Arnold Schwarzenegger
Governor

NATURAL GAS IN CALIFORNIA: ENVIRONMENTAL IMPACTS AND DEVICE PERFORMANCE

LITERATURE REVIEW AND INDUSTRIAL BURNER EVALUATIONS

PIER PROJECT REPORT

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Preface

The Public Interest Energy Research (PIER) Program 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.

The PIER Program, managed by the California Energy Commission (Energy Commission), conducts public interest research, development, and demonstration (RD&D) projects to benefit electricity and natural gas customers.

The PIER program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

Natural Gas in California: Environmental Impacts and Device Performance: Literature Review and Industrial Burner Evaluations is the final report for the Natural Gas in California: Environmental Impacts and Device Performance project (contract number 500-05-026) conducted by the Gas Technology Institute. The information from this project contributes to PIER's Energy-Related Environmental Research Program.

For more information about the PIER Program, please visit the Energy Commission's website at www.energy.ca.gov/pier/ or contact the Energy Commission at 916-654-5164.

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Abstract

The burners that serve California's industrial manufacturing sector have not been tested for use with fuel gas compositions common in currently available liquefied natural gas. Interchangeability tests for industrial burners will be performed by the Gas Technology Institute to provide the necessary data to determine these burners' gas quality needs. This report summarizes preliminary work to select appropriate test gases, representative burners, and reasonable test protocols, so that the tests address California's particular needs.

Keywords: burner, industrial, interchangeability, liquefied natural gas, LNG

Executive Summary

Liquefied Natural Gas (LNG) imports from suppliers in Asia and the Pacific Rim are expected to supplement California's natural gas supply in one to five years. These gases differ in composition from California's historical fuel gas composition, and equipment adjusted to local gas quality could respond differently when firing the imported fuel. Possible 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. The Public Interest Energy Research (PIER) group of the California Energy Commission funded a study by the Gas Technology Institute (GTI) to research potential performance and operational issues associated with using imported LNG. This first report from that study discusses its preliminary steps—that is, the literature review and the industrial burner evaluations conducted by GTI to determine (1) current and projected fuel gas compositions in California, and (2) which burners are both prevalent in California and sensitive to changes in fuel gas composition. Fuel gas compositions and burners identified in this report shall be considered for inclusion in the study. Future reports for this project will focus on the experimental evaluation of natural gas-fired burners commonly used by California's industrial sector and will identify, by sector, how gas quality affects burner performance.

To maximize the study's relevance, combustion equipment, test gas compositions, and burner protocols should be chosen carefully. This preliminary phase of the project assembled information to inform that selection process by (1) reviewing existing interchangeability studies, (2) determining how to select the chemical composition of the test fuels by examining likely LNG import compositions, (3) classifying burners according to their operation, use, and sensitivity and assessing the most prevalent burners in California, and (4) determining test protocols, informed by a survey of existing protocols and methodologies. The following results are highlighted:

- **Prior interchangeability studies.** Prior studies indicate that the primary measure of interchangeability, regardless of application, is the fuel's Wobbe Number. Fuels with the same Wobbe Number will have equivalent heat input rates through the orifice of a burner. Application-specific performance indices have been studied, but not for industrial burners.
- **Test Fuel compositions.** Previous studies selected at least one adjustment gas to represent the existing pipeline fuel gas composition and provide a baseline to compare with the substitute gas compositions. Substitute gases are chosen to represent either regulatory extremes or import possibilities. If the substitutes are not interchangeable, different amounts of gas conditioning are tried: inert gas or air injection, blending with the adjustment gas, or removing the heavy hydrocarbons. A correlation between conditioning and performance is presented as an outcome of the previous studies.
- **Burner classification and ranking.** Industrial burners have diverse applications and operate in a number of distinct modes that imply different piping and air setup and different control schemes. Each burner type was ranked by its expected

response to an unanticipated change in gas quality. The research team developed a table to summarize each burner's relevance to California industry, and categorizes each in terms of its potential response to imported LNG.

CATEGORY I: possible damage	Category II: possible performance change	Category III: change unlikely		
Industry	**Sites**	**Relative Gas Use**	**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*
Fabricated Metal	7,931	3.4%	I and *II* I and *II* II	BOILER BURNER (PRESSURE) RADIANT TUBE BURNER *Thermal radiation 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*

- **Test protocols.** Most standards specify equipment requirements, such as valve placement and pressure strength, rather than procedures for measurement, although a number of fuel interchangeability protocols exist for burners in refinery service. Experimental procedures for various burner tests at GTI and elsewhere are combined to form a basic test sequence.

1.0 Introduction

The U.S. Energy Information Administration forecasts that domestic production of natural gas and Canadian imports will not keep pace with the growth of demand through 2023. A number of proposed Liquefied Natural Gas (LNG) receiving terminals along the United States' west coast are intended to accommodate this demand, and may lead to use of vaporized LNG as a fuel in California. Because the available LNG differs in composition from California's historical fuel gas composition, 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 Work 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" (NGC+ 2005). The Public Interest Energy Research (PIER) group of the California Energy Commission funded the Gas Technology Institute (GTI) to conduct an interchangeability study of potential performance and operational issues associated with using imported LNG. 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." The interchangeability study can also investigate what would need to happen to make a substitute gas acceptable.

This report summarizes the background work conducted by GTI to perform an experimental evaluation of natural gas-fired burners commonly used by California's industrial sector. The study will investigate how gas quality affects burner performance, to identify the sector's gas quality needs as California prepares to add regasified LNG to its energy portfolio. To maximize the study's relevance to California's industrial burners, combustion equipment, test gas compositions, and burner protocols must be chosen carefully; this report informs that selection process.

The document is organized into five parts: (1) a review of existing interchangeability studies, (2) a discussion of how to select the chemical composition of the test fuels by examining likely LNG import compositions, (3) a classification of burners according to their operation, use, and sensitivity, (4) an assessment of the most prevalent burners in California, and (5) a discussion of anticipated test protocols, informed by a survey of existing protocols and methodologies.

Preliminary work on classifying burners and determining the population of industrial combustion systems in California was carried out by GTI in work sponsored by a consortium of companies and utilities. That work served as a basis for the more extensive work presented in this report. The sponsors of the earlier work were the Southern California Gas Company; Occidental of Elk Hills, Inc.; California Independent Petroleum Association; BP Energy Company; Sempra LNG; Chevron Texaco USA; Pacific Gas & Electric Company; KeySpan Energy; SES Terminal, LLC; Shell NA LNG, LLC; and the Western States Petroleum Association.

2.0 Previous Interchangeability Studies

To the authors' knowledge, no extensive study of fuel gas interchangeability for industrial burners has been undertaken. There does exist, however, extensive research in other areas of end-use that can inform GTI's upcoming industrial burner study. This research is listed in Table 1.

Table 1. Selected prior interchangeability test results

Study or Regulation	Index	Range	Comment
AGA 36 (1946)	Lifting, Yellow Tipping, Flashback	I_L<1.0<1.12, I_F<1.18<1.2, I_Y>1.0>0.7	Preferable and objectionable limits for higher Btu natural gas; the more restrictive limits indicate the preferable range and the less restrictive ones the objectionable range. Formulas for the indices are given in the publication. I_Y bounds heating value from above, and I_L from below.
PG&E (1996)	HHV	I_L<1.06, I_Y>0.8	No flashback was observed for any test gas.
SoCalGas (2005)	Wobbe Number	Below 1400	This is a change from the Rule 30 limit of 1437, because of objectionable carbon monoxide.
CARB (2005)	Methane Number (MN)	above 80	To ensure no engine knock in reciprocating engines. The MN > 80 is met by all of the potential LNGs.

Combustion equipment is tuned for optimum performance when using an "Adjust Gas," and interchangeability measures whether the equipment will perform acceptably when a "Substitute Gas" is used. Each end-use sector must define its particular needs to ensure imported LNG interchangeability.

The NGC+ Interchangeability Working Group has collaborated on such efforts and written a report (NGC+ 2005) to outline steps that should be performed in order to ensure the interchangeability of LNG with industrial and commercial burners. These steps (and work group comments) are paraphrased below:

1. <u>Review and Classify Equipment</u>
    a. Classify burners and combustion systems by types
    b. Consider legacy, operating burners, and new types under development

2. <u>Collect Available Data</u>

   a. (Data may not currently be available)

   b. Performance data from different manufacturers may not be consistent

3. <u>Determine Testing Needs and Standardized Testing Protocols</u>

   a. (Methodology development may be necessary)

   b. Test methods to be based on combustion practice and made public

4. <u>Test Equipment</u>

   a. Representative examples of the most sensitive types of burners and combustion systems shall be tested in the laboratory

   b. Most sensitive burners should be field tested

5. <u>Analyze Data and Report Results</u>

   a. Recommend equipment

   b. (Retrofits and additional long-term testing may be required)

   c. (New types of indices may be developed)

The earliest natural gas interchangeability research was performed by the American Gas Association (AGA) and published in a series of reports and bulletins. AGA Bulletin 10 (AGA 1940) described how the design features and operation of an atmospheric gas burner affects the characteristics of its flame. Such variables as fuel source, primary air, orifice sizes, surface finishes, and both size and location of the port area were studied. AGA Bulletin 36 (AGA 1949) reports the results of interchangeability tests on a custom test burner, and presents three gas interchangeability indices, to make a more descriptive gas quality envelope than could be obtained by one index alone. Single index values used at the time included the heating value of the gas, the Wobbe Number, and the AGA "C" and Knoy "C" values, which attempted to quantify flame speed. The new AGA indices were the Lifting Index (IL), Flash-Back Index (IF) and Yellow Tip Index (IY). The AGA Precision test burner (also used in Bulletin 10) was tested with a series of fuel gases with different heating values to establish yellow tipping and lifting limit curves that relate the maximum and minimum fuel/air ratio to the firing rate for different fuel gases. The researchers determined that for acceptable fuel interchangeability, values for each index must fall within the numerical limits established for a specific adjustment gas. E. Weaver of the U.S. Bureau of Mines derived a series of six index values that added three more flame characteristics to the work of AGA (Weaver 1951). The additional indices are the Weaver Incomplete Combustion Index, the Weaver Primary Air Ratio, and the Weaver Heat Rate. Weaver's estimate for flame speed is also in use in the United States.

The Pacific Gas and Electric Company (PG&E) uses the specifications set by AGA Bulletin 36 to regulate gas quality on their distribution circuit. In 1996 they presented findings (Estrada 1996) from tests on ten gas-fired appliances to examine the acceptability of the AGA indices: pipeline gas was blended with either propane or nitrogen to achieve high and low heat content fuel gases, and each appliance was tested with successive blends until it failed the liftoff or yellow-tip test, or if its CO emissions were unacceptable. No appliance tested exhibited flashback. AGA's liftoff limit of 1.06, which corresponds to a higher heating value (HHV) of 1138 British thermal units per standard cubic foot (Btu/scf), was found to be more restrictive than necessary, but the yellow tip limit of 0.80 was too permissive, meaning the lower HHV should be raised from 953 Btu/scf.

A study reported in 2005 by SoCalGas (Miller and Welch 2005) assessed how residential and small commercial gas-fired equipment respond to changes in gas composition. The main objective of this study was to determine the safety and performance of the gas-fired equipment when operated with different fuel gases and verify the relevance, accuracy, and universality of the traditional interchangeability indices. The approach taken by SoCalGas was to test the target gas-fired equipment with gas compositions that fall within the boundaries of the current SoCalGas Rule 30. Thirteen gas-fired appliances were tested in a formal test program according to established protocols set forth by ANSI, AOAC, ASHRAE, ASTM, SCAQMD, UL,[1] and manufacturer test guidelines as they relate to each appliance. The evaluation criteria were developed and agreed upon by equipment manufacturers, industry experts, and the Air Emissions Advisory Committee. The gas compositions used for the tests were selected to represent the extreme Wobbe Number and HHV permitted by Rule 30, plus intermediate blends between these in the case that the extreme gases were not interchangeable. The report concludes the following major findings: SoCalGas' restriction on the upper Wobbe Number of 1437 is too permissive, and should be lowered to 1400, and neither HHV or Wobbe Number is an absolute predictor of equipment performance. The test procedure comprised five general steps: (1) install equipment per manufacturers' guidelines, (2) test equipment on a "as-received" basis, (3) vary fuel gas composition and measure the effect on emissions, ignition, efficiency, and traditional interchangeability indices, (4) perform additional tests per protocol requirements on a variety of fuel gas compositions, and (5) test hot/cold ignition while adjusting fuel gas composition and monitoring all parameters.

Another study conducted for Washington Gas Light (TIAX 2003) dealt with defining and developing interchangeability indices to accommodate LNG blending with nitrogen. This study focused on residential appliances, and its main objective was to determine how much nitrogen can be blended with pipeline quality gas without adversely affecting the target performance characteristics (yellow tipping, emissions,

[1] American National Standards Institute; Association of Official Analytical Chemists; American Society of Heating, Refrigerating & Air Conditioning Engineers; American Society for Testing and Materials; South Coast Air Quality Management District; and Underwriter's Laboratories Incorporated.

and flame lifting). The study found that LNG blended with nitrogen performed equally well with traditional pipeline gas on the tested appliances.

In 2003, the Gas Technology Institute (Johnson and Rue 2003), investigated the degree to which residential and small commercial appliances are affected by changes in fuel composition, using three typical North American pipeline gas compositions and six simulated LNG compositions. The LNG compositions were selected to cover the entire range of LNGs expected to be imported in the United States in the near future. Nine interchangeability indices were examined (three by AGA and six by Weaver) to determine to what extent the traditional pipeline gas can be mixed with simulated LNG or to what extent a simulated LNG can be blended with nitrogen or air to lower its heating value and Wobbe Number, without the tested appliances operating outside the standards set for operation and safety. The general finding of this study was that only a few appliances exhibited changes in performance or safety, in particular the appliances with a closed combustion chamber. This study also found that fuel gases with similar Wobbe Number behave the same on the tested appliances regardless of their composition, and that changes in carbon monoxide correlate with other performance changes.

In June 2005, emissions data were collected at four gas turbines at four different California power plants, to take advantage of a three-day natural gas liquid extraction plant failure in Canada. A 5% excursion in HHV and a 2% excursion in Wobbe Number occurred in less than four hours and lasted for three days (Walters 2006). NO_X emissions were unchanged downstream of controlled ammonia-injection systems; upstream of the systems NO_X increased by up to 4%, in proportion to HHV.

