PB 198 109

Bulletin 653

REDUCTION OF AIR POLLUTANTS FROM GAS BURNER FLAMES

Including Related Reaction Kinetics

UNITED STATES DEPARTMENT OF THE INTERIOR
BUREAU OF MINES

1970

Reproduced by
NATIONAL TECHNICAL
INFORMATION SERVICE
Springfield, Va. 22151

13

Harris, Margaret E., and others—REDUCTION OF AIR POLLUTANTS FROM GAS BURNER FLAMES—B. of M. Bull. 653

Bulletin 653

REDUCTION OF AIR POLLUTANTS FROM GAS BURNER FLAMES

Including Related Reaction Kinetics

By Margaret E. Harris, Valeria R. Rowe,
E. B. Cook, and J. Grumer

BUREAU OF MINES

UNITED STATES DEPARTMENT OF THE INTERIOR

The work upon which this report is based was done by the Bureau of Mines, U.S. Department of the Interior, under a working fund agreement with the National Air Pollution Control Administration, U.S. Department of Health, Education, and Welfare.

This publication has been cataloged as follows:

Harris, Margaret E.

Reduction of air pollutants from gas burner flames including related reaction kinetics, by Margaret E. Harris and others. [Washington] U.S. Dept. of the Interior, Bureau of Mines [1970]

67p. illus. (U.S. Bureau of Mines. Bulletin 653)

1. Air—Pollution. 2. Gas burners. I. Title. (Series)

TN23.U 4 no. 653 622.06173

U.S. Dept. of the Int. Library.

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402 - Price 70 cents (paper cover)

CONTENTS

	Page
Abstract	1
Introduction	2
Equipment and procedures	4
Experimental findings	9
Reduction of oxides of nitrogen	9
Roles of flame temperature and equilibrium concentration	11
Reduction of carbon monoxide	17
Role of equilibrium concentration	17
Role of excess oxygen	20
Ingress of secondary air	25
Reduction of hydrocarbons	26
Role of flame stability	27
Effect of simulated recycle of flue gas	29
Results using multiport-ring burner	30
Ingress of secondary air	31
Comparison of flat-flame and multiport-ring burners	31
Results using ceramic infrared burner	32
Comparison of noninfrared and infrared flat-flame burners	32
Reaction kinetics of flames	35
Kinetics of formation of nitric oxide in flames	35
Past studies	35
This study	35
Kinetics of decay of carbon monoxide in flames	39
Past studies	39
This study	41
Summary	48
Acknowledgments	48
Bibliography	49
Appendix A.—Products of combustion in propane-air flames on a flat-flame burner	52
Appendix B.—Hydrocarbons in products of combustion in propane-air flames on a flat-flame burner	55
Appendix C.—Products of combustion in methane-air flames on a flat-flame burner	56
Appendix D.—Hydrocarbons in products of combustion in methane-air flames on a flat-flame burner	58
Appendix E.—Thermodynamic equilibrium concentrations of products in lean, stoichiometric, and rich methane-air flames	59
Appendix F.—Thermodynamic equilibrium concentrations of products in propane-air flames	60
Appendix G.—Products of combustion in methane-air flames on a multiport-ring burner	65
Appendix H.—Products of combustion in methane-air flames on a ceramic infrared flat-flame burner	66
Appendix I.—Thermodynamic equilibrium concentrations of products in lean, stoichiometric, and rich propane-air and methane-air flames at adiabatic flame temperatures	67

ILLUSTRATIONS

Figure — Page

1. Flat-flame burner 5
2. Cross section of multiport-ring burner 6
3. Comparison of vertical concentration profiles of nitrogen oxides from propane-air and methane-air flames using a flat-flame burner 9
4. Comparison of vertical concentration profiles of nitrogen oxides from propane-air flames and propane-air flames with simulated recycle using a flat-flame burner 10
5. Comparison of vertical temperature profiles in propane-air flames and propane-air flames with simulated recycle on a flat-flame burner 12
6. Comparison of vertical temperature profiles in propane-air and methane-air flames on a flat-flame burner 13
7. Comparison of vertical concentration profiles of carbon monoxide from propane-air flames and propane-air flames with simulated recycle using a flat-flame burner 18
8. Comparison of vertical concentration profiles of carbon monoxide from propane-air and methane-air flames using a flat-flame burner 19
9. Vertical concentration profiles of secondary oxygen in lean flames on a flat-flame burner. 22
10. Vertical concentration profiles of secondary oxygen in stoichiometric flames on a flat-flame burner 23
11. Vertical profiles of ratios of carbon/nitrogen in the primary reactants to the carbon/nitrogen in the products of combustion in rich flames on a flat-flame burner 24
12. Comparison of radial concentration profiles of total hydrocarbons from lean propane-air flames and propane-air flames with simulated recycle on a 2.84-inch-id flat-flame burner 27
13. Comparison of radial concentration profiles of total hydrocarbons from stoichiometric and rich propane-air flames and propane-air flames with simulated recycle on a 2.84-inch-id flat-flame burner 28
14. Comparison of radial concentration profiles of total hydrocarbons at primary flame height in propane-air and methane-air flames on a 2.84-inch-id flat-flame burner 29
15. Comparison of predicted curve and experimental points for nitrogen oxide concentrations in propane-air flames with 15 percent flue gas A added 38
16. Comparison of predicted curve and experimental points for nitrogen oxide concentrations in rich propane-air flames 39
17. Comparison of predicted curve and experimental points for nitrogen oxide concentrations in methane-air flames 40
18. Comparison of predicted curve and experimental points for carbon monoxide concentrations in a lean methane-air flame 44
19. Comparison of predicted curve and experimental points for carbon monoxide concentrations in a stoichiometric methane-air flame 45
20. Comparison of predicted curve and experimental points for carbon monoxide concentrations in a lean propane-air flame with 15 percent flue gas A added 46
21. Comparison of predicted curve and experimental points for carbon monoxide concentrations in a stoichiometric propane-air flame with 15 percent flue gas A added 47

TABLES

1. Reported concentrations of nitrogen oxides from gas-fired equipment 3
2. Significance of fuel composition on concentrations of nitrogen oxides in flame gases as compared to propane-air flames 11
3. Equilibrium constants for formation and decomposition of nitric oxide and time required for equilibrium 14
4. Peak temperatures and peak concentrations of nitrogen oxides observed in the core of secondary combustion zones 14
5. Comparison of theoretical and observed temperatures and concentrations of nitrogen oxides at axis of primary combustion zones of flames 15
6. Comparison of vertical concentrations at axis of nitrogen oxides with equilibrium concentrations of nitric oxide 16
7. Significance of fuel composition on concentrations of carbon monoxide in flame gases as compared to propane-air flames 17
8. Comparison of theoretical and observed temperatures and concentrations of carbon monoxide at axis of primary combustion zones of flames 20
9. Influence of available oxygen on rate of oxidation of carbon monoxide in the core zones of flames 21
10. Comparison of unburned gases and gases from adiabatic combustion for stoichiometric mixtures 25

Page

11. Comparison of percentage of excess oxygen and observed concentrations of carbon monoxide in the core region of lean and stoichiometric flames 26
12. Comparison of blowoff limits, g_B, of propane-air and methane-air flames 29
13. Effect on concentrations of nitric oxide in propane-air flames of chemical and thermal perturbations 30
14. Peak flame temperatures and peak concentrations of nitrogen oxides, carbon monoxide, and total hydrocarbons in methane-air flames on a multiport-ring burner 31
15. Comparison of concentrations of nitrogen oxides, carbon monoxide, hydrocarbons, secondary oxygen, and flame temperatures at axis in methane-air flames on flat-flame and multiport-ring burners 32
16. Peak flame temperatures and peak concentrations of nitrogen oxides, carbon monoxide, and total hydrocarbons in methane-air flames on a ceramic infrared flat-flame burner .. 33
17. Comparison of peak concentrations of nitrogen oxides, carbon monoxide, and hydrocarbons and peak flame temperatures in methane-air flames on metallic noninfrared and ceramic infrared flat-flame burners at two flame heights 33
18. Comparison of percentage of excess oxygen (excess primary oxygen plus secondary oxygen) in methane-air flames on metallic noninfrared and ceramic infrared flat-flame burners 34
19. Summation of kinetic studies of formation and decomposition of nitric oxide 35
20. Data for the formation of nitric oxide in the primary combustion zone of hydrocarbon-air flames 37
21. Observed temperatures and concentrations of nitrogen oxides in the core of secondary combustion zones of propane-air and methane-air flames 38
22. Combustion characteristics pertaining to the decay of carbon monoxide across the primary combustion zone of hydrocarbon-air flames 42
23. Concentrations pertaining to the decay of carbon monoxide across the primary combustion zone of hydrocarbon-air flames 42

Products of combustion in propane-air flames on a flat-flame burner—

A–1. Lean propane-air flames 52
A–2. Stoichiometric propane-air flames 53
A–3. Rich propane-air flames 54

B–1. Hydrocarbons in products of combustion in propane-air flames on a flat-flame burner. 55

Products of combustion in methane-air flames on a flat-flame burner—

C–1. Lean methane-air flames 56
C–2. Stoichiometric methane-air flames 56
C–3. Rich methane-air flames 57

D–1. Hydrocarbons in products of combustion in methane-air flames on a flat-flame burner. 58
E–1. Thermodynamic equilibrium concentrations of products in lean, stoichiometric, and rich methane-air flames 59

Thermodynamic equilibrium concentrations of products in propane-air flames—

F–1. 0.85 stoichiometric propane-air flame 60
F–2. 0.85 stoichiometric propane-air flame plus 15 percent flue gas A 61
F–3. 0.85 stoichiometric propane-air flame plus 15 percent flue gas B 61
F–4. Stoichiometric propane-air flame 62
F–5. Stoichiometric propane-air flame plus 15 percent flue gas A 62
F–6. Stoichiometric propane-air flame plus 15 percent flue gas B 63
F–7. 1.20 stoichiometric propane-air flames 63
F–8. 1.20 stoichiometric propane-air flame plus 15 percent flue gas A 64
F–9. 1.20 stoichiometric propane-air flame plus 15 percent flue gas B 64

G–1. Products of combustion in methane-air flames on a multiport-ring burner 65
H–1. Products of combustion in methane-air flames on a ceramic infrared flat-flame burner. 66
I–1. Thermodynamic equilibrium concentrations of products in lean, stoichiometric, and rich propane-air and methane-air flames at adiabatic flame temperatures 67

REDUCTION OF AIR POLLUTANTS FROM GAS BURNER FLAMES

Including Related Reaction Kinetics

by

Margaret E. Harris,[1] Valeria R. Rowe,[1] E. B. Cook,[1] and J. Grumer [2]

ABSTRACT

The formation of nitrogen oxides, the decay of carbon monoxide, and the concentrations of residual hydrocarbons in the secondary combustion zones of propane-air and methane-air flames were studied in three enclosed burners designed to simulate gas appliances such as space and water heaters. The effect of thermally or chemically perturbing the combustion gases above these flames was determined theoretically and by means of factorial experiments. The concentrations of air pollutants and the flame temperatures were measured, and the effects of ingress of secondary air into the primary and secondary combustion zones, flame stability, burner port surface, and simulated recycling of combustion gases were noted.

Based on this study, four principles were derived that, applied to gas appliance design, will insure minimal emissions of these air pollutants:

1. Oxides of nitrogen can best be kept low by depressing peak temperatures to about 3,050° F.
2. If this is not possible, then the secondary combustion zone should be cooled rapidly to this temperature.
3. Carbon monoxide concentrations can be limited by rapid induction of secondary air.
4. Hydrocarbon concentrations can be controlled by designing for well-seated, stable flames.

In addition, empirical reaction rates were derived that predict the concentrations of nitrogen oxides and carbon monoxide in the primary and secondary combustion zones.

[1] Research chemist, Safety Research Center, Bureau of Mines, Pittsburgh, Pa.
[2] Project coordinator and supervisory research chemist, Flame Dynamics, Safety Research Center, Pittsburgh, Pa.

INTRODUCTION

Gas burner flames are simple systems in which to explore the potential of combustion gases to pollute the atmosphere and to investigate means of avoiding or reducing such pollution. Although at the present time gas-fired appliances such as space and water heaters are not major sources of atmospheric pollutants, future increases in the use of all fuels may make it necessary to reduce emission even from minor sources of air pollution. Concern about such future problems led the Bureau of Mines to develop a body of fundamental knowledge that can be applied in the design of gas appliances to lower the emission of nitrogen oxides, carbon monoxide, and light hydrocarbons. A systematic examination was made of a flat-flame burner in which secondary air was gained slowly and the temperature was dropped slowly. This provided time and space in which to study flame reactions without the complications of high gradients of temperature and concentration. The principles derived from the flat-flame burner studies were supplemented and confirmed by experiments with a multiport-ring burner and a ceramic infrared flat-flame burner.

Previous investigators have found that a wide variety of gas appliances emit nitrogen oxides in concentrations ranging from almost 0 to about 1,000 ppm (table 1). Excluding the extremes, about 100 ppm seems to be the average emission level observed for gas appliances. Assuming 100 ppm (gas) and 2,000 ppm (gasoline) in air-free combustion products, the relative pollution of the atmosphere by oxides of nitrogen from gas- and gasoline-burning equipment can be estimated from the actual and projected consumption (*71*) [3] of gas and gasoline for 1963 and 1980, as follows:

	1963	*1980*
Natural gas consumption, Btu	14.8×10^{15}	25.5×10^{15}
Gasoline consumption, Btu	8.5×10^{15}	15.4×10^{15}
Ratio of NO_x produced, natural gas to gasoline	0.09	0.08

Thus, gas-burning equipment emits less than 10 percent as much nitrogen oxides to the atmosphere as does gasoline-burning equipment. This estimate may be low; George and Chass (*34*) have reported figures leading to an estimate of 32 percent. Because about twice as much of each fuel may be consumed in 1980 as in 1963, the actual burden to the atmosphere will be doubled unless steps are taken to reduce emission levels per unit of fuel burned.

One method for controlling oxides of nitrogen that has been considered by a number of researchers is the recycling of combustion gases either into the primary or the secondary combustion zone. Recycling 15 percent of auto exhaust reportedly reduces the emission of oxides of nitrogen (*51*, *76*). An inexpensive recycling device has been developed that reportedly reduces nitrogen oxides in auto exhaust by about 85 percent (*53*). Recycling about 25 percent of flue gas is also reported to reduce oxides of nitrogen from large boilers by 90 percent (*2–3*). Because recycling is feasible in gas appliances, simulated recycling of two synthetic flue gases was examined using an experimental flat-flame burner.

Tolerable concentrations of carbon monoxide in breathing air are generally estimated on the basis that exposure to about 50 ppm of carbon monoxide in a working day is noninjurious (*46*). Limits of 5 to 30 ppm have also been proposed (*10*) for long-term exposure on the basis that such exposure will not affect general well-being and health. Whether or not the acceptable limits should be about 5 or 50 ppm, it should be noted that existing gas appliances probably emit less than 5 percent of the carbon monoxide in the atmosphere (*10*).

Most studies of residual hydrocarbons from gaseous hydrocarbon flames have been prompted by interest in the formation of carbon or smoke by very rich fuel-air or diffusion flames. Little information is available on hydrocarbons from aerated blue flames. For example, in one study of carbon formation, diffusion flames and

[3] Italicized numbers in parentheses refer to items in the bibliography.

smoking, premixed flames of ethylene and propane were examined (*65*). Rather high concentrations of a variety of hydrocarbons were found. The minimum fuel concentration in the premixed flames was about double that in the stoichiometric flames, whereas the maximum fuel concentration in the present study was 1.2 times that of a stoichiometric flame. In the United States, a well-adjusted conventional gas appliance operates with premixed blue flames having a primary fuel-air composition which is closer to that of the rich flames of this study than of yellow or smoking flames. Diffusion flame burners are uncommon in this country. The emission of hydrocarbons by gas appliances is minor compared to emission by other sources (*34*).

The results of this investigation should apply to the emission of nitrogen oxides, carbon monoxide, and hydrocarbons from liquid hydrocarbon and solid-fuel flames, as well as those from gaseous hydrocarbon flames, except as the liquid hydrocarbons and solid fuels are complicated by liquid spray or particulate burning.

Table 1.—Reported concentrations of nitrogen oxides from gas-fired equipment

Equipment	Concentration, ppm	Investigator
Furnace	50–100	Bacon (*2*).
Heaters	62–164	Connolly and Nobe (*11*).
Appliances	15–90	Faith and Hall (*15*, *39*).
Power station	160–1,140	Barnhart and Diehl (*5*).
Experimental model	31–79	Richter and coworkers (*58*).
Appliances	18–46	Hangebrauck and coworkers (*41*).
Experimental model	0–15	Rosenberg and Hacker (*60*).

EQUIPMENT AND PROCEDURES

The flat-flame burner shown in figure 1 is basically a Meeker burner. The small, closely packed, conical flames approximate a flat flame with a primary combustion zone in a plane very close to the burner port. This design, in contrast to the Bunsen burner, minimizes uncertainties about reaction sequence and local temperature owing to back diffusion of burned gases into a large conical volume of unburned gas. The secondary combustion zone extended to a height of 1 foot or more and varied in diameter from 3 to almost 6 inches. The large volume of secondary combustion gases facilitated probing for temperature and concentration profiles. The port was a stainless steel grid of ⅛-inch-square openings, formed by ⅜-inch-high strips, 1/32-inch thick. The port was surrounded by a water-cooled, 3-inch-od, stainless steel tube. The flame and burner tube were enclosed in a cylindrical steel duct equipped with a viewing window on one side and a traversing slit for probes on the other side. Fuel and air flowed separately into a mixing chamber and were metered by rotameters accurate to within 1 percent of the instantaneous reading. The premixed flow rate through the burner was 4.5 cfm, making the average linear flow velocity about 20 ips (inches per second) at the burner port. The flat flame stood above the burner port as a uniform array of discrete flamelets that were 0.12 inch high for unperturbed propane flames and 0.08 to 0.12 inch high for unperturbed methane flames. Coaxial (secondary) air streamed upward around the flames through a glass-bead calming bed at a volumetric rate of 3.9 cfm or a linear rate of 5 ips. The flow of coaxial air plus primary air was always more than was required for complete combustion. The propane-air and methane-air concentrations, expressed as fractions of stoichiometric (the fraction of the fuel percentage required for complete combustion), were 0.85 for the lean flame, 1.0 for the stoichiometric flame, and 1.2 for the rich flame. This corresponded to concentrations of air equivalent respectively to 118, 100, and 83 percent of the primary air required for complete combustion.

