), and to young children (aged 0–5 years) in the household who are at home and assumed to be near the cooking adult. The proximity effect was expressed only for pollutants emitted from the burners. The effect of being near the cooking burners was calculated by multiplying the well-mixed concentration in the home by a proximity multiplier; this was applied only to the well-mixed concentration of pollutants emitted by the cooking burners. We selected multipliers based on a review of relevant published research. The baseline proximity multipliers were 2.0 for the adult cook and 1.5 for young children. Thus, during a cooking event, one adult who was assigned as the "cook" was assumed in the model to be exposed to cooking burner pollutants at twice the level that persists throughout the rest of the home. The nearby child was assumed to have exposure that was 50 percent higher during cooking. In the model, the cook and young children were exposed to pollutants from outdoors at the home average level.

Once the cooking event ended, the model calculated exposure for both the cook and the child at the home average level. Since the values of these proximity multipliers were uncertain, the research team conducted a sensitivity analysis to assess the extent to which final results would vary if these multipliers were higher or lower than the estimated values of 2.0 and 1.5. To assess this sensitivity, the team conducted runs with proximity values set to twice the baseline values (4.0 for the cook, 3.0 for young children) or to 1.0; that is, with no higher exposure assumed for the person cooking or young children nearby. The model considered that everyone else in the home – excluding the cooking adult and children 0–5 years old – were exposed to the well-mixed pollutant concentration in the home. While the exact magnitude of the effect is uncertain, the near-source or proximity effect is known to occur and to be important to exposure. The inclusion of this effect and the analysis of uncertainty about its magnitude reflect a best effort to achieve accurate and transparent results.

6.1.2 Summary and Conclusions of IAQ Impacts

Table 6-2 shows summary results for the calculated indoor pollutant concentrations resulting from gas cooking burner use in Southern California. Results are presented for CO, NO_2, and formaldehyde (HCHO) considering only emissions from cooking burners, and for CO and NO_2 considering both cooking burner emissions and entry from outdoors. Results are presented as the averages of the values calculated for 6,634 Southern California homes selected from the Residential Appliance Saturation Survey database. Results are presented for acute (highest one-hour concentration) and chronic (time-averaged over one week of simulations) durations and for the variations in season (winter, summer) and air exchange conditions (calculated based on infiltration only or selected from an empirical distribution of measurements) as described

above. In each cell, the first value shown is the average of the concentrations calculated for all the homes using emission factors measured for conventional natural gas; in parentheses is the change in the average concentration resulting from LNG use in all of the homes.

Total concentrations – including outdoor sources and the concentrations resulting only from cooking burner emissions – are higher in winter than in summer. Total concentrations are also higher for the infiltration-only scenario as compared to empirical air exchange rate scenarios, owing to lower air exchange rates (in winter compared with summer, or with infiltration only compared to empirical distributions in winter) and thus slower removal of the pollutants emitted in residences by gas cooking burners.

In almost all cases, use of LNG is found to have a discernible but small impact on average pollutant concentrations in residences. On a relative basis, LNG use is predicted to change average concentrations by less than 5 percent in most cases, and by less than 10 percent in almost all cases. Larger relative increases in indoor pollutant concentrations are seen only when the concentrations resulting from conventional natural gas combustion are very small.

Table 6-2. Model Predicted Indoor Pollutant Concentrations Averaged Across a Cohort of 6,634 Southern California Homes from the 2003 Residential Appliance Saturation Survey Database

Pollutant	Season	Summer	Winter	
Metric	AER[a]	Empirical	Infiltration	Empirical
		(a) Only gas cooking burners		
CO (ppm)				
Highest 1-hr		2.9 (+0.5)	5.1 (+0.9)	4.3 (+0.7)
1-week average		0.2 (+0.03)	0.9 (+0.1)	0.5 (+0.1)
NO_2 ($\mu g/m^3$)				
Highest 1-hr		148 (+11)	207 (+16)	190 (+14)
1-week average		6.4 (+0.4)	10.8 (+0.8)	9.3 (+0.7)
HCHO ($\mu g/m^3$)				
Highest 1-hr		23.2 (+0.7)	40.8 (+1.1)	33.9 (+1.0)
Highest 8-hr		6.9 (+0.2)	24.0 (+0.6)	14.9 (+0.5)
1-week average		1.6 (+0.1)	6.8 (+0.2)	3.7 (+0.2)
		(b) Gas cooking burners and outdoors[b]		
CO				
Highest 1-hr		3.2 (+0.5)	5.9 (+0.9)	5.1 (+0.8)
Highest 8-hr		1.1 (+0.2)	3.9 (+0.6)	2.9 (0.3)
1-week average		0.43 (+0.04)	1.70 (+0.15)	1.33 (+0.08)
NO_2 ($\mu g/m^3$)				
Highest 1-hr		158 (+12)	215 (+16)	204 (+15)
Highest 8-hr		40.4 (+2.2)	55.2 (+3.3)	54.9 (+2.2)
1-week average		17.6 (+0.4)	17.0 (+0.9)	20.8 (+0.7)

Concentrations resulting (a) solely from gas cooking burner emissions and (b) from gas cooking burners plus entry from outdoors. Each column presents results for a scenario defined by season and home air exchange rate (AER) estimation method. The first number in each cell is the modeled value with conventional natural gas; in parentheses is the change resulting from LNG use. These results can be compared against the health-based benchmarks in Table 6-1.

[a] Air exchange rate scenarios. For Empirical, an AER is assigned to each home from age- and seasonally resolved distributions of measurements compiled from studies of California homes. The Infiltration-only scenario first assigns to each home an air tightness value based on the building age and type, then calculates air exchange with a validated physical model that assumes no window or fan use. See the text of the main report for additional details.

[b] Results presented under (b) include pollutant emissions from the gas cooking burner, in addition to pollutants coming indoors from outdoors with ventilation air. Outdoor pollutant levels were derived from data collected at ambient air monitoring stations, resolved to a county level.

Table 6-3 provides analogous summary statistics for the 19,288 individual residents of the homes included in this modeling study, but presents only the contribution of gas cooking burners to exposure concentrations. Average concentrations are higher for individuals (Table 6-3) relative to values for homes (Table 6-2), owing to the proximity effect. Each time a cooking burner is used, there must be at least one adult close to the source, and thus more highly exposed. The effect is larger for acute exposures and larger for NO_2 relative to the other two pollutants because the proximity multiplier is applied only for the duration of cooking, and thus more reflects the conditions extant before deposition to surfaces removes much of the emitted NO_2 from the air.

Table 6-3. Model Predicted Indoor Exposure Concentrations Attributable to Gas Cooking Burner Emissions Averaged Across 19,288 Individuals Living in Southern California

Pollutant and Metric	Season	Summer	Winter			
	AER[a]	Empirical	Infiltration	Empirical		
	F_{prox}[b]	(2, 1.5)	(2, 1.5)	(2, 1.5)	(4, 3)	(1, 1)[c]
CO (ppm)						
Highest 1-hr		3.5 (+0.6)	5.8 (+1.1)	4.9 (+0.6)	6.8 (+1.2)	4.2
1-week average		0.3(+0.04)	0.9 (+0.1)	0.5 (+0.1)	0.5 (+0.1)	0.5
NO_2 ($\mu g/m^3$)						
Highest 1-hr		183 (+14)	251 (+19)	231 (+18)	336 (+26)	185
1-week average		7.5 (+0.6)	12.1 (+0.9)	10.5(+0.8)	13.8 (+1.0)	9.0
HCHO ($\mu g/m^3$)						
Highest 1-hr		27.8(+0.7)	46.5 (+0.8)	39.0(+1.0)	54.2 (+1.4)	33.1
1-week average		1.8 (+0.1)	6.8 (+0.2)	3.8 (+0.1)	4.3 (+0.1)	3.6

The cohort was developed from data included in the 2003 Residential Appliance Saturation Survey database. The first number in each cell is the modeled value with conventional natural gas; in parentheses is the change resulting from LNG use. Each column presents results for a scenario defined by season, home air exchange rate estimation method, and assumed multipliers for higher exposures of the person cooking and nearby young children. These results can be compared against the health-based benchmarks in Table 6-1.

[a] Air exchange rate (AER) scenarios. For Empirical, an AER is assigned to each home from age- and seasonally resolved distributions of measurements compiled from studies of California homes. The Infiltration-only scenario first assigns to each home an air tightness value based on the building age and type then calculates air exchange with a validated physical model that assumes no window or fan use. See text of main report for additional details.

[b] Proximity effect multiplier. During cooking, household average concentrations multiplied by the two values shown to estimate, respectively, the higher exposures of adult cook and 0- to 5-year-old children assumed to be in same room or nearby to cook. See the text for additional details.

[c] Only the conventional natural gas scenario was modeled.

Table 6-3 also provides an estimate of the sensitivity of results to the specific values selected for proximity effect multipliers. Using the winter empirical air exchange scenario as a basis, the rightmost columns show that variation in the proximity multiplier has a larger impact on average NO_2 concentrations than on average concentrations of other pollutants, and a larger

impact on acute exposure metrics than on chronic exposure metrics. As noted above, the base and bounding values for proximity multipliers were developed from a review of relevant published data. The proximity effect and the correct multipliers to use will vary based on the layout of the home, occupant activities, and many other factors. The intent of the sensitivity analysis was to assess the extent to which uncertainty in the proximity multiplier affects overall results.

As with the home air concentrations, the effect of LNG on individual exposure concentrations is discernible and varies by pollutant. Liquefied natural gas is found to increase average formaldehyde exposure concentrations by a few percent or less, to affect NO_2 concentrations by 5–10 percent, and to affect CO by as much as 20 percent relative to baseline natural gas, depending on the scenario.

Table 6-4 shows the frequency, among 1,000 simulated individuals, of being exposed to concentrations exceeding a relevant acute air quality standard or guideline, based solely on emissions from gas cooking burners. Results indicate exceedance rates of 2.6–5.5 percent for CO, 15–25 percent for formaldehyde, and 31–46 percent for NO_2 across scenarios, when conventional natural gas use and base (best estimate) proximity multipliers are assumed. When LNG is used, exceedance rates increase by 0.5–1.2 percent for CO, 0.5–2.0 percent for formaldehyde, and 3.2–3.4 percent for NO_2, in absolute percentages. Relative to exceedance rates for baseline natural gas, these increases are discernible and vary from a roughly 20 percent relative increase for CO to roughly 10 percent or less relative increases for NO_2 and formaldehyde. Thus, among those households that use natural gas cooking burners, the fraction of the population that will be exposed to pollutants at concentrations exceeding health-based standards and guidelines will increase marginally when LNG is used.

Table 6-4. Model-predicted Rate per 1000 at which Southern California Residents are Exposed in Their Homes to Pollutant Concentrations Exceeding an Acute Air Quality Standard or Guideline

Pollutant and standard[a]	Season	Summer	Winter			
	AER[b]	Empirical	Infiltration	Empirical		
	F_{prox}[c]	(2, 1.5)	(2, 1.5)	(2, 1.5)	(4, 3)	(1, 1)[d]
CO 1-hr (CA)		26 (+5)	55 (+12)	43 (+9)	75 (+16)	33
NO_2 1-hr (U.S.)		312 (+32)	456 (+35)	416 (+34)	493 (+30)	334
HCHO 1-hr		147 (+5)	248 (+20)	210 (+13)	271 (+12)	181

The rate is the number of residents exposed above the standard per 1,000 residents living in homes that use gas cooking burners at least once per week. Results are based solely on pollutant emissions from gas cooking burners, excluding all other sources. The first number in each cell is the modeled value with conventional natural gas; in parentheses is the change resulting from LNG use. Each column presents results for a scenario defined by season, home air exchange rate (AER), estimation method, and assumed multipliers (Fprox).