Fuel flexibility tests for blowout in a high-velocity premixed gas turbine combustor were reported at the ASME Turbo Expo in June 2006 (Lieuwen et al. 2006); theoretical analyses predict that blowoff in these systems should scale with the Damköhler number. The Damköhler number is the ratio of residence time to chemical time, and scales with the square of the laminar flame speed. Experimental data using mixtures of methane, hydrogen, and carbon monoxide in different concentrations correlate with the prediction and corroborate results from previous interchangeability studies that use flame speed as a second interchangeability index after the Wobbe Number. Flame speed is temperature and composition dependent, but methane and all of the hydrocarbon fuels typically present in LNG compositions have maximum flame speeds between 1.1 and 1.3 feet per second (ft/sec).

3.0 Pipeline Gas and Anticipated LNG Quality

Substitute gas compositions for GTI's industrial burner study need to reflect the range of LNG compositions potentially available for import, as well as reflect known interchangeability concerns of other end-use sectors. For example, if it is known that interchangeability for another sector prescribes a maximum Wobbe Number, it may not be relevant that an industrial burner can be fired at a higher Wobbe. Rather, it could be more useful to simulate different LNG conditioning methods that achieve this maximum Wobbe to determine whether, for example, NO_X emissions requirements are still met when the LNG is blended with nitrogen. 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.

3.1. Potential Sources of LNG for California Gas Consumers

Companies have proposed that several 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. In California's jurisdiction, the terminal proposed by Sound Energy Solutions in Long Beach, sponsored by Mitsubishi and ConocoPhillips, has progressed furthest: a 2007 start-up date has been proposed, but construction has not yet begun. It will have an average send out capacity of 0.7 billion cubic feet per day (BCF/day) and a maximum send out of 1 BCF/day. The LNG will most likely come from the Darwin project in Australia, where ConocoPhillips has an interest.

In Mexico, Sempra Energy's receiving terminal at Ensenada, Baja California, will start 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, a decision has not yet been made on how much of the revaporized LNG will be sold in Mexico.

Other projects under consideration are the Cabrillo Port, California, offshore terminal proposed by BHP Billiton (an Australian company); Excelerate Energy, LLC's Golden Gateway project offshore Mexico; and a 1 BCF/day offshore terminal proposed by Crystal Energy near Oxnard. It is not certain whether any or all of these projects will be implemented. The Energy Commission estimates that more than a hundred permits would be needed to build a new LNG plant in the state. Australia-based energy developer Woodside Petroleum Ltd. has recently unveiled a unique plan to build a receiving terminal with no permanent floating platform to receive, store, or gasify the LNG off the coast of Southern California that could supply the region with up to 15% of its LNG needs by 2011.

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% 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% 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 2 lists all potential sources of LNG supply, along with composition and major properties, obtained from each export terminal's major owner.

Table 2. 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, 2008	Fields have high liquids content. LNG could be "hot".	*Unknown at present*
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% C1, 5% N2*	*HHV=964 Btu/scf* *SpG=0.576* *Wobbe=1270*

3.2. Gas Quality in California

Table 3 shows gas measurements from California collected by GRI in 1992**,** and Table 4 summarizes the range in composition values currently found in California. The information contained in Table 3 was compiled by GRI under funded work by the Energy Commission, while the information in Table 4 was compiled by the Energy Commission independently. California is divided into Btu districts, in compliance with 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 2, when compared with the values in Table 4, 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 SoCalGas' Gas Quality Standards and Rule 30 (Southern California Gas Company, no date).

Table 3. 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 4. 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

Figure 1 illustrates the ranges in Wobbe Number found in California (taken from pipeline data or Btu district data posted on the Internet[2]), plus the potential LNG Wobbe Numbers. Five-pointed stars denote proposed offshore import terminals; the green star site is nearly operational, red star sites have not been sited, yellow star sites have been sited but without application for permit, and the blue star sites are under discussion for permit.

3.3. Blending Considerations

Liquefied Natural Gas can be conditioned before or after vaporization to make it acceptable for transmission and end use. In Japan, where imported LNG sometimes does not meet a minimum Wobbe Number requirement, the vaporized LNG is blended with propane. In California, the opposite problem is more likely; to reduce its Wobbe Number, vaporized LNG could be blended with pipeline natural gas, air, or nitrogen. If demand is sufficient, LNG exporters may also decide to strip the LNG of heavy hydrocarbons before shipment, or importers could strip the LNG during vaporization.

These different methods of LNG conditioning are summarized and compared in a recent report (Domnick 2006). The report states that blending LNG with pipeline natural gas is not a viable solution, for two reasons: first, because the LNG and pipeline gas compositions are similar so the bulk of the blend would need to be pipeline gas; and second, because blending those quantities would require facilities that currently exist at just a few stations on the Gulf Coast. Blending with air is resisted by distributors because oxygen can corrode the pipeline, so the only two reasonable ways to lower an LNG's Wobbe Number are to strip out the heavy hydrocarbons (C3+) or to inject nitrogen. Figure 2 illustrates the effect of petroleum and ethane extraction on gas quality. It is also possible to strip ethane and propane at the receiving terminal.

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[2] TransCanada GTN: http://www.gastransmissionnw.com/gasquality/data/gasqualityMMDDYYYY.txt;
Kern River: http://services.kernrivergas.com/services/postings/GasQuality/GasQualityLog.aspx;
Mojave Topock: http://passportebb.elpaso.com/GasQuality/GQQuery.asp?sPipelineCode=MOPC;
PG&E: http://www.pge.com/pipeline/operations/gas_quality/index.shtml;
Questar: http://www.questarpipeline.com/FERCSharedOrg/2FrameQPCGasQualityData.html.

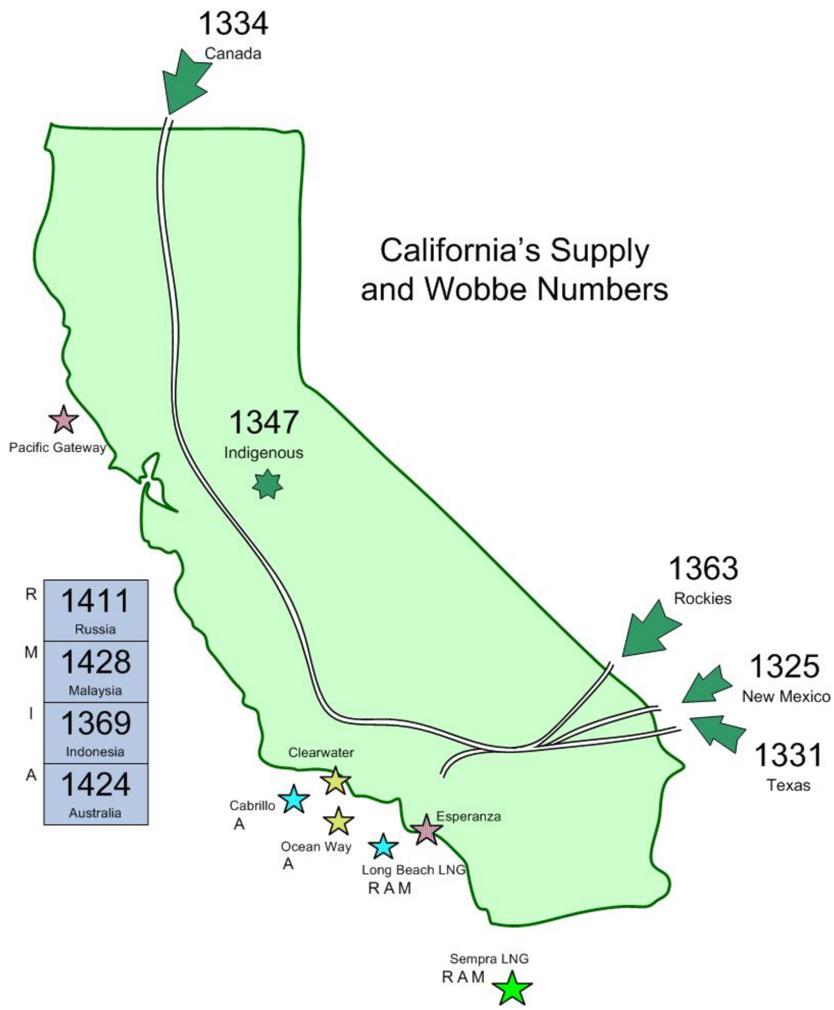


Figure 1. California's gas supply and representative Wobbe numbers

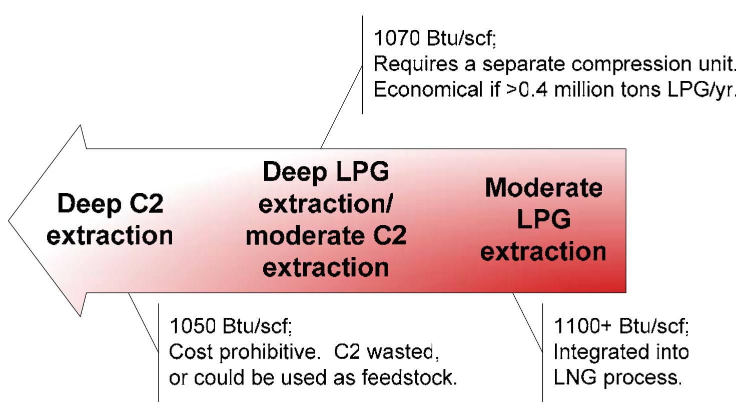


Figure 2. LNG conditioning by stripping at the compression site

Ballasting with nitrogen requires additional facilities at the LNG receiving terminal and adds cost. Since natural gas is sold by heat content and nitrogen adds none, ballasting also makes distribution more costly; the maximum inert content is 4% mole fraction, both according to SoCalGas Rule 30, and also according to the NGC+ whitepaper's interim interchangeability guidelines (NGC+ 2005). The project team intends to simulate both ballasting and stripping as part of the interchangeability study. Current NGC+ guidelines recommend a Wobbe range no greater than ±4% and SoCalGas Rule 30 requires a range of ±10%.

3.4. Selecting Test Compositions

In California, gas quality standards are specified in PG&E Rule 21 and SoCalGas Rule 30, for transmission of customer-owned gas. Rule 21 cites the gas quality ranges recommended by AGA Bulletin 36, while SoCalGas specifies a ±10% variation in Wobbe Number and a gross higher heating value (HHV) between 970 and 1150 Btu/scf.

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 3 shows the Wobbe Number and higher heating value for the LNG compositions available to California, and how they relate to the NGC+ interim limits and Rule 30's limit.

With California's average Wobbe Number of 1337 chosen to define the Rule 30 envelope, all of the potential import LNG qualities are acceptable according to Rule 30; they are denoted by blue squares. The NGC+ whitepaper's interim guidelines are more restrictive, however, and exclude all but the Tannguh LNG composition. Other markers (the X's) indicate test compositions used in a recent University of California (UC), Riverside, study (Miller and Welch 2005), and natural gases currently used in California or used in 1992 (denoted by various green triangles and blue triangles).

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 University of California Riverside's four selections represented an adjustment gas and three points on the boundary of Rule 30's specifications; the study's goal was to determine whether or not compositions at Rule 30's boundaries gave acceptable performance. If performance was unacceptable, either the Wobbe Number or the heating value was held the same, and the other parameter lowered or raised through appropriate changes in composition. 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.

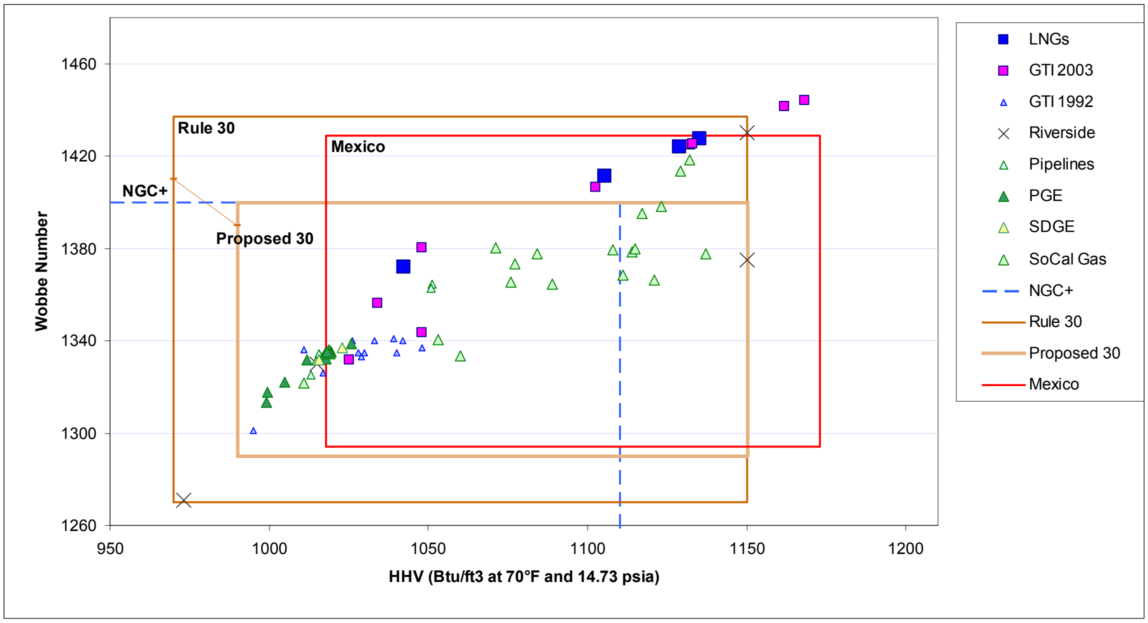


Figure 3. LNG quality, UC Riverside test compositions, and an example Rule 30 envelope, given current gas quality in California

Figure 4 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% nitrogen or air blending; 4% is the maximum recommended mole percent inert, both according to the current SoCalGas Rule 30 limit and the NGC+ white paper guidelines.

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

Figure 5 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% methane, 15% ethane, and 5% propane; the bottom left corner is pure methane diluted by 3% nitrogen and 1% 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.