A multiport-ring burner (fig. 2), designed to produce flames with subadiabatic temperatures and to accelerate entrainment of secondary air into the primary and secondary combustion zones, was used in the same 6-inch duct as the flat-flame burner. It was composed of a heavy-walled, doughnut-shaped ring with thirty ⅛-inch holes spaced ⅜ inch apart. Most of the secondary air flowed through the center of the doughnut. This design permitted equal and rapid induction of secondary air into the primary and secondary combustion zones of the individual flamelets. The premixed methane-air flow rate through the burner was 0.32 cfm, making the average linear flow velocity about 25 ips at the burner port. The height of the primary flames varied from 0.11 to 0.35 inch, depending on the fuel composition. The volumetric flow rate of coaxial air was 0.27 cfm or a linear rate of 0.6 ips. The flow of coaxial air plus primary air was always more than was required for complete combustion. The primary methane-air concentrations, expressed as fractions of stoichiometric, were 1.0, 1.2, 1.5, and 2.0. Flame temperatures and concentrations of air pollutants were measured at six radial and two vertical positions. These sampling points covered a range from one to two diameters from the center of one of the ports.

A ceramic infrared burner, in which a flat flame was formed above the pores of a ceramic honeycomb, was used to determine if burner surfaces have a catalytic effect on the formation of nitrogen oxides. The 5- by 7-inch burner was composed of 0.05-inch holes, 210 holes per square inch, and was enclosed in a 9.5- by 12-inch duct, 2 feet high. The height of the primary flat flames above the burner surface was 0.06 inch. The premixed methane-air flow rate through the burner was 4.5 cfm, making the average linear flow velocity about 3.7 ips at the burner port. The methane-air concentrations, expressed as fractions of stoichiometric, were 0.85, 1.0, and 1.2. Coaxial air streamed upward around the flames through a glass-bead calming bed at a volumetric rate of 3.9 cfm or a linear rate of 1.4 ips. The flow of coaxial air plus primary air was always more than was required for complete combustion. Concentrations of air pollutants and flame temperatures were measured at six positions between the midline and edge of the burner and at two vertical positions above the primary flames.

Temperature profiles of the burned gases in the three burners were determined with 0.003-inch-diameter iridium, iridium–40-percent-rhodium thermocouples (*24*). The thermocouples were

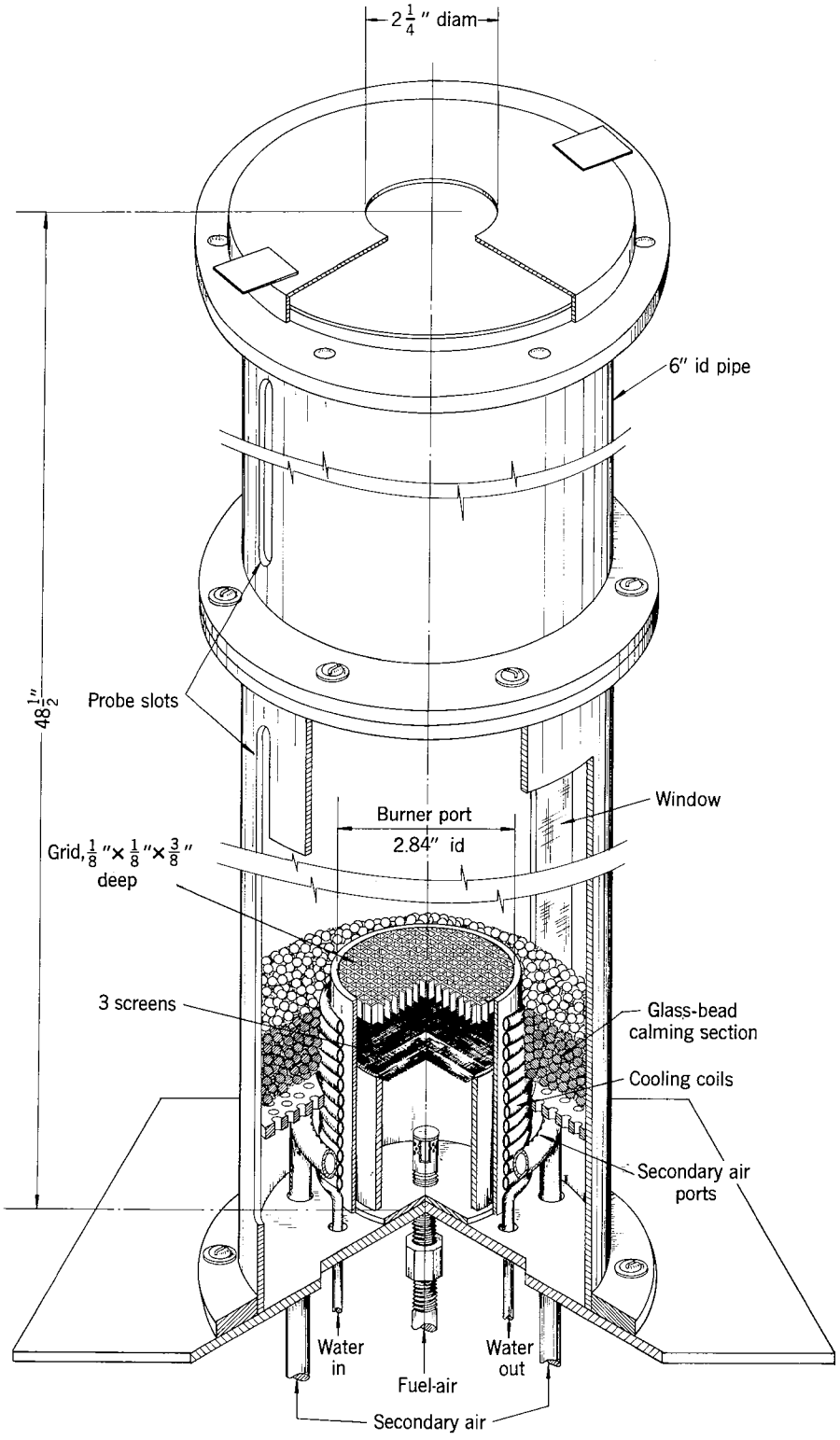

Figure 1.—Flat-flame burner.

small enough so that corrections for radiation and conduction were not necessary (*72*). Errors due to catalytic effects of the thermocouples were assumed to be negligible in a fluid consisting largely of nitrogen, water, and carbon dioxide. The thermocouples were inserted through the side-traversing slit and manipulated by means of a micrometer-vernier stage. Temperatures were taken at the same coordinates in the flames as those used for sampling pollutants and were averaged for a residence time of 1 minute for each position.

The probe for sampling combustion gases was a 0.02-inch-id tube of recrystallized alumina. This was connected to lines that were heated during sampling to avoid condensation and possible solution of gases in water. Each sample took about 3 minutes to collect. This method was not likely to alter appreciably the composition of the flame gases being sampled. Halperin and Ruegg (*40*) established that samples taken with 0.012- to 0.028-inch-id probes have a composition close to that of the flame gas. When the flame gases are below 3,600° F, the rate of sampling has little influence on the composition of the samples, if there are no major temperature and composition gradients near the sampling point. Major differences arise when the flame temperature is about 5,000° F. According to Friedman (*25*), the accuracy of the reaction rates based on sampling of flame gases is not affected by changes in the sampled gas resulting from the

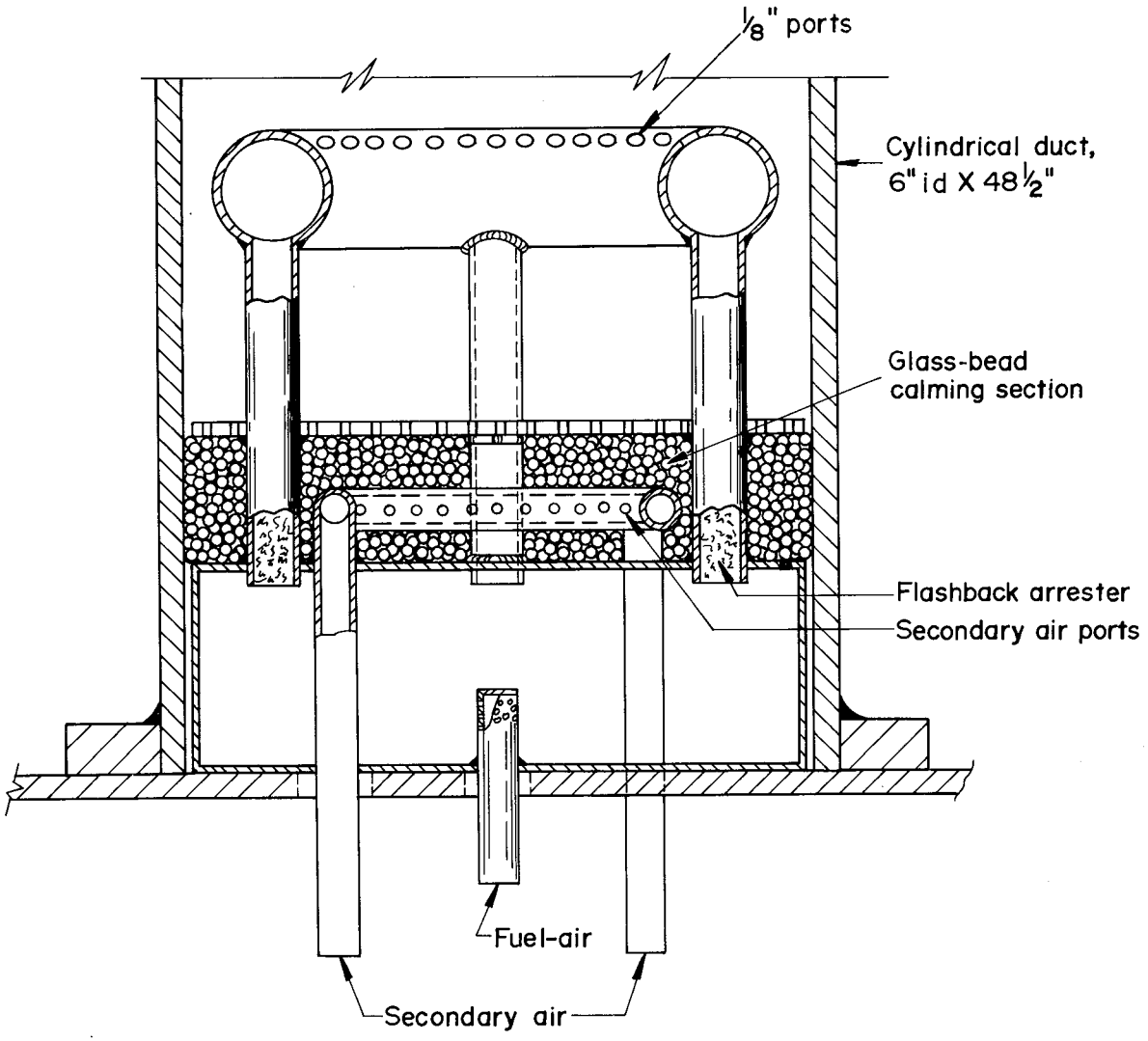

Figure 2.—Cross section of multiport-ring burner.

sampling, a point that has bearing on the reaction rates given later in this report.

One sample of the burned gases was used to measure concentrations of nitrogen oxides; another was used to measure concentrations of carbon monoxide and hydrocarbons. The nitric oxide samples were led through the heated lines into an evacuated 2-liter, round-bottom flask, brought to a pressure of ½ atmosphere, and diluted to 1 atmosphere with air prior to analysis. The oxides of nitrogen (nitric oxide plus nitrogen dioxide) were analyzed by the phenoldisulfonic acid method (*7*); this method was in satisfactory agreement with the modified Saltzman method (*61–62*) and the Rider-Mellon method (*59*). A few separate analyses with a nitrogen dioxide detector showed only traces of nitrogen dioxide, indicating that little was to be gained by determining the nitric oxide and nitrogen dioxide contents separately. The 95-percent confidence limit for the analytical method, determined with standard solutions of potassium nitrate, was ±10 ppm.

The carbon monoxide and the hydrocarbon samples were led into an evacuated 250-cc bottle and brought to 1 atmosphere. Hydrocarbon concentrations were determined with a flame ionization detector gas chromatograph with a dimethylsulfolane column. The 95-percent confidence limit for the analytical method, determined with known calibration mixtures, was ±5 ppm. Carbon monoxide, hydrogen, oxygen, and nitrogen concentrations were determined with a thermal conductivity detector gas chromatograph with a molecular sieve column; the carbon dioxide concentration was determined with an activated charcoal column. The 95-percent confidence limit for the analytical method for carbon monoxide, determined with known calibration mixtures, was ±100 ppm. The dilution of the combustion gases by secondary air was computed from a mass balance based on an analysis of the sample for carbon monoxide, hydrocarbons, hydrogen, oxygen, nitrogen, and carbon dioxide.

The concentrations of secondary air in lean, stoichiometric, and rich flames were calculated by dividing the nitrogen in the products by [(C/N_2) in primary reactants / (C/N_2) in products], in which C is the atom mole concentration of carbon and N_2 is the mole concentration of nitrogen. This equals the nitrogen in the products due to primary air. Nitrogen in the products due to secondary air is equal to the difference between the nitrogen in the products and the nitrogen in the products due to primary air. Finally, the concentration of secondary air in the products is equal to 100/79.1 times the nitrogen in the products due to secondary air. The corresponding concentration of secondary oxygen is 0.209 times the secondary air. Concentrations of secondary oxygen in lean, stoichiometric, and rich flames for all burners are given in appendixes A, C, G, and H. Data for lean and stoichiometric flames were corrected for dilution by secondary air except for the radial distance of 1.78 inches and when ratios of carbon to nitrogen in the primary reactants to ratios of carbon to nitrogen in the products were greater than 2. At these ratios the sample is so excessively diluted that a reliable correction cannot be made. Data for rich flames cannot be put on a secondary-air free basis because some of the secondary oxygen occurs in the combustion products as carbon oxides and water. The dilution by secondary air for rich flames can be roughly estimated from the ratios of carbon to nitrogen in the primary reactants to ratios of carbon to nitrogen in the products of combustion. The higher the ratio, the more secondary air has entered the flame gases.

Recycling cooled combustion gases into the primary mixture was simulated by experiments in which one of two synthetic flue gases was added to the prestated flows of primary air and propane in the flat-flame burner. Flue gas A had a volume-percent composition of 12.4 CO_2 and 87.6 N_2. Flue gas B had a volume-percent composition of 6.3 CO_2, 10.5 O_2, and 83.2 N_2. Flue gas B corresponded to flue gas A diluted with about an equal volume of air. Because the oxygen in flue gas B affected the primary fuel-air ratio, the fraction of stoichiometric for these flames was 0.78 instead of 0.85 for lean flames, 0.92 instead of 1.0 for stoichiometric flames, and 1.1 instead of 1.2 for rich flames. Enough flue gas (0.79 cfm) was added to constitute 15 percent of the total primary flow of propane-air plus flue gas. The primary flames were generally lengthened by the addition of flue gases. The lean-flame height was increased to 0.87 inch by both flue-gases; the stoichiometric-flame height was increased to 0.32 and 0.28 inch by flue gases A and B, respectively; and the rich-flame height was increased to 0.43 inch by flue gas A, but it remained at its initial height of 0.12 inch with flue gas B.

The effect of recycling flue gases in the flat-flame burner on concentrations of the three air pollutants was evaluated by a factorial design involving three factors: the presence of flue gas and the radial and vertical positions of the sampling point in the flame. The effect of the first factor was determined at three levels: without flue gas, with 15 percent flue gas A, and with 15 percent flue gas B. The effect of the second factor was determined at three levels for concentrations of nitrogen oxides: at 0, 0.5, and 1.0 radii from the axis.

Concentrations of carbon monoxide and hydrocarbons were determined at a fourth level at 1.25 radii from the axis. The effect of the third factor was determined at six levels—at the top of the primary flame and at 0.5, 1, 6, 11, and 26 inches above it. Three blocks of the full factorial design were used, representing the three primary mixture compositions. For each block the treatments were assigned randomly with two replicates for oxides of nitrogen and hydrocarbons and three replicates for carbon monoxide. The same design was used for the methane-air experiments on the flat-flame burner, but without the simulated recycling of flue gases. Three replicates were made for each air pollutant.

Analysis of the variance calculations was made to determine whether the trends observed in the recycling experiments and the propane-air versus methane-air experiments on the flat-flame burner were statistically different from the experimental error. The analysis of variance is a technique for estimating the fraction of the total variation in a set of data that can be attributed to one or more assignable causes of variation, in this case either the addition of flue gas or the use of methane, plus the main effects of radial and vertical positions and their interactions. The remainder, not attributable to any assigned cause, is the residual or error variation. This method also provides a test of significance, the F-test, by which it can be decided whether the assignable causes result from real variation, or whether the apparent variation is due only to chance causes which produce the error variation. The F-test also indicates the relative significance among the assigned causes of variation.

EXPERIMENTAL FINDINGS

REDUCTION OF OXIDES OF NITROGEN

Vertical concentration profiles for the nitrogen oxides from propane-air and methane-air flames using the flat-flame burner are compared in figure 3; these and associated data are tabulated in appendixes A and C. As the graphs show, nitrogen oxide concentrations are higher for propane than for methane. The highest concentrations are observed for the stoichiometric flames of both fuels. The concentration profiles for lean and stoichiometric flames rise very sharply near the primary combustion zone and then tend to level off downstream from the primary combustion zone. For rich flames the concentration profiles are flat by comparison.