[a] From Table 6-1, CAAQS for CO (1 hour, 20 ppm); NAAQS for NO_2 (190 micrograms per cubic meter averaged over 1 hour); ATSDR HCHO guideline (49 micrograms per cubic meter over 1 hour).

[b] Air exchange rate scenarios. For Empirical, an AER is assigned to each home from age- and seasonally resolved distributions of measurements compiled from studies of California homes. The Infiltration-only scenario first assigns to each home an air tightness value based on the building age and type, then calculates air exchange with a validated physical model that assumes no window or fan use. See the text of the main report for additional details.

[c] Proximity effect multiplier. During cooking, household average concentrations multiplied by the two values shown to estimate, respectively, the higher exposures of adult cook and 0- to 5-year-old children assumed to be in same room or nearby to cook. See text for additional details.

[d] Only the conventional natural gas scenario was modeled

Exposure to pollutants emitted by natural gas cooking burners represents a substantial public health concern in California. The modeling results of this study indicate that when natural gas cooking burners are used without kitchen exhaust ventilation, a substantial fraction of users will be exposed to pollutant concentrations that exceed health-based standards and guidelines. Modeling for Southern California suggests that among the population that lives in households that have and use gas cooking burners, each winter roughly 40—45 percent will be exposed to concentrations that exceed the U.S. national ambient air quality 1-hour standard for nitrogen dioxide, roughly 20—25 percent will be exposed to formaldehyde that exceeds federal guideline levels for acute exposure, and roughly 3—6 percent will be exposed to acute CO levels above established outdoor standards. The switch from conventional natural gas to liquefied natural gas is projected to increase the fraction of this sub-population exposed at levels that exceed the aforementioned standards by roughly 3.5 percent for NO_2 (1-hour standard), by about 2 percent for formaldehyde, and by about 1 percent for CO (in absolute percentages). While these LNG-related increases are small relative to the fraction of this group (Californians that use gas cooking burners) that is already exposed to pollutant levels that exceed health-based standards and guidelines, the direction of the LNG effect is consistently negative at a population level.

6.2 Evaluation of Kitchen Exhaust Fans as Potential Mitigation Measure

Since existing data suggests very low usage rates for kitchen exhaust ventilation during cooking, and since the key physical parameters that affect concentrations are similar throughout the state, the results of the modeling study described in the previous sub-section likely apply to the majority of homes with gas cooking burners throughout California.

6.2.1 Overview of Task Effort

The hazard posed by natural gas and exacerbated by LNG use in gas stoves can be mitigated through use of venting range hoods and other kitchen exhaust devices that can remove cooking burner combustion products (as well as cooking-related pollutants) before they mix throughout the home. While many installed range hoods may capture only a fraction of the emitted pollutants, performance of most can be substantially improved by (1) starting the fans at or before the start of cooking, (2) leaving the fan on for at least a few minutes after cooking, and (3) preferentially cooking on back burners to improve pollutant capture.

The goal of this task was to quantify the performance of a diverse sample of kitchen exhaust fans installed in California residences. Specific objectives included the following:

- Measure airflow rates of installed equipment and compare them to product specifications.
- Measure sound levels during installed equipment use.
- Quantify capture efficiency, defined as the fraction of burner-generated pollutants that are removed by the exhaust system during use.

On-site performance evaluations were conducted on a diverse sample of 15 cooking exhaust systems installed in California residences. The sample included two downdraft exhaust units, two microwave-over-range exhaust fans, three installations of the same model of under-cabinet system with no substantial collection hood and grease screens covering the bottom, and eight units with collection hoods. Comprising these eight were two island chimney units, one wall-mount chimney unit, and five under-cabinet units. These devices span a range of retail price from less than $100 to $2,900. The sample includes three units installed at the time of building or addition construction, six units installed as part of a major kitchen remodel, two units installed by the current homeowners to replace a previously installed device, and four units installed by current homeowners into a kitchen that did not have an exhaust fan. Eight of the 13 above-the-cooktop devices were installed according to manufacturer specifications (the downdraft systems are incorporated into the cooking appliances).

6.2.2 Task Outcomes

Measured airflows ranged from 74 to 382 cubic feet per minute at the highest fan settings. The ratio of measured to nominal (nameplate or manufacturer specified) airflow at the highest fan setting ranged from a high of 100 percent to a low of 30 percent. Of the six units (four unique models) having airflow ratings certified by the Home Ventilating Institute (using an industry

standard test procedure), one had maximum airflow that was only 39 percent of the rated value, another had a maximum airflow at 71 percent of its rating, and the remaining four (including the three units of the same model) had airflows exceeding 90 percent of rated values. Of the seven devices with the highest nominal flows, ranging from 550 to 760 cubic feet per minute, none were certified and only two of the seven had measured airflows that exceeded 50 percent of the nominal value. The nominal airflows for these products appear to be free air delivery; that is, the amount of air that can be moved by the component fan when not installed in the appliance housing or attached to ductwork that produces pressure resistance and reduces flow. For devices with multiple speed settings, airflows were typically much lower on the lowest speed compared with the highest speed setting; three units had airflows of 50 cubic feet per minute or less at low fan speed.

Sound levels – measured as dB(A) – under background conditions of no fan use and with fan operation varied substantially across locations and installations. Background values were 33 to 49 dB(A) in the kitchens in which evaluations were conducted. Sound levels measured at the position of a cook were 57 to 71 db(A) with fans on highest setting and 40 to 73 dB(A) on lowest fan setting. Fans on high setting caused an increase in sound levels of 18 to 29 dB(A) above background. Interpretation of these results is not straightforward; the measured values are presented primarily for purposes of documentation and reference.

Capture efficiency was determined for each hood for a variety of burner use configurations including single front cooktop burner, single rear cooktop burner, combination of one front and one rear cooktop burner, and oven burner. Capture of cooktop burner pollutants was evaluated with the burners operated on the highest setting and a pot of water placed atop the burner to simulate typical use. Each burner configuration was evaluated at multiple exhaust fan settings as available.

Capture efficiency varied widely across models, installations, and conditions. Models with actual collection hoods generally performed better than flat profile (including microwave exhaust fan combination units) and downdraft systems. Of the two microwave-fan combination units, one was found to be generally effective, with very high capture efficiency for back burners, and the other was found to be only somewhat effective, with capture efficiencies in the range of 10—65 percent. Despite achieving maximum airflow rates roughly 230—250 cubic feet per minute, the three installations of a modestly priced flat-bottom under-cabinet model had peak capture efficiencies of only 50—65 percent, and efficiencies below 50 percent for many burner and fan setting combinations. Capture efficiencies exceeded 70 percent for one hood and 80 percent for another across all tested configurations; both of these were high-end models. Among the models with capture hoods, very poor performance was observed for only one of the tested units: an economy model with an exhaust inlet at the same vertical level as the bottom of the hood (that is, not situated to draw air from within the hood). For many models, performance varied substantially across conditions. The downdraft systems were generally effective at removing cooking exhaust from the back burners but ineffective for front burners. For most of the above-the-cooktop models, capture efficiencies were highest for back burner and oven operation, and for the highest fan speed. For devices with multiple fan settings,

capture efficiencies were higher at the higher fan settings. Consistent with these effects, the lowest capture efficiencies generally occurred for front burners and lower flow rates.

6.2.3 Task Summary and Conclusions.

Overall, these results indicate that range hoods have the potential to serve as an effective mitigation for gas quality related increases in pollutant emissions from natural gas cooking burners. The efficiency results indicate that meeting industry standard guidance on minimum airflow requirements is not sufficient to ensure adequate pollutant capture efficiency. And since there is essentially no information available about the capture efficiency of available range hoods, consumers and contractors have limited ability to discern which products will be most effective. Users can have a substantial impact on effectiveness by preferentially cooking on back instead of front cooktop burners and operating hoods already installed on higher speed settings for more airflow. This is likely an undesirable solution in many cases because higher speed settings are very loud.

CHAPTER 7:
Outdoor Air Quality Impacts of Changing Fuel Gas Compositions in the South Coast Air Basin

7.1 Overview

The purpose of this task was to investigate the possible effects of projected LNG use on overall pollutant emissions and ambient air quality in the South Coast Air Basin of California. This investigation combined results from interchangeability experiments conducted on industrial, commercial, and residential natural gas burners with a baseline planning emission inventory developed by the South Coast Air Quality Management District for the year 2023.

The spatial extent of LNG receipt into the South Coast Air Basin modeling domain was estimated for a range of expected LNG delivery scenarios. The baseline inventory was updated to account for spatial and temporal differences between scenarios without and with LNG at the varied levels of distribution and use. These emission inventories were used as inputs to a state-of-the-art air quality model to investigate the potential impacts of LNG on ozone and secondary particulate matter formation.

The task had the following specific objectives:

- Apply technology-specific results of recent emissions experiments and quantify the impact of these changes to the South Coast Air Quality Management District baseline planning emission inventory for 2023, which does not include LNG.
- Apply results of controlled emission experiments with simulated LNG (higher Wobbe index) fuels to assess the impact of LNG use on the overall emission inventory.
- Use state-of-the-art air quality modeling to investigate the impact of LNG use on ambient ozone and particulate matter concentrations in the South Coast Air Basin.

7.2 Task Outcomes: Update of Emissions Inventories

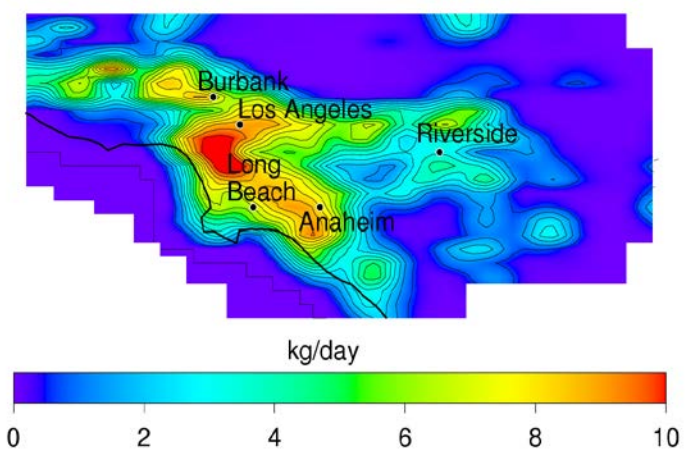
As a starting point for this work, the South Coast Air Quality Management District provided a compliance emission inventory for the year 2023. This inventory was developed as part of a plan to meet U.S. federal ambient air quality standards and did not include any LNG impacts. The emissions in this compliance inventory were calculated using both emission factors from the U.S. EPA AP-42 compilation and annual emissions reported to the district for specific facilities. This inventory projected that in 2023, 58 percent of NG-related NOx emissions will be from area sources and 42 percent will be from point sources. The point sources are primarily in the electrical utility, manufacturing and industrial, and service and commercial sectors, while the area sources are primarily in the residential sector and service and commercial sector. Residential fuel combustion is estimated to be the largest sub-category, accounting for 33 percent of all NOx from natural gas burners in the South Coast Air Basin.

While compiling emission information on natural gas sources for this task, it became clear that, in general, the natural gas sector is one that lacks the type of emissions testing data to support emission factors for the range of combustion technologies in use. This is perhaps unsurprising, since natural gas-fueled area and point sources are projected to account for only about 13 percent of the total NOx in the basin, with mobile sources accounting for the vast majority of the remainder. Of particular importance is the use of a single AP-42 emission factor for all residential appliances based on measurements of residential furnaces in the 1970s. The residential appliance experiments performed by Lawrence Berkeley National Laboratory (LBNL) provided technology-specific emission factors that were used to update the baseline South Coast Air Quality Management District emission inventory.