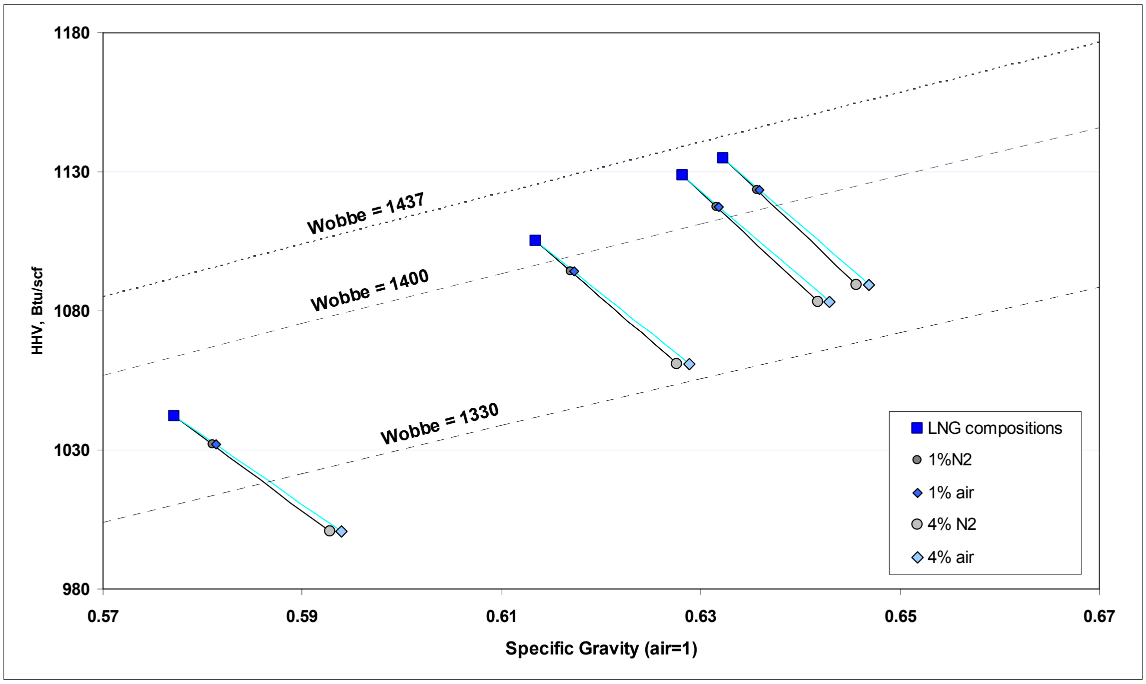


Figure 4. Effect of conditioning with air or nitrogen on gas quality

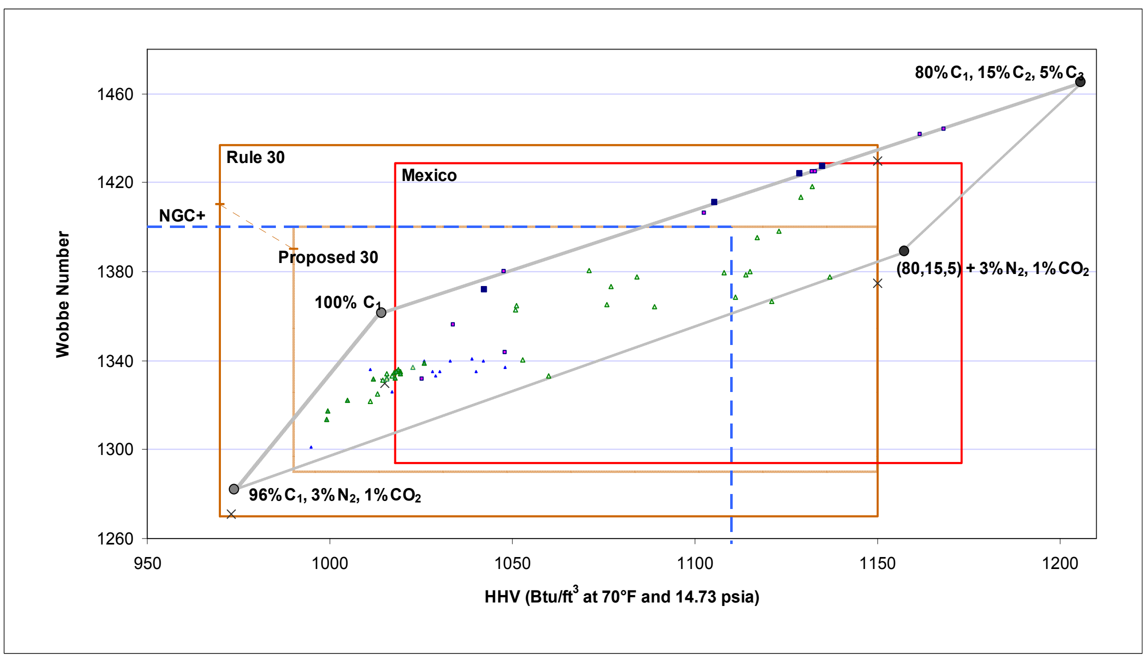


Figure 5. Effects of stripping C4+ hydrocarbons and blending with nitrogen

4.0 Burner Classification

Selecting which burners to test is crucial for this interchangeability study to have the most relevance. The burners tested must between them address all of the things that could go wrong when the fuel gas changes composition, so that they define a relevant interchangeability envelope. The interchangeability study will measure three things: (1) whether the burner still makes a flame safely or at all, comprised in its operating mode, (2) whether the burner still does what it was intended to do, comprised in its primary feature, and (3) whether airborne emissions change.

In this section, burners are classified first by operating mode and then by primary feature. The primary feature lends itself to a number of common end uses that are identified in these classifications, although end use is limited only by the ingenuity of the furnace designer.

4.1. Burner Classification by Operating Mode

The classification tree diagram in Figure 6 identifies general burner operating modes by juxtaposing burner classifications from Baukal et al. 2004, Reed 1997, and IHEA 2006. 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 of these six categories. A brief summary of the meaning of each category follows, with definitions available in the glossary.

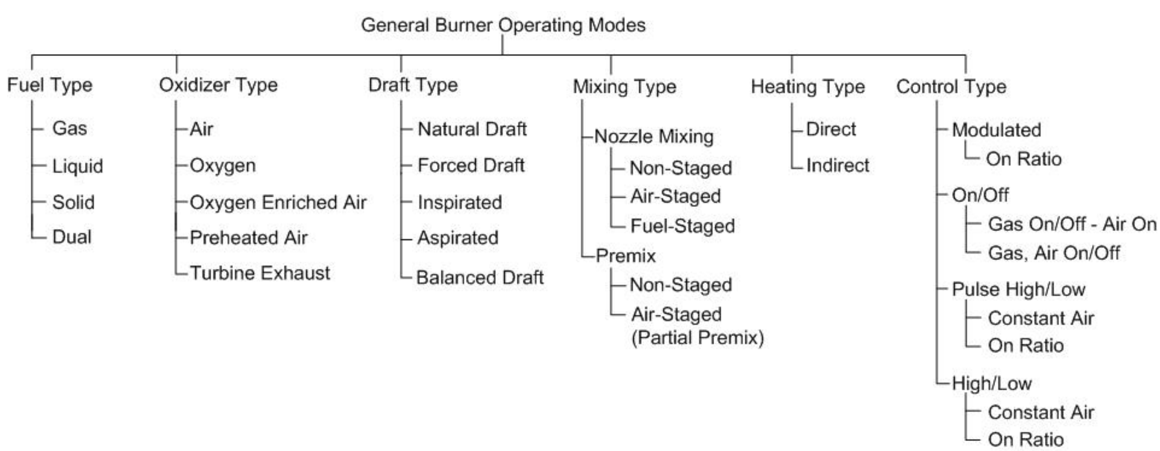


Figure 6. General burner operating modes

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 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 (NFPA 1999), 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 (Reed 1997).

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.

4.2. Burner Classification by Primary Performance Feature

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. This section classifies burners according to the performance feature that the equipment vendor emphasizes. Burner application was gathered from GTI experience, various recommended applications in burner manufacturers' brochures, and references for the food industry (Fellows 2000), paper industry (Nilsson et al. 1995), chemical process and refinery industries (Baukal 2001), industrial furnaces (Trinks et al. 2004), and burners in general (Baukal et al. 2004).

Eight major types have been identified; descriptions of their most common applications and associated performance needs are on the following pages.

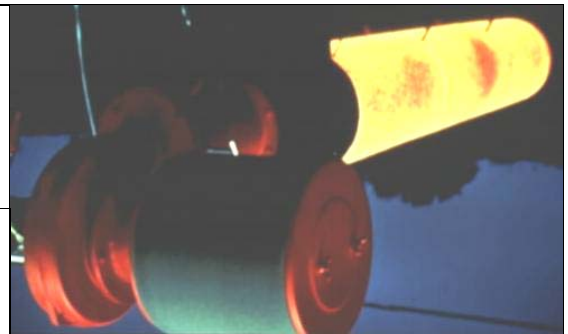
1. Radiant burners
    a. Burners for radiant tubes
    b. Thermal radiation burners
    c. Radiant wall burners
2. Nozzle mix [low, medium, high] velocity burners
3. Regenerative burners
4. Natural draft burners
5. Boiler burners
6. Linear grid/in-duct burners
7. Oxygen enhanced (oxy-fuel) burners
8. Flare burners

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 and final category includes the types of burners that are unlikely to be affected. The following list summarizes the three categories and assigns color codes to aid recognition of each category:

CATEGORY I: Types of burners that may sustain burner/equipment damage
Category II: Types of burners that may be affected in terms of combustion performance
Category III: Types of burners unlikely to be affected

Radiant tube burners

CATEGORY I:
May experience burner/equipment damage
Category II:
Possible change in combustion performance



Pyrocore single-ended radiant tube system

Capacity:
up to 8 million Btu per hour (MM Btu/hr)

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

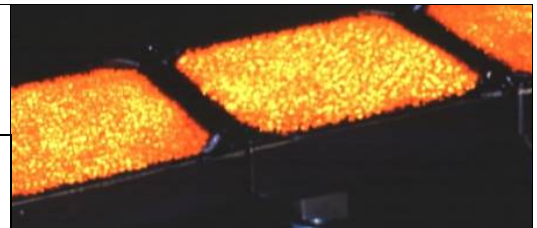
Radiant Tube Burner
- Tube Type
  - Non-circulating
    - Straight Tube
    - Single Ended
    - U-tube
    - Trident
    - W-tube
  - Recirculating
    - Single Ended
    - P-tube
    - Double P-tube
    - A-tube
- Draft Type
  - Forced
  - Inspirated
- Heat Recovery Type

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. Inspirited 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


Eclipse thermal radiation burners

Capacity:
4,000–65,000 Btu per hour per square foot (Btu/hr/sq. ft)

Major industrial applications:
Paper drying, wood drying, plastic thermoforming, paint curing, food processing.

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

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

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

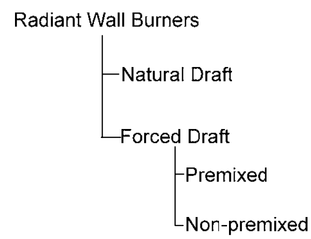
Major industrial applications:
Chemical industry applications, including ethylene production, cracking furnaces.

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.

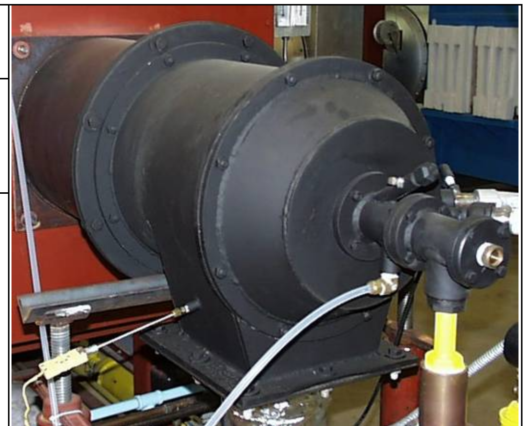
Regenerative burners

Category II:
Possible change in combustion performance

Capacity:
0.1 to 50 MMBtu/hr

Process Temperature:
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

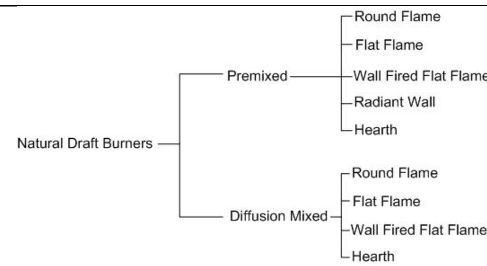
CATEGORY I: (Premixed)
May experience burner/equipment damage
Category III: (Non-Premixed)
Unlikely to be affected

A Zeeco natural draft burner

Capacity:
Up to 10 MMBtu/hr

Major industrial applications:
Chemical and petrochemical process heat.

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

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

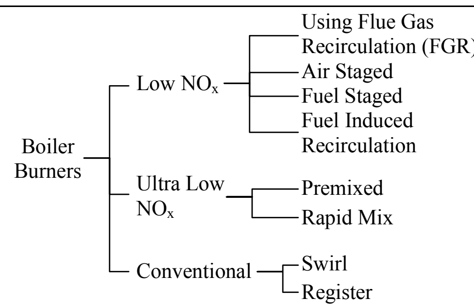
Boiler Capacity (industrial applications):
2 to 40 MMBtu/hr (firetube)
10 to 1,000 MMBtu/hr (large watertube)

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 pounds per square inch gauge (psig).

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.

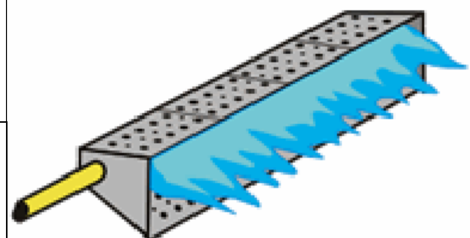
Linear grid/In-duct burners

Category II: (Linear grid)
Possible change in combustion performance
Category III: (In-duct)
Unlikely to be affected

A Flynn Burner Corp. ribbon burner

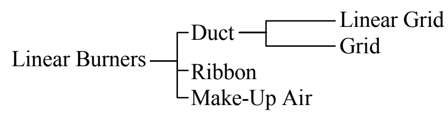
Capacity:
Linear grid: Up to 500,000 Btu/hr/ft
In-duct: Up to 1 MMBtu/hr/ft

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.



Sketch of a duct burner

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.



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 cogeneration 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

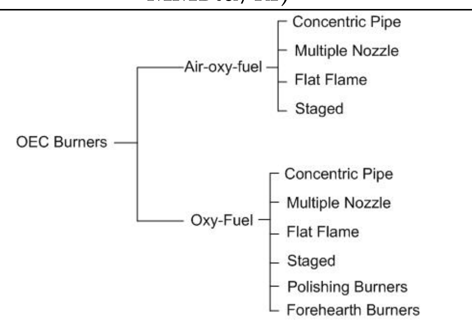
Category II:
Possible change in combustion performance

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

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.

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, the research teams 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.