Vertical concentration profiles for nitrogen oxides from propane-air flames with and without simulated recycle using the flat-flame burner are given in figure 4; these and associated data are tabulated in appendix A. Figure 4 shows that simulated recycling of flue gas lowers concentrations of nitrogen oxides. The difference between the lean flames with and without simulated recycling is about the same for the two flue gases. For stoichiometric propane flames, recycling results in concentrations of nitrogen oxides considerably lower than in stoichiometric methane flames without recycling; flue gas B is less effective than flue gas A. In the case of lean and rich flames, there is little difference between the effect of the two flue gases or of methane.

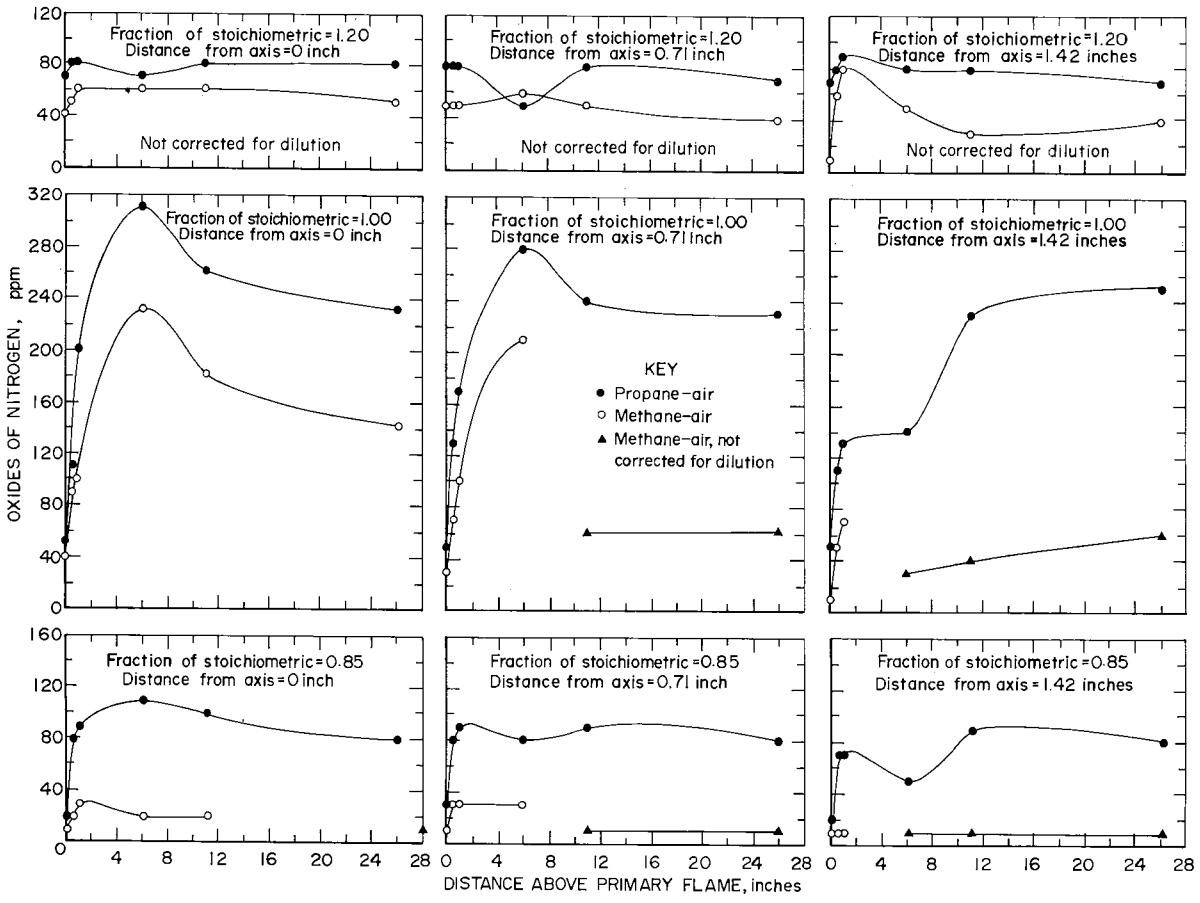

Figure 3.—Comparison of vertical concentration profiles of nitrogen oxides from propane-air and methane-air flames using a flat-flame burner.

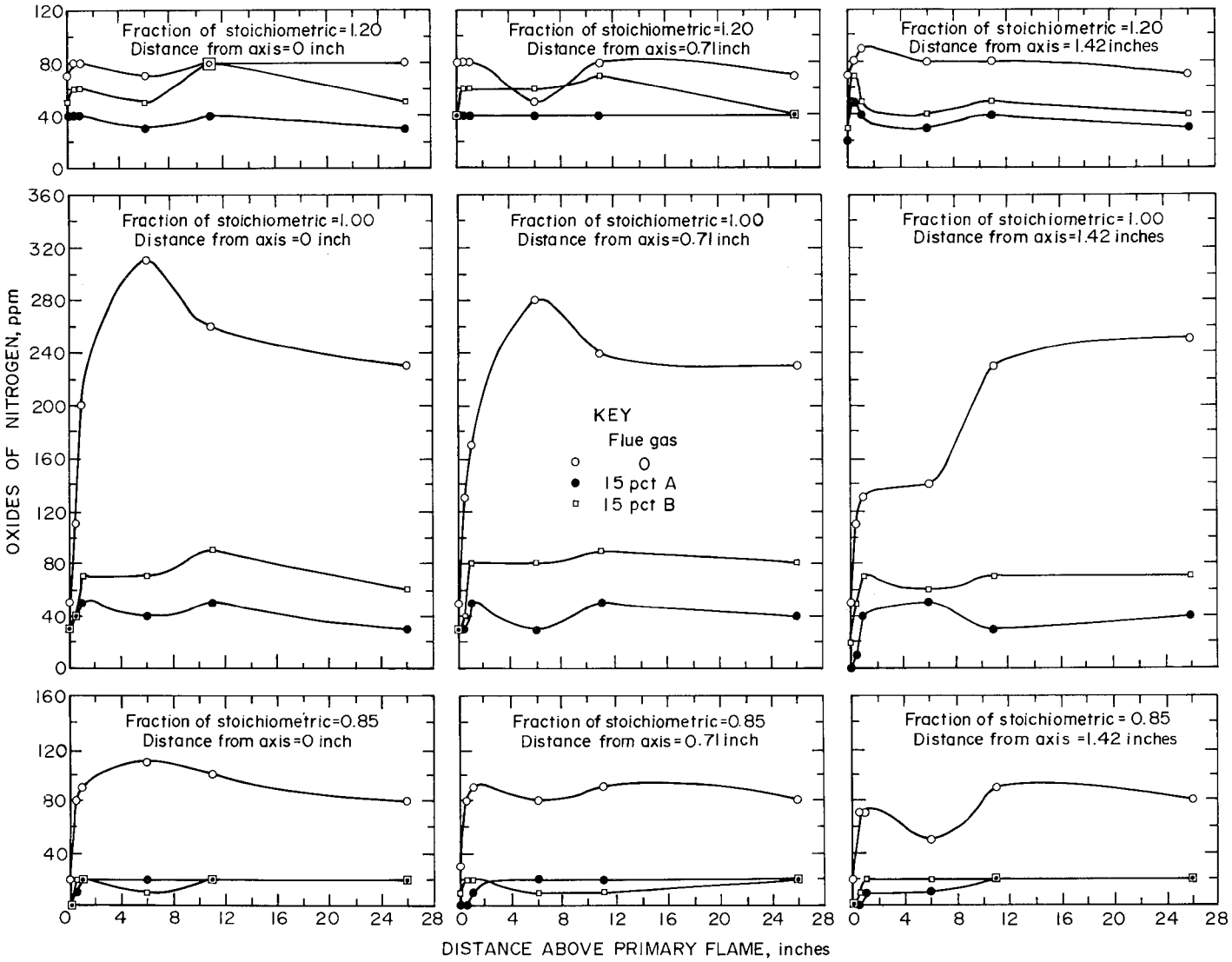

Figure 4.—Comparison of vertical concentration profiles of nitrogen oxides from propane-air flames and propane-air flames with simulated recycle using a flat-flame burner.

The extent, as compared to propane-air flames, to which the simulated recycle of flue gases and the substitution of methane affect the concentrations of nitrogen oxides is shown by the variance ratios in table 2. For the number of experiments in this factorial design at a confidence level of 99 percent, a variance ratio greater than about 7 indicates a real variation in the effect considered. Therefore the differences in concentrations of nitrogen oxides from propane-air flames compared to propane-air flames with simulated recycle and methane-air flames are significantly higher than the experimental error. The variance ratios in table 2 demonstrate statistically the trends observed in figures 3 and 4.

Table 2.—Significance of fuel composition on concentrations of nitrogen oxides in flame gases as compared to propane-air flames

Gas	Lean flames		Stoichiometric flames		Rich flames	
	Variance ratios	Experimental errors [1]	Variance ratios	Experimental errors [1]	Variance ratios	Experimental errors [1]
Propane + 15 percent flue gas A	2, 860	±10	6, 170	±20	2, 150	±10
Propane + 15 percent flue gas B	2, 160	±10	4, 280	±20	800	±10
Methane	3, 590	±10	1, 300	±20	1, 810	±10

[1] 95-percent confidence limit.

For lean flames, there is little difference in the variance ratios, but for stoichiometric and rich flames the variance ratios are highest for flue gas A, indicating that it has a stronger effect in reducing nitrogen oxides than flue gas B or methane. For stoichiometric flames, variance ratios are lowest for methane-air flames, indicating a weaker effect in reducing nitrogen oxides for this fuel than for corresponding propane-air flames with flue gas B. These trends are explained in the following section on the basis of stoichiometry, flame temperature, and equilibrium concentration.

Roles of Flame Temperature and Equilibrium Concentration

Vertical flame-temperature profiles in the flat-flame burner for propane-air and propane-air with simulated recycle are given in figure 5 and for propane-air and methane-air in figure 6. On the average, the axial temperatures observed close to the primary combustion zone were less than those computed for adiabatic combustion within 5±3 percent, showing that chemically the system was nearly ideal. Cooling was gradual with temperatures falling off at a rate of 40° to 130° F/inch. Radial temperature gradients were quite flat within about 6 inches from the primary flame fronts. As a result of these flat temperature profiles, flame gases could be sampled in the core of the stream (the core being within the ½-port-radius stream tube) without the complication of averaging concentrations associated with sharp temperature changes. Near the stream boundary, temperatures and other parameters changed sharply due to mixing with secondary air and heat loss to the duct walls. The core region, which was insulated from such changes by the rest of the stream, was particularly useful in evaluating reaction rates.

The concentration profiles of nitrogen oxides in figures 3 and 4 show that within the core zones of lean and stoichiometric flames there are zones where concentrations of nitrogen oxides increase with time, others where they decrease, and still others where they remain fairly stable. For rich flames the concentration profiles show that the relative amounts of nitrogen oxides formed at the primary combustion zone change very little with time. The prime considerations in understanding these zones are the flame temperatures and whether observed concentrations of nitrogen oxides are much above, about equal, or below equilibrium concentrations of nitric oxide.

How drastically the rate at which equilibrium is reached among nitric oxide, nitrogen, and oxygen depends on the temperature is illustrated in table 3 (*50*). In our experiments, the residence time per inch was about 7 milliseconds, and the total residence time for the entire axial traverse was about 0.22 second. In the usual gas appliance, the residence time is probably a few tenths of a second. The data in table 3 show that, for such appliances, when the flame temperature is between 3,320° and 2,960° F, lowering the temperature just a bit slows down the reaction between nitrogen and oxygen considerably.

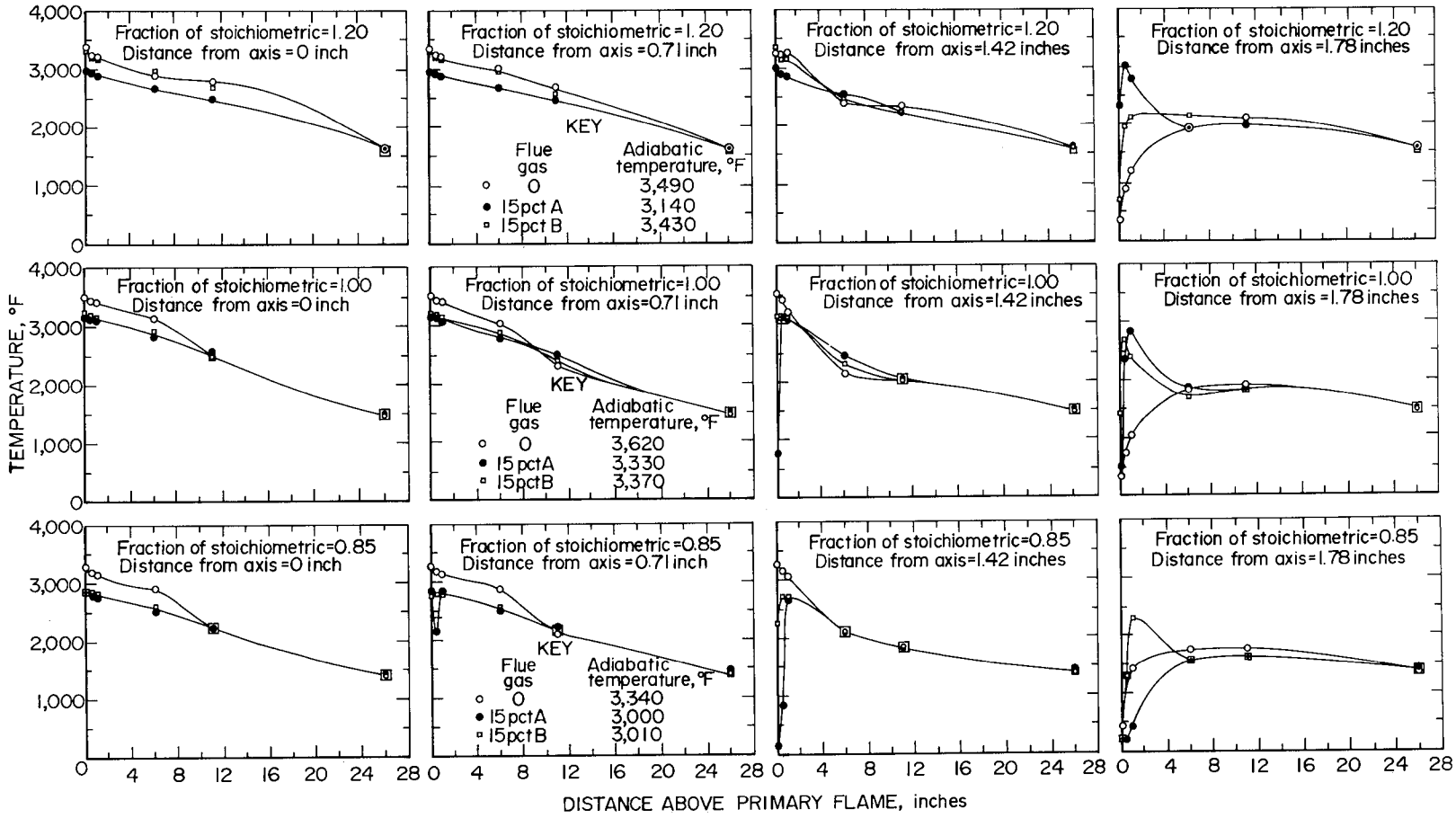

Figure 5.—Comparison of vertical temperature profiles in propane-air flames and propane-air flames with simulated recycle on a flat-flame burner.

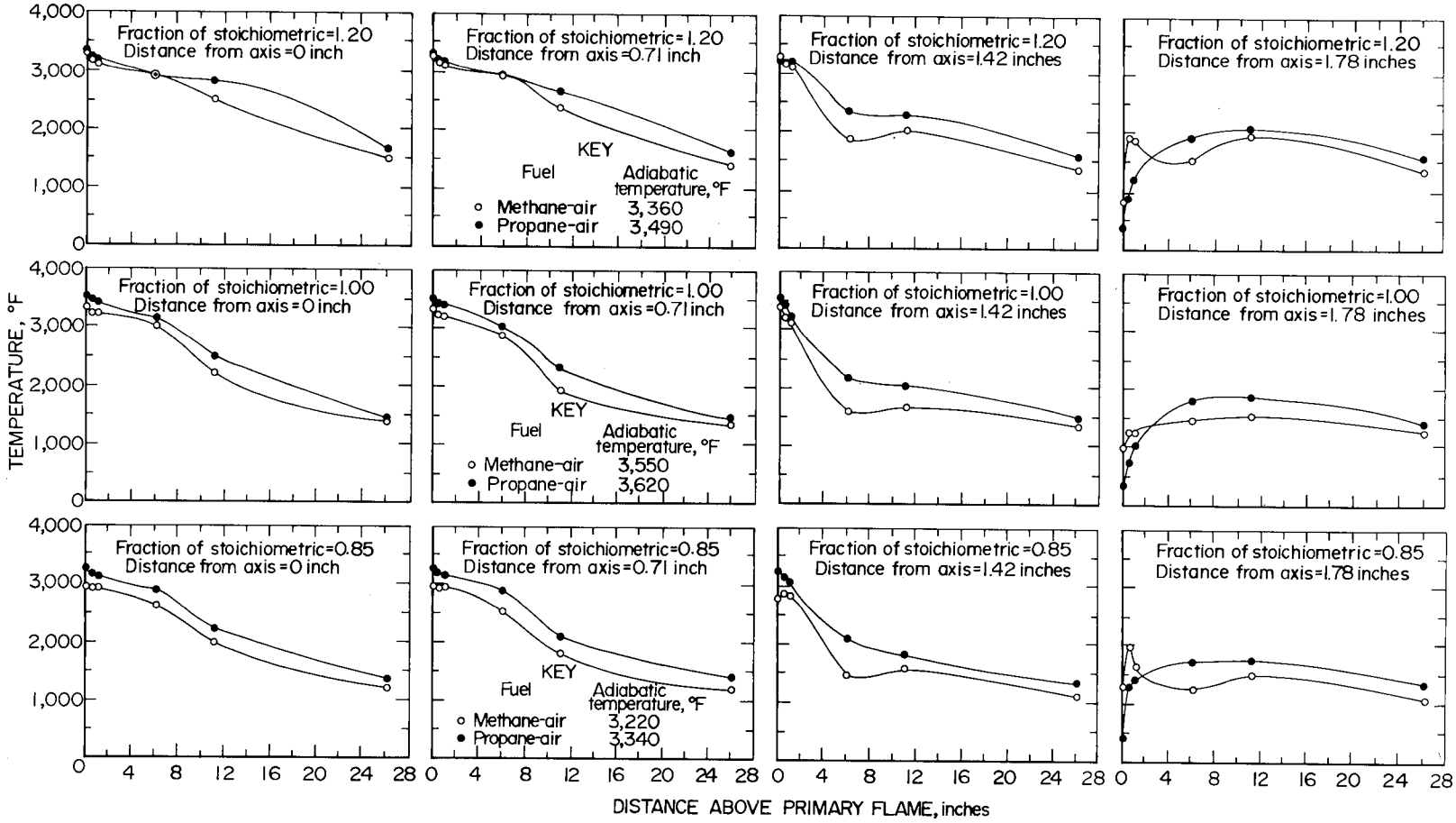

Figure 6.—Comparison of vertical temperature profiles in propane-air and methane-air flames on a flat-flame burner.