For most technologies, the more relevant NOx emission factors were lower than the AP-42 values. Updating the emission factors for residential natural gas appliances used in the original inventory with emission factors obtained in experimental measurements decreased projected NOx emissions by a total of 2.4 tons/day in the South Coast Air Basin. This reduction translates to a reduction of 1.2 percent in projected NOx emissions from all sources in the basin.

Figure 7-1 shows the spatial distribution of the daily decreases in NOx emissions due to updating emission factors in the inventory. The updated emission inventory for 2023, termed the *LBNL Baseline inventory,* was used as a reference to evaluate the impacts of using liquefied natural gas on emissions from natural gas combustion.

Figure 7-1. Decrease in Daily NOX Emissions in the LBNL Baseline Emissions Inventory with Respect to the South Coast Air Quality Management District Baseline Inventory



Changes in emissions due to projected use of fuels with higher Wobbe number (associated with LNG with Wobbe number of 1385 BTU/scf) were assessed using available experimental data. Experimental data from LBNL provided emissions changes as a function of Wobbe index for residential NG appliances. These values were also used for commercial space and water heating, which were assumed to respond in a manner similar to the residential technologies. Emissions testing of the effect of Wobbe index on selected low and ultra-low NOx commercial

and industrial burners and boilers by SoCal Gas were used to provide an upper bound of the impact of LNG in the commercial and industrial sectors for boilers and process heaters, as well as for unspecified industrial area sources.

The use of LNG not only affects emissions from natural gas combustion, it can also impact fugitive sources emissions from the transmission and distribution of natural gas. The emissions inventory received from the South Coast Air Quality Management District does include estimates of fugitive emissions. However, in California, the generally available natural gas has a lower fraction of non-methane hydrocarbons than most of the potential supply of LNG available from the Energía Costa Azul terminal in Mexico. Emissions of non-methane hydrocarbons are potentially relevant because these compounds can act as precursors to ozone formation; large increases in non-methane hydrocarbons can lead to increases in ozone concentrations.

Increases in emissions from fugitive sources of non-methane hydrocarbons due to LNG were modeled, assuming that the LNG will have the maximum composition specified by the ARB. (The ARB was allowing exceptions to this maximum composition as of 2009, but these exceptions were not considered in the modeling work.) For air quality modeling purposes, these emissions are lumped into a group that represents short-chain alkanes. These additional fugitive emissions were restricted to the areas of the basin expected to receive LNG, as calculated for each scenario.

7.3 Task Outcomes: Realistic LNG Delivery Scenarios

All of the LNG that enters the South Coast Air Basin is assumed to originate from the Energía Costa Azul terminal. Eight realistic scenarios were selected to represent the expected distribution of LNG into the basin; these scenarios span the parameters that influence natural gas flow through the distribution system. These three parameters are the LNG output of Energía Costa Azul terminal, the amount of natural gas entering the Southern California system from El Paso through Blythe, and total in-basin demand during the summer modeling period. The total capacity of the Energía Costa Azul terminal was assumed to vary from 800 to 950 million cubic feet per day (MMcf/day), of which between 400 and 500 MMcf/day were expected to be available for import into the United States. The typical demand in a summer month was projected to be 2700 MMcf/day, with a maximum demand of 3200 MMcf/day during periods of increased natural gas consumption due to electricity generation. (It should be noted that based on these estimates, the maximum capacity of the Energía Costa Azul terminal is well below the demand for all of Southern California.) The details of these eight realistic delivery scenarios are listed in Table 7-1.

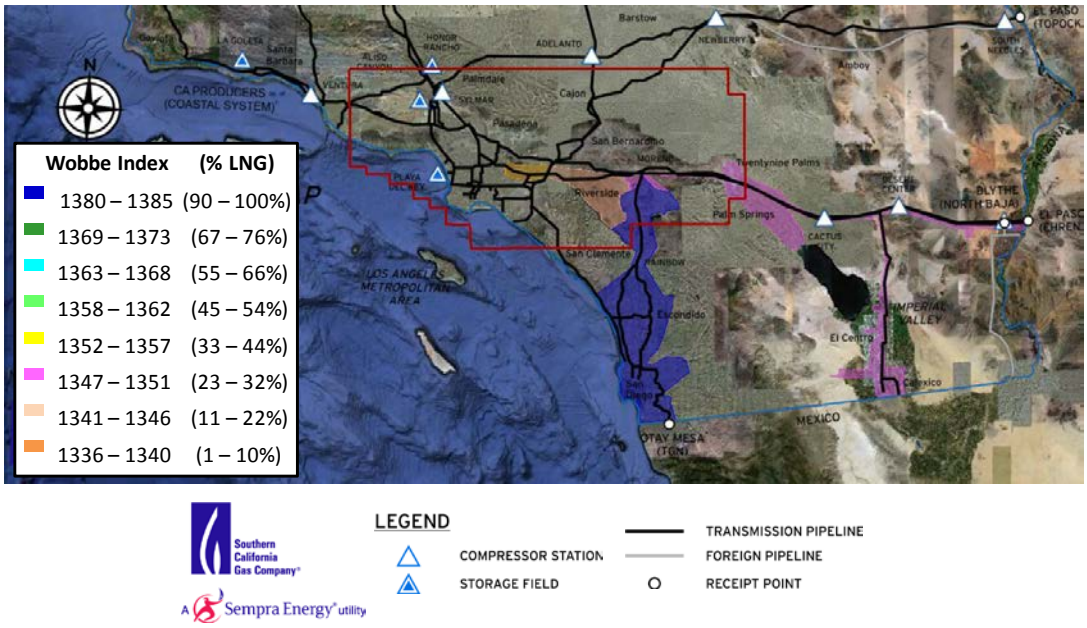
Table 7-1. Parameters for the Eight Realistic LNG Scenarios Projected for the Year 2023 in the SoCal Gas and SDG&E System (Gas Volumes in MMcf/day)

	Scenarios							
	Base		Min Domestic		Max ECA Deliveries		Max ECA Deliveries & Min Domestic	
	1	2	3	4	5	6	7	8
SoCalGas/SDG&E	Typical	Maximum	Typical	Maximum	Typical	Maximum	Typical	Maximum
Summer Demand	2679	3212	2679	3212	2679	3212	2679	3212
ECA Supply	Typical	Typical	Typical	Typical	Maximum	Maximum	Maximum	Maximum
Otay Mesa	312	312	312	312	400	400	400	400
Blythe	112	112	112	112	84	84	84	84
Receipts from El	Typical	Typical	Minimized	Minimized	Typical	Typical	Minimized	Minimized
Paso (EP) at Blythe	508	508	140	220	478	478	140	220
Other Supplies	1747	2280	2115	2568	1717	2250	2055	2508

ECA = Energía Costa Azul terminal

The parameters for these eight realistic scenarios were used as inputs into a SoCal Gas transmission system model, resulting in the predicted penetration of LNG into the modeling domain of the South Coast Air Basin. Figure 7-2 shows the results for Scenario 7, which represents the largest penetration of LNG into the domain based on maximum supply of LNG from the Energía Costa Azul terminal, minimum receipts of natural gas at Blythe, and typical summer demand in Southern California. The results show limited spatial extent of LNG distribution into the basin, primarily restricted to southeast Riverside County, even at this maximum expected penetration. It should be noted we assumed that San Diego County receives close to 100 percent LNG in all eight realistic scenarios. These eight realistic scenarios are used as the basis for assessing expected impacts of LNG use on ambient air quality in the South Coast Air Basin.

Figure 7-2. Zones of Influence in the SoCal Gas/ SDG&E System for Scenario 7: Scenario with the Maximum Penetration of Liquefied Natural Gas



7.3.1 Hypothetical LNG Delivery Scenarios

For the purpose of exploratory and bounding analysis, additional modeling was conducted on several hypothetical scenarios. These scenarios included:

- (a) 100 percent penetration (use) of LNG throughout the South Coast Air Basin
- (b) An increase in the Wobbe index of distributed LNG from 1385 to 1400
- (c) 100 percent LNG penetration throughout the South Coast Air Basin and an increase in Wobbe index of distributed LNG from 1385 to 1400 combined with the mitigation measure of adjusting all burners in the area to optimize operation with LNG

Scenario (a) is not feasible with current or planned LNG receiving infrastructure, and scenario (b) is not allowable under current gas quality tariff limits. Scenario (c) is an idealized, theoretical control option.

7.4 Summary and Conclusions

7.4.1 Impacts of Liquefied Natural Gas on Emissions

Under all eight realistic scenarios, the impact of LNG on overall basin-wide emissions is assessed to be marginal. To illustrate, the changes in NOx emissions for all LNG delivery scenarios are listed in Table 7-2. Nitrogen oxide emissions are projected to increase by less than 0.1 percent. Recall that the current planning inventory is estimated to overstate projected emissions by 2.1 percent as a result of using generic emission factors for residential and commercial burners instead of the newer technology specific emission factors. Note that the increase in nitrogen oxide emissions due to LNG use is significantly less that these possible discrepancies in the emission inventories. The primary reason for this small increase is the low penetration of liquefied natural gas expected in the modeling domain. The maximum increase in basin-wide NOx emissions projected for the hypothetical scenario of 100 percent penetration of LNG is estimated to be 2.8 tons per day (2.5 percent), giving an indication of the magnitude and type of LNG use that would be required to cause discernible changes in the basin-wide emission inventory. The hypothetical mitigation measure of readjusting all commercial and industrial burners to operate on LNG has the potential to counter almost all of the emission increase at 100 percent distribution of 1385 Wobbe LNG.

Case	**NO_x Increase (tons/day) w.r.t. LBNL Baseline**	**NO_x Increase (%) w.r.t. LBNL Baseline**
LBNL Baseline Total NOx = 112 tons/day	--	--
Realistic LNG Distribution Scenarios		
Scenario 1	0.037	0.03
Scenario 2	0.027	0.02
Scenario 3	0.044	0.04
Scenario 4	0.039	0.03
Scenario 5	0.084	0.07
Scenario 6	0.046	0.04
Scenario 7	0.092	0.08
Scenario 8	0.034	0.03
Hypothetical Scenarios		
100% LNG	2.76	2.5
Scenario 7 (WN_{max}=1400)	0.12	0.11
100% LNG (WN_{max}=1400)	3.58	3.2
100% LNG with Tuning	0.17	0.15

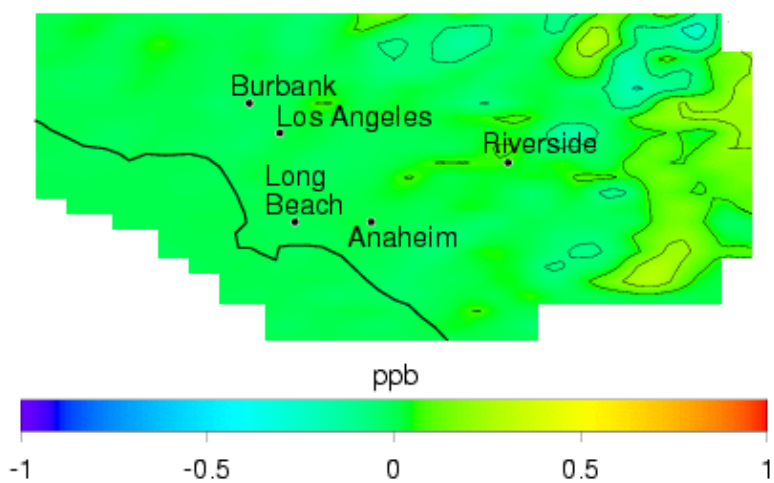
Note: Increases in Emissions are Expressed with respect to (w.r.t.) the LBNL Baseline Case

7.4.2 Impacts of Liquefied Natural Gas on Air Quality

The changes in emissions based on LNG use in the eight realistic delivery scenarios were very small. As a result, the impacts on ozone and secondary particulate matter concentrations due the use of LNG are not discernable. The average change in ozone concentration for all of the realistic scenarios was less than 0.1 parts per billion (ppb), with no predicted change in the domain-wide average of the 24-hour average concentration of particulate matter smaller than 2.5 micrometers ($PM_{2.5}$). The predicted change in ozone concentration varied spatially across the modeling domain, ranging from -0.3 ppb to 0.5 ppb. The spatial variability in the predicted 24-hour $PM_{2.5}$ concentrations varied from -0.6 micrograms per cubic meter (µg/m3) to 0.6 µg/m3. Figure 7-3 shows the spatial results of this scenario on peak ozone concentration.