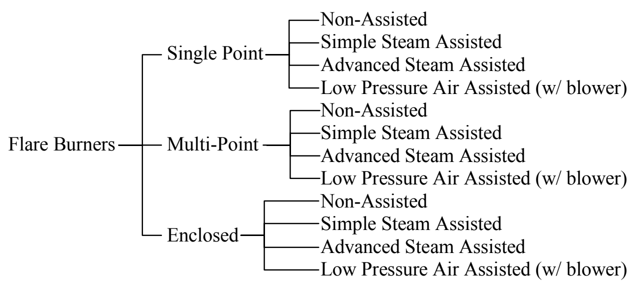
Industrial flare burners

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.



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.

5.0 California Industrial Natural Gas Demand

Burners selected for testing must actually be in service for the test results to be useful. This section infers California's industrial burner population by combining census results with common burner applications. Table 5 lists the burner types that usually serve each industrial manufacturing sector; it summarizes and augments the industrial applications information from the previous chapter.

Table 5. Common industrial burner applications, by sector

Industry	Burners Often Used	Application
Petroleum	Natural draft burner, Radiant wall burner Flare burner	 Heat chemical process furnace walls Combust unwanted process by-products
Oil and Gas Extraction	Boiler burner Flare burner	Generate pressure for extraction Combust unwanted products
Food and Beverage	Boiler burner Thermal radiation burner, Radiant tube burner Line burner In-duct burner	Generate steam for food-drying drums. Generate steam to pasteurize or cook Generate heat to dry low-moisture food Baking and roasting Baking in a forced-convection oven
Cement, Mineral, and Glass	Oxy-fuel burner Regenerative burner High velocity burner	Calcining and melting; low emissions Calcining and melting; energy efficient Calcining and melting; long flame (staged)
Sugar and Frozen Food	Boiler burner	Generate steam for sugar drying drums Generate steam to blanch vegetables
Paper and Textile	Boiler burner Thermal radiation burner, Radiant tube burner	Steam for paper or textile-drying drums. Generate heat to dry inks and dyes.
Chemical	Radiant wall burner Thermal radiation burner, Radiant tube burner	Heat chemical process furnace walls Generate heat for drying
Primary Metal	Boiler burner Radiant tube burner Oxy-fuel burner Regenerative burner High-velocity burner	Generate pressure for machine drives Clean, intense heat Intense heat; low NO_X and high efficiency Intense heat with higher efficiency Intense heat with circulation in the furnace
Fabricated Metal	Boiler burner Thermal radiation burner, Radiant tube burner	Generate pressure to shape and cut parts Generate heat to cure paints and finishes
Pulp	Boiler burner	Black liquor
Semiconductor	Radiant tube burner	Very clean heat
Construction	High-velocity burner	Heat with high circulation for area drying

Figure 7 summarizes California industries' natural gas demand between the years 2000 and 2004; statistics were obtained from the California Energy Commission. Some industries are more energy-intense than others, so it is also useful to know the number of establishments in each industrial sector.

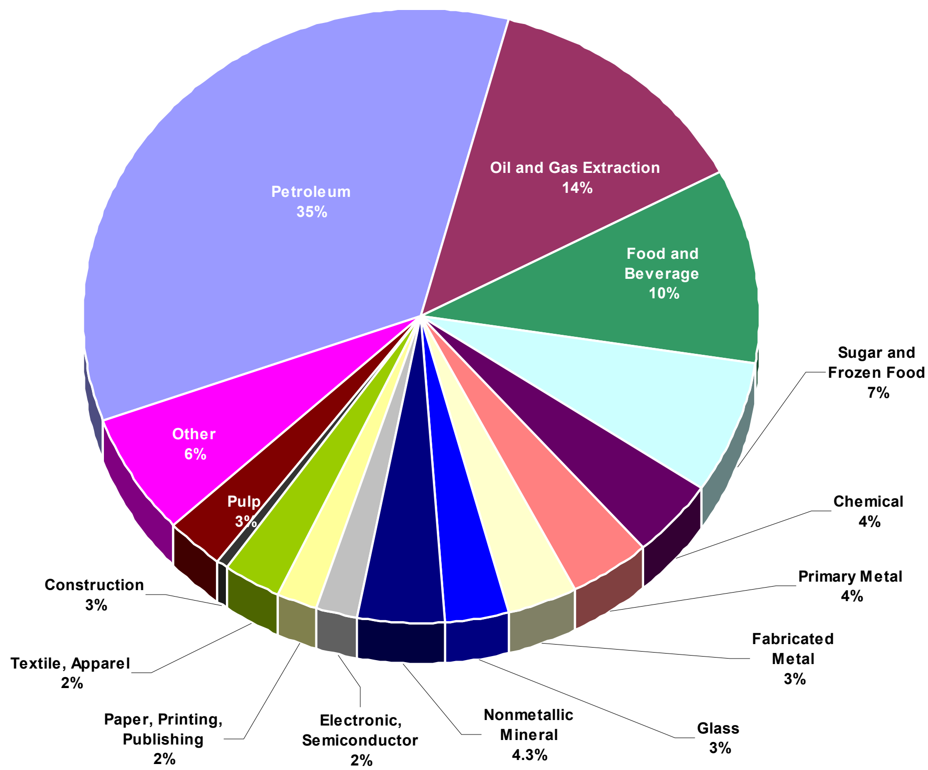


Figure 7. Industrial natural gas demand by sector in California

Figure 8 shows 2002 census data for the number of establishments in each of the same sectors; grouped by NAICS category (Appendix E contains the raw census data). These materials suggest the amount of education and paperwork that would be necessary if the use of vaporized LNG were to require equipment adjustment or special emissions exceptions.

Some industries are much more fuel-intensive than others. For example, the 2.7% natural gas demand from the pulp industry is from one single plant, but the construction industry, which comprises 70% of the entire industrial sector, used only 0.6% of the sector's total natural gas. The total number of establishments in each NAICS category is shown in logarithmic scale in Figure 8. For another perspective on scale, the number of employees on payroll in each sector is shown in Figure 9; these statistics are relevant because burner performance impacts operating cost and product quality, which can impact employment.

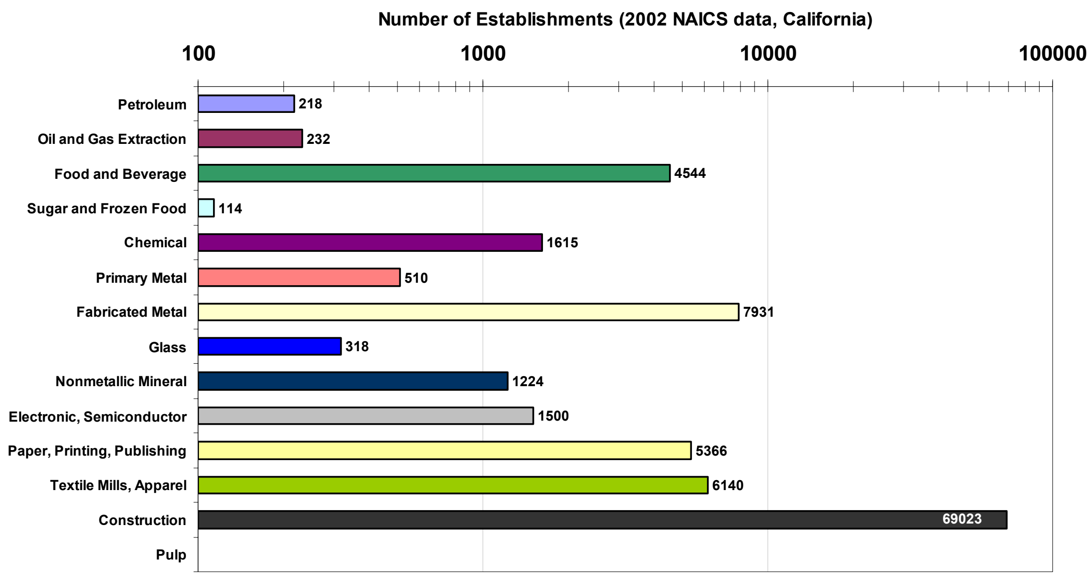


Figure 8. Industrial establishments in California (logarithmic scale)

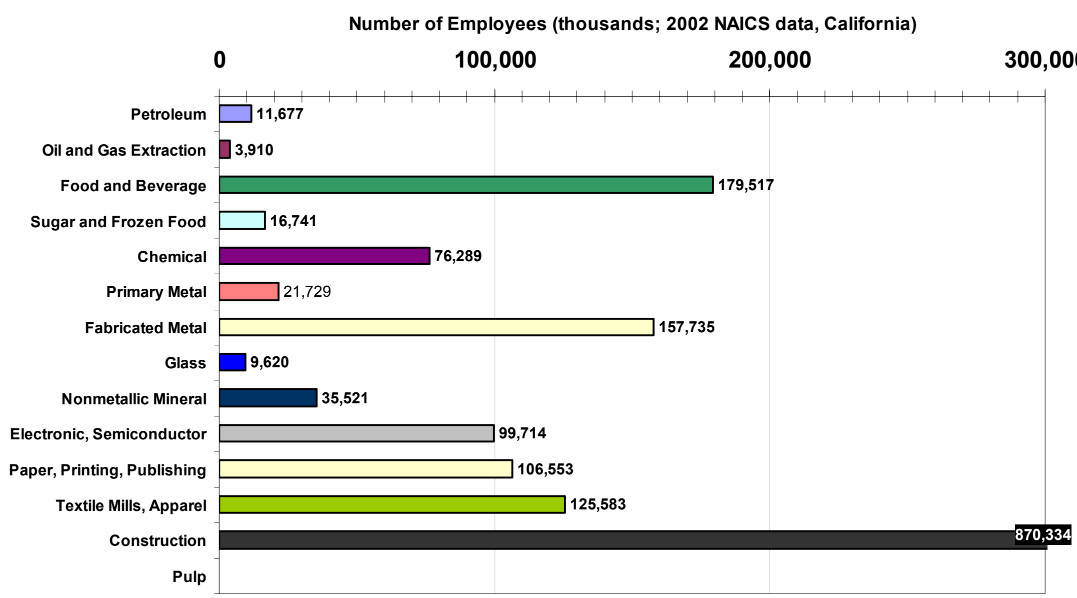


Figure 9. Employment in California's industrial sectors

Total use identifies the sectors most dependent on natural gas for their process, and number of establishments identifies California's industrial population. It is important that both metrics be used together to assess and rank burners according to their relevance to California. Table 6 collects the relevant data from this section into one table, for a more compact presentation. The industries are listed in descending order of gas use, with the number of sites noted, and the burners they use colored according to the sensitivity categories. The parenthesized "pressure" and "heat" after the boiler entries denote whether boilers in that sector are more likely to be used to generate pressure for machine drives, or to generate heat for pasteurization or drying. Often, watertube boilers are used to generate the high pressures, and firetube boilers are used for heat, and the appropriate one should be used for testing.

Table 6. Presumed burner types in California's industrial sector

CATEGORY I:	Types of burners that may sustain burner/equipment damage
Category II:	Types of burners that may be affected in terms of combustion performance
Category III:	Types of burners unlikely to be affected

Industry	Sites	Relative Gas Use	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*
Fabricated Metal	7,931	3.4%	**I** and *II* **I** and *II* II	**BOILER BURNER (PRESSURE)** **RADIANT TUBE BURNER** *Thermal radiation 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*

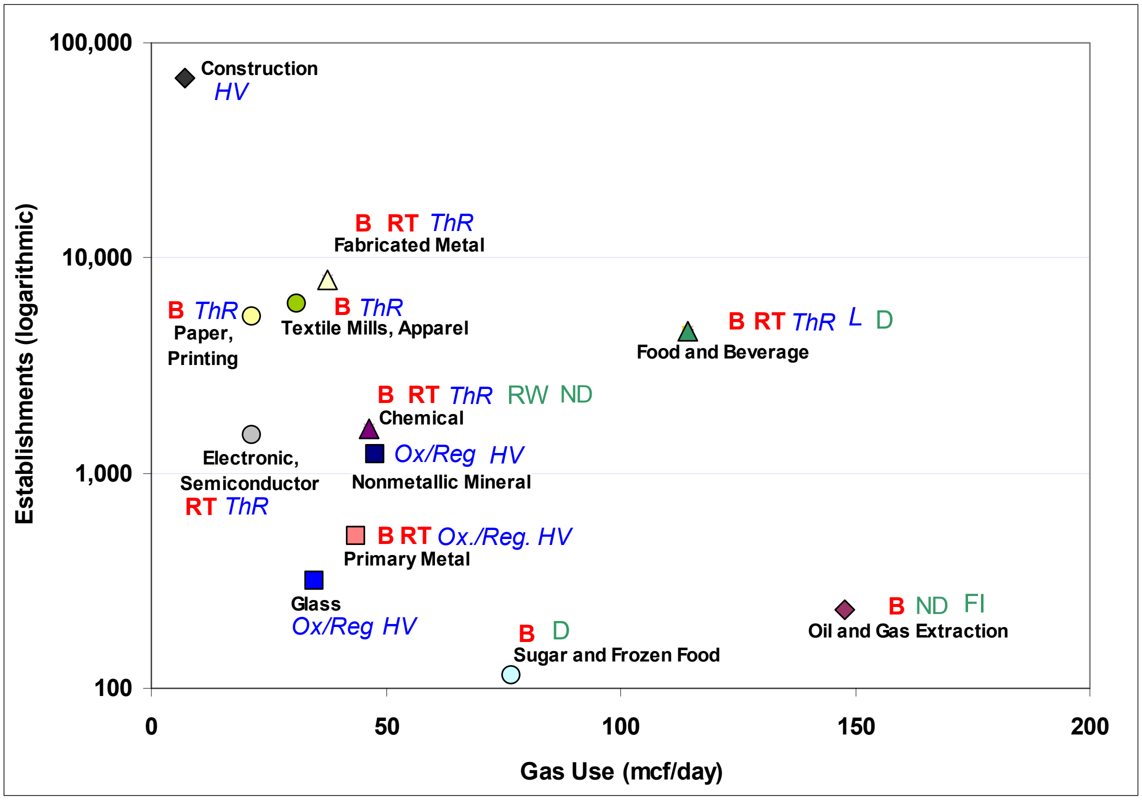


Figure 10. Burner population

Figure 10 shows this same chart with the gas use and the number of sites placed on the abscissa and ordinate, respectively. The different burner types are denoted as follows: B Boiler Burners, RT Radiant Tube Burners, RW Radiant Wall Burners, ThR Thermal Radiation Burners, Ox/Reg Oxy-Fuel and/or Regenerative Burners, HV High Velocity Burners, L Line Burners, D Duct Burners, ND Natural Draft Burners, and Fl Flare Burners. Frequency of occurrence, distance from the origin, and color indicate different measures of sensitivity. It would be reasonable to choose one or more burners from each of the types represented in Figure 10, and more from the Category I and Category II types.