Table 3.—Equilibrium constants for formation and decomposition of nitric oxide and time required for equilibrium [1]

$$N_2 + O_2 \underset{K_1}{\overset{K_2}{\rightleftarrows}} 2NO$$

Temp., ° F	K_1	K_2	Time
1, 340	4.00×10	1.74×10^{-7}	81.6 years
2, 240	3.78×10^{4}	2.33×10^{-1}	1.26 days
2, 960	9.06×10^{6}	1.20×10^{3}	2.08 min
3, 320	1.40×10^{8}	5.55×10^{4}	5.06 sec
4, 040	3.37×10^{10}	6.98×10^{7}	0.0106 sec

[1] Time for formation from air of ½ the equilibrium concentration.

Selected data for the core zones were used to determine the minimum temperature below which nitrogen oxides do not form in the secondary combustion zone within the time available for reaction in our system and in gas appliances generally. The temperatures used were the temperatures observed for peak concentrations of nitrogen oxides in flames where these concentrations had been increasing with time, and the equilibrium concentration of nitric oxide for this temperature was greater than the corresponding observed concentration of nitrogen oxides. Data for 10 flames met these conditions. The average temperature for these 10 flames was 3,050° F with a standard deviation of ±100° F. This minimum temperature agrees with a calculated minimum temperature of 3,050° F for the formation of nitrogen oxides in gas appliances (*66*) based on reaction rates obtained by Zeldovich (*78*). This minimum temperature can also be determined from the minimum temperature observed at the end of the primary combustion zone of any of the 12 flames studied when the nitrogen oxide concentration was greater than 10 ppm; this concentration is our experimental uncertainty. The lowest observed temperature was 2,940° F, which almost falls within the temperature range of 3,050° F ±100°.

The data in table 4 give additional information on the relationship between observed flame temperatures, the minimum temperature of 3,050° F, and equilibrium and observed concentrations. Peak temperatures observed in lean and stoichiometric flames are tabulated in decreasing order in one group. Those for rich flames are in another group. The minimum temperature of 3,050° F and the temperatures corresponding to an equilibrium concentration of 10 ppm are included for purposes of comparison. Observed peak concentrations of nitrogen oxides are also included. The

Table 4.—Peak temperatures and peak concentrations of nitrogen oxides observed in the core of secondary combustion zones

Fraction of stoichiometric	Fuel	Peak observed: Temperature, ° F	Peak observed: NO_x concentration, ppm	Equilibrium NO at peak temp., ppm
LEAN AND STOICHIOMETRIC FLAMES				
1.00	C_3H_8	3, 510	310	[1] 1, 903
1.00	CH_4	3, 320	230	[2] 1, 230
.85	C_3H_8	3, 270	110	[1] 3, 504
.92	C_3H_8+B [3]	3, 230	90	[1] 2, 220
1.00	C_3H_8+A [4]	3, 160	50	[1] 766
.85	C_3H_8	[5] 3, 050	----	[1] 2, 523
.85	CH_4	[5] 3, 050	----	[2] 2, 718
1.00	C_3H_8	[5] 3, 050	----	[1] 547
1.00	CH_4	[5] 3, 050	----	[2] 560
.85	CH_4	2, 950	30	[2] 2, 339
.78	C_3H_8+B [3]	2, 850	20	[1] 2, 107
.85	C_3H_8+A [4]	2, 840	20	[1] 1, 692
1.00	C_3H_8	[6] 2, 060	----	[1] 10
1.00	CH_4	[6] <1, 140	----	[2] 10
.85	C_3H_8	[6] 1, 340	----	[1] 10
.85	CH_4	[6] <1, 140	----	[2] 10
RICH FLAMES				
1.20	C_3H_8	3, 360	80	[1] 112
1.10	C_3H_8+B [3]	3, 340	80	[1] 204
1.20	CH_4	3, 280	60	[2] 95
1.20	C_3H_8	[5] 3, 050	----	[1] 20
1.20	CH_4	[5] 3, 050	----	[2] 22
1.20	C_3H_8+A [4]	2, 970	40	[1] 11
1.20	C_3H_8	[6] 2, 960	----	[1] 10
1.20	CH_4	[6] 2, 900	----	[2] 10

[1] Appendix F.
[2] Appendix E.
[3] 15 percent flue gas B.
[4] 15 percent flue gas A.
[5] Selected value.
[6] Temperature for selected value of equilibrium concentration.

observed peak concentrations of oxides of nitrogen for lean and stoichiometric flames show a marked decrease with decreasing temperature. The highest concentrations of nitrogen oxides occur at flame temperatures above 3,050° F. Equilibrium concentrations at these temperatures are always much higher than the observed concentrations. Conversely, below 3,050° F, peak concentrations of nitrogen oxides are low even though equilibrium concentrations are much higher than the observed concentrations. Thus, the formation of nitrogen oxides in the secondary combustion zone essentially ceases when the temperature drops below 3,050° F.

The information in table 4 for rich flames presents a different aspect of the relationship between flame temperatures, the minimum temperature of 3,050° F, and equilibrium and observed

concentrations. The higher peak concentrations of nitrogen oxides still occur in flames with temperatures above 3,050° F, but these concentrations are much lower and do not show the sharp decrease with temperatures observed for lean and stoichiometric flames. It is possible that nitrogen oxides form a little faster in rich flames than in lean and stoichiometric flames because there are more oxyhydrocarbon radicals in the primary combustion zone, and the equilibrium concentrations for rich flames at their peak temperatures are much lower than in lean and stoichiometric flames. In the secondary combustion zone of rich flames, concentrations tend to remain fairly steady with time because equilibrium concentrations decrease more slowly with decreasing temperature than in lean and stoichiometric flames.

The above observations led to the first of four design principles for gas appliances; namely, that depressing peak temperatures below about 3,050° F reduces the emission of nitrogen oxides significantly.

Another important point about nitrogen oxides in flames is illustrated in table 5. The theoretical (or adiabatic) flame temperatures on the average are within 5±3 percent of the temperatures actually observed near the top of the primary combustion zone. The theoretical concentrations of nitric oxide correspond to thermodynamic equilibrium at the adiabatic flame temperatures. The concentrations of nitrogen oxides observed at the tops of the primary combustion zone are considerably lower than the concentrations to be expected if the system attained thermodynamic equilibrium. For lean and stoichiometric flames, the observed concentrations are about two orders of magnitude less than theoretical. Thus, unless the reaction is frozen by lowering temperatures rapidly, the concentration of nitrogen oxides will tend to increase with time.

Table 5.—Comparison of theoretical and observed temperatures and concentrations of nitrogen oxides at axis of primary combustion zones of flames

Fuel	Temperature, ° F		Concentration, ppm	
	Theoretical [1]	Observed	Theoretical [2]	Observed
LEAN FLAMES				
C_3H_8	3, 340	3, 270	3, 830	20
CH_4	3, 220	2, 950	3, 280	10
C_3H_8+A [3]	3, 000	2, 840	2, 220	0
C_3H_8+B [4]	3, 010	2, 850	2, 750	0
STOICHIOMETRIC FLAMES				
C_3H_8	3, 620	3, 510	2, 460	50
CH_4	3, 550	3, 320	2, 000	40
C_3H_8+A [3]	3, 330	3, 160	1, 210	30
C_3H_8+B [4]	3, 370	3, 230	2, 730	30
RICH FLAMES				
C_3H_8	3, 490	3, 360	210	70
CH_4	3, 360	3, 280	100	40
C_3H_8+A [3]	3, 140	2, 970	40	40
C_3H_8+B [4]	3, 430	3, 340	330	50

[1] Adiabatic flame temperature.
[2] Thermodynamic equilibrium values of nitric oxide; appendix I.
[3] 15 percent flue gas A.
[4] 15 percent flue gas B.

The concentration profiles of nitrogen oxides in figure 3 for propane-air and methane-air flames show a zone in which nitrogen oxides decompose in stoichiometric flames. It would be advantageous to know the conditions under which this decomposition takes place, as it might be better to cool slowly in this zone in order to take advantage of the decomposition. The data in table 6 for stoichiometric flames show the conditions that existed when decomposition of nitrogen oxides exceeded their formation. Temperatures had been above 3,050° F and considerable quantities of nitrogen oxides had formed while equilibrium concentrations were more than the actual concentrations. When the temperatures dropped below 3,050° F, equilibrium concentrations of nitric oxide were less than the actual concentrations of nitrogen oxides.

To determine the minimum temperature below which the decomposition rate is too slow for a significant reaction to occur, selected data in the core zones of lean and stoichiometric flames were examined. The temperatures used were the highest temperatures in flames in which concentrations of nitrogen oxides did not change appreciably with time, although the equilibrium concentrations for the observed temperature were much lower than the observed concentrations of nitrogen oxides. Data for five flames met these conditions. The average temperature was 2,140° F with a standard deviation of ±300° F. One theoretical analysis, using reaction rates taken from the literature,

Table 6.—Comparison of vertical concentrations at axis of nitrogen oxides with equilibrium concentrations of nitric oxide

Sampling points above primary flame, inches	Residence time between sampling points, msec	Observed		Equilibrium NO, ppm
		Temperature, ° F	NO_x concentration, ppm	
STOICHIOMETRIC PROPANE-AIR FLAME				
0	[1] 0. 159	3, 510	50	1, 903
6. 0	39. 7	3, 140	310	720
[2] 7. 0	[2] 6. 7	3, 050	[2] 304	547
11. 0	[2] 30. 0	2, 490	260	76
26. 0	133	1, 460	230	0
STOICHIOMETRIC METHANE-AIR FLAME				
0	[1] 0. 220	3, 320	40	1, 230
[2] 5. 5	[2] 39. 8	3, 050	[2] 228	560
6. 0	[2] 3. 6	3, 000	230	497
11. 0	41. 1	2, 200	180	19
26. 0	145	1, 380	140	0
LEAN PROPANE-AIR FLAME				
0	[1] 0. 172	3, 270	20	3, 504
[2] 2. 5	[2] 17. 8	3, 050	[2] 100	2, 523
6. 0	[2] 24. 1	2, 900	110	1, 979
11. 0	40. 0	2, 220	100	458
26. 0	142	1, 390	80	15
LEAN METHANE-AIR FLAME				
0	[1] 0. 257	2, 950	10	2, 339
6. 0	48. 1	2, 630	20	1, 316
11. 0	45. 2	1, 990	20	[3] 235
26. 0	160	1, 220	[4] 10	[3] 7

[1] Across primary flame front.
[2] Estimated value.
[3] Propane value was used because concentrations for methane at these temperatures were not available.
[4] Not corrected for dilution by secondary air.

predicts that below 2,300° F, irrespective of cooling rates between 10^3 and $10^{6°}$ F/sec, the formation of nitric oxide effectively ceases in the secondary combustion zone during the residence time in a conventional gas appliance (*66*). In our experiments, cooling rates of about 7,000° to 10,000° F/sec were observed down to about 2,000° to 2,200° F. This minimum temperature agrees well with the temperature of about 2,000° to 2,100° F in coal dust flames, derived by Perry and Field (*57*) from the work of Bienstock, Amsler, and Bauer (*8*).

Lean propane-air flames show the same sharp increase in concentration of nitrogen oxides close to the primary combustion zone as stoichiometric flames and for the same reasons (table 6). The primary flame temperature is above 3,050° F and equilibrium concentrations are much higher than the observed concentrations. Subsequently, however, concentrations remain fairly stable because, unlike stoichiometric flames, these flames have higher equilibrium concentrations than the concentrations observed between 3,050° and 2,140° F. Equilibrium concentrations for the same temperature are much higher in lean flames than in stoichiometric flames. By the time temperatures decrease to a point where equilibrium concentrations are less than actual concentrations, the temperature is too low (below 2,140° F) for decomposition to occur. Concentrations of nitrogen oxides in the lean methane-air flame are very low even though equilibrium concentrations are much higher than observed concentrations because the primary flame temperature is below 3,050° F.

Therefore, for those flames in which equilibrium concentrations are relatively low at the

primary combustion zone temperature and become less than observed concentrations with cooling, it would be better to cool slowly between 3,050° and 2,140° F. However, if initial concentrations are high because of high primary flame temperatures, there may not be sufficient time for much decomposition in the usual gas appliance. Relatively high concentrations will still remain. Thus, there would be no great advantage if cooling were slow between these two temperatures.

The concentration profiles of nitrogen oxides in figure 3 and 4 also show that there is a zone where concentrations remain fairly steady with time. The prime considerations in understanding this zone are threefold. Concentrations do not increase with time if flame tempertures never exceed 3,050° F. Even if flame temperatures are initially above 3,050° F, concentrations remain fairly steady if the actual concentrations are about the same as the equilibrium concentrations. Finally, nitrogen oxides will not decompose if the temperature falls below 2,140° F, even though equilibrium concentrations are less than observed concentrations.

REDUCTION OF CARBON MONOXIDE

Vertical concentration profiles of carbon monoxide are compared for propane-air flames and propane-air flames with simulated recycle in figure 7 and for propane-air and methane-air flames in figure 8; these and associated data are tabulated in appendixes A and C. For all 12 flames studied, carbon monoxide concentrations decrease very rapidly with both vertical and radial distance and with decreasing stoichiometry. Concentrations of carbon monoxide are highest for propane-air flames and propane-air flames with flue gas A. Concentrations are significantly lower and about equal when methane is used as the fuel or when flue gas B is added to propane-air flames.

The data in table 7 show the effect on the carbon monoxide concentration by the simulated recycle of flue gas A or B in propane-air flames and the effect of substituting methane as a fuel. As before, a variance ratio greater than about 7 indicates a real variation in the effect considered. Concentrations of carbon monoxide in lean and stoichiometric propane-air flames with flue gas A are not significantly different from the observed concentrations for propane-air flames, but they are significantly different in rich flames. The differences observed between propane-air flames and either propane-air with flue gas B or methane-air flames are significantly larger than the experimental error for all flames. In fact, for all flames the effects of radial and vertical position have about as much effect on the concentrations of carbon monoxide as the fuel composition does. This agrees with the observation that carbon monoxide concentrations decrease very rapidly with radial and vertical distance. The variance ratios in table 7 demonstrate statistically the trends observed in figures 7 and 8. The variance ratios for propane-air flames with flue gas B and methane-air flames are always higher, indicating a stronger effect in reducing carbon monoxide concentrations than those for propane-air flames with flue gas A. These trends will be explained in following sections on the basis of stoichiometry, equilibrium concentration, the amount of excess oxygen (primary plus secondary), and the ingress of secondary air into the secondary combustion zone.

Role of Equilibrium Concentration

Table 8 presents a comparison of equilibrium and observed concentrations of carbon monoxide at the primary combustion zones of lean, stoichiometric, and rich flames. Unlike the data in table 5 for nitrogen oxides, the observed concentrations of carbon monoxide are generally a little higher or about equal to the equilibrium concentrations. Thus, one means of reducing concentrations of carbon monoxide in the primary combustion zone is to maintain high temperatures long enough for

Table 7.—Significance of fuel composition on concentrations of carbon monoxide in flame gases as compared to propane-air flames

Gas	Lean flames		Stoichiometric flames		Rich flames	
	Variance ratios	Experimental errors [1]	Variance ratios	Experimental errors [1]	Variance ratios	Experimental errors [1]
Propane +15 percent flue gas A	2	±1,400	2	±3,100	50	±4,100
Propane +15 percent flue gas B	80	±700	360	±2,100	270	±6,200
Methane	490	±590	350	±2,000	830	±3,710

[1] 95-percent confidence limit.