The hypothetical scenario with 100 percent LNG penetration resulted in an increase in the average ozone concentration of 0.36 ppb and in the 24-hour average $PM_{2.5}$ concentration of 0.07 µg/m3, primarily due to the increase in NOx emissions. The emissions that would result from increasing the Wobbe index limit to 1400 would enhance ozone formation; for this hypothetical scenario the model predicted an increase in the average ozone concentration of 0.46 ppb. Equipment tuning is estimated to counter most of the increase in NOX emissions, with a resulting impact on ozone and PM formation that is less than the scenario with maximum expected LNG delivery and no mitigation.

Figure 7-3. Changes in Peak Ozone Concentrations (ppb)
Based on LNG Distribution Projected by Sempra for the Year 2023



Note: The LNG distribution assumes typical summer demand of natural gas in the South Coast Air Basin and maximum capacity at the Energía Costa Azul LNG terminal of 950 million cubic feet per day.

These results indicate that the impact of LNG on overall basin-wide NOx emissions should be very small, and may be below the level at which the models can discern. Uncertainty in the emission inventory – owing to a lack of solid technology-specific emissions data – appears to be much larger than any expected change in emissions associated with LNG use. The difference in emissions between the 2023 South Coast Air Quality Management District inventory and the

Lawrence Berkeley National Laboratory baseline is larger than the difference in basin-wide emissions estimated for the realistic scenario with the maximum penetration of LNG. The differences in the two emissions inventories approach the same order of magnitude as the difference in basin-wide emissions estimated for the hypothetical 100 percent LNG scenario. Thus, barring a substantial increase in the capacity to deliver LNG into the South Coast Air Basin, there appear to be no discernable outdoor air quality impacts.

GLOSSARY

Term	Definition
AGA	American Gas Association
AER	Air exchange ratio
ANSI	American National Standards Institute
ATSDR	Agency for Toxic Substance and Disease Registry
Btu	British thermal unit
CAAQS	California Ambient Air Quality Standards
Cal/EPA	California Environmental Protection Agency
CARB	California Air Resources Board
CO	Carbon monoxide
CO2	Carbon dioxide
FSTC	Foodservice Technology Center
GTI	Gas Technology Institute
HCHO	Formaldehyde
HP	Horse power
HHV	Higher heating value
LBNL	Lawrence Berkeley National Laboratory
LNG	Liquefied natural gas
MMcf/day	Million cubic feet per day
NAAQS	National Ambient Air Quality Standards
NAFEM	North American Association of Foodservice Equipment Manufacturers
NG ng/j	Natural gas Nanogram per joule
NO_2	Nitrogen dioxide
NOx	Nitrogen oxides
OEHHA	Office of Environmental Health Hazard Assessment
OEM	Original equipment manufacturer
PG&E	Pacific Gas and Electric Company

ppb	Parts per billion
ppm	Parts per million
ppmv	Parts per million by volume
ppsi psig	Pounds per square inch Pound-force per square inch gauge
SDG&E	San Diego Gas & Electric
SoCal Gas	Southern California Gas Company
U.S. EPA	United States Environmental Protection Agency

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Logue JM, Klepeis NE, Lobscheid AB, Singer BC. Pollutant exposures from unvented gas cooking burners: A simulation-based assessment for Southern California. Environmental Health Perspective; DOI:10.1289/ehp.1306673. Final published version will be available via Lawrence Berkeley National Laboratory Reports Database

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APPENDIX A:
Project Publications

The following reports and publications cover each of the project tasks. For ease of location, reports and publications are divided into categories of interest rather than chronologically or by alphabetical author listing. These reports and publications provide detailed information on testing protocols, combustion equipment tested, and testing results. The California Energy Commission approval process was not yet complete for all reports at the time this summary was submitted. Reports published by the Energy Commission at the time this report was submitted are indicated by their Commission publication designation.

Literature Review

Rue, D., Chudnovsky, Y., Soupos, V., Tickel, T., Natural Gas In California: Environmental Impacts and Device Performance: Literature Review and Industrial Burner Evaluations, October 2006, 66p, CEC-500-2006-096.

Singer BC. 2006. Natural Gas Variability in California: Environmental Impacts and Device Performance: Literature Review and Evaluation for Residential Appliances. California Energy Commission, PIER Energy-Related Environmental Research, Interim Report. CEC-500-2006-110.

Industrial Combustion Systems (Appendix D)

Wagner, J., Tickel, T., Industrial Burner Evaluations: Infrared Burner Interchangeability Test Report, September 2009, 40p

Tickel, T., Aronchik, G., Wagner J., Industrial Burner Evaluations: Radiant Tube Burner Interchangeability Test Report, September 2009, 37p

Wagner J., Kozlov, A., Industrial Burner Evaluations: Boiler Interchangeability Test Report, May 2010, 45p

Wagner, J., Kozlov, A., Aronchik, G., Industrial Burner Evaluations: High Velocity Test Report, July 2010, 39p

Wagner, J., Chudnovsky, Y., Aronchik, G., Industrial Burner Evaluations: Line Burner Test Report, May 2010, 35p

Wagner, J., Kozlov, A., Aronchik, G., Industrial Burner Evaluations: Oxy-Gas Test Report, October 2010, 37p

Wagner, J., Kozlov, A., Aronchik, G., Industrial Burner Evaluations: Packaged Boiler Burner Test Report, April 2011, 39p

Wagner, J., Industrial Field Trials: Radiant Tube Burner Interchangeability Test Report, July 2011, 32p

Wagner, J., Industrial Field Trials: Water Tube Boiler Interchangeability Test Report, April 2012, 34p

Commercial Foodservice Equipment (Appendix E)

Rue, D., Chudnovsky, Y., Johnson, F., Commercial Foodservice Equipment Evaluation, December 2011, 80p

Residential Appliances

Singer BC, Apte MG, Black DR, Hotchi T, Lucas D, Lunden MM, Mirer AG, Spears M, Sullivan DP. 2009. Natural Gas Variability in California: Environmental Impacts and Device Performance: Experimental Evaluation of Pollutant Emissions from Residential Appliances. California Energy Commission, PIER Energy-Related Environmental Research, Interim Report. CEC-500-2009-099. Also available via Lawrence Berkeley National Laboratory Reports Database as LBNL-2897E*.

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Indoor Air Quality (Including Range Hoods) and Ambient Air Quality

Klug VL, Lobscheid AB, Singer BC. Cooking Appliance Use in California Homes – Data Collected from a Web-Based Survey. Lawrence Berkeley National Laboratory, Berkeley, CA. August 2011. LBNL-5028E.

Klug VL, d'Cruz C, Bedrosian T, Singer BC. Characteristics of Range Hoods in California Homes – Data Collected from a Real Estate Web Site. Lawrence Berkeley National Laboratory, Berkeley, CA. August 2011. LBNL-5067E.

Sospedra MC, Lunden MM, Brauer J, Singer BC, Dabdub D. 2011. Air Quality Impacts of Liquefied Natural Gas Use in the South Coast Air Basin of California. California Energy Commission, PIER Energy-Related Environmental Research, Interim Report, Contract CEC-500-05-026. Report number CEC-500-2011-041. Also available via Lawrence Berkeley National Laboratory Reports Database as LBNL-4950E.

Singer BC, Delp WW, Apte MG. 2011. Natural Gas Variability in California: Environmental Impacts and Device Performance: Experimental Evaluation of Installed Cooking Exhaust Fan Performance. California Energy Commission, PIER Energy-Related Environmental Research, Interim Report. Contract CEC-500-05-026. Report Number CEC-2013-033. Available via Lawrence Berkeley National Laboratory Reports Database as LBNL-4183E.

Singer BC, Lobscheid AB, Klepeis NE. Natural Gas Variability in California: Environmental Impacts and Device Performance: Simulation-Based Estimates of Indoor Exposures to Pollutants from Natural Gas Cooking Burners. California Energy Commission, PIER Energy-Related Environmental Research, Interim Report. (This Interim Report can be found in Appendix F)

Lobscheid AB, Klepeis NE, Singer BC. Modeling population exposures to pollutants emitted from natural gas cooking burners. (2011) *Proceedings of Indoor Air 2011*, *The 11th International Conference on Indoor Air Quality and Climate, Paper 888.* Austin TX. International Academy of Indoor Air Sciences. Corsi RL and Morrison GC, eds. Available via Lawrence Berkeley National Laboratory Reports Database as LBNL-4885E.

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Logue JM, Klepeis NE, Lobscheid AB, Singer BC. Pollutant exposures from unvented gas cooking burners: A simulation-based assessment for Southern California. Environmental Health Perspective; DOI:10.1289/ehp.1306673. Final published version will be available via Lawrence Berkeley National Laboratory Reports Database.

APPENDIX B:
Classes of Industrial Burners

The classification tree diagram in Figure A-1 identifies general burner operating modes by juxtaposing burner classifications. The six categories shown in this figure (fuel type, oxidizer type, draft type, mixing type, heating type, and control type) imply fundamental differences in burner operating modes that will change their test protocol. A burner's operation can be described by combining elements from each category. A brief summary of the meaning of each category follows.

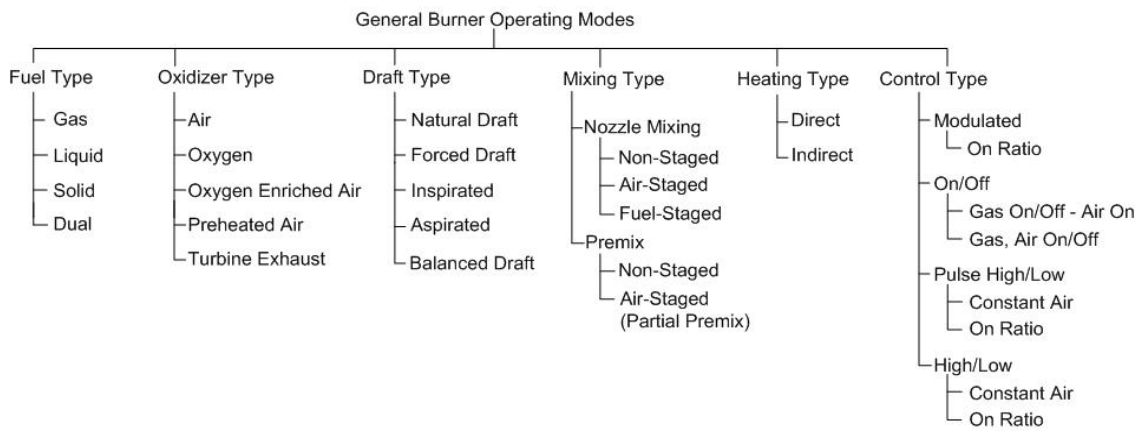


Figure A-1. General Burner Operating Modes

Fuel type: Only natural gas-fired burners are within the scope of this study.