Table 7 lists the preliminary selection of burners to be tested, and their typical firing rate.

Table 7. Typical burner types and sizes to be chosen

Thermal Radiation Burners	5,000–10,000 Btu/hr/sq.ft
Boiler Burners	5–10 MMBtu/hr
Radiant Tube Burners	0.15–0.35 MMBtu/hr
Linear Burners	1,000–5,000 Btu/hr/in
High Velocity Burners	0.1–0.5 MMBtu/hr
Oxy-Fuel Burners	0.5–5 MMBtu/hr
Regenerative Burners	0.3–0.6 MMBtu/hr
Natural Draft Burners	3–7 MMBtu/hr

6.0 Test Protocols and Testing Procedures

Section 6.1 presents the overall sequence of testing, to give an overview of the plan for the whole test, including the different test platforms available. Section 6.2 describes the protocols associated with the fuel gas preparation. This will be different from most other interchangeability trials because of the fuel volume needed for industrial burners. Sections 6.3 through 6.5 will describe emissions measurement and tests for the burner's operating envelope and flame shape.

6.1. Sequence of Testing

Before any testing occurs, it is necessary to create the test gas blending station and verify that it works. Once the blends are assured, the sequencing should be such that every test platform be set up only once. Also, blend compositions will be verified periodically throughout the burner tests. Figure 11 shows a sample of the overview of the test sequence; each platform will measure performance differently. For example, when using the Infrared Test Facility, a thermal imaging system will acquire the temperature distribution on the burner's radiant surface and the Boiler Burner Simulator will have places to sample pressure. The test platforms are summarized in Table 8.

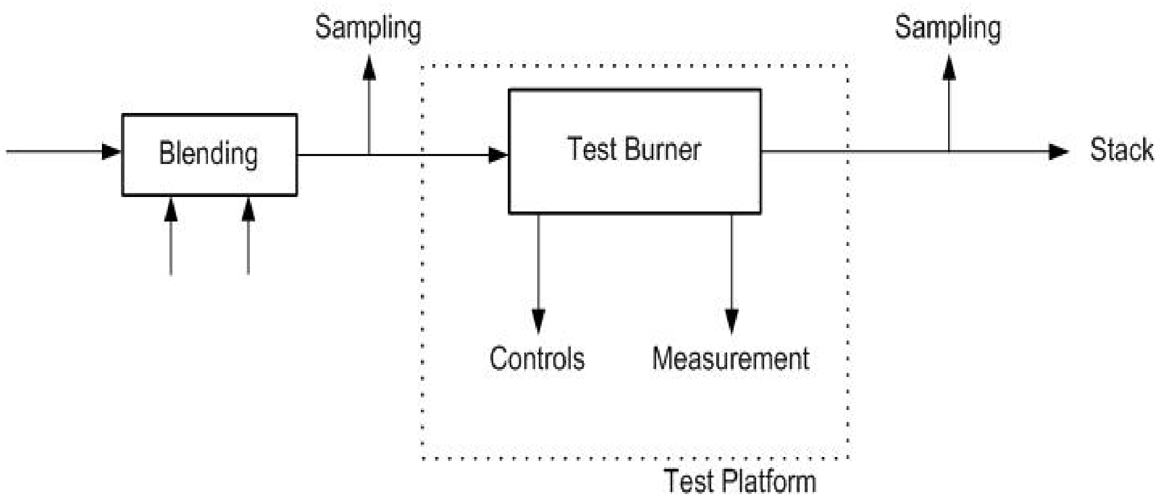


Figure 11. Example sequence of testing

Table 8. Available test platforms

<table>
<tr>
<td>
Infrared Test Facility</td>
<td>GTI has a custom-built infrared burner testing facility, shown here. This testing platform can accommodate individual infrared heaters and is equipped to measure emissions, radiant heat flux and thermal response (heat-up time), total radiated power and thermal efficiency, fuel flow rate, and spectral radiation intensity. Test procedures that were written for this test platform when it was installed (Fayerman et al. 2002) will be modified for interchangeability tests.</td>
</tr>
<tr>
<td>
Flex-Furnace</td>
<td>Each square panel on GTI’s state-of-the-art Flex-Furnace by Seco-Warwick, shown here, is removable to allow burner installation in any orientation. The round structures next to each panel are viewing ports for visual observation of the flame and optical measurement using spectroscopic techniques. The columns that extend to the ceiling are water-cooled rods that can be lowered partially into the furnace to simulate a heat load, measure heat transfer, and increase furnace capacity up to approximately 10 MMBtu/hr.

This platform can accommodate: High Velocity Nozzle-Mixed Burners, Regenerative Burners, Natural Draft Burners, Oxygen Enhanced Burners, Linear Grid/In-Duct Burners, Radiant Wall, and Radiant Tube Burners.</td>
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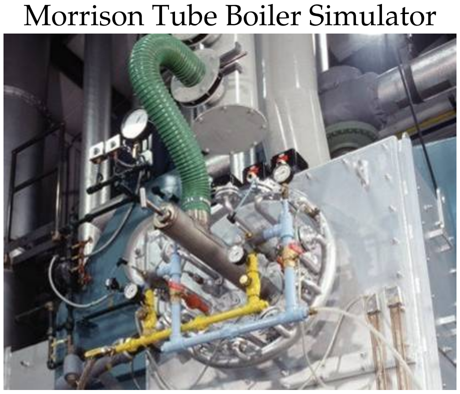
<tr>
<td>

Morrison Tube Boiler Simulator

Watertube package boiler</td>
<td>The Morrison Tube Boiler Simulator test platform can accommodate boiler burners up to 10 MMBtu/hr. Each water coil can be drained at the bottom to prevent freezing, or vented at the top to remove any accumulated steam. Additionally, each module is equipped with a thermocouple to measure cooling water temperature. Gas composition and gas temperature sampling ports were installed on several of the modules to facilitate data acquisition. City water is circulated through each module of the heat recovery section to provide cooling and heat removal. The city water is piped through individual rotameters to each of the water coils. Heat flux can therefore be measured for each module, allowing a detailed mapping of the heat release profile of the burner.

Another testing opportunity is a watertube package boiler installed in the GTI laboratory and equipped for the extensive performance testing of boiler burners up to 20 MMBtu/hr.</td>
</tr>
</table>

Each burner test will follow the same test sequence, shown as a flow chart in Figure 12. Appendix A contains a sample data recording sheet to be filled prior to the test; it should be adjusted so that the manufacturer specifications for each burner are noted, and Appendix B contains an example sheet that will be similar to the one used in the planned tests. The shakedown procedure will be performed prior to testing as a "dry run," to make sure the actual test will go as planned. During the shakedown, the manufacturer-specified air/fuel ratio will be set for to the adjustment gas—the products of combustion are measured and air adjusted to yield 3% O_2, or the manufacturer-specified value. In between every changeover to a substitute gas, the fuel gas will first be returned to the adjustment gas, and held for at least 15 minutes. This duplicates the protocol used by UC Riverside to test appliance interchangeability (Miller and Welch 2005). Secondary substitute gas blends can be used when the substitute gas is not interchangeable with the adjustment gas.

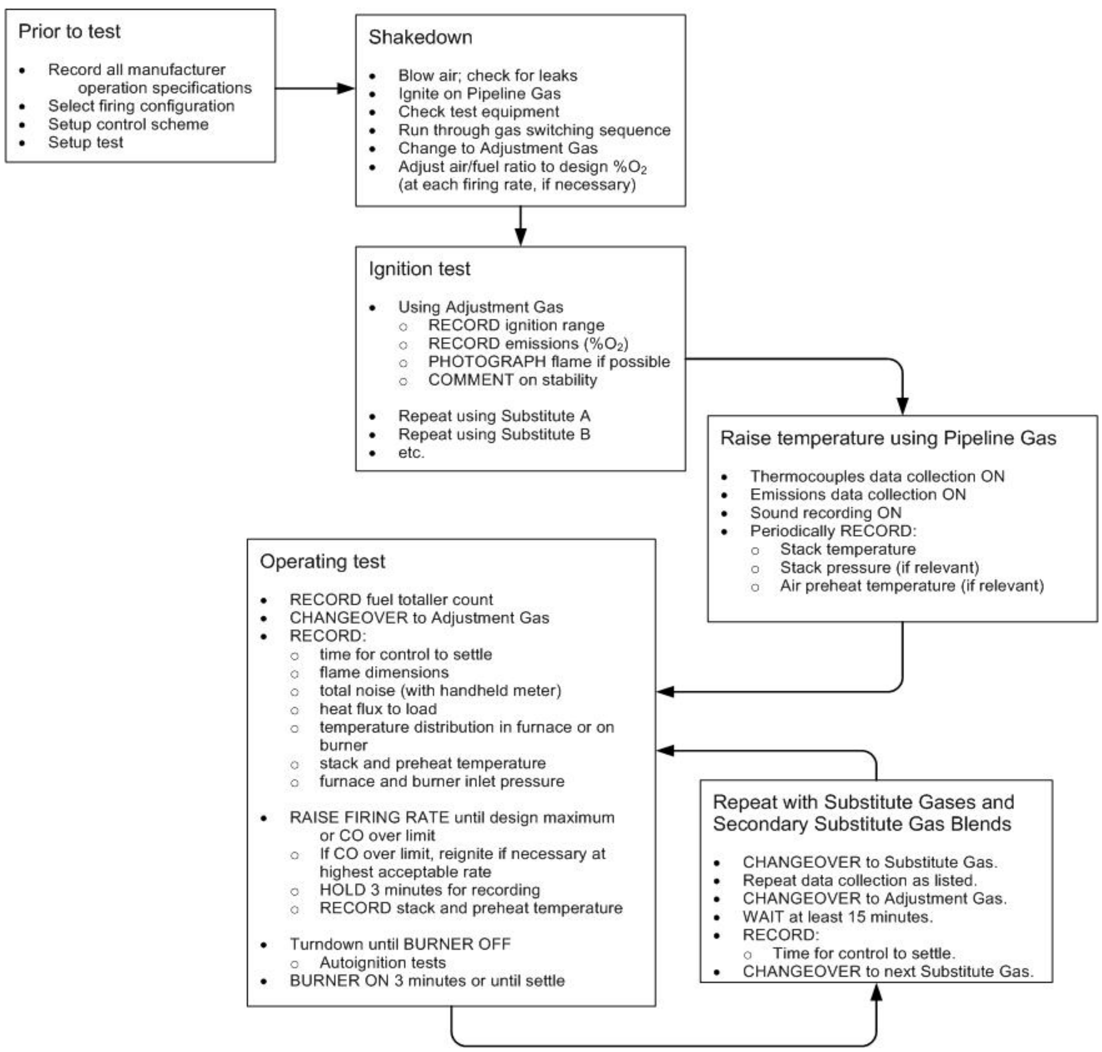


Figure 12. Example test sequence for one burner

6.2. Gas Preparation, Metering, Blending, and Switching

There are three ways to obtain the LNG mixture: (1) buy a tank truck filled with the desired gas composition, or flow in each component of the flow from a separate tank or cylinder either by (2) manually setting valves to control the pressure across orifice plates, or (3) using computer-controlled mass flow meters. The cost of using a tank truck precludes its use, plus blending individual fuel components allows flexibility to try secondary and tertiary gas blends for a richer data set, so a blending station will be used for this study. The schematic in Figure 13 shows one way that the blending can be accomplished: individual components that make up the desired fuel gas composition, or one or two lines with appropriately chosen mixture compositions, will be added to the pipeline natural gas. If it is deemed necessary, a gas chromatograph or other composition monitor device can be installed, to allow real-time flow adjustments to accommodate the measured pipeline gas composition.

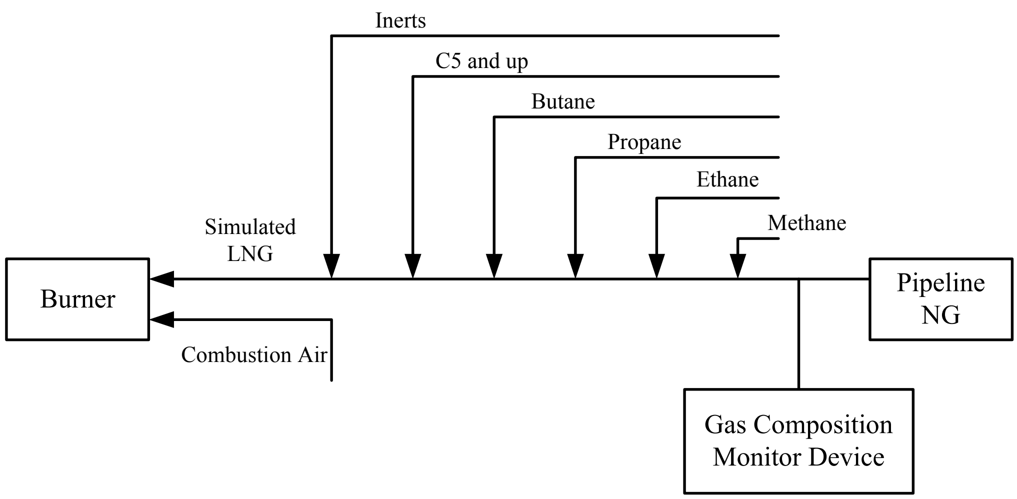


Figure 13. LNG composition simulation concept

Figure 14 shows a blending station designed for a GTI study (Wagner 2004) requiring fuel compositions commonly found in petroleum refineries; it will be similar to the station used in this test. The arrows in the figure indicate flow direction (from left to right) to represent different gases: nitrogen, hydrogen, propane, and pipeline natural gas. All of the components except for the natural gas are fed from tanks or cylinders to the blending station, and when they exit the station they are blended in a static mixer before being fed to an industrial burner. The pressure regulators maintain the same constant pressure for each line. There are pressure gages downstream of the pressure regulators that measure differential pressure across an orifice plate allowing users to determine the component's flow rate.

Figure 14. Blending station to simulate refinery fuel

There is no provision to switch between two gases in the blending station in Figure 14, so the blending station in this study's test will need additional features. It is possible to have two parallel lines—one with valves set to the adjustment gas composition and the other set to a substitute gas composition—and then switch between these two lines with a three-way valve to add one or the other to the pipeline gas. This configuration would be economical, but would mean only a high-speed switch between fuel gases could be simulated, and also that each time another simulated gas composition is needed, some time would be spent adjusting valves.