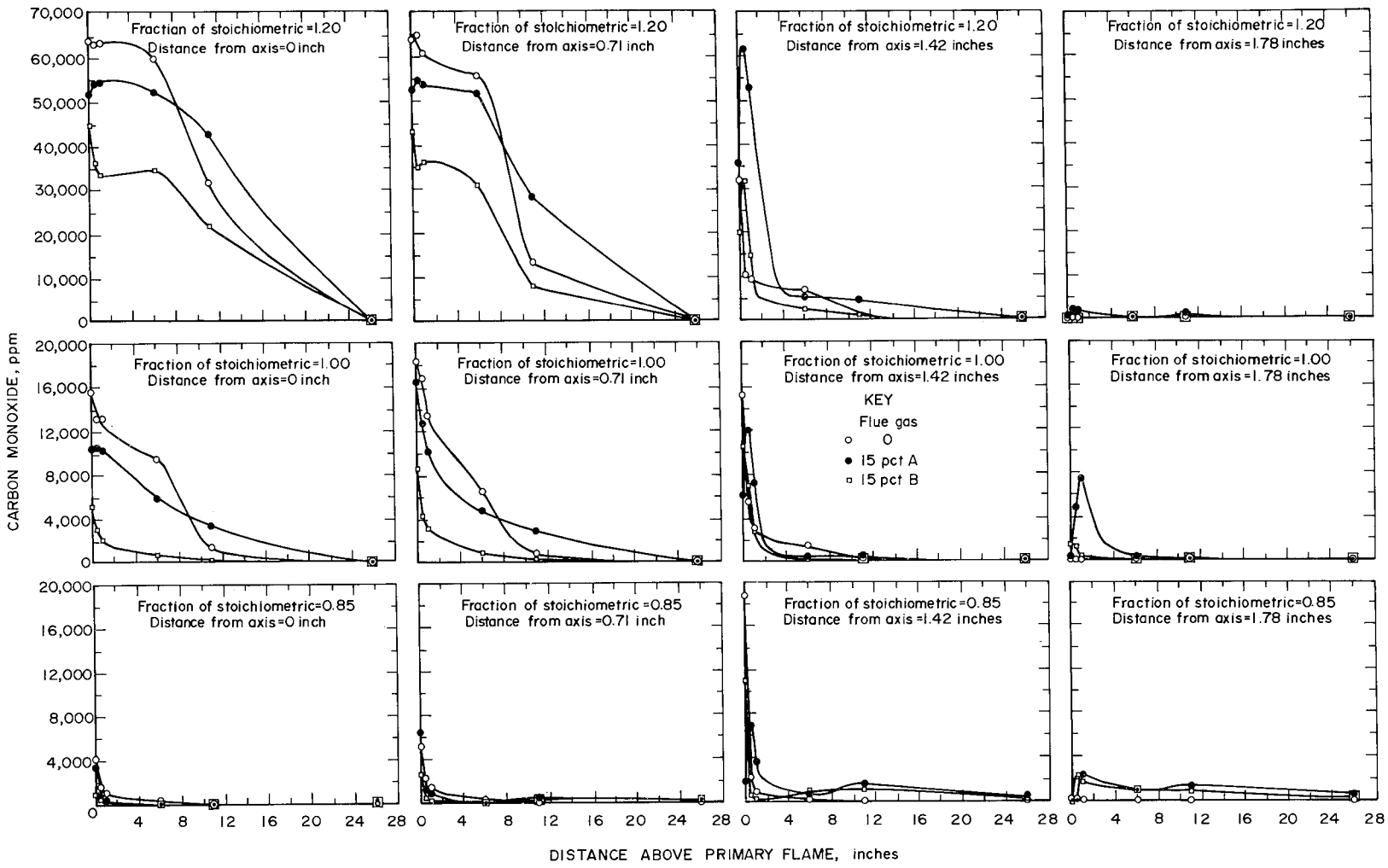

Figure 7.—Comparison of vertical concentration profiles of carbon monoxide from propane-air flames and propane-air flames with simulated recycle using a flat-flame burner.

371-272 O - 70 - 4

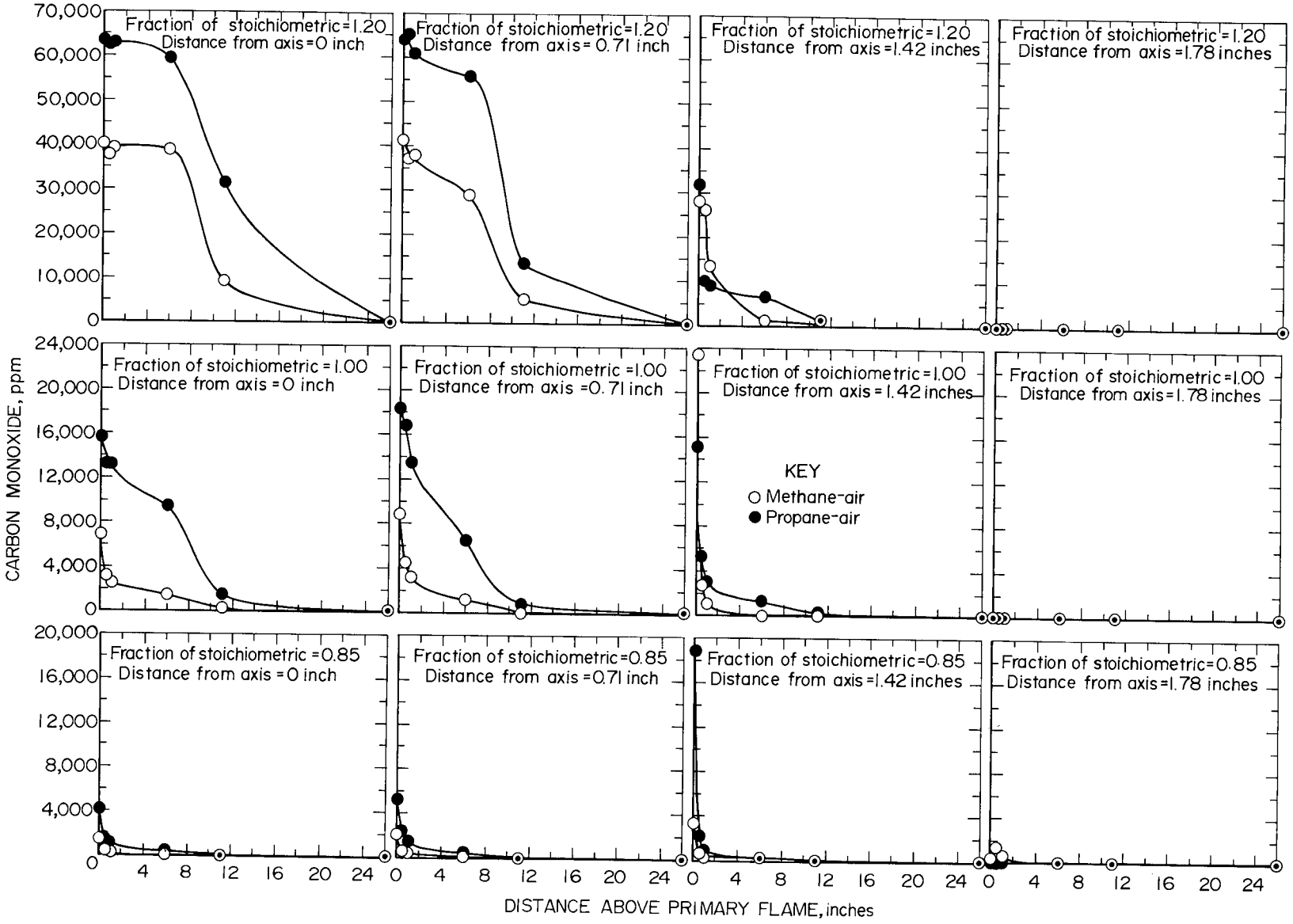

Figure 8.—Comparison of vertical concentration profiles of carbon monoxide from propane-air and methane-air flames using a flat-flame burner.

Table 8.—Comparison of theoretical and observed temperatures and concentrations of carbon monoxide at axis of primary combustion zones of flames

Fuel	Temperature, ° F		Concentration, ppm	
	Theoretical [1]	Observed	Theoretical [2]	Observed
LEAN FLAMES				
C_3H_8	3, 340	3, 270	1, 760	4, 200
CH_4	3, 220	2, 950	730	1, 500
C_3H_8+A [3]	3, 000	2, 840	430	3, 500
C_3H_8+B [4]	3, 010	2, 850	330	900
STOICHIOMETRIC FLAMES				
C_3H_8	3, 620	3, 510	12, 480	15, 600
CH_4	3, 550	3, 320	9, 210	6, 800
C_3H_8+A [3]	3, 330	3, 160	6, 090	10, 400
C_3H_8+B [4]	3, 370	3, 230	3, 230	5, 100
RICH FLAMES				
C_3H_8	3, 490	3, 360	55, 580	63, 400
CH_4	3, 360	3, 280	49, 030	40, 200
C_3H_8+A [3]	3, 140	2, 970	49, 320	51, 400
C_3H_8+B [4]	3, 430	3, 340	33, 140	44, 200

[1] Adiabatic flame temperature.
[2] Thermodynamic equilibrium values of carbon monoxide; appendix I.
[3] 15 percent flue gas A.
[4] 15 percent flue gas B.

equilibrium to be reached. Rapid cooling is undesirable because supraequilibrium concentrations are likely to be frozen. This observation is in direct opposition to the design principles proposed for reducing the formation of nitrogen oxides. Fortunately, there is a way to reduce concentrations of both types of oxides.

According to theory (*66*), a cooling rate of 1,000° F/sec lowers the temperature too fast for equilibrium to be reached and furthermore cooling at this rate below about 2,500° F drastically slows down the rate of oxidation. Although cooling rates of 7,000° to 10,000° F/sec were encountered in our experiments, carbon monoxide formed in the primary combustion zones of all 12 flames were completely oxidized by the time flame gases had flowed to a position 26 inches above the primary flame. The prime factor underlying complete oxidation appears to be the excess oxygen concentration; temperature is a secondary factor. Examination of the carbon monoxide concentration profiles in figures 7 and 8 shows that increasing the oxygen concentration facilitates the oxidation of carbon monoxide, particularly when excess oxygen is present. Carbon monoxide concentrations decrease with both vertical distance from the primary flame and radial distance from the axis because of the progressive ingress of secondary oxygen. The effect of primary oxygen is evident from the decreasing carbon monoxide concentrations with decreasing primary fuel-to-air ratio. Very little carbon monoxide is present beyond the primary combustion zones of lean propane-air, propane-air with simulated recycle, or methane-air flames; the rather high excess primary oxygen accelerates the oxidation. Comparison of the carbon monoxide concentrations resulting from the simulated recycle of flue gases A and B also shows the role of oxygen concentration; flue gas B, which contains oxygen, lowers carbon monoxide concentrations significantly more than flue gas A. Because excess oxygen in the primary and secondary combustion zones of flames slows the formation of nitrogen oxides by lowering local flame temperatures, "diluting" with excess oxygen reduces both types of oxides.

Role of Excess Oxygen

Oxygen anywhere in a flame, in excess of that needed for complete combustion to carbon dioxide and water, may originate as secondary or primary oxygen, or both. Primary oxygen can react largely in the primary combustion zone and finish reaction in the secondary zone (*31*); secondary oxygen may diffuse into the primary zone and react there. The percentage of excess primary oxygen in the lean flames used in this study was

2.6 for propane-air plus flue gas A, 3.1 for propane-air and methane-air, and 4.2 for propane-air plus flue gas B. Vertical concentration profiles of secondary oxygen inducted into the secondary combustion zones of lean and stoichiometric propane-air and methane-air flames and propane-air flames with simulated recycle are given in figures 9 and 10. For rich flames the percentage deficiency in the primary mixture of oxygen necessary for the complete combustion of the fuel is 2.0 for propane-air flames plus flue gas B, 3.6 for propane-air flames plus flue gas A, and 4.2 for propane-air and methane-air flames. As noted earlier, ratios of carbon to nitrogen in the primary reactants to ratios of carbon to nitrogen in products of combustion were used in this study as an indication of dilution by secondary air; such vertical profiles are shown in figure 11 for rich flames. The ingress of secondary air is at about the same rate as for lean and stoichiometric flames.

Figures 9–11 indicate that the concentration of secondary oxygen and the dilution ratios at the top of the primary combustion zone and farther downstream are higher for methane-air flames than for propane-air flames or propane-air flames with simulated recycle. In the core region the profiles for all flames are fairly flat for the first 6 inches above the primary flame front. A sharp increase in secondary oxygen concentration and dilution ratios takes place between the 6- and 11-inch positions, with methane-air and propane-air flames showing the greatest increase. Outside the core region, the sharp increase in secondary oxygen concentration and dilution ratios occurs between the 1- and 6-inch levels, indicating the more rapid induction of secondary air into these regions. Further discussion of these trends and the differences in ingress of secondary air into the various flames will be presented in a later section.

The data in table 9 illustrate the role of excess oxygen (excess primary plus excess secondary) on the rate of oxidation of carbon monoxide for lean

Table 9.—Influence of available oxygen on rate of oxidation of carbon monoxide in the core zones of flames

Oxygen [1], percent	Specific reaction rate, $-\Delta$ [CO], percent/inch: Primary flame front to— 0.5 inch	1.0 inch	Observed: CO [1], percent	Temperature [1], ° F
EXCESS OXYGEN IN LEAN AND STOICHIOMETRIC FLAMES				
[2] 0. 3	0	0	1. 04	3, 160
. 5	31	15	1. 56	3, 510
[2] . 8	45	38	1. 64	3, 140
1. 2	16	27	1. 83	3, 500
[3] 2. 4	101	65	. 85	3, 180
3. 0	109	63	. 68	3, 320
[2] 3. 0	143	89	. 35	2, 840
[3] 3. 1	82	57	. 51	3, 230
3. 1	99	64	. 87	3, 320
[2] 3. 4	160	86	. 65	2, 830
3. 8	124	74	. 42	3, 270
4. 0	112	71	. 52	3, 260
[3] 4. 8	89	67	. 09	2, 850
[3] 5. 1	162	92	. 26	2, 760
6. 1	143	81	. 21	2, 950
6. 6	147	80	. 15	2, 950
OXYGEN DEFICIENCY IN RICH FLAMES				
3. 2	−3. 7	5. 0	6. 41	3, 340
3. 0	2. 5	. 6	6. 34	3, 360
[2] 2. 6	−8. 4	−2. 5	5. 26	2, 940
[2] 2. 3	−9. 3	−5. 3	5. 14	2, 970
[3] 1. 2	34. 0	16. 0	4. 30	3, 320
[3] 1. 1	38. 0	25. 3	4. 42	3, 340
1. 1	20. 4	8. 3	4. 11	3, 280
. 4	13. 4	2. 7	4. 02	3, 280

[1] At primary flame front.
[2] 15 percent flue gas A.
[3] 15 percent flue gas B.

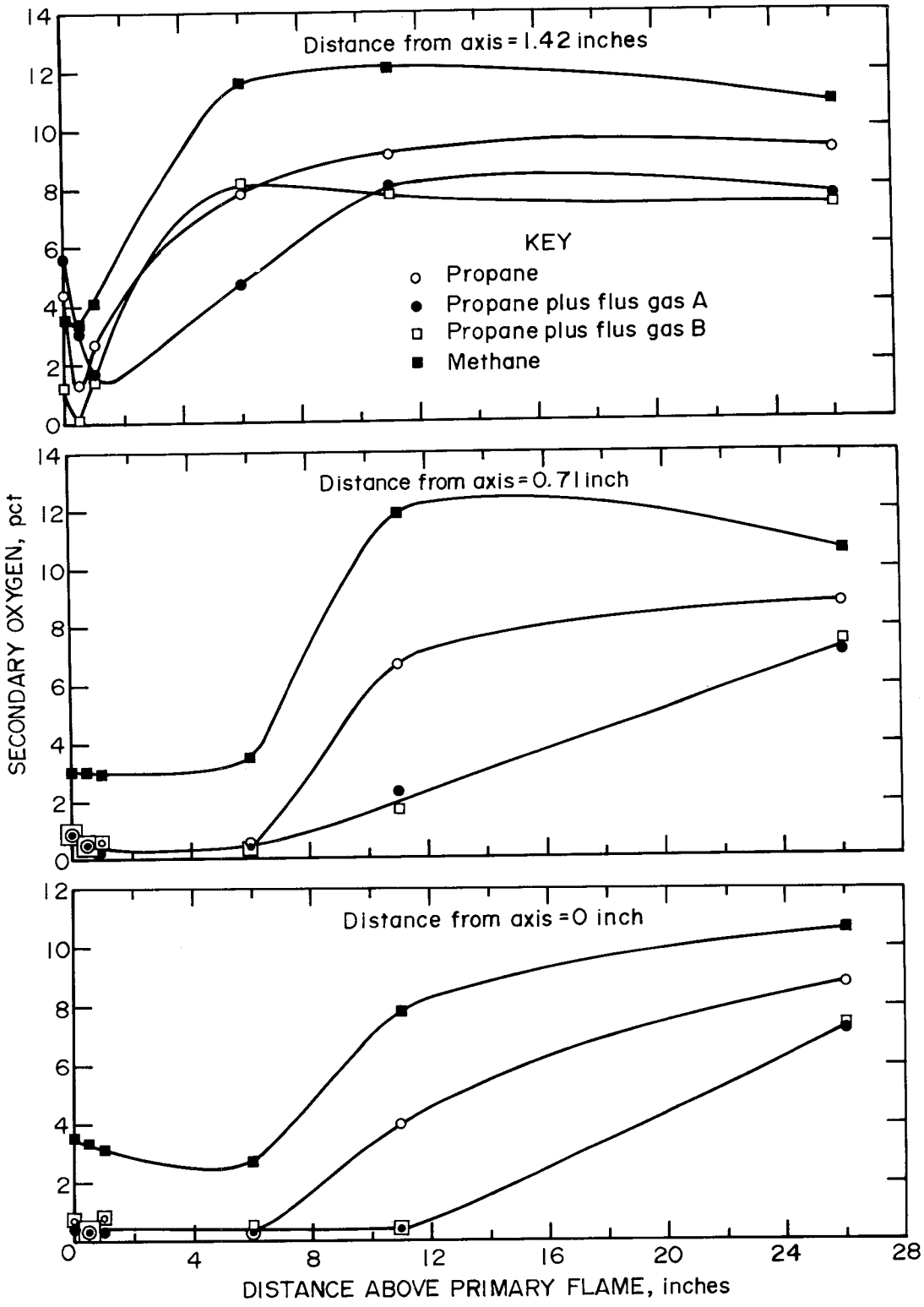

Figure 9.—Vertical concentration profiles of secondary oxygen in lean flames on a flat-flame burner.