Oxidizer type: Oxygen is supplied in compressed tanks, so with oxygen, no air blower is needed. Also, oxygen and fuel are not premixed for safety reasons. Combustion air is preheated either via an external heating unit or piping that directs the exhaust gases near, or even through, the burner's air inlet to transfer heat from the combustion products to the incoming air.

Draft type: Draft is defined as the pressure difference that draws combustion air into the furnace and causes combustion products to be exhausted out of the furnace. Each draft type implies a different mechanism of air supply and thus a different control type to maintain an acceptable air/fuel ratio. The amount of air supplied to a natural draft burner is controlled by the pressure difference across the burner and the degree that side doors are open, so air/fuel ratio in a natural draft burner is controlled by adjusting a damper in the furnace exhaust stack to control furnace pressure. The oxidizer supplied to a forced draft burner is blown in, and controlled by changing the degree to which a valve is open. Inspirated burners use the motive force of the fuel to entrain their air into a Venturi throat for premixing. Conversely, aspirated burners use the motive force of blown air to entrain fuel. Both inspirated and aspirated burners have spuds or doors on the burner to control the air/fuel ratio in their primary stream; they are

adjusted upon installation and should be checked periodically to accommodate the current fuel composition.

Mixing type: If any fuel and gas meet before the burner, according to the National Fire Protection Association, the burner is classified as premixed, otherwise it is a nozzle-mix burner. Flashback is only a possibility for premixed burners, and occurs when the flame speed exceeds the burner's exit velocity and the flame enters the burner. The flame could then exist anywhere downstream of the pre-mixing device; this damages the burner and is a safety hazard. The staging subtypes adjust flame shape and decrease emissions. An accepted rule of thumb for natural gas is that flashback occurs when the mixture pressure is below 0.25 inches water column.

Heating type: Indirect heating means the burner is accessorized to protect the load from the combustion products. For example, the burner can fire into a metal or a ceramic tube, or the flame can be restrained by a screen. Flame impingement on the intermediate accessories is a design consideration, because impingement can raise temperatures so that material creep is rapid for even small loads.

Control type: Usually the furnace or process temperature is measured by a thermocouple, and the burner's firing rate is adjusted. Update speed for an industrial furnace is on the order of 30 seconds, except in pulsed control, where the burner can turn on and off every 3 seconds. The control system must both adjust the firing rate and maintain an acceptable air/fuel ratio. The most common way to do this is to throttle the air from its high set value to its low set value whenever the temperature is above a set point. The fuel flow is coupled to the air flow with either a pressure regulator or a cam that links the air and the fuel valves to turn in proportion. The cross-links are adjusted upon installation and should be checked periodically to accommodate the local fuel composition.

Industrial burners vary tremendously in firing capacity, laminar flame speed, method of mixing, flame shape, flame temperature, and other characteristics. Since the wide range of industrial burners can have multiple end uses, from making gypsum or melting glass to drying paint or pasteurizing food, burners exist that favor performance needs for each of these applications. Tradeoffs in burner design must be made between cost, durability, energy efficiency, temperature distribution, versatility, emissions, and other metrics. Burners have become highly engineered for increasingly competitive performance, and often must push the envelope of material properties to accommodate energy economics and regulatory standards. Burner application was gathered from Gas Technology Institute experience, various recommended applications in burner manufacturers' brochures, and references for the food industry, paper industry, chemical process and refinery industries, industrial furnaces, and burners in general.

Eight major types of burners have been identified; descriptions follow of their most common applications and their associated performance needs.

1. Radiant burners
    a. Burners for radiant tubes

b. Thermal radiation burners

c. Radiant wall burners

2. Nozzle mix [low, medium, high] velocity burners
3. Regenerative burners
4. Natural draft burners
5. Boiler burners
6. Linear grid/in-duct burners
7. Oxygen enhanced (oxy-fuel) burners
8. Flare burners

Descriptions of the major classes of industrial burners are presented below. Information was obtained from manufacturer websites and product sheets.

Radiant tube burners

Category I:

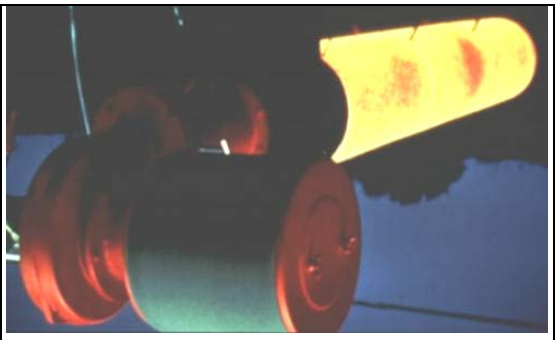
May experience burner/equipment damage

Category II:

Possible change in combustion performance

Capacity:

up to 8 MM Btu/hr



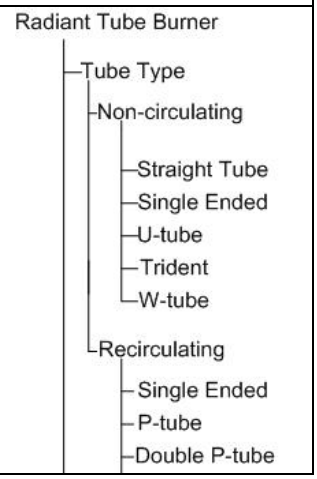
Pyrocore single-ended radiant tube system

Major industrial application:

Indirect product heating: metal heat treating, porcelain.

Control methods:

Burners usually are fired in on/off or high/low mode to maintain a set temperature. For forced-draft models, air is controlled and the air/fuel ratio maintained by a cross-connected pressure regulator that is adjusted to the local gas quality upon installation. For inspirated models, a stub in the Venturi tube is adjusted to draw in the correct proportion of air.



Representative burner models:	
Bloom Engineering: 2300,2310,2320,2350,2370,2305 Eclipse: AutoRecupe (SER) Hauck Manufacturing: RTR, SER, RTPR, RTG Maxon: Unirad North American Manufacturing: TBRT III, Evenglow Pyronics: UHF	

Description:

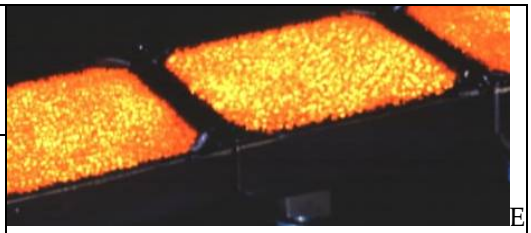
Radiant tube and burner systems provide high temperature heat to loads that must not come into contact with the combustion products or the flame, either because of a chemical reaction, as with steel, or because of a fine product finish, as with porcelain. The tubes must endure high temperatures and sometimes corrosive chemical environments, so they are made of expensive alloys or ceramics. A typical limiting factor for radiant tubes is the maximum temperature that the tube material can withstand, given the imposed mechanical and thermal load; burners for radiant tubes should provide a uniform heat release profile along the length and around the circumference of the radiant tube to promote an even temperature distribution. Prolonged firing of a fuel gas with higher heating value might decrease tube life.

Burners for radiant tubes are usually nozzle-mix burners with air staged to delay combustion and produce long flames. Inspirated burners exist; when using them draft must be controlled both to maintain the optimum air/fuel ratio and to avoid flashback. Also, since NO_x formation increases with flame temperature, and a higher heating value fuel makes hotter flames, it is likely that NO_x emissions from radiant tube burners will increase when the input fuel changes from its current composition to vaporized LNG.

Thermal radiation burners

Category II:

Possible change in combustion performance



E

clipse thermal radiation burners

Capacity:

4,000-65,000 Btu/hr/sq.ft

Major industrial applications:

Paper drying, wood drying, plastic thermoforming, paint curing, food processing.

Control methods:

Operation is usually on/off, according to timers, humidity measurement, or direct product temperature. Air flow is controlled, and the air/fuel ratio maintained by a cross-connected pressure balance regulator.

Representative burner models:

Maxon: Radmax

Pyronics: 3207,3209-IRC,3208 RL-130

Eclipse Combustion: QC-12, InfraRed

Thermal Radiation Burners
- Porous Ceramic
- Ported Ceramic
- Ported Metal
- Fiber Metal
- Flame Impigement
- Catalytic
- Perforated Ceramic
- Porous Refractory
- Wire Mesh

Description:

Thermal radiation burners are designed to provide a uniform temperature over a surface that is built in to the burner, operate at lower temperatures, and are popular for drying applications. They are premixed burners, with the combustible mixture forced through a porous plate enclosing the mouth of the burner plenum. There are two kinds of thermal radiation burners; either combustion takes place within or on the surface of the porous plate, or else the ejected flames impinge a second, solid plate and provide indirect heating, for example to protect combustible loads, like drying inks. Temperature uniformity, heat-up time, and power output per unit area and per unit energy input are important performance metrics for thermal radiation burners.

In thermal radiation burners, fuel and air are premixed and combusted either just inside a radiating surface or just above the surface, depending on the operating conditions and specific radiant burner design. Fuel composition affects the amount of air needed for combustion, and thus the mixture velocity through the burner. If the mixture velocity is too low, flashback or flame extinguishment can occur, depending on the design of the burner. In addition to the operational considerations, flashback is an obvious safety concern. If the mixture velocity is too high, the flame may blow off or the radiant performance may be severely reduced because the burner surface is not being directly

heated by the hot exhaust products. Depending on the specific design of the burner, optimum performance is achieved when the flame is stabilized just inside or just above the outer burner outlet. Based on this information, thermal radiation burners are likely to be affected by changing input fuel composition to levels found in LNGs that will likely be introduced in California.

Radiant wall burners

Category III: Unlikely to be affected

Capacity:

Up to 3 MMBtu/h

Major industrial applications:

Chemical industry applications, including ethylene production, cracking furnaces.

Control methods:

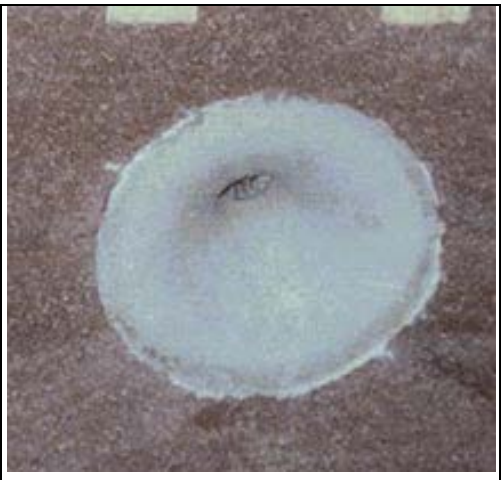
These burners are usually inspirated; the air to gas ratio is controlled by adjusting a stub in the Venturi tube. Fuel pressure is adjusted to maintain a set process temperature. Typical turndown ratio is 10:1.

Representative burner models:

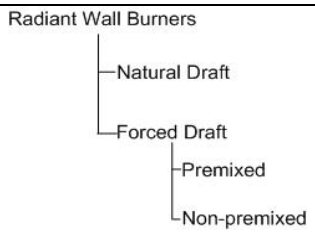
Hauck Manufacturing: WHG

Zeeco: RW, GLSF

Callidus Technology: CARW



A radiant wall burner block



Description:

Radiant wall or hearth burners are designed to fire outward to heat a furnace wall which then radiates heat to process tubes that contain reacting chemical flows. Dozens of these burners can be installed in several rows along the furnace wall or hearth, and since they are in service at a chemical plant, any available combustible is used as fuel.