In a previous GTI study of appliance interchangeability (Johnson and Rue 2003), MKS brand metering valves for gas flow were used to control the flow rate of each fuel to blend different gases at the desired rate. Voltage from mass flow sensors on each metered valve can be calibrated so that a controller can automatically adjust for flow rate. This method has proven to provide accurate and repeatable flows, and metering valves exist with capacities that are appropriate for industrial-scale tests. A flow meter downstream of the combined fuel inlets can provide a real-time double check of the total flow rate of the combined gases. This method would allow a controlled switch between gases, if desired. Because control system response to a step input is a standard metric of performance, comprising many frequencies and a rapid change, and since UC Riverside's appliance tests also used a high-speed switch, this study will likely switch instantaneously between fuel gas compositions, regardless of whether a simple blending system with hand-turned valves and orifice plates or a computer-controlled system with metered valves is used.

When the burner performance is deemed unacceptable, or to collect more data, associated secondary and tertiary blends that simulate nitrogen ballasting, propane stripping, or both can be tried in place of the original substitute gas composition. A gas chromatograph or a Wobbe analyzer can monitor fuel gas composition in real time, as it is fed to the burner.

6.3. Pollutant Emissions, Noise/Vibration, and Heat Measurement

Figure 15 below is an example schematic of piping and sensor locations for a burner test, adapted from Wagner (2004). Fuel gas from the blending station enters at the top left, and flows through a series of safety monitors and switches before reaching the burner, which is colored black on the figure. The computer data acquisition system can sample the output of each of the sensors, denoted by circles, to record pressure (PI) in the air and fuel lines and in the furnace, and temperature (TE) at the many locations in the furnace. The rotameters measure the water flow to the furnace, which combined with temperature measurements can estimate heat flux to the load. A sampling probe in the stack connects to emissions analyzers on the bottom left that can also be connected to the computer data acquisition system. The dotted lines indicate connections to the furnace control system; typically the air/fuel ratio is maintained with a pressure regulator and air flow adjusted according to furnace temperature.

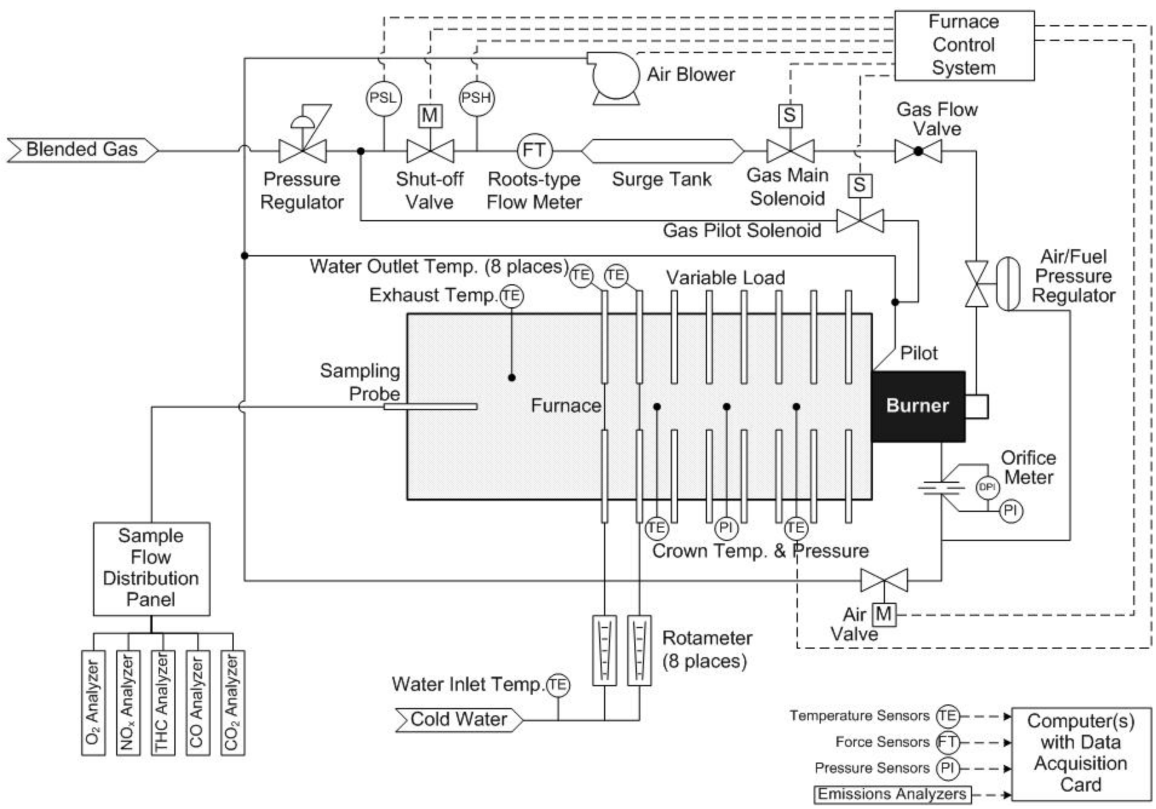


Figure 15. Example setup of a GTI test furnace

6.3.1. Pollutant Emissions

The Gas Technology Institute utilizes state-of-the-art gas emission analyzers on a variety of combustion systems. Combustion gases are drawn through a conditioning train for drying before being pumped to a set of continuous emission monitors (CEMs). A sampling probe can be inserted into the exhaust stack or anywhere in the furnace where emissions data are desired. From the sampling probes, the sample enters two dry filters followed by a membrane dryer to remove water vapor from the sample. Samples are analyzed for nitrogen oxide (NO), nitrogen oxides (NO_x = NO + nitrogen dioxide [NO_2]), oxygen (O_2), carbon monoxide (CO), carbon dioxide (CO_2), and total unburned hydrocarbons (THC). Table **9** lists each analyzer and its detection technique; the techniques adhere to industry standards for testing laboratories. Aerosol particles from combustion are expected to be below 1 micron (μm) in diameter. The TSI scanning mobility particle sizer (SMPS) model 3936 counts ultrafine particles (UFP) in the size range from 2.5 nanometers (nm) to 1000 nm.

Table 9. Continuous emission monitors to be used during testing

Make and Model #	Detection Technique	Gases Analyzed
Thermo Environmental 42C	Chemiluminescence	NO and NO_2
Beckman Industrial 755	Paramagnetic	O_2
Rosemount Analytical 880A	Infrared	CO
Rosemount Analytical 880A	Infrared	CO_2
Rosemount 400A	Flame ionization	THC
TSI 3936	Electrical Mobility	UFP

6.3.2. Noise and Combustion Control System Stability

No source for testing control system stability for industrial burners could be found, but GTI has a long history in boiler development where burner noise is a crucial parameter related to system stability. Glow of gas through the orifice and flow of air through the burner nozzles both contribute to high frequency noise, and the combustion itself emits a low frequency "roar." Acoustic measurements can be obtained with an OROS OR25 PC-Pack 8 channel portable signal analyzer with a real-time bandwidth up to 20 kHz with signals conditioning from the OR7933 real-time acoustic software package. Both time-history and spectrum data can be recorded for all testing.

In addition to acoustics measurements, the dynamic pressure fluctuations of combustion air, natural gas fuel line, and the combustion chamber are recorded with quartz element pressure transducers: the transducer used at the combustion chamber location is a high-temperature sensor rated for 750°F, with a sensitivity of 6 picocoulombs for every pound per square inch of pressure (pC/psi) and resolution ± 0.0003 psi (PCB Piezotronics, Model 116B03). The fuel line and combustion air dynamic pressures are measured with an ICP pressure sensor with 300 milliVolt (mV)/psi sensitivity, and a resolution of ± 0.00007 psi (PCB Piezotronics, Model 106B50). Frequency of pulsations is commonly given as a function of the firing rate; in this interchangeability study it can also be given for a constant firing rate, but as a function of gas composition.

6.3.3. Furnace Temperature/Exhaust Gas Temperature

A series of thermocouples embedded in the furnace refractory at different depths provide a good estimate of the furnace temperature. The exhaust temperature and air preheat temperature (when using preheated air) will be measured using aspirated thermocouples; these are designed to measure gas temperatures without the effect of radiation, and are standard methods used in industry.

In addition, GTI has two 2-D thermal cameras to capture thermal images of the operating combustion equipment interior, or radiant burner surfaces. Both cameras are capable of accurate thermal images of solid surfaces and are most suitable for applications where the heating is done indirectly; that is for measuring the temperature of a radiant tube, a radiant wall burner block, or for thermal radiation burners. The MikroScan 7550 is calibrated in the range from -4°F to 1000°F, and the FTI-6 can monitor and record temperatures up to 3600°F.

6.3.4. Heat Release and Heat Flux

The burner heat release is defined as the total flow rate of energy in to the burner, and has units of power (Btu/hr), and is calculated from the fuel composition and flow rate.

Heat flux is defined as the rate of heat transfer through a unit area. When integrated over the a surface, such as the burner plenum of a thermal radiation burner, it can be used to calculate efficiency (= heat flux × area ÷ heat release). The Medtherm H-201 Digital Heat Flux Meter converts heat flux sensor readings to digital values in heat flux units of Btu per square foot per second (Btu/ft^2/sec). Total heat flux (radiative and convective) up to 10 Btu/ft^2/sec can be measured using Medtherm transducer number 64-10SB-18 and radiative heat alone can be measured using transducer number 64P (CaF2)-5SB-22, up to 5 Btu/ft^2/sec.

6.3.5. Equipment Wear Due to Impingement or Vibration

Long-duration tests with a simulated LNG composition are cost-prohibitive because firing rates for industrial burners are often above a million Btu/hr. As with prior GTI appliance tests, propane, rather than ethane, can be blended with pipeline gas to fire a line burner or a small radiant tube burner for a number of days, but other options are likely too costly. Instead, equipment wear can be inferred from temperature and vibration measurements: flame impingement is a concern for radiant tube burners, boiler burners, and thermal radiation burners. For these burners, thermal images of the radiant surface or boiler burner tubes will be taken, and the occurrence and duration of excessive surface temperature will be noted. Temperature limits are specified by the tube manufacturer for radiant tubes, ANSI standards for boiler burners, or the burner vendor for thermal radiation burners. Excessive vibration of the combustion system can also shorten equipment lifetime. The experiment will set a threshold amplitude of vibration as a metric for equipment wear.

6.4. Operating Envelope: Ignition, Turndown, and Flame Stability

Care is imperative when performing tests to define the operating envelope of a burner. For premixed burners, flashback is a concern: the flame can enter the burner and continue to burn in the pre-mixing line. This is both damaging to equipment and an explosion hazard. For any type of burner, an extinguished flame means natural gas is collecting inside the furnace—also an explosion hazard.

6.4.1. Ignition and Autoignition

There are two types of ignition limits: ignition from a cold start, and autoignition. They are simple to measure; with all other things set constant, the air/fuel ratio or the firing rate is changed until the burner cannot ignite. The ratio or the firing rate where this stops is the ignition limit. Burner manufacturers usually include the recommended settings for ignition from a cold start in the burner's specification sheet. The instructions specify the kind of pilot or spark needed, plus pilot placement, instructions for adjustment of the air register doors (usually 75% open) recommended firing rate at ignition. With these parameters fixed, the ignition limits are the percent stoichiometry that can sustain ignition from a cold start. Although few test protocols exist for other burner performance metrics, safety concerns mean ignition test procedures are described in detail. A flow chart for an ignition test, based on instructions in NPFA (1999), is included in Appendix C as an example. If no ignition firing rate is specified, trials can be performed either at the burner's designed firing rate or the maximum turndown.

Autoignition limits are different; these would be to restart the burner without a pilot in a hot furnace, and would be done at the design stoichiometry but at different firing rates. The typical furnace temperature is above 1450°F; or any furnace temperature with a premixed fuel/air stream at or above 1200°F.

6.4.2. Turndown Ratio and Flame Stability

Turndown ratio is defined as the ratio of the maximum firing rate of a burner to the lowest firing rate where a stable flame can be sustained at the specified furnace temperature and draft pressure. The test methodology can examine turndown ratio at a few furnace temperatures and draft pressures; the firing rate can be first increased from design until blowoff and then decreased from the design rate until flashback, or until CO emissions exceed 250 volumetric parts per million (vppm) to indicate unacceptable incomplete combustion, or until the draft pressure becomes less than the design value specified by the burner manufacturer, for safety reasons.

Flashback, yellow tipping, and liftoff were the metrics of flame stability for appliances, but only flashback can be observed with traditional instrumentation, because at high temperatures the flame will be invisible against the radiating background of the furnace or other hot surfaces; if the flame detector signals an alarm but emissions do not indicate the flame is out, flashback has occurred. It is expected that flashback will be recorded at the same time as the turndown ratio, when firing at the low rates. Yellow tipping is associated with carbon monoxide or soot production, and so emissions monitoring can replace the visual observation of flame yellow tipping. Liftoff is associated with low heating value gas, but LNGs have high heating value, so liftoff is not expected. Liftoff, if it occurs, will be detected when the flame detector signals an alarm even though the burner is firing and combustion is complete. Many industrial flames normally operate with "yellow" flames or lifted flames, so this must be considered in testing.

6.5. Flame Shape

The most common way to measure flame shape in industry is to set the burner on a surface, fire it in the open air, and photograph it with a ruler beneath it to record scale. This successfully measures the luminous portion of the flame, but could be dangerous without proper facilities. In a hot furnace, it is not possible to measure the flame shape by detecting visible light, so flame shape could be measured just after ignition, or another method must be used. It is possible to place ultraviolet and infrared flame detectors in the furnace view ports to monitor the flame's radiation at those wavelengths. The end of the flame would be defined as the distance where the flame detector first signals an alarm.

The first two options measure the flame according to its radiation, but since luminosity does not always correlate with flame temperature, it may not be the most relevant way to define flame shape. Two additional methods; one traditional and one state-of-the-art, are available to measure the flame's chemical length.

In the traditional method, a sampling probe, just like the one used to measure emissions, can be inserted into the furnace, and traverse the flame. Emissions can be recorded at each point, and the edge of the flame is defined as the place where fuel and oxidizer are completely consumed. The newer method uses absorption spectroscopy to collect data instantly from up to fifteen laser beams that traverse the furnace from view ports. This technology was developed in collaboration with Stanford University, and is licensed to Zolo Technologies, Inc.

7.0 Final Remarks

The LNG interchangeability study will examine the industrial end-user's gas quality needs as California prepares to add LNG to its energy portfolio. Issues for the industrial sector are their product quality and operating cost; which are both affected by burner performance. Operating cost is also affected by the price of fuel. The LNG compositions likely to be imported in California have more ethane and less methane and C3+ than the current pipeline composition, meaning revaporized LNG has a higher Wobbe Number and Higher Heating Value than pipeline gas.