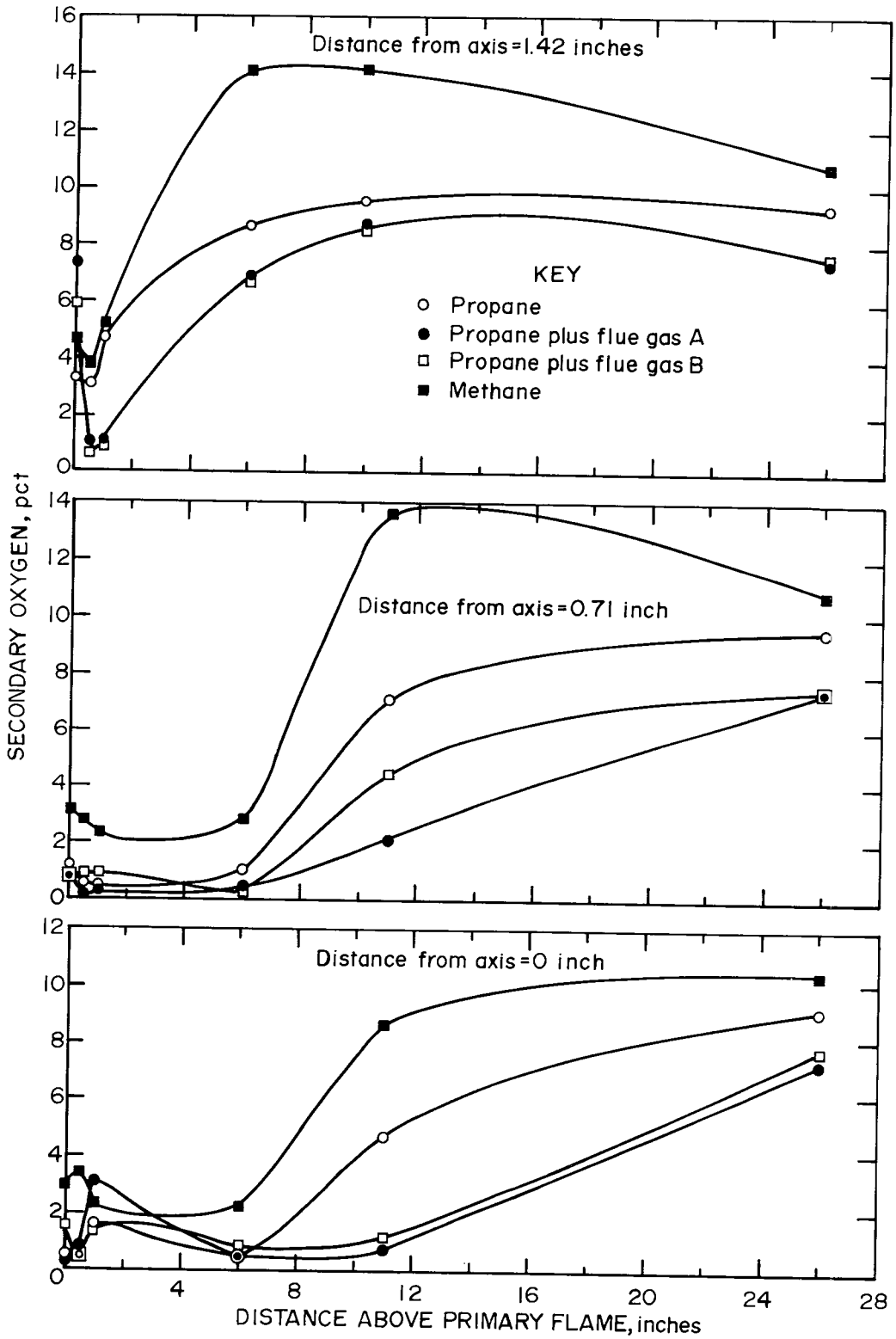

Figure 10.—Vertical concentration profiles of secondary oxygen in stoichiometric flames on a flat-flame burner.

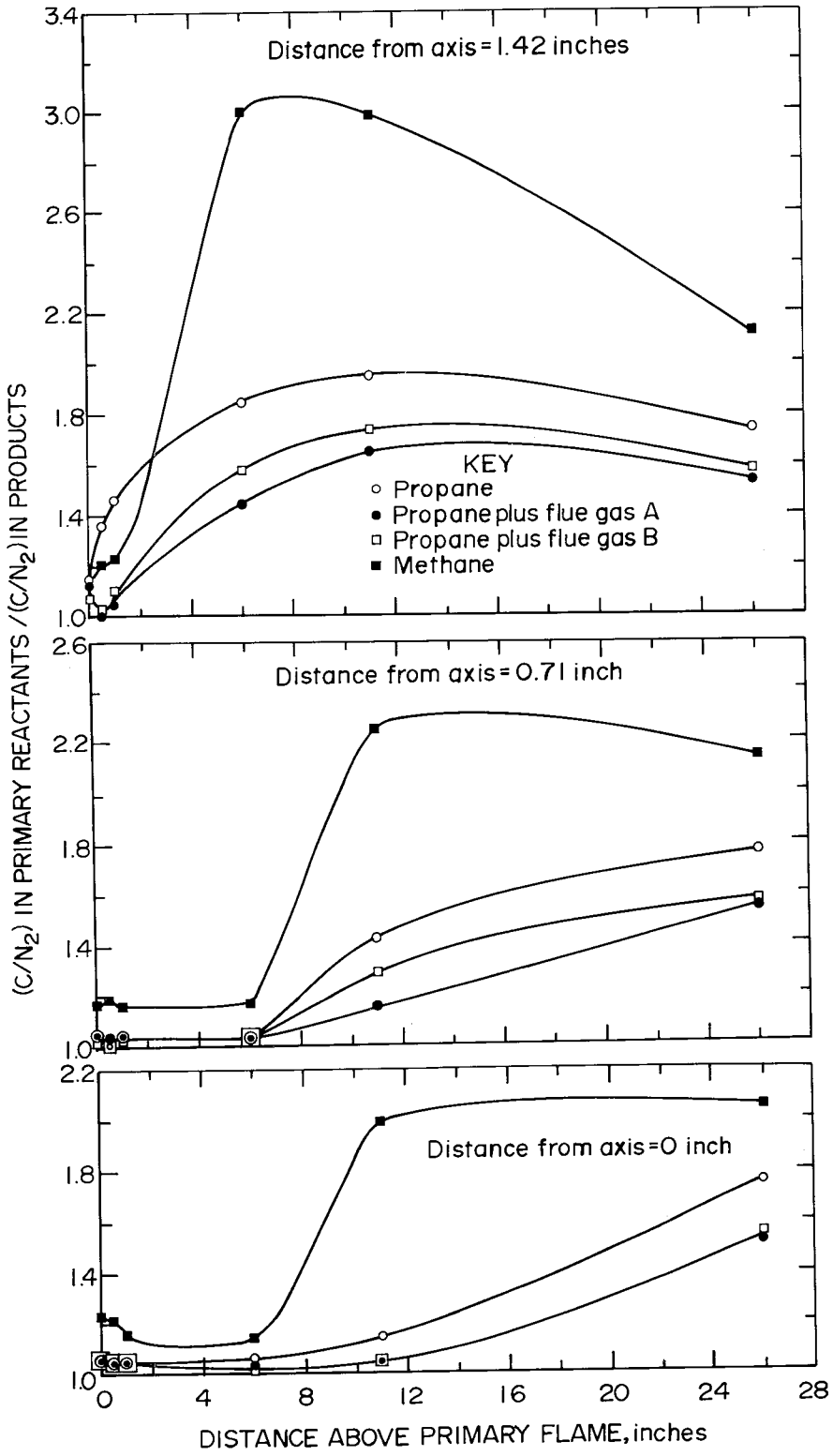

Figure 11.—Vertical profiles of ratios of carbon/nitrogen in the primary reactants to the carbon/nitrogen in the products of combustion in rich flames on a flat-flame burner.

and stoichiometric flames. The rate of reaction of carbon monoxide with oxygen generally increases with increasing excess oxygen, and correspondingly the observed concentrations of carbon monoxide decrease. There is little correlation between excess oxygen and flame temperature, indicating that the effect of temperature is not as critical a factor in the oxidation of carbon monoxide as it is for preventing the formation of nitrogen oxides. Generally, for about the same concentration of excess oxygen, more carbon monoxide remains as the temperature increases, and for about the same temperature, less carbon monoxide remains as the percentage of excess oxygen increases.

A similar analysis was made for rich flames using the oxygen deficiency, which is equal to the primary oxygen deficiency lessened by the secondary oxygen (appendixes A and C). The relation between decreasing oxygen deficiency and concentrations of carbon monoxide are about the same as for excess oxygen in lean and stoichiometric flames. Again, there is little correlation between decreasing oxygen deficiency and flame temperature.

These observations led to the third design principle which applies when the primary mixture is not fuel-lean. Induct secondary air quickly into the primary and secondary combustion zones to oxidize the carbon monoxide formed in the primary combustion zone. When the inducted secondary air lowers local temperatures towards 3,050° F, the formation of nitrogen oxides will also be suppressed.

Ingress of Secondary Air

The vertical concentration profiles of secondary oxygen and dilution ratios in figures 9–11 show that, level for level, the concentration of secondary oxygen was higher in methane flames than in the other three flames. Because the amount of excess oxygen in flames is very significant in reducing concentrations of carbon monoxide, it is important to understand the reasons for this difference. The primary flows were about the same for all fuels, and secondary flows and burner geometry were the same. The difference cannot be attributed to any modifications other than the choice of fuel. Evidence of an aerodynamic difference may be derived from the data in table 10 where the relevant characteristics of the gases from stoichiometric flames are compared. Because the composition of gases formed by adiabatic combustion is about the same for all flames, there is no significant difference in their rates of molecular diffusion and their buoyancy. There is a significant difference for the unburned gases. Propane-air flames and propane-air flames with recycle are heavier than air, whereas methane is lighter. Because the fuel-air flows are fairly slow, one could anticipate that the heavier-than-air fluid should show more radial spreading than the lighter-than-air fluid. Because of the greater radial expansion of the streams containing propane, less secondary air enters through the dead space and less is drawn into the secondary combustion zone farther downstream. This small additional amount of secondary air at the top of the primary flame and in the secondary combustion zone of the methane system is important (table 11). The percentage of excess oxygen in methane-air flames is considerably higher than that for the other fuels. Propane-air flames containing flue gas B have more excess oxygen than propane-air flames or propane-air flames with flue gas A because flue gas B contains oxygen.

A second difference occurs among these flames. The influx of secondary air is greater into the methane-air and propane-air flames at the 11-inch height than into the flames containing flue

Table 10.—Comparison of unburned gases and gases from adiabatic combustion for stoichiometric mixtures

	Methane	Propane	Propane+A[1]	Propane+B[2]
Unburned gases:				
Percent	9. 46	4. 02	3. 42	3. 42
Heating value, Btu/ft³	96	103	88	88
Specific gravity	0. 96	1. 02	1. 05	1. 04
Gases from adiabatic combustion:				
Flame temperature, ° F	3, 550	3, 620	3, 330	3, 370
Expansion ratio	7. 48	7. 97	7. 34	7. 42
Carbon dioxide, percent	8. 52	10. 27	11. 06	10. 60
Water, do	18. 31	14. 80	13. 23	13. 28
Oxygen, do	0. 48	0. 59	0. 29	1. 33
Nitrogen, do	70. 05	71. 27	73. 64	73. 12
Density, lbs/ft³	. 0092	. 0092	. 0099	. 0096

[1] 15 percent flue gas A. [2] 15 percent flue gas B.

Table 11.—Comparison of percentage of excess oxygen and observed concentrations of carbon monoxide in the core region of lean and stoichiometric flames

Vertical distance, inches	Fuel	At axis				At half-radius			
		Lean		Stoichiometric		Lean		Stoichiometric	
		Excess O_2	CO	Excess O_2	CO	Excess O_2	CO	Excess O_2	CO
0	C_3H_8+A [1]	3.0	0.35	0.3	1.04	3.4	0.65	0.8	1.64
	C_3H_8	3.9	.42	.5	1.56	4.0	.52	1.2	1.83
	C_3H_8+B [2]	4.8	.09	3.1	.51	5.1	.26	2.4	.85
	CH_4	6.6	.15	3.0	.68	6.1	.21	3.1	.87
0.5	C_3H_8+A [1]	2.9	.10	.8	1.05	3.0	.13	.2	1.27
	C_3H_8	3.4	.16	.5	1.32	3.5	.23	.6	1.68
	C_3H_8+B [2]	4.5	.05	2.1	.30	4.7	.05	2.5	.42
	CH_4	6.4	.04	3.4	.31	6.1	.06	2.8	.44
1.0	C_3H_8+A [1]	2.9	.04	3.1	1.03	2.8	.09	.3	1.01
	C_3H_8	3.9	.11	1.6	1.32	3.7	.15	.5	1.34
	C_3H_8+B [2]	4.9	.03	2.9	.22	4.7	.02	2.5	.30
	CH_4	6.2	.03	2.3	.25	6.0	.04	2.3	.31
6.0	C_3H_8+A [1]	2.9	.01	.4	.59	3.0	.01	.5	.47
	C_3H_8	3.4	.04	.5	.95	3.7	.04	1.0	.64
	C_3H_8+B [2]	4.7	.01	2.4	.08	4.6	.01	1.9	.09
	CH_4	5.8	.01	2.2	.14	6.6	.01	2.8	.11
11.0	C_3H_8+A [1]	3.0	.01	.7	.34	4.9	.04	2.1	.29
	C_3H_8	7.1	.01	4.7	.15	9.8	0	7.1	.08
	C_3H_8+B [2]	4.6	.01	2.7	.03	5.9	.02	6.0	.03
	CH_4	10.9	0	8.6	.02	15.0	0	13.6	0
26.0	C_3H_8+A [1]	9.8	.03	7.2	0	9.7	.02	7.4	0
	C_3H_8	11.9	0	9.0	0	11.9	0	9.5	0
	C_3H_8+B [2]	11.6	.02	9.2	0	11.7	.02	9.1	0
	CH_4	13.7	0	10.3	0	13.7	0	10.7	0

[1] 15 percent flue gas A. [2] 15 percent flue gas B.

gases. Velocities in the burned gases are about 10 ft/sec, too slow for jetlike entrainment of secondary air to occur. Molecular diffusion of secondary air should proceed at the same rate in all these flames because the flame gases are at about the same temperature, and the average molecular weight of the mixtures is about the same. The main difference may be that convective mass transfer is greater for the flames without simulated recycle. Convective mixing is by slow cross motion of stream tubes. The stiffer the stream tube due to its momentum, the less likely it will be to mix with another stream tube. It is significant, in this connection, that because of the 15-percent additional mass flux in the flames with recycle, the momentum flux is about 32 percent higher than in the methane-air and propane-air flames. This difference in momentum can make the flames with simulated recycle stiffer and present a weak but effectual barrier to the influx of secondary air. If this reasoning is valid, the amount of secondary air entrained into the flames with either flue gas A or B should be about the same. The profiles in figures 9–11 show this to be generally so.

REDUCTION OF HYDROCARBONS

Data for hydrocarbons are presented as radial profiles instead of the vertical profiles which were used for nitrogen oxides and carbon monoxide because the differences in concentration radially are more informative than the changes vertically. The vertical profiles can be constructed by cross-plotting the data in figures 12 and 13. Concentration profiles of total hydrocarbons from lean propane-air flames and propane-air flames with simulated recycle are compared in figure 12 and from stoichiometric and rich flames in figure 13; these and associated data are tabulated in appendix A. Concentrations of individual hydrocarbons are tabulated in appendix B. Hydrocarbons were observed only above the burner port wall and beyond, except in the case of the lean propane-air flame with flue gas A, where hydrocarbons were observed across the entire top of the primary combustion zone. More hydrocarbons were omitted from flames with flue gas A than from those with flue gas B.

Concentration profiles of total hydrocarbons for lean, stoichiometric, and rich propane-air and methane-air flames are compared in figure 14;

these and associated data are tabulated in appendixes A and C. Concentrations of individual hydrocarbons are tabulated in appendixes B and D. Again, hydrocarbons appear rather strongly over the burner wall and then fall off sharply. More hydrocarbons are present in the combustion gases of the methane-air flames than of propane-air flames or propane-air flames with simulated recycle. These trends can be explained by stoichiometry and flame stability considerations.