An important parameter in the operation of a radiant wall burner is the available fuel pressure and specified fuel composition that is used. In many petrochemical and refinery operations, the fuel gas composition that a radiant wall burner is required to fire can vary widely because it is made up of various gas streams from different processes that change with time. A burner may be required to operate on both very heavy fuels with high heating value contents and light fuels containing high levels of hydrogen during periods of startup normal operation or upset conditions. This poses a significant design challenge because the fuel is used as the primary motive force to inspirate the required combustion air. Variability in fuel gas compositions can significantly affect fuel density, and thus indirectly affect the amount of air that can be inspirated and premixed. For high BTU content fuels (heavy fuels) the limit is often due to constraints in air induction, while for low BTU content fuels (light fuels) the firing rate may be limited due to the maximum available fuel pressure. The range in composition for LNGs that are likely to be introduced in the California pipelines,

however, would not produce a gas mixture different enough in Wobbe Number or Higher heating Value (HHV) to cause problems for radiant wall burners. Therefore, radiant wall burners are not expected to be affected by a change in fuel gas composition.

High velocity and general nozzle-mix burners

Category II:

Possible change in combustion performance

Capacity:

Up to 25 MMBtu/hr

Major industrial applications:

Kiln firing, metal heat-treating, ladle drying, chemical process heating, and any other application where temperature uniformity, circulation, and a large turndown are useful.

An Eclipse ThermJet model TJ040 high velocity nozzle-mixed burner

Control methods:

Furnace temperature is usually controlled by firing in high/low mode about a set temperature. Air flow speed is adjusted, and the air/gas ratio maintained by a cross-connected pressure balance regulator. A smaller percentage of burner control systems modulate firing rate for finer control, or keep the air high for circulation, and modulate only the fuel supply pressure; air and fuel supply would not be connected.

Representative burner models:

Eclipse: Thermjet, ThermThief, Extensojet,

Deepblock (Medium/High Velocity)

Pyronics: 3505

Hauck Manufacturing: HMG

Maxon: Ramfire

Nozzle-Mixed Burners
- Non-Staged
- Air-Staged
- Fuel-Staged

Description:

A burner's nozzle geometry can be engineered to shape the flame according to a specific design need. High velocity burners are the most common; they produce exit velocities in the range of 400-500 ft/sec, and are used to circulate combustion products through the furnace and promote temperature uniformity. Nozzle-mix burners have no risk of flashback, and can fire with high excess air; circulation can thus be maintained even at a low firing rate. When impingement is a concern, burners that redirect the momentum with their nozzle geometry can be selected instead.

Because high velocity burners can run under significant excess air conditions, these burners can likely fire fuel gases of higher heat content without any flame stability or ignition issues. Higher BTU content gases will likely raise the local flame temperature, however, to promote thermal NO_x formation. Overall flame length may increase, especially in air staged burners. High velocity burners are simply nozzle-mix burners with a modified burner block to enhance flame speed, so higher local temperatures, a change in flame shape, and increased NO_x formation can be generalized to all nozzle-mix burners.

Regenerative burners

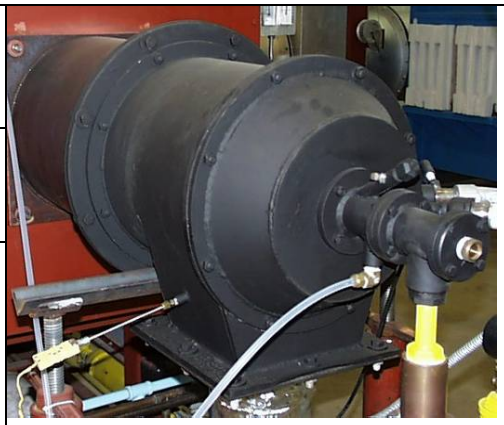
Category II:

Possible change in combustion performance

Capacity:	**Process Temperature:**
0.1 to 50 MMBtu/hr	Up to 3000°F

Major industrial applications:

Zinc distillation, reheating iron and steel, glass furnaces, radiant tubes, and any other high temperature applications where heat recovery is desired.



A Zedtec regenerative burner

Control methods:

The controller ensures only one burner of the pair fires at a time, and the burners will switch either after a certain time, or after the exhaust reaches a set temperature; whichever happens first. Not all of the exhaust exits through the opposite burner's refractory; pressure inside the furnace is controlled by actuating a damper in the furnace stack, and valves can adjust the amount of combustion products permitted to exhaust through the burner. Both on/off and pulse width modulating control of the fuel feed stream are employed, with firing cycles as fast as twice a minute. In batch furnaces, periods of cycling with no fuel and just heat recovery can extend turndown.

Representative burner models:

Bloom Engineering: 1080,1100,1150
NAMCO: TwinBed II (3.0-30 MMBtu/hr) Zedtec (aka Dyson Hotwork): RCB

Regenerative Burners
- One Box
- Two Box
- Rotary/Heat Wheel
- Radiant Tube

Description:

Regenerative burner systems are installed in pairs, and fired one after the other. The principle is to recover heat by directing exhaust from the other burner through the refractory of the opposite burner, where it passes over a heat-storing medium that will preheat the other burner's combustion air when it fires. This heat recovery technique nearly halves fuel consumption. The one-box and two-box styles denote different ways to direct the flue gases, rotary wheel heat recovery systems are not common in the United States.

Regenerative burner systems are typically nozzle-mix. Because of the high preheat temperatures, thermal NO_x formation is an issue. Fuel staging and direct fuel injection into a sufficiently hot furnace reduces NO_x formation. Burning higher BTU content fuel will make the local flame temperature even higher, meaning NO_x formation should increase. An additional consideration for regenerative burner systems is the control system: if the fuel gas suddenly changes quality, particularly to a higher calorific value, a pressure spike from both the increased temperature and the increase in molar product of combustion could change the valve response, also, since the local flame temperature is expected to rise by using higher calorific value LNG gas, the cycle time is expected to decrease.

Natural draft burners

Category I: (Premixed)

May experience burner/equipment damage

Category III: (Non-Premixed)

Unlikely to be affected

Capacity:

Up to 10 MMBtu/hr

Major industrial applications:

Chemical and petrochemical process heat.

A Zeeco natural draft burner

Control methods:

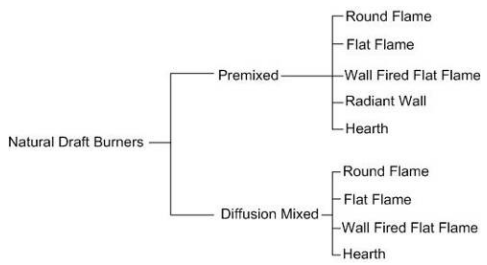
Modulation based on furnace or load temperature.

Representative burner models:

John Zink: XMR, COOLStar™

Zeeco: GB, GLSF, PSR

Callidus: LE-SFSG-W, LE-CARW



Description:

Natural draft burners are attractive because they do not require a blower. In natural draft burners, combustion air is induced or drawn into the burner via suction created by the incoming fuel jets plus the partial vacuum in the furnace created when buoyant combustion products draft up the stack. They are primarily used in petrochemical process heating furnaces. The fuel/air ratio in these burners is controlled by adjusting the opening of air registers on the burner. Premixed and nozzle mixed natural draft burners will likely respond differently to a change in fuel gas composition:

Premix natural draft burners

A higher Wobbe Number fuel gas will increase the heat input to the furnace, and the control system should reduce pressure to compensate. At low enough pressures, a premixed burner risks flashback. Natural draft premixed burners pose a higher risk of flashback than other premix burners because they operate with low pressure drops across the burner.

Diffusion mix/nozzle mix natural draft burners

Nozzle mixed natural draft burners typically provide for the major, or metering, pressure drop for both the fuel and air immediately prior to the ignition zone. By

separating the fuel from the combustion air prior to the ignition zone, there is no possibility of flashback; nozzle mixed natural draft burners can accommodate a wide range of fuels without concern for adverse combustion performance.

Boiler Burners

Category I:

May experience burner/equipment damage

Category II:

Possible change in combustion performance

Boiler Capacity (industrial applications):

2 to 40 MMBtu/hr (firetube)

10 to 1,000 MMBtu/hr (large watertube)

Major industrial applications:

All industries; steam for process heat or to drive pressurized equipment. Large systems can reach temperatures above 700°F and pressures above 3,000 psig.

Hamworthy Peabody Combustion, Inc 20 MM Btu/hr water tube boiler burner

Control methods:

The air flow is modulated according to boiler steam pressure; set points on a cam maintain the proper air/fuel ratio by cross-linking the air and fuel valves.

Representative burner models:

Coen: Delta Power

Cleaver-Brooks: (S)70/LOG/20/915

M4/85/HOG/26/1321

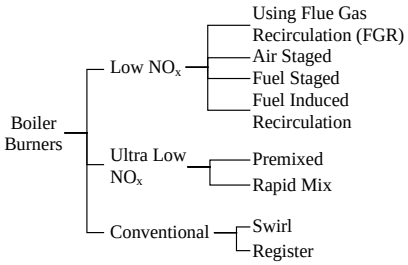
Hamworthy Peabody Combustion:

Envirojet, MSC, APR

John Zink: RMB, Variflame

Power Flame: CMAX

Iron Fireman: WhirlPower, PA, EED



Description:

"Firetube" boiler burners can fire into tubes that pass through a chamber of water one to four times. The heat from combustion is transferred through the tubes to the water to make steam; the pressure of the steam is measured and controls the firing rate. "Watertube" boiler burners are larger, and fire into an open chamber surrounded by tubes for water. Boiler emissions are regulated, and boiler burners are classified by their emissions: low NO_x, ultra-low NO_x and conventional. NO_x -reduction is accomplished through flue-gas recirculation, plus a number of mixing and staging techniques listed in the tree diagram above. The most common operating mode in practice is a conventional burner with flue gas recirculation. Gasified LNG with injected nitrogen could increase NO_x, especially if the injected fuel burns hotter. Since boiler NO_x emissions are tightly regulated, this could be of concern. In addition, lengthened flames may impinge fire tubes to decrease tube life, and abrupt composition changes may trigger an unstable response in the pressure controller, because of the higher heat input, the increase in molar product, and the decrease in air/fuel ratio that would occur with vaporized LNG. ANSI standard Z21.13.2004 details experimental setup and procedure for thermal efficiency and ignition tests on small boiler packages that can be cited and possibly modified for industrial-scale units. The Underwiters Laboratory standard 795 will also be followed. In-stack NO_x reduction will not be examined, because it is post-combustion and unrelated to the burner.

Linear grid/In-duct burners

Category II: (Linear grid)

Possible change in combustion performance

Category III: (In-duct)

Unlikely to be affected

Capacity:

Linear grid: Up to 500,000 Btu/hr/ft

In-duct: Up to 1 MMBtu/hr/ft

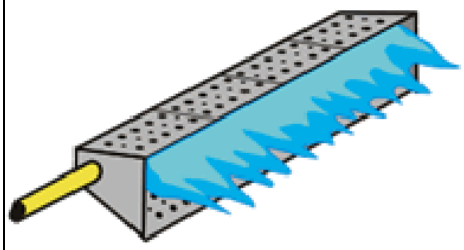
Major industrial applications:

General use where it is desired to spread heat uniformly (food processing, packaging, tube heating). In-duct burners, in addition, are designed to hold their flame in high flow ducts, and in depleted oxygen/humid environments, for example downstream of gas turbines.