Gas distribution companies currently maintain gas quality guidelines that specify a permissible range of fuel gas HHV and composition limits that can be achieved by blending vaporized LNG with nitrogen or air or stripping out heavier hydrocarbons. Since gas conditioning can be costly, LNGs that require less manipulation are more attractive candidates for importation.

The goal of the interchangeability study is to collect performance data from industrial burners fired with both representative LNG compositions and with compositions that represent likely gas conditioning methods, so that vaporized LNG can be used without adversely affecting California's industrial sector.

Review of anticipated LNG compositions and current California natural gas compositions shows that the LNGs can be adjusted by either nitrogen addition or heavy hydrocarbon stripping to have properties similar to current natural gases. The project team will select a wide range of gas compositions to cover the full range of LNGs and the low end of natural gas, and then both simulated stripping and nitrogen blending will be used to evaluate impacts of LNG adjustment. The final procedures for selecting gas compositions and adjusting the gases will cover the widest possible range of LNGs and natural gases anticipated in actual situations. The final blending methods used during industrial burner testing will be selected based on practicality, minimization of blending components, and gas cost.

The burner types and industries in the State of California are emphasized. California's natural-gas intensive industries, by number of establishments, mostly produce food and beverages, fabricated metal products, and chemical products. At least one burner of each type listed in this report, except for flare burners and duct burners, will be tested. Because of their prevalent use, Thermal Radiation Burners, Boiler Burners, and Radiant Tube Burners will likely have more than one representative type tested.

In this report, the necessary equipment and experimental set-ups to quantify each of the above parameters was identified. A literature review of testing methodologies and national standards revealed that methodologies and standards exist for some of these parameters; however, available protocols and testing methodologies will need to be modified (or developed) for many of the parameters that can vary with LNG imports.

Some key findings of the literature review and burner evaluations are:

- The primary measure of interchangeability, regardless of application, is the fuel's Wobbe Number, defined as its higher heating value divided by the square root of its specific gravity. Fuels with the same Wobbe Number will have equivalent heat input rates through the orifice of a burner.

- Application-specific performance indices have been studied: flame liftoff, flashback, and incomplete combustion in atmospheric burners such as those used in appliances, knock in reciprocating engines, and emissions for utility-scale gas turbines.

- Previous studies selected at least one adjustment gas to represent the existing pipeline fuel gas composition and provide a baseline to compare with the substitute gas compositions. Substitute gases are chosen to represent either regulatory extremes or import possibilities. If the substitutes are not interchangeable, different amounts of gas conditioning are tried: inert gas or air injection, blending with the adjustment gas, or removing the heavy hydrocarbons. Previous studies show that there exists a correlation between conditioning and performance.
- Industrial burners have diverse applications and operate in a number of distinct modes that imply different piping and air setup and different control schemes. These are not always the same as the way they are classified in standard textbooks, but will affect test methodology, so both operation and application are described.
- Most standards specify equipment requirements, such as valve placement and pressure strength, rather than procedures for measurement, although a number of fuel interchangeability protocols exist for burners in refinery service.

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9.0 Acronyms

AGA	American Gas Association
ANSI	American National Standards Institute
AOAC	Association of Official Analytical Chemists
API	American Petroleum Institute
ASHRAE	American Society of Heating, Refrigerating & Air Conditioning Engineers
ASTM	American Society for Testing and Materials
BCF	Billion Cubic Feet
Btu	British Thermal Unit
C_2*	Carbon Radical
CARB	California Air Resources Board
CCD	Charge-Coupled Device
CEC	California Energy Commission
CE-CERT	Center for Environmental Research and Technology
CEM	Continuous Emissions Monitoring
CFR	Code of Federal Regulations
CH*	Hydrocarbon Radical
CO	Carbon Monoxide
CO_2	Carbon Dioxide
EIA	Energy Information Agency
FGR	Fuel Gas Recirculation
GRI	Gas Research Institute
GTI	Gas Technology Institute
HHV	Higher Heating Value
ID	Internal Diameter
IR	Infrared
ISO	International Organization for Standardization
LDC	Local Distribution Company
LNG	Liquefied Natural Gas
MM	Million
NGC+	The Natural Gas Council Interchangeability Working Group
NO_x	Nitrogen Oxides
OEC	Oxygen Enhanced Combustion
OH*	Hydroxyl Radical
PIV	Particle Image Velocimetry
PG&E	Pacific Gas and Electric
POC	Products of Combustion
PSI	Pounds Per Square Inch
PVC	Polyvinyl Chloride
SCAQMD	Southern California Air Quality Management District
scf	Standard Cubic Foot
SDG&E	San Diego Gas & Electric
SMPS	Scanning Mobility Particle Sizer
SoCalGas	Southern California Gas Company
SpG	Specific Gravity
THC	Total Hydrocarbons
UC	University of California
UFP	Ultrafine Particles
UHC	Unburned Hydrocarbons
UL	Underwriters Laboratories Incorporated
UV	Ultraviolet

10.0 Glossary

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Air Register	The part of a burner that can admit combustion air through openings around the burner assembly.
Air, Combustion	All the air introduced with fuel to supply heat in a furnace.
Air, Preheated	Air heated prior to its use for combustion. The heating is most often done by heat exchange with hot flue gases.
Air, Primary	The portion of the total combustion air that first mixes with the fuel.
Air, Secondary	All the combustion air that is intentionally allowed to enter the combustion chamber in excess of primary air.
Air, Secondary	That portion of the total combustion air that is supplied to the products of combustion downstream of the primary combustion zone.
Air, Stoichiometric	The chemically correct amount of air required for complete combustion with no unused fuel or air.
Air, Tertiary	A third portion of the total combustion air that is supplied to the products of combustion in addition to primary and secondary air.
Analyzer, Gas	A device that measures concentrations, directly or indirectly, of some or all components in a gas or mixture.
Auto-Ignition Temperature	The lowest temperature required to initiate self-sustained combustion in the absence of a spark or flame.
Blowoff	The lifting of a flame due to the velocity of the fuel-air mixture exceeding the flame velocity. This usually results in the flame being extinguished.
Burner Heat Release, Design	The specified "design" heat release for the burner with the air register set for the design excess air with design draft loss.
Burner Heat Release, Maximum Stable	The maximum heat release for the burner at the point of CO breakthrough with the air register at the same setting as "design" heat release or 100% open.
Burner Heat Release, Maximum	The heat release for the burner with design excess air and design draft loss with air register 100% open.
Burner Heat Release, Minimum Stable	The minimum heat release for the burner at the point of CO breakthrough with the air register at the same setting as the "normal" heat release.
Burner Heat Release, Minimum	The specified "minimum" heat release for the burner with the air register set at the same setting as the "normal" heat release or with the air register set for the design excess air.
Burner Heat Release, Normal	The specified "normal" heat release for the burner with the air register set for the design excess air with design draft loss.
Burner Throat	A restriction in the air flow path formed by the burner block and other burner components. The restriction initiates turbulence for the mixing of the fuel and air.
Burner, Atmospheric	A burner used in the low-pressure fuel gas or atmospheric system that requires secondary air for complete combustion.
Burner, Blast	A burner delivering a combustible mixture under pressure, normally above 0.3 in. w.c. (75 kPa) to the combustion zone.
Burner, High Intensity	A burner in which combustion is completed within a fixed-volume resulting in a combustion intensity greater than 1,000,000 Btu/hr/scf.
Burner, Line	A burner whose flame is a continuous line.

Burner, Low NO_x	A burner which is designed to reduce the formation of NO_x below levels generated during normal combustion in conventional burners.
Burner, Nozzle Mixing	A burner in which the fuel and air are introduced separately to the point of ignition.
Burner, Premix	A gas burner in which all or a portion of the combustion air is inspirated into a Venturi-shaped mixer by the fuel gas flow. The fuel and air are mixed prior to entering the initial combustion zone.
Burner, Radiant Tube	A burner designed to provide a long flame within a tube to ensure substantially uniform radiation from the tube surface.
Burner, Radiant Wall	A premix burner where the flame does not project into the firebox but fans out alongside the wall on which it is installed.
Burner, Radiant	A burner designed to transfer a significant part of the combustion heat in the form of radiation.
Burner, Regenerative	One of a burner pair. The system recovers heat from exhaust air by passing the hot exhaust through a heat-absorbing medium, and then passing the combustion air through that same medium to absorb heat. The burners face each other, and alternate between firing and exhaust.
Burner, Staged Air	A low NO_x burner in which a portion of the combustion air is injected downstream of the burner block to mix with the combustion products from the primary combustion zone.
Burner, Staged Fuel	A low NO_x burner in which a portion of the fuel is mixed with all of the combustion air within the burner block while the remainder of the fuel is injected downstream of the burner block to provide delayed combustion.
Burner	A device or group of devices used for the introduction of fuel, air, oxygen, or oxygen-enriched air into a furnace at the required velocities, turbulence, and concentration to maintain ignition and combustion of fuel.
CO Break Through	The point at which the CO level begins to increase rapidly upon reduction of excess air. This break through will vary depending upon the fuel and the type of burner.
Controller, Excess Temperature Limit	A device designed to cut off the source of heat if the operating temperature exceeds a predetermined temperature set point.
Controller, Programmable	A digital electronic system designed for use in an industrial environment that uses a programmable memory for the internal storage of user-oriented instructions for implementing specific functions to control, through digital or analog inputs and outputs, various types of machines or processes.
Controller, Temperature	A device that measures the temperature and automatically controls the input of heat into the furnace.
Draft	The difference in pressure that causes the flow of combustion air into the heater and flue gases through the heater. The pressure differential is caused by the difference in the densities of the combustion products in the heater and stack and the air external to the heater in natural draft heaters.
Draft, Balanced	Both forced draft from an air blower into the burner and induced draft from a fan in the exhaust stack.
Draft, Forced	The difference in pressure produced by mechanical means that delivers air into a burner at a pressure greater than atmospheric.
Draft, Induced	The difference in pressure (between inside and outside of the heater) produced by mechanical means resulting in a negative pressure in the heater that causes the flow of combustion into the heater.
Draft Loss	Generally referred to as the air side pressure drop across a burner or the flue gas pressure drop across a portion of the heater system depending which heater component is being referred to.

Draft, Natural	A difference in pressure resulting from the tendency of hot furnace gases to rise thus creating a partial vacuum in the heater. This serves to draw combustion air into the burner.
Excess Air	The amount of air above the stoichiometric requirement for complete combustion, expressed as a percentage.
Flame Velocity	The rate at which a flame propagates through a combustible mixture.
Fuel Gas System, High Pressure	A system using the kinetic energy of a jet of 1 psig (7kPa) or higher gas pressure to entrain from the atmosphere a portion of the air required for combustion.
Fuel Gas System, Low Pressure or Atmospheric	A system using the kinetic energy of a jet of less than 1 psig (7kPa) gas pressure to entrain from the atmosphere a portion of the air required for combustion.
Fuel Gas	Gas used for heating, such as natural gas, manufactured gas, undiluted liquefied petroleum gas (vapor phase only), liquefied petroleum gas-air mixtures, or mixtures of these gases.
Fuel, Secondary	The remaining portion of fuel that is injected downstream of the burner block in a staged fuel burner.
Heater, Direct-Fired External	A heating system in which the burners are in a combustion chamber effectively separated from the work chamber and arranged so that products of combustion from the burners are discharged into the work chamber by a circulating fan or blower.
Heater, Direct-Fired Internal	A heating system in which the burners are located within the work chamber.
Heating System, Direct-Fired	A heating system in which the products of combustion enter the work chamber.
Heating System, Indirect-Fired Internal	A heating system of gastight radiators containing burners not in contact with the oven atmosphere. Radiators might be designed to withstand explosion pressures from ignition of air-fuel mixtures in the radiators.
Heating System, Indirect-Fired	A heating system in which the products of combustion do not enter the work chamber.
Heating Value, Higher	The total heat obtained from the combustion of a specified fuel at 60°F, expressed as Btu per pound or per cubic foot which includes the latent heat of vaporization of water; also called gross heating value.
Hydrogen/Carbon Ratio	The weight of hydrogen in a hydrocarbon fuel divided by the weight of carbon.
Inspirator	A Venturi device used in premix burners that utilizes the kinetic energy of a jet of gas issuing from an orifice to entrain all or part of the combustion air.
Light Off	Initial ignition of a fuel.
Purge	The replacement of a flammable, indeterminate, or high-oxygen bearing atmosphere with another gas that, when complete, results in a nonflammable final state.
Range, Explosive	The range of concentration of a flammable gas in air within which a flame can be propagated. The lowest flammable concentration is the lower explosive limit (LEL). The highest flammable concentration is the upper explosive limit (UEL).
Regulator, Pressure	A device that maintains a constant outlet pressure under varying flow.
Specific Gravity	The ratio of the density of a gas to the density of dry air at standard temperature and pressure.
Standard Cubic Foot	This document regards a standard cubic foot fo gas as one measured at 70°F and 14.73 psia.
Stoichiometric Ratio	The ratio of fuel and air required for complete combustion such that the combustion products contain no oxygen.
Turndown, Burner	The ratio of maximum to minimum burner fuel-input rates for safe, stable operation.
Wobbe Number	The Wobbe Number is equal to the higher heating value in Btu/cubic foot (or MJ/cubic meter) divided by the square root of the gas specific gravity.

Appendix A
Example Manufacturer Burner Specification Record Sheet

Below is a sample sheet adapted from API 560 to record the manufacturer's specifications for a burner. Specified operating conditions and design conditions will be incorporated into the burner tests; otherwise default values will be used.

1	**General data**
2	Burner Type
3	Altitude Above Sea Level (feet)
4	Barometric Pressure
5	Fuel Supply:
6	Fuel versatility without modification (propane/syngas/liquid)
7	Air Supply:
8	Ambient / Preheated / Recirculated
9	Ambient Air / Oxygen Enhanced (max. % enhancement)
10	Design Temperature (°F)
11	Minimum Temperature (°F)
12	Maximum Temperature (°F)
13	Relative Humidity %
14	Draft type: Forced / Natural / Induced
15	Draft available:
16	across burner (inches H2O)
17	across plenum (inches H2O)
18	Design Turndown
19	Design Air/Fuel Ratio (% excess air)
19	Air/Fuel Ratio maintained by (regulator / cam / none)
20	Control Mode:
21	Pulsed / On/Off / High/Low
22	Fuel controlled / Air controlled
23	Controlled parameter (temperature / pressure; range)
24	**Burner data**
25	Manufacturer
26	Burner type
27	Model number
28	design firing rate
29	Burner dimensions
30	Pilots:
31	Number required
32	Type of heater
33	Ignition method (flaming rag / pilot / spark)
34	Ignition Fuel
35	Fuel Pressure (Psig)
36	Capacity (MMBtu/hr)
37	**Operating Data**
38	Fuel (record the test designation)
39	Heat Release Per Burner:

40 Design (MMBtu/hr)
41 Minimum (MMBtu/hr)
42 Maximum (MMBtu/hr)
43 Excess Air at Design Heat Release, %
44 Air Preheat Temperature °F
45 Draft loss (Pressure drop across nozzle)
46 Design (inches H_2O)
47 Required Fuel Pressure at Burner (psig)
48 Flame length at design heat release, feet
49 Flame shape (round, flat, etc.)
50 Flame temperature at design heat release
51 Furnace temperature at design heat release
52 Emissions at design heat release

Appendix B
Example Fuel Gas Composition Record Sheet

This sample sheet is adapted from Baukal (2001) to record the fuel compositions prior to testing. It also specifies operating performance metrics that will be adapted for this test.