Role of Flame Stability

For the flames considered, concentrations of hydrocarbons corresponding to thermodynamic equilibrium at adiabatic flame temperatures are

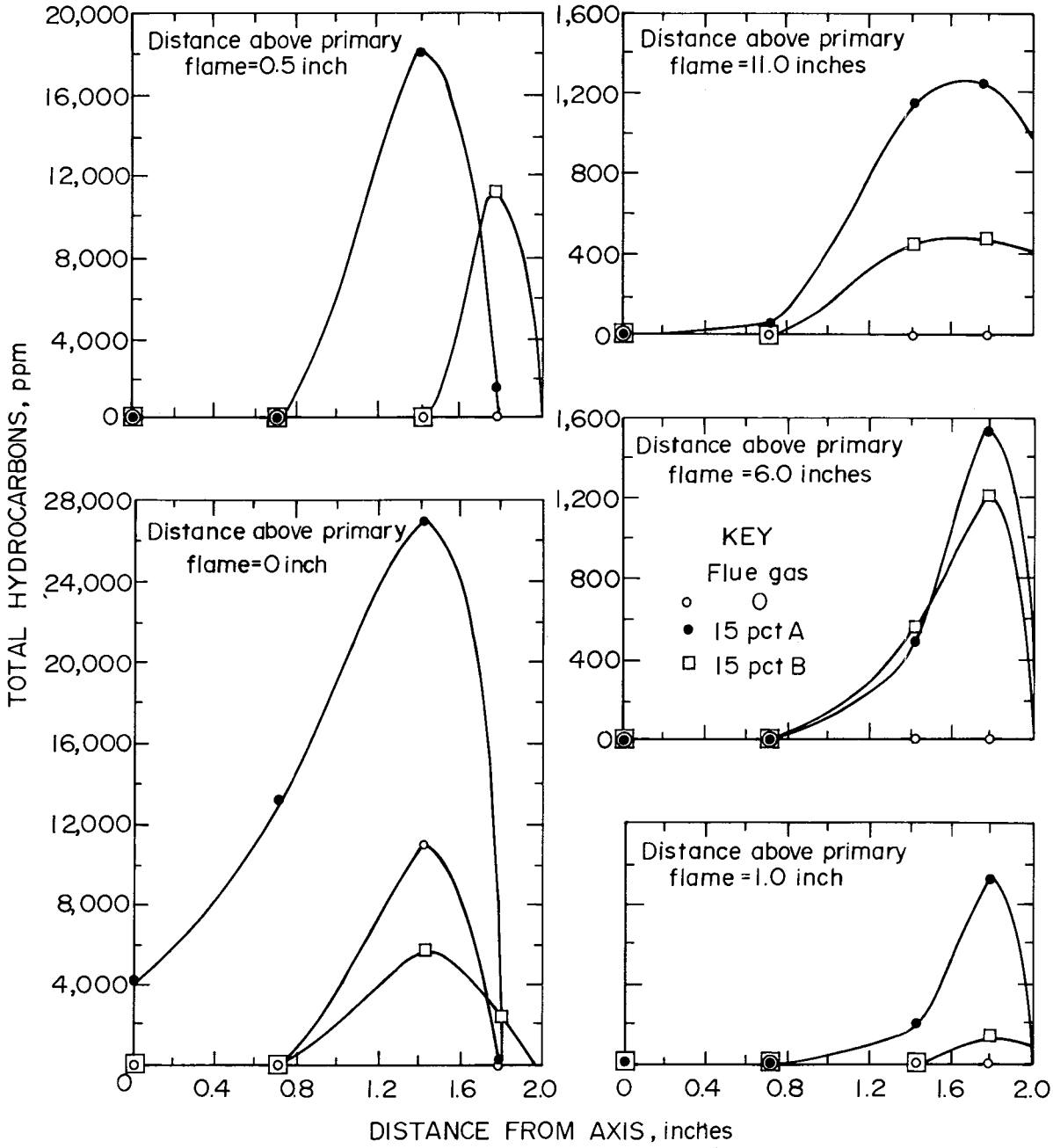

Figure 12.—Comparison of radial concentration profiles of total hydrocarbons from lean propane-air flames and propane-air flames with simulated recycle on a 2.84-inch-id flat-flame burner.

less than 10^{-4} ppm. Because this is well below the experimental sensitivity of about 5 ppm available with the experimental equipment, it is not possible to say whether the observed concentrations do or do not exceed equilibrium concentrations. At any rate both observed and theoretical values are extremely low except under certain circumstances.

As shown by the concentration profiles in figures 12–14, the greater concentration of hydrocarbons above the burner port wall and beyond indicate that hydrocarbons from the preheat zone upstream of the flame base are escaping through the dead space under the flame—the space between the burner port and the base of the flame. No significant concentrations of hydrocarbons were found at any of the 24 sampling points other than those indicated in figures 12–14. The escape of hydrocarbons through the dead space will be increased by lifting the flame. Accordingly, the greatest escape of hydrocarbons was from lean propane-air

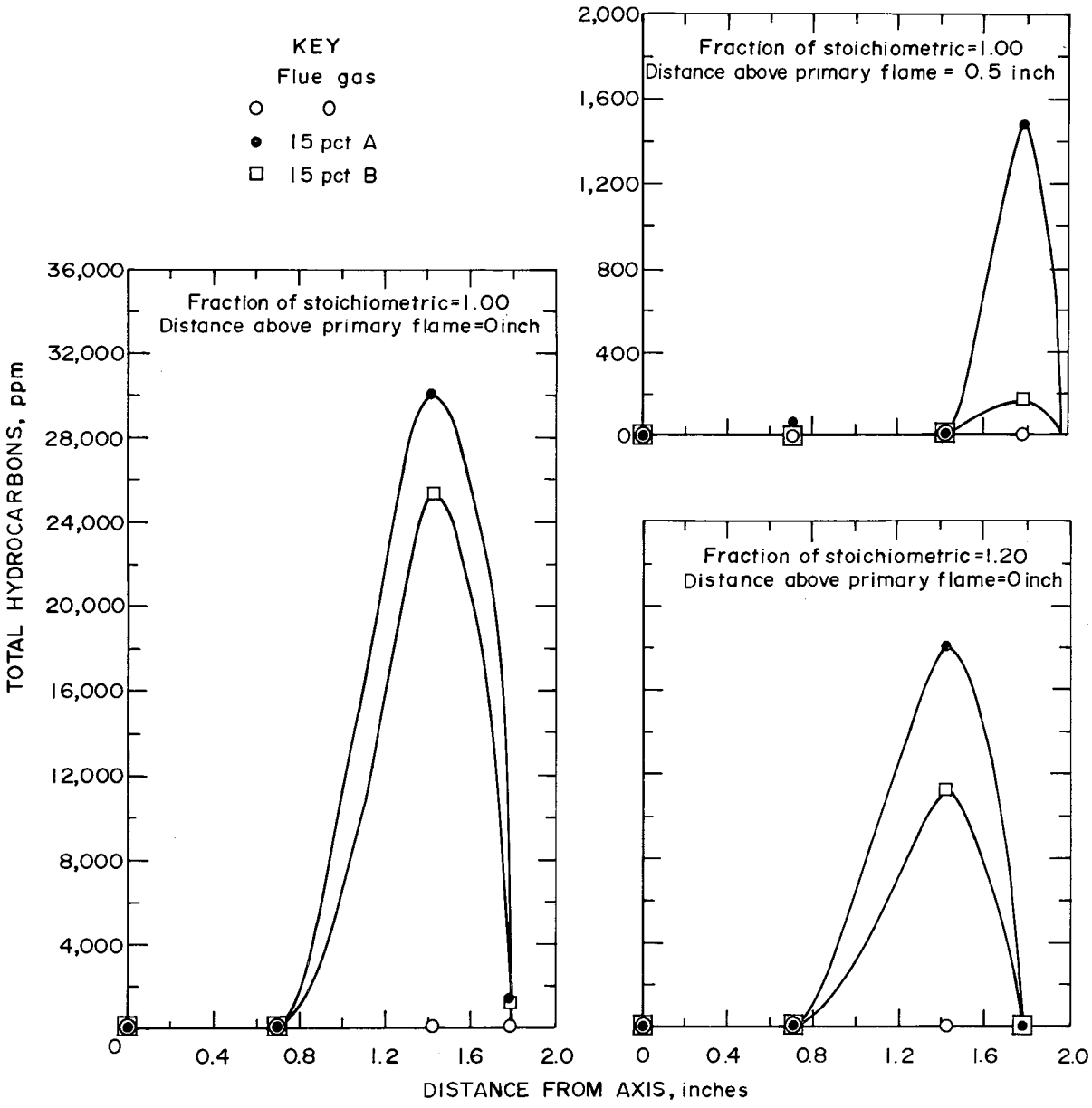

Figure 13.—Comparison of radial concentration profiles of total hydrocarbons from stoichiometric and rich propane-air flames and propane-air flames with simulated recycle on a 2.84-inch-id flat-flame burner.

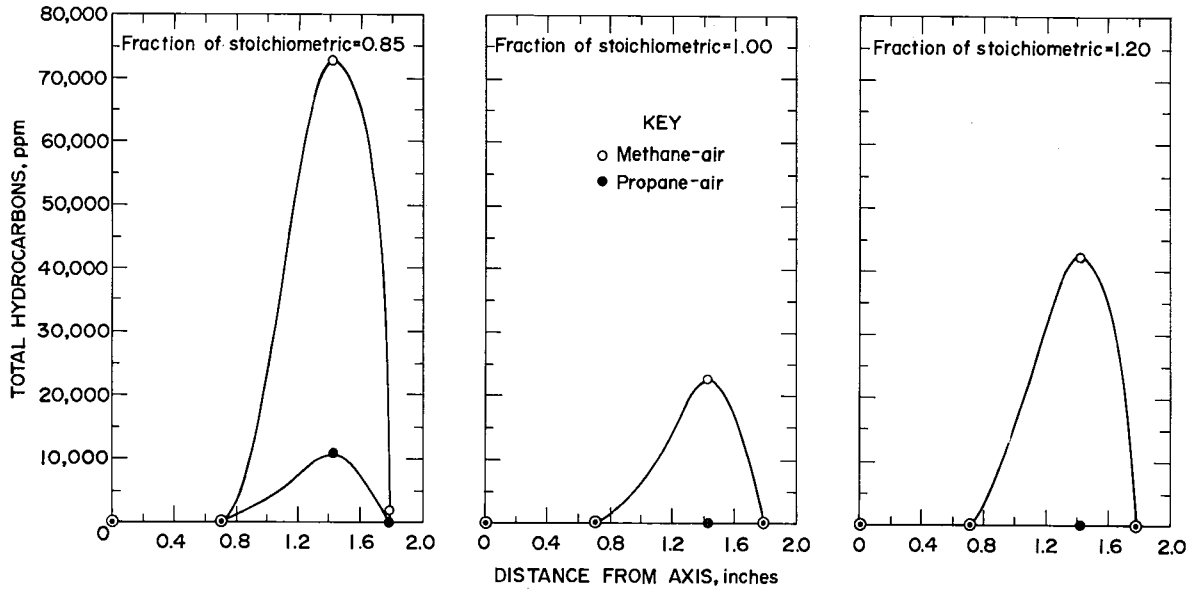

Figure 14.—Comparison of radial concentration profiles of total hydrocarbons at primary flame height in propane-air and methane-air flames on a 2.84-inch-id flat-flame burner.

flames with simulated recycle, which were partially lifted from the burner port. Hydrocarbons were detected in these flames up to the 11-inch station, showing that hydrocarbons escaping through the dead space need not necessarily diffuse or flow into the secondary combustion zone. Hydrocarbons were practically eliminated within the space of one-half inch from the primary zones of stoichiometric and rich flames of all fuels.

The observation (fig. 14) that methane-air flames release more hydrocarbons than propane-air flames is attributed to two factors. First and more important, methane diffuses faster than propane, and thus a greater amount of methane diffuses out through the dead space; most of the hydrocarbons observed were the unburned parent fuel. Second, the closer a flame is to blowoff, the greater the dead space is. Flow rates, stoichiometry, and burner dimensions were the same, but the methane flames were closer to their blowoff limits than the propane flames were. As shown by the flame stability limits (*38*) in table 12, the blowoff limit is between 20 and 50 percent less for methane than for propane.

A fourth design principle was drawn from these considerations, namely that hydrocarbons can be prevented from escaping by designing for flames that are well within the stable flame region for the particular fuel under consideration. This design principle can be implemented because flame stability data are now available for a wide variety of fuel-air systems (*38*). Theoretical considerations

Table 12.—Comparison of blowoff limits, g_B[1], of propane-air and methane-air flames

	Flames, fraction of stoichiometric		
	0. 85	1. 0	1. 2
Blowoff limit, propane	1, 200	2, 600	4, 600
Blowoff limit, methane	800	2, 000	3, 800
Ratio of blowoff limits	1. 5	1. 3	1. 2

[1] Critical boundary velocity gradients, sec^{-1}.

in the literature (*16–17*, *19*, *52*) support the experimental finding that oxidation of hydrocarbons is very rapid in the secondary combustion zones of lean, stoichiometric, and rich flames.

EFFECT OF SIMULATED RECYCLE OF FLUE GAS

As noted earlier, concentrations of nitrogen oxides in propane-air flames on the flat-flame burner were reduced the most by simulated recycling of flue gases. This is consistent with the first design principle because peak flame temperatures were lowest in these flames. However, it is possible that the decrease in nitrogen oxides was caused by the change in chemical composition of the fuel due to recycling. If a chemical mechanism is involved, combustion gases may be the best agents for the purpose, but not necessarily so. If the mechanism is thermal, other thermal means could accomplish the same end.

There are two objections to recycling flue gases in air-entraining gas burners. First, the amount of air entrained by the fuel jet is reduced by the back pressure of any recycle apparatus. This does not apply to power burners in which combustion air is pumped into the burner; some of the power can be used to pump flue gases into the primary mixture. The second objection is that recycling brings the flame closer to blowoff and lengthens it. The latter effect reduces the space heating rate within the appliance. These objections justify searching for means other than recycling to reduce nitrogen oxides.

Using theory (*66*), our calculations, which are summarized in table 13, show that flue-gas recycle acts by a thermal mechanism. Inert substances in the recycle gas absorb heat, thereby cooling the primary and secondary combustion zones. The resulting lower temperatures lead to lower concentrations of nitric oxide. The calculations in table 13 were made for a lean and a stoichiometric propane-air flame cooled at 1,000° and 5,500° F/sec. The second and third columns in the table are for the unperturbed flames and give the adiabatic flame temperatures in the primary combustion zone and the nitric oxide concentrations in the secondary combustion zone which result from each cooling rate. The next two columns are for 15-percent recycle of flue gas A. The primary flame temperature is lower and the nitric oxide concentration is greatly decreased. In the last two columns, the primary flame temperature is assumed to be the same as when the flue gas A is recycled, but the chemical composition is assumed to be the same as when there was no recycling (second and third columns). The nitric oxide concentration computed on this basis matches that resulting from the recycle computation. It appears therefore that the recycle mechanism is basically thermal.

Concentrations of carbon monoxide were also lowered significantly by simulated recycling using flue gas B. The vital factor in reducing carbon monoxide concentrations was that some oxygen was present in flue gas B. The emission of hydrocarbons from flames was increased significantly by recycling the flue gas because of partial lift of the flame.

Therefore, nothing is to be gained in the way of reducing nitrogen oxides by recycling that cannot be obtained by lowering temperatures in other ways. For example, fuel-rich mixtures can be used instead of stoichiometric primary fuel-air mixtures (*1*, *5*). Recycling with an oxygen-containing flue gas is not the only way to reduce concentrations of carbon monoxide by oxidation; appliance designs which allow rapid induction of secondary air into the primary and secondary combustion zones also are effective. Recycling had an unfavorable effect with respect to hydrocarbons. On the other hand, appliance designs which provide for well-seated flames prevent the emission of residual hydrocarbons.

RESULTS USING MULTIPORT-RING BURNER

A multiport-ring burner was designed which incorporated the following design principles for gas appliances derived from studies with the flat-flame burner:

1. Induct secondary air into the primary combustion zone to depress peak temperatures in order to prevent the formation of nitrogen oxides

Table 13.—Effect on concentrations of nitric oxide in propane-air flames of chemical and thermal perturbations

Cooling rate, ° F/sec	Unperturbed flame		Chemically perturbed flame [1]		Thermally perturbed flame	
	Initial temperature, ° F	NO concentration, ppm	Initial temperature, ° F	NO concentration, ppm	Initial temperature, ° F	NO concentration, ppm
FRACTION OF STOICHIOMETRIC=0.8						
1, 000	3, 190	104	2, 810	6	2, 810	6
5, 500	3, 190	35	2, 810	1	2, 810	1
FRACTION OF STOICHIOMETRIC=1.0						
1, 000	3, 620	328	3, 330	47	3, 330	46
5, 500	3, 620	64	3, 330	9	3, 330	8

[1] 15-percent flue gas A.

and carbon monoxide and to facilitate the oxidation of carbon monoxide in the primary combustion zone.

2. Initiate rapid cooling in the secondary combustion zone by the rapid induction of secondary air to reduce the concentration of nitrogen oxides, and at the same time oxidize carbon monoxide originating in the primary combustion zone.

3. Design for well-seated stable flames to reduce the escape of light hydrocarbons from the dead space of flames.

The first two principles were tested by using small flames on a multiport burner with enough spacing between ports to permit the rapid ingress of secondary air. The third principle was achieved by suitable arrangement of ports, spacing, flow rate, and composition of the primary mixture. This burner is described under "Equipment and Procedures." Concentrations of nitrogen oxides, carbon monoxide, and hydrocarbons in methane-air flames were measured on this burner.

Peak flame temperatures and peak concentrations of nitrogen oxides, carbon monoxide, and hydrocarbons in four methane-air flames on the multiport burner are given in table 14; these and associated data are tabulated in appendix G. No hydrocarbons were observed. Carbon monoxide was completely eliminated one-half inch above the primary flame front. Concentrations of nitrogen oxides were reduced to about 10 ppm, which is the reproducibility of the analytical method. Concentrations of air pollutants in a lean methane-air mixture were not determined because these flames blew off. Flame temperatures for the stoichiometric and the 1.2-times-stoichiometric flames are much lower than the adiabatic flame temperatures. The opposite is observed for the very rich mixtures of 1.5- and 2.0-times-stoichiometric flames.

Ingress of Secondary Air

The explanation of these observations of flame instability and temperature is that ambient "secondary" air enters the primary combustion zones of these small flames rapidly and shifts the overall stoichiometry towards leaner flames and also lowers the combustion temperature when the initial primary mixture is stoichiometric or lean. The secondary air found at the top of the primary cone of the initially stoichiometric mixture corresponded to a mixture of methane and air that is 0.68 times stoichiometric. When the initial primary mixture is fuel-rich, the ingress of "secondary" air into the primary combustion zone shifts the primary-flame stoichiometry towards stoichiometric and may raise the primary flame temperature above the adiabatic flame temperature for the initial mixture (table 14). The 1.2-times-stoichiometric primary mixture corresponded to a 0.81-times-stoichiometric mixture, the 1.5 mixture shifted to 0.98 times stoichiometric, and the 2.0 mixture to 1.2 times stoichiometric.