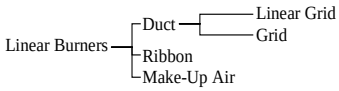
Control methods:

In linear burners, fuel and air are premixed in the burner plenum. Air flow is on/off, or modulates to maintain a set temperature, with fuel/air ratio maintained by a pressure balance regulator. Air flow for in-duct burners is continuous, and is controlled independent from the firing rate, with just fuel or a partial premix fed to the burner.

A Flynn Burner Corp. ribbon burner



Sketch of a duct burner



Representative burner models:

Coen: Powerplus

Eclipse: Airheat, Minnox, AH-MA, Flue Fire

Flynn Burner Corp.: BB102A1, BB123A1, BB133C1, BB406B, BB300A1

John Zink: LDRW

Maxon: APX, LO-NOx ,AIRFLOW, CROSSFIRE Low NOx , COMBUSTIFUME

MidCo: HMA-1, HMA-2

Pyronics: Pyro-Line

Description:

Linear grid burners

Linear burners used to spread heat uniformly in ambient air, and can operate at very low, even near zero, gas pressure. Air and fuel are mixed inside of the burner nozzle, and these burners emit blue flame. Flame luminosity and shape will be affected by a change in fuel gas composition.

In-duct burners

In-duct burners are linear burners specifically designed to hold a flame in high velocity streams that can be humid or oxygen-depleted; some linear burners can be fit with wings to serve as in-duct burners. Historically, they served to heat air for drying operations, and now they also reheat steam in co-generation systems for process use in industrial applications, or to drive steam turbines for electrical peaking combined cycle plants. They are designed for service in humid, oxygen depleted, and chemical environments, so variation in fuel composition is not expected to adversely affect burner performance.

Oxygen enhanced (and oxy-fuel) burners

Category II:

Possible change in combustion performance

Capacity:

Up to 20 MMBtu/hr

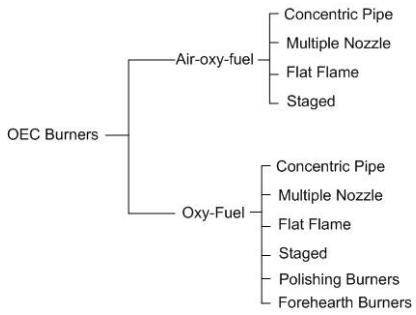
Major industrial applications:

Metal heating and melting, glass melting, mineral calcining, incinerators, combusting black liquor (wood pulp industry); any application where high-intensity additional heat with reduced NO_x and increased energy efficiency are desired.

An Eclipse Primefire 400 Oxy-Gas burner (20 MMBtu/hr)

Control methods:

Modulating operation based on furnace, crown, or load temperature. Oxygen is supplied from a pressurized tank, so with pure oxygen, no blower is needed. The burner's oxidizer/fuel ratio is usually controlled by pressure regulators or flow regulators.



Representative burner models:

Eclipse: PrimeFire 100 Series, 150 series, 300 series, 400 series

Maxon: Oxy-Therm 300 Series, Oxy-Therm LE Flat Flame Burner

Air Liquide: Alglas, Alglas FC

Air Products: Cleanfire

Description:

Oxygen enhanced combustion (OEC) burners are becoming more common in a variety of industries. Traditional air/fuel combustion systems can be modified for oxygen enhancement or replaced by oxy-fuel or duel oxygen/air burners to increase thermal efficiency, increase processing rates, reduce flue gas volumes, and reduce pollutant emissions. Air compressors and preheaters are not needed, reducing capital cost, but care must be taken to ensure safety when handling oxygen, and oxygen must be produced or purchased, meaning operating cost is higher. The cost is offset partially by decreased energy use, but mostly by the gain in production rate.

Oxygen enhanced and oxy-fuel burners employ the basic nozzle-mix burner design. As such, we expect these types of burners to respond to a change in fuel composition with different flame shape, flame temperature, and emissions. Flame shape is not a critical consideration; these burners are intended to provide intense heat, and are used when furnace temperature uniformity is not critical. Furthermore, since these burners produce higher temperature flames by virtue of the higher oxidant concentration, the thermal NO_x emissions are expected to increase more than for typical nozzle-mix design burners.

Industrial flare burners

Category III: Unlikely to be affected

Capacity:

Up to several billions Btu/hr

Major industrial applications:

Combust unwanted process by-products in the petrochemical industry and metals industries.

Control methods:

The burner is on when flaring.

- Flare Burners
  - Single Point
    - Non-Assisted
    - Simple Steam Assisted
    - Advanced Steam Assisted
    - Low Pressure Air Assisted (w/ blower)
  - Multi-Point
    - Non-Assisted
    - Simple Steam Assisted
    - Advanced Steam Assisted
    - Low Pressure Air Assisted (w/ blower)
  - Enclosed
    - Non-Assisted
    - Simple Steam Assisted
    - Advanced Steam Assisted
    - Low Pressure Air Assisted (w/ blower)

Industrial flare; NETL photo archive

Representative burner models:

John Zink: JZ Hydra, JZ Poseidon, LRGO, LHLB, LH, LS, LHTS,

Kaldair Indair, Kaldair Mardair, Kaldair KMI, Kaldair Azdair

Zeeco: UF, QFS, HCS, UFA

Description:

Flare burners combust unwanted process by-products in the petrochemical industry. In the hydrocarbon and petrochemical industries, flares are considered to be separate devices from burners. They differ from process and boiler burners in several aspects:

a. Fuel gas compositions vary over a much wider range.
b. Flares are required to operate over a very large turndown ratio.
c. Flare burners must operate over long periods of time without maintenance.
d. Flare burners operate at high levels of excess air.
e. Many flare burners have an emergency relief flow rate that produces a flame hundreds of feet long with a heat release of billions of Btu per hour.

The design requirements for a given facility that produces waste gas to be incinerated in a flare are seldom identical to those of any other facility. This variation, plus the wide range of flare applications, site conditions, and waste gas/liquid composition, often requires that the flare system be custom designed. Flare burners are therefore

outside the scope of this project.

APPENDIX C:
Specification of Adjust and substitute Gases

Companies have proposed that several liquefied natural gas (LNG) import projects be located off the west coast: nine in the jurisdiction of Canada, Oregon, or Mexico; five off the coast of Southern California; and one off the coast of Northern California. The only working LNG import terminal operating to date is in Mexico. Sempra Energy's receiving terminal at Ensenada, Baja California, will started operations in 2007. Shell has reserved its entire 1 BCF/day capacity and could supply LNG from projects in Russia (Sakhalin Island), Malaysia, Australia, or Indonesia. However, the fraction of the revaporized LNG sold in Mexico is expected to vary.

Currently, only fourteen countries produce and export LNG, though several more projects are being built or planned. The distance between the production wells and the import terminals is a critical factor in the economics of LNG imports since transportation can account for up to 30 percent of the total cost of delivered LNG. Because of the distances involved, compounded by the fact that LNG tankers cannot pass through the Panama Canal, it would not be feasible for California to import LNG on a regular basis from producers in Algeria, Egypt, Nigeria, Trinidad & Tobago, or the Middle East (Oman, Qatar, Yemen), although occasional spot purchases might be made from the Middle East. California's most likely LNG suppliers are located in Asia or the Western Hemisphere.

Alaska would be an ideal LNG source for California. The Kenai project in Alaska, one of the world's first LNG projects, now exports all of its LNG to Japan. This LNG is probably the "driest" in the world: 99.8 percent methane with a trace of ethane. However, production is declining and reserves are unlikely to be found in the region. For nearly twenty years, there have been discussions of another LNG project in Alaska based on reserves in the Prudhoe Bay that would be pipelined to an export terminal at Valdez. For various reasons, especially economics, this project has not materialized. Table B-1 lists all potential sources of LNG supply, along with composition and major properties, obtained from each export terminal's major owner.

Table B-1. Likely LNG Exporters to California

Project Name	Location	Major Owners	Status	Typical LNG Composition	LNG Values
Sakhalin Energy	Russia, off east coast	Shell, Mitsui, Mitsubishi	Under construction, startup 2008	92.2% C1, 4.9% C2, 0.8% C3, 1.9% C4.	HHV=1105 Btu/scf SpG=0.613 Wobbe=1411
Darwin	Australia	ConocoPhillips	Under construction,	Fields have high liquids content. LNG could be	*Unknown at present*

Project Name	Location	Major Owners	Status	Typical LNG Composition	LNG Values
			2008	"hot".	
Malaysia TIGA	Malaysia	Petronas, Shell, Mitsubishi	Operational	91.2% C1, 5.2% C2, 3.3% C3, 1.4% C4+.	HHV=1137 Btu/scf SpG=0.633 Wobbe=1428 (EIA: 1122 HHV)
Northwest Shelf Train 5	Australia	Woodside, Shell, BP, BHP, Chevron, Mitsubishi/Mitsui	Under construction, 2006	89.3% C1, 7.1% C2, 2.5% C3, 1.0% C4+.	HHV=1128 Btu/scf SpG=0.628 Wobbe=1424 (EIA: 1132 HHV)
Tangguh Project	Indonesia	BP, CNOOC, MI Berau B.V. Nippon Oil Corp. KG Berau/Wiriagar LNG Japan Corp.	In EPC phase Startup 2008-2009	96.3% C1, 2.6% C2, 0.5% C3, 0.2% C4+, ,0.4% N2.	HHV=1039 Btu/scf SpG=0.590 Wobbe=1369 (EIA reports 1118 HHV)
Peru LNG	Peru	Hunt Oil, Repsol, SK	Planned; 2009	*Unknown at present*	*Unknown at present*
Pilbara	Australia	BHP Billiton, ExxonMobil	Pre-feasibility study	*95% C4, 5% N2*	*HHV=964 Btu/scf* *SpG=0.576* *Wobbe=1270*

Table B-2 shows gas measurements from California collected by GRI in 1992, and Table B-3 summarizes the range in composition values currently found in California. The information contained in Table B-2 was compiled by GRI under funding by the California Energy Commission (Energy Commission), while the information in Table B-3 was compiled by the Energy Commission independently. California is divided into Btu districts, in compliance with California Public Utility Commission (CPUC) general order 58-A, which requires that the delivered gas must be identified and monitored. The range of each district is contractural information that is not made publicly available, although the heating value of the gas in each district must be published periodically. The information contained in Table B-1, when compared with the values in Table B-3, shows the difference between domestic gas quality and imported LNG quality. Substantial differences in the heating content or Wobbe number could affect the performance, emissions, safety, or longevity of the combustion equipment. It is for this reason that local distribution companies have developed and maintain guidelines that specify the boundaries in fuel gas compositions and fuel gas properties–most notably the HHV

and Wobbe number. An example of such a guideline is Southern California Gas Company's (SoCal Gas) Gas Quality Standards and Rule 30 (Southern California Gas Company, no date).