Sample Interchangeability Reporting Sheet

Testing Organization:	
Location:	
Customer:	
Burner Manufacturer:	
Burner Model No:	

		Additional Notes
Test Engineer:		
Date:		
Elevation: (feet)		
Barometric Pressure:		
Temperature: (°F)		

Specifications

Test Fuel Designation			Fuel A	Fuel B	Fuel C	Fuel D	Fuel E
Component:	HHV	MW	(mole %)	(mole %)	(mole %)	(mole %)	(mole %)
Nitrogen	--	28.01					
Carbon Dioxide	--	44.01					
Methane	1012.3	16.04					
Ethane	1773.8	30.07					
Propane	2521.9	44.10					
i-Butane	3259.4	58.12					
n-Butane	3269.8	58.12					
i-Pentane	4010.2	72.15					
n-Pentane	4018.2	72.15					
Hexane + heavier	4766.9+	86.18+					
Higher Heating Value		(Btu/scf)					
Lower Heating Value		(Btu/scf)					
Molecular Weight		(#/# mol)					
Specific Gravity (with respect to air)		--					
Measured Wobbe # (Btu/scf)		--					
Pressure Available:		(usig)					
Temperature		(degF)					
Theoretical Adiabatic Flame Temperature		(degF)					

Heat Release Per Burner

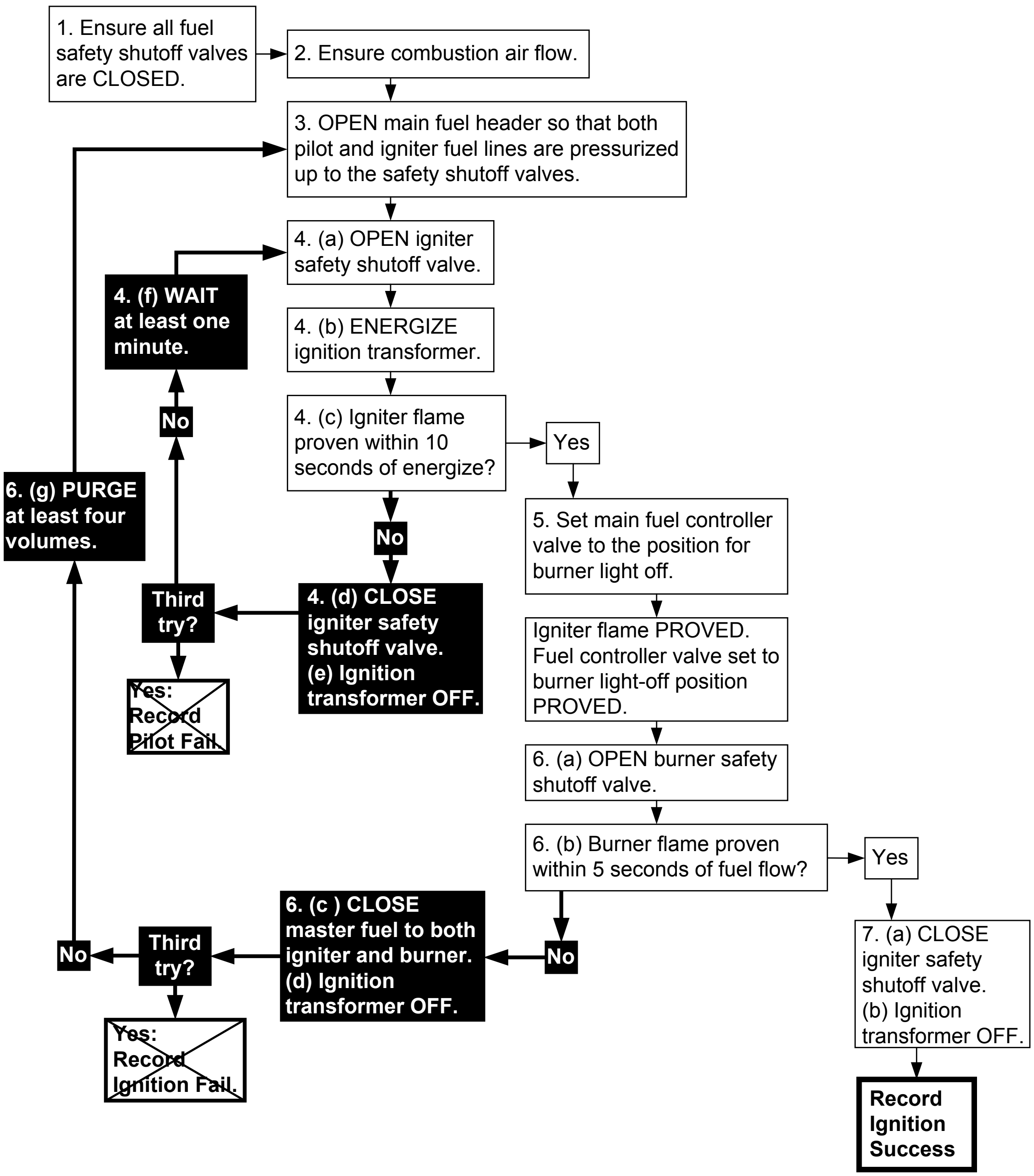
Test Fuel Designation	Fuel A	Fuel B	Fuel C	Fuel D	Fuel E
Design Maximum:					
Normal:					
Minimum:					
Measured Maximum:					

Average:					
Minimum:					
Heat Flux Profile (low fire)					
Test Fuel Designation	Fuel A	Fuel B	Fuel C	Fuel D	Fuel E
X1" from burner (?)					
Y" from centerline at X1"					
X2" from burner (?)					
Y" from centerline at X2"					
Heat Flux Profile (high fire)					
Test Fuel Designation	Fuel A	Fuel B	Fuel C	Fuel D	Fuel E
X1" from burner (?)					
Y" from centerline at X1"					
X2" from burner (?)					
Y" from centerline at X2"					
Flame Dimensions (low fire)					
Test Fuel Designation	Fuel A	Fuel B	Fuel C	Fuel D	Fuel E
Widest cross section (dia):					
Length to widest cross section:					
Total Length:					
Flame Dimensions (high fire)					
Test Fuel Designation	Fuel A	Fuel B	Fuel C	Fuel D	Fuel E
Widest cross section (dia):					
Length to widest cross section:					
Total Length:					
Emissions (at 3% O2, low fire)					
Test Fuel Designation	Fuel A	Fuel B	Fuel C	Fuel D	Fuel E
CO					
NOx					
Particulate					
THC					
UHC					
Emissions (at 3% O2, high fire)					
Test Fuel Designation	Fuel A	Fuel B	Fuel C	Fuel D	Fuel E
CO					
NOx					
Particulate					
THC					
UHC					
Flame Stability (measure at 5 firing rates between turndown limits)					
Test Fuel Designation	Fuel A	Fuel B	Fuel C	Fuel D	Fuel E
Pressure fluctuations					
Flashback					

Lifting					
Blowout					
Yellow tipping					
Noise (Corrected For Background Noise)					
Test Fuel Designation	Fuel A	Fuel B	Fuel C	Fuel D	Fuel E
sound pressure at 3 feet from burner (μ Pa)					
Sound Pressure Level = 20 $\log_{10}(p/20)$					
Highest Frequency					
Dominant Frequency					
Turndown Ratio					
Test Fuel Designation	Fuel A	Fuel B	Fuel C	Fuel D	Fuel E
Excess Air at Design:					
Conditions at Burner:					
Heater Draft Available (w.c)					
Burner dP @ Design (w.c.)					
Combustion Air Temperature (degF)					
Ignition Limits (at Designed Firing Rate)					
Test Fuel Designation	Fuel A	Fuel B	Fuel C	Fuel D	Fuel E
Spark Ignition Minimum % Stoichiometry					
Autoignigion Minimum % Stoichiometry					

Appendix C
Example Ignition Test Sequence

Basic starting sequence; modeled after NFPA 85-99, section 5.11.5.8
(for duct burners operated in heat recovery steam generators)



Appendix D
2004 U.S. Industrial Boiler Population Raw Data

Number of Boilers in the U.S. (2004)

Capacity	Food	Paper	Chemicals	Refining	Metals	Other Manufacturing	Total
< 10 MMBtu/hr	6570	820	6720	260	1850	7275	23495
10–50 MMBtu/hr	3070	1080	3370	260	920	3650	12350
50–100 MMBtu/hr	570	530	950	260	330	930	3570
100–250 MMBtu/hr	330	540	590	200	110	440	2210
> 250 MMBtu/hr	70	490	350	220	120	110	1360
Total	10610	3460	11980	1200	3330	12405	

Sum total capacities

Capacity	Food	Paper	Chemicals	Refining	Metals	Other Manufacturing	Total
< 10 MMBtu/hr	31070	4105	28660	1255	7505	29710	102305
10–50 MMBtu/hr	64970	24490	81690	6670	19405	80585	277810
50–100 MMBtu/hr	37885	36665	64970	18390	22585	62630	243125
100–250 MMBtu/hr	47950	81500	86840	30480	17775	62790	327335
> 250 MMBtu/hr	27860	229590	150915	114720	45365	47760	616210
Total	209735	376350	413075	171515	112635	283475	

Average capacity (MMBtu/hr)

Capacity	Food	Paper	Chemicals	Refining	Metals	Other Manufacturing
< 10 MMBtu/hr	4.73	5.01	4.26	4.83	4.06	4.08
10–50 MMBtu/hr	21.16	22.68	24.24	25.65	21.09	22.08
50–100 MMBtu/hr	66.46	69.18	68.39	70.73	68.44	67.34
100–250 MMBtu/hr	145.30	150.93	147.19	152.40	161.59	142.70
> 250 MMBtu/hr	398.00	468.55	431.19	521.45	378.04	434.18

Source: Energy and Environmental Analysis, Inc. Characterization of the U.S. industrial/commercial boiler population, 2005. Oak Ridge National Laboratory. www.eea-inc.com/natgas_reports/BoilersFinal.pdf.

Appendix E
California Manufacturer Raw Data from the 2002 U.S. Census

California NAICS data
www.census.gov/econ/census02/data/ca/CA000_31.HTM

NAICS code	Description	Establish ments	Shipment Value	Annual Payroll	Paid Employees
311	Food mfg	3,814	46,520,912	5,158,330	164,517
312	Beverage & tobacco product mfg	846	15,054,126	1,350,137	31,741
313	Textile mills	491	1,752,974	361,006	13,170
314	Textile product mills	894	2,265,170	437,233	16,890
315	Apparel mfg	4,755	11,859,871	2,091,951	95,523
316	Leather & allied product mfg	229	665,796	139,378	5,472
321	Wood product mfg	1,339	6,067,473	1,143,729	39,605
322	Paper mfg	560	8,586,559	1,226,398	29,379
323	Printing & related support activities	4,806	10,361,182	2,798,504	77,174
324	Petroleum & coal products mfg	218	24,125,455	781,315	11,677
325	Chemical mfg	1,615	22,946,136	3,684,040	76,289
326	Plastics & rubber products mfg	1,846	13,908,306	2,768,350	86,768
327	Nonmetallic mineral product mfg	1,542	9,397,354	1,726,382	45,141
331	Primary metal mfg	510	5,626,949	842,044	21,729
332	Fabricated metal product mfg	7,931	22,549,209	5,919,246	157,735
333	Machinery mfg	2,833	17,675,619	4,430,394	93,681
334	Computer & electronic product mfg	3,893	89,898,195	16,717,179	298,577
335	Electrical equipment, appliance, & component mfg	936	6,834,097	1,496,797	39,256
336	Transportation equipment mfg	1,589	33,407,897	6,908,701	127,394
337	Furniture & related product mfg	3,054	8,035,678	1,946,680	68,157
339	Miscellaneous mfg	4,777	21,122,456	4,540,767	116,629

United States NAICS data
www.census.gov/econ/census02/data/us/US000.HTM

NAICS code	Description	Establish ments	Shipment Value	Annual Payroll	Paid Employees
311	Food mfg	27,915	458,786,540	45,519,634	1,506,932
312	Beverage & tobacco product mfg	3,025	105,714,263	6,923,024	160,305
313	Textile mills	3,932	45,652,142	7,666,079	269,064
314	Textile product mills	7,304	32,273,047	4,759,988	183,333
315	Apparel mfg	13,038	44,521,126	7,454,143	343,450
316	Leather & allied product mfg	1,522	6,254,100	1,160,833	44,543
321	Wood product mfg	17,202	89,085,026	16,054,554	540,565
322	Paper mfg	5,520	153,766,022	21,497,243	491,436
323	Printing & related support activities	37,538	95,726,203	25,627,770	715,777
324	Petroleum & coal products mfg	2,262	215,312,899	6,151,468	102,836
325	Chemical mfg	13,476	460,424,786	44,556,764	852,297
326	Plastics & rubber products mfg	15,529	174,369,289	32,619,736	983,757
327	Nonmetallic mineral product mfg	16,706	95,261,480	17,929,311	483,161
331	Primary metal mfg	5,194	139,343,112	21,399,636	490,417
332	Fabricated metal product mfg	62,219	247,059,502	57,534,861	1,574,827
333	Machinery mfg	28,306	252,476,407	49,838,051	1,172,889
334	Computer & electronic product mfg	15,910	358,414,047	64,562,501	1,262,063
335	Electrical equipment, appliance, & component	6,499	102,879,191	18,082,952	494,370
336	Transportation equipment mfg	12,639	636,758,285	82,067,852	1,676,198
337	Furniture & related product mfg	22,523	75,964,713	17,400,405	595,915
339	Miscellaneous mfg	32,569	126,094,532	27,363,736	755,401