Table B-2. Natural Gas Methane Content, Heating Value, and Wobbe Number in California Regions, 1992 (Liss et al. 1992)

	Site	Methane (vol. %)	Heating Value (Btu/scf)	Wobbe Number (Btu/scf)
Northern California Region	1	93.92	1033	1340
	2	94.33	995	1301
	3	95.53	1017	1326
	4	96.64	1011	1336
	5	94.94	1026	1340
Southern California / San Diego Region	6	93.10	1039	1341
	7	93.73	1028	1335
Southern California / L.A. Region	8	93.60	1030	1335
	9	92.25	1040	1335
	10	91.19	1048	1337
	11	93.48	1029	1333
	12	92.34	1042	1340
Summary				
Average		93.09	1035	1337
Minimum		90.31	986	1290
Maximum		96.88	1060	1358

Table B-3. Natural Gas Composition Statistics in the California Region (CEC/CPUC 2005)

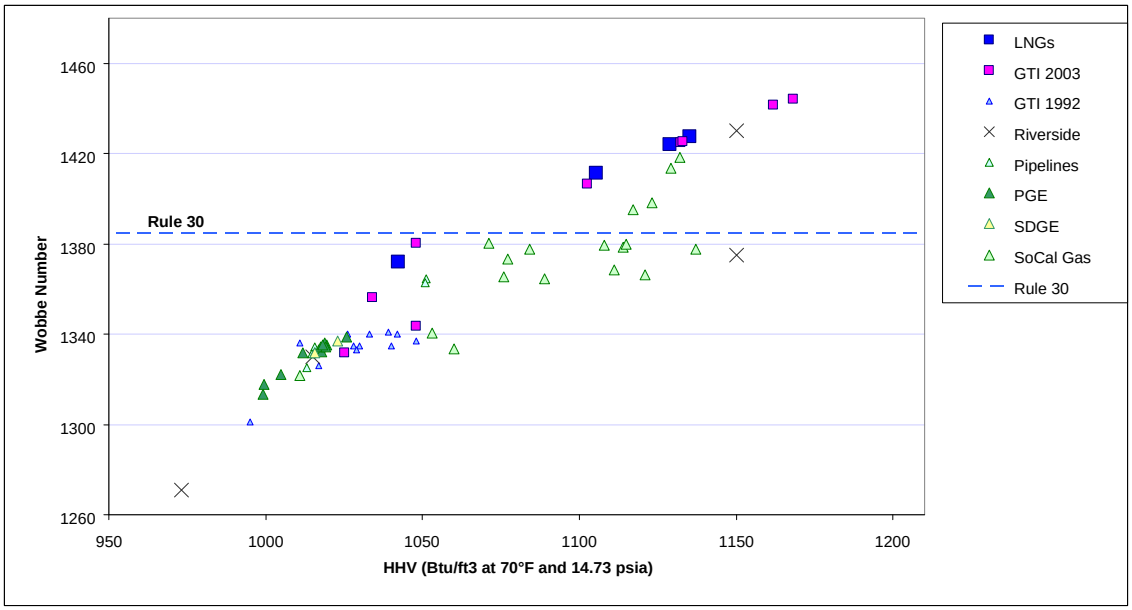
	Minimum	National Average	California Average	Maximum
Methane	74.5	93.9	93.1	98.1
Ethane	0.5	3.2	3.4	13.3
Propane	0.0	0.7	0.7	2.6
C_4 and higher	0.0	0.4	0.3	2.1
$N_2 + CO_2$	0.0	2.6	2.5	10.0

In California, gas quality standards are specified in Pacific Gas and Electric Company (PG&E) Rule 21 and SoCal Gas Rule 30, for transmission of customer-owned gas. Rule 21 cites the gas quality ranges recommended by American Gas Association (AGA) Bulletin 36, while SoCal Gas specifies a ±10 percent variation in Wobbe number and a gross higher heating value (HHV) between 970 and 1150 Btu/scf with a maximum Wobbe number of 1385.

The NGC+ whitepaper's interim guidelines are more restrictive: the Wobbe number must be below 1400, and the HHV below 1110 Btu/scf, plus restrictions on gas composition that amount to a Wobbe number of about 1200. Figure B-1 shows the Wobbe number and higher heating value for the LNG compositions available to California, and how they relate to the Rule 30's limit.

With California's average Wobbe number of 1337 chosen to define the Rule 30 envelope, none of the potential import LNG qualities are acceptable according to Rule 30; they are denoted by blue squares. The NGC+ whitepaper's interim guidelines exclude all but the Tannguh LNG composition. Other markers (the X's) indicate test compositions used in a University of California (UC), Riverside, study (Miller and Welch 2005), and natural gases currently used in California noted in 1992 (denoted by various green triangles and blue triangles).

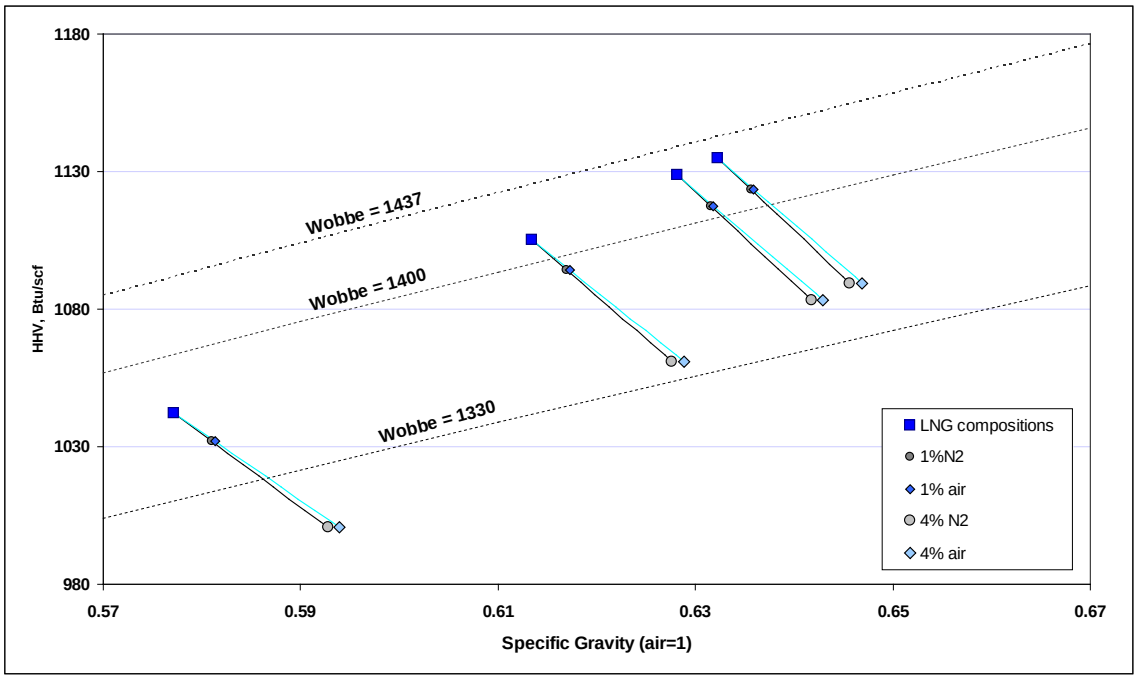
Figure B-1. LNG Quality, UC Riverside Test Compositions, and an Example Rule 30 envelope, Given Current Gas Quality in California



The way test gases are chosen and the methodology for determining interchangeability will affect the type of results that can be reported: either they can speak to the adequacy of designated regulatory limits, or they can speak to the feasibility of importing LNGs with extreme compositions. The GTI selections were six blends that simulated available LNG compositions plus three adjustment gases; that study's intent was to determine the minimum degree of blending needed to condition the LNGs for acceptable performance. Both substitute+adjust and substitute+inert blends were tested.

Figure B-2 illustrates the effect of air or nitrogen blending on gas quality; the axes are specific gravity and higher heating value, with lines of constant Wobbe number as indicated. It is possible to condition all four of the potential LNGs to achieve California's average Wobbe number with less than 4 percent nitrogen or air blending; 4 percent is the maximum recommended mole percent inert, both according to the current SoCal Gas Rule 30 limit and the NGC+ white paper guidelines.(NGC+, 2005)

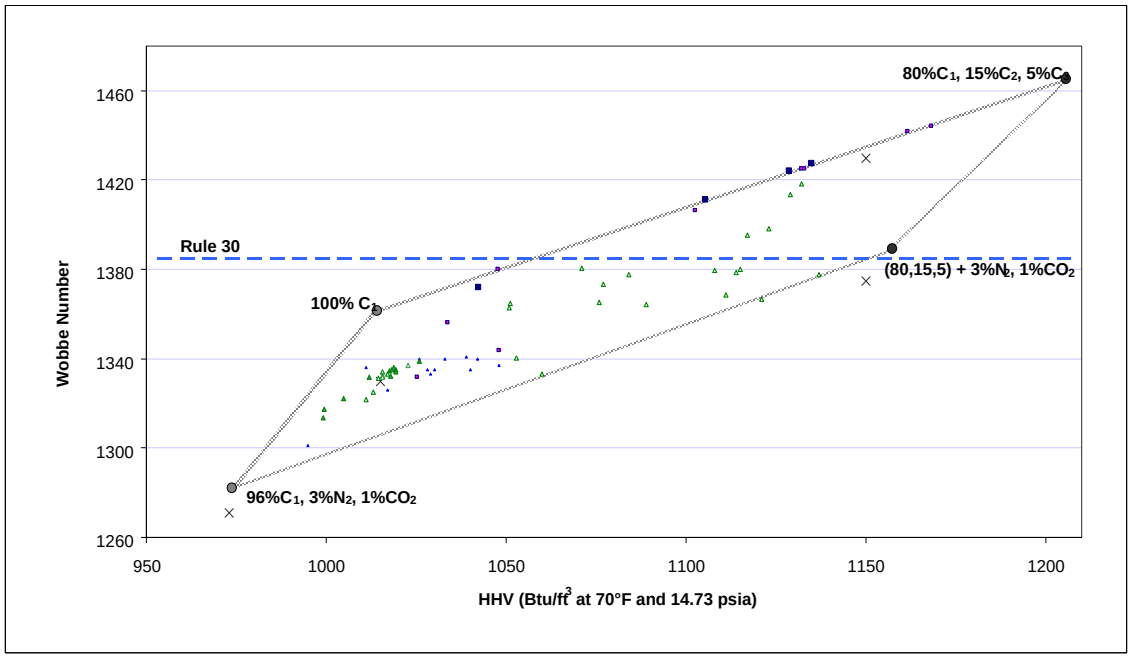
Figure B-2. Effect of Conditioning with Air or Nitrogen on Gas Quality



In the industrial burner study, the project team selected representative gas compositions covering the range of anticipated LNGs and the current natural gases used in California. Gas compositions were varied following methods simulating both nitrogen blending and heavy hydrocarbon stripping.

Figure B-3 shows examples of how inert blending and C4+ stripping can move a gas composition and heating values relative to the Rule 30 box. The gray diamond encloses all of the historical, current, and foreign natural gas compositions. The top right corner is 80 percent methane, 15 percent ethane, and 5 percent propane; the bottom left corner is pure methane diluted by 3 percent nitrogen and 1 percent carbon dioxide; and the other two corners are the same compositions with and without added inert gas. The final selection of blending and stripping choices has not yet been made, but all gas modifications will be derived from actual LNG and natural gas compositions.

Figure B-3. Effects of Stripping C4+ Hydrocarbons and Blending with Nitrogen



References

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Miller and Welch 2005

NGC+ Interchangeability Work Group. 2005. White Paper on Natural Gas Interchangeability and Non-Combustion End Use. http://www.aga.org/SiteCollectionDocuments/KnowledgeCenter/OpsEng/0502NGINTERCHANGE.pdf

APPENDICES

Appendix D: Burner Testing Reports

Appendix E: Commercial Foodservice Equipment

Appendix F: Simulation-Based Estimates of Indoor Exposures to Pollutants from Natural Gas Cooking Burners

These appendices are available as a separate volume, publication number CEC-500-2015-021-APD-F.