Comparison of Flat-Flame and Multiport-Ring Burners

Concentrations of nitrogen oxides, carbon monoxide, and total hydrocarbons in stoichiometric and 1.2-times-stoichiometric methane-air flames on the flat-flame and multiport-ring burners are compared in table 15. Only concentrations for the stoichiometric flame are corrected for dilution with secondary air because with rich flames some of the secondary oxygen occurs in the combustion products as oxides of carbon and water. The overall composition, at the tip of the primary combustion zone of the stoichiometric flame, including the secondary air, is 0.87 times stoichiometric for the flat-flame burner and 0.68 times stoichiometric, as previously stated, for the multi-

Table 14.—Peak flame temperatures and peak concentrations of nitrogen oxides, carbon monoxide, and total hydrocarbons in methane-air flames on a multiport-ring burner

Vertical distance, inches	Fraction of stoichiometric	Flame temperature, ° F		Concentration, ppm [1]		Total hydrocarbons, ppm	Secondary O_2, percent
		Adiabatic	Observed	NO_x	CO		
0	1.0	3,550	2,940	10	2,000	0	10.0
	1.2	3,360	3,170	30	5,000	0	10.2
	1.5	2,860	3,200	30	5,800	0	11.0
	2.0	2,120	3,150	40	5,200	0	14.3
0.5	1.0	----------	1,390	10	0	0	15.4
	1.2	----------	1,540	10	0	0	15.5
	1.5	----------	1,860	10	0	0	16.4
	2.0	----------	1,970	20	0	0	17.2

[1] Not corrected for dilution with secondary air.

Table 15.—Comparison of concentrations of nitrogen oxides, carbon monoxide, hydrocarbons, secondary oxygen, and flame temperatures at axis in methane-air flames on flat-flame and multiport-ring burners

Vertical distance, inches		Temperature, °F		NO_x concentration, ppm		CO, concentration, ppm		Total hydrocarbons, ppm		Secondary oxygen, percent	
Flat-flame	Multiport-ring	Flat-flame	Multiport-ring	Flat-flame	Multiport-ring	Flat-flame	Multiport-ring	Flat-flame	Multiport-ring	Flat-flame	Multiport-ring
FRACTION OF STOICHIOMETRIC = 1.0 [1]											
0	0	3,320	2,940	40	[2] 10	6,800	[2] 3,800	0	[2] 0	3.0	10.0
26.0	.5	1,380	1,390	140	[3] 10	0	0	0	0	10.3	15.4
.5	.5	3,220	1,390	90	[3] 10	3,100	0	0	0	3.4	15.4
				[2] 230		[2] 23,500		[2] 22,660			
FRACTION OF STOICHIOMETRIC = 1.2 [3]											
0	0	3,280	3,170	40	[2] 30	40,200	[2] 5,000	0	[2] 0	3.8	10.2
26.0	.5	1,480	1,540	50	10	0	0	0	0	10.4	15.5
.5	.5	3,160	1,540	50	10	37,500	0	0	0	3.6	15.5
				[2] 80		[2] 41,100		[2] 42,415			

[1] Air pollutant concentrations corrected for dilution with secondary air.
[2] Peak concentrations of pollutants for burner.
[3] Air pollutant concentrations not corrected for dilution with secondary air.

port-ring burner. In all cases the concentrations of nitrogen oxides, carbon monoxide, and hydrocarbons were significantly less with the multiport-ring burner than with the flat-flame burner. Peak concentrations from the multiport-ring burner were drastically reduced for all three pollutants. Comparison of the flame temperatures of the two burners shows that the design employed for the multiport-ring burner lowered primary flame temperatures. Similarly, a comparison of secondary oxygen concentrations shows a more rapid influx and higher concentration of secondary air in the multiport-ring burner flames. Flames were well seated, and no hydrocarbons were found. These results very definitely corroborate the design principles that lower primary temperatures and faster ingress of secondary air can significantly lower concentration levels of air pollutants in gas appliance flames.

RESULTS USING CERAMIC INFRARED BURNER

Because of the increasing number of gas appliances using infrared burners, experiments were done to determine whether burner surfaces have a catalytic effect on the formation of nitrogen oxides in flames. The infrared burner used in these experiments is described under "Equipment and Procedures."

Peak concentrations of air pollutants and peak flame temperatures in the infrared ceramic burner for lean, stoichiometric, and rich methane-air flames are given in table 16; these and associated data are tabulated in appendix H. Concentrations of nitrogen oxides in the flame gases from the infrared burner are low at all sampling points. At the 1-inch height, concentrations of carbon monoxide are either zero or have greatly decreased for lean and stoichiometric flames. For rich flames, high concentrations of carbon monoxide are formed at the primary combustion zone and remain about the same at the 1-inch height. Concentrations of hydrocarbons occur mainly at the edge of the burner at the primary flame height and are composed mostly of unburned methane with some ethane, ethylene, and acetylene.

Comparison of Noninfrared and Infrared Flat-Flame Burners

In table 17, peak concentrations of nitrogen oxides, carbon monoxide, and hydrocarbons at the primary flame level and 1 inch above it and peak flame temperatures of methane-air flames are compared for metallic noninfrared and ceramic infrared flat-flame burners. All nitrogen oxide values were lower for the infrared burner than for the noninfrared flat-flame burner, and no catalytic effect on the formation of nitrogen oxides by the burner sur-

Table 16.—Peak flame temperatures and peak concentrations of nitrogen oxides, carbon monoxide, and total hydrocarbons in methane-air flames on a ceramic infrared flat-flame burner

Vertical distance, inches	Fraction of stoichiometric	Flame temperature, ° F		NO_x concentration, ppm	CO concentration, ppm	Total hydrocarbons, ppm
		Adiabatic	Observed			
0	0. 85	3, 220	2, 650	10	[1] 2, 600	[1] 750
	1. 00	3, 550	2, 930	10	6, 700	[1] 370
	1. 20	3, 360	2, 790	[1] 30	[1] 36, 500	[1] 310
1. 0	0. 85	----------	2, 410	10	0	0
	1. 00	----------	2, 580	20	700	0
	1. 20	----------	2, 720	[1] 30	[1] 34, 000	0

[1] Not corrected for dilution with secondary air.

Table 17.—Comparison of peak concentrations of nitrogen oxides, carbon monoxide, and hydrocarbons and peak flame temperatures in methane-air flames on metallic noninfrared and ceramic infrared flat-flame burners at two flame heights

Vertical distance, inches	Temperature, ° F		NO_x concentration, ppm		CO concentration, ppm		Total hydrocarbons, ppm	
	Noninfrared	Infrared	Noninfrared	Infrared	Noninfrared	Infrared	Noninfrared	Infrared
			LEAN FLAMES [1]					
0	[2] 2, 950	2, 650	10	10	[2] 3, 300	[3] 2, 600	[2] 72, 900	[3] 750
1.0	2, 940	2, 410	[2] 30	10	400	0	0	0
			STOICHIOMETRIC FLAMES [1]					
0	[2] 3, 380	2, 930	40	10	[2] 23, 500	6, 700	[2] 22, 660	[3] 370
1.0	3, 210	2, 580	100	20	3, 100	700	0	0
----------			[2] 230	----------				
			RICH FLAMES [3]					
0	[2] 3, 320	2, 790	50	30	[2] 41, 100	36, 500	[2] 42, 415	310
1.0	3, 150	2, 720	[2] 80	30	39, 100	34, 000	0	0

[1] Air pollutant concentrations corrected for dilution with secondary air.
[2] Peak temperatures and peak concentrations of pollutants for burner.
[3] Air pollutant concentrations not corrected for dilution with secondary air.

face is indicated. Had catalysis occurred at the observed temperatures, concentrations of nitrogen oxides would be fairly close to equilibrium concentrations. Instead, observed concentrations are two to three orders of magnitude less for the lean and the stoichiometric flames (appendix E). A conclusion relative to catalyzing the formation of nitrogen oxides cannot be drawn from the data for the rich flame because the equilibrium concentration for nitric oxide is zero.

It was shown previously that the minimum temperature in the absence of catalysis for the formation of nitrogen oxides in the secondary combustion zone of flames was 3,050° F. In all instances, the flame temperatures of the ceramic infrared burner were below 3,050° F. As a result, the concentrations of nitrogen oxides are lower in this burner than in the metallic noninfrared flat-flame burner, and they do not increase with time.

Again, as with the multiport ring burner, concentrations of carbon monoxide and hydrocarbons were lower for the infrared burner than for the flat-flame burner. These reductions can be explained on the basis of the design principles

developed in this investigation for noninfrared burners. It was found that the rapid induction of secondary air into the primary and secondary combustion zones of flames will speed up the oxidation of carbon monoxide. Table 18 shows that the flame gases from the infrared burner contained more excess oxygen than the gases from the noninfrared burner; this accounts for the lower concentrations of carbon monoxide in the infrared burner. Another principle was that hydrocarbons can be prevented from escaping by designing for flames that are well within the stable flame region for the particular fuel under consideration. Infrared appliances are characterized by primary combustion within the pores of the ceramic honeycomb; this makes the flames more stable. As shown in table 17, the emission of hydrocarbons from the infrared burner was considerably lower than from the noninfrared flat-flame burner. The data do not allow conclusions to be drawn about the burner surface catalyzing the oxidation of carbon monoxide or the emission of hydrocarbons.

Table 18.—Comparison of percentage of excess oxygen (excess primary oxygen plus secondary oxygen) in methane-air flames on metallic noninfrared and ceramic infrared flat-flame burners

Distance above flame, inches	1.42 inches in from edge of flame		Edge of flame	
	Noninfrared	Infrared	Noninfrared	Infrared
LEAN FLAMES				
0	6.7	6.9	6.7	14.9
1.0	6.3	8.0	7.2	23.3
STOICHIOMETRIC FLAMES				
0	3.0	4.5	4.6	11.7
1.0	2.3	3.9	5.2	20.2
RICH FLAMES [1]				
0	−0.3	0.6	−1.4	7.6
1.0	−1.2	.3	−.1	16.0

[1] Secondary oxygen minus the deficiency in primary oxygen.

The data from the study of methane-air flames and propane-air flames, with and without simulated recycle of flue gas, on the flat-flame burner were used to derive reaction-rate equations for predicting concentrations of nitrogen oxides and carbon monoxide formed in lean, stoichiometric, and rich flames. The initial calculations were based on kinetic and thermodynamic data in the literature (*66*); these met with better than order of magnitude success and will not be repeated here. Subsequently, the experimental data were used to derive empirical activation energies and pre-exponential coefficients for Arrhenius-type reaction-rate equations. Thermodynamic data employed in the following section are summarized in appendixes E, F, and I.

KINETICS OF FORMATION OF NITRIC OXIDE IN FLAMES

Past Studies

Several investigators have obtained reaction rates (*4, 13, 18, 23, 36–37, 43, 47, 49, 54, 56, 75, 77–78*) that agree within an order of magnitude (table 19). The rate based on data obtained by Zeldovich (*78*) is the fastest; even this rate results in predicted concentrations which are 3 to 7 times lower than concentrations obtained in this study.

The differences may be attributed to the fact that experimental techniques, temperature ranges, and concentrations of nitric oxide varied considerably. Furthermore, few studies involved combustion. In most instances the rate of decomposition of nitric oxide was followed; the investigators assumed that the ratio of the rate constant of formation to the rate constant of decomposition equaled the equilibrium constant. However, this relationship is inapplicable when the reaction mechanisms of formation and decomposition differ. Camac and Feinberg (*9*) have shown that in air heated by shock waves at temperatures of 2,300° to 6,000° K, nitric oxide decomposes according to the equation $2NO \rightarrow N_2O + O$ instead of the equation $2NO \rightarrow N_2 + O_2$. The reverse of the latter equation is generally accepted to be the mechanism for the formation of nitric oxide. This inconsistency and the differences in the relevant reaction rates in the literature justify an attempt to obtain overall reaction rates for the formation of nitrogen oxides, mainly as nitric oxide, in hydrocarbon-air flames.

This Study

The Bureau of Mines data are the first direct measurements of rates of formation of nitric oxide in flame gases under conditions in which vessel-

Table 19.—Summation of kinetic studies of formation and decomposition of nitric oxide

Experimental technique	Temperature range, ° K	Rate of formation of NO at 2,030° K, ppm/sec	Source of kinetic data
Explosion in metallic vessels	2, 000–2, 900	1, 053	Zeldovich (*78*).
Hydrocarbon air flames with added NO	2, 200–2, 400	758	Fenimore (*18*).
(1)	(1)	652	Marrone (*54*), as employed by Bahn (*4*).
Single pulse shocks in air	2, 000–2, 800	560	Glick (*37*), as employed by Davidson (*13*).
Decomposition of NO in packed alundum vessels.	1, 700–2, 000	371	Yuan (*77*).
Decomposition of shock-heated NO	3, 000–4, 300	440	Freedman (*23*).
Air heated in quartz vessels	[2] 900–1, 300	342	Wise (*75*) and Zeldovich (*78*).
Decomposition of NO in porcelain and metallic vessels.	[3] 1, 000–2, 000	354	Hirschfelder (*43*) and Jellinek (*47*), as employed by Gilbert (*36*).
Do	[4] 1, 800–2, 200	500	Jellinek (*47*) and Nernst (*56*), as employed by Gilbert (*36*).
Decomposition of NO in porcelain vessels	1, 500–1, 700	90	Kaufman (*49*).

[1] Not specified in Bahn (*4*).
[2] Wise (*75*).
[3] Jellinek (*47*).
[4] Nernst (*56*).

wall effects were probably minor. The range of temperatures from about 2,800° to 3,500° F employed in the kinetic analysis is representative of peak temperatures in gas appliances.

In calculating flow velocities, the velocity just above the primary flame front was taken to be equal to the volumetric flow rate of the cold primary fuel-air mixture multiplied by the expansion ratio and divided by the area of the burner. Elsewhere the flow velocity was taken to be the velocity just above the primary flame front multiplied by the ratio of the local temperature to the temperature at the flame front:

$$U = U_j \frac{T}{T_j}, \tag{1}$$

in which U equals the local velocity in inches per second, T equals the local absolute temperature in degrees Kelvin, and subscript j refers to the primary flame front.

If the effect of the back reaction may be ignored, the rate of the formation reaction can be written in the form of an Arrhenius-type equation:

$$\frac{d(\mathrm{NO})}{dt} = A(\mathrm{O_2})^{1/2}(\mathrm{N_2})\,exp(-E/RT), \tag{2}$$

in which (O_2), (N_2), and (NO) are the partial pressures for each of these molecules in atmospheres, R is the gas constant (0.001987 kcal/mole/°K), t is the time in seconds, A is the preexponential coefficient, and E is the activation energy. Equation 2 is based on the rate-controlling step proposed by Fenimore and Jones (*18*), namely $N_2+O \longrightarrow NO+N$ and their assumption that oxygen atoms are in equilibrium with molecular oxygen; the concentration of oxygen atoms is proportional therefore to the square root of the concentration of molecular oxygen. The preexponential coefficient includes the equilibrium constant for the dissociation of molecular oxygen. Experimental values were used for (O_2), (N_2) and T. Equation 2 can be written as,

$$d(\mathrm{NO}) = \frac{A(\mathrm{O_2})^{1/2}(\mathrm{N_2})\,U_j}{U_j U}[exp(-E/RT)]dh, \tag{3}$$

in which h is the distance from the flame front in inches. The velocity ratio, U_j/U, in equation 3 may be replaced by T_j/T (equation 1). Because in these experiments the oxygen concentration is practically constant for any small vertical distance within the secondary combustion zone, equation 3 can be integrated as follows:

$$[(\mathrm{NO})_2-(\mathrm{NO})_1]\frac{U_j}{(\mathrm{O_2})^{1/2}(\mathrm{N_2})T_j} = A\int_{h_1}^{h_2}\frac{exp(-E/RT)}{T}dh, \tag{4}$$

in which $(NO)_1$ and $(NO)_2$ are the partial pressures of nitric oxide in atmospheres at h_1 and h_2, respectively, and (O_2) and (N_2) are the average partial pressures of these molecules within this interval in atmospheres.

An Algol computer program was developed to solve for A with assumed values of E between 100 and 160 in intervals of 5 kcal. Values for the left-hand side of equation 4 were taken from our experimental quantities. The integral on the right-hand side was evaluated by Simpson's rule. The sampling intervals from 0 to 0.5 inch and from 0.5 to 1.0 inch were subdivided into four subintervals and the interval from 1 to 6 inches was divided into 10 subintervals because an odd number of points, at least five, are needed to use Simpson's rule. Using the data taken in three flames at the axis and the half-radius, 18 values of A were obtained for each preselected value of E. The three flames were the lean and stoichiometric propane-air flames and the stoichiometric propane-air flames with added flue gas B (appendix A). The solution was taken to be that value of E which gave the minimum standard error of the mean of A. This minimum was in a fairly flat curve. Because of the flatness, the likely error in E is about 10 kcal. The calculation gave,

$$\frac{d(\mathrm{NO})}{dt} = (\mathrm{O_2})^{1/2}(\mathrm{N_2})\,exp(-110/RT+24.088), \tag{5}$$

in which the probable error in the rate is 38 percent. This equation applies to the region in the secondary flame zone from 0 to 6 inches above the primary flame front.

At 2,100° K the nitric oxide concentration calculated by equation 5 is about 4.5 times higher than the value calculated with rates given by Zeldovich (*78*).

The following equation can be derived from equation 4 for the rate of formation of nitric oxide across the primary reaction zone:

$$\frac{(\mathrm{NO})}{(\mathrm{O_2})_e^{1/2}(\mathrm{N_2})_e} = \frac{A\,L\,exp(-E/RT_a)}{U_a}, \tag{6}$$

in which T_a equals the adiabatic flame temperature in degrees Kelvin, U_a equals the flame speed for adiabatic conditions in inches per second, $(O_2)_e$ and $(N_2)_e$ equal the equilibrium partial pressures of combustion products immediately downstream from the primary combustion zone in atmospheres, L equals the thickness of the reaction zone in inches, and (NO) equals the partial pressure of nitric oxide just above the primary flame in atmospheres. U_a was obtained by the relationship,

$$U_a = E_a S_u, \tag{7}$$

in which E_a equals the adiabatic expansion ratio, and S_u equals the adiabatic burning velocity in inches per second.

The rate equation obtained for the primary flame zone is

$$\frac{d(NO)}{dt} = (O_2)_e^{1/2}(N_2)_e \, exp(-115/RT + 27.219), \quad (8)$$

with a probable error of 24 percent. Primary reaction zone data for the flames used to derive equation 8 are given in table 20. Burning velocities and reaction zone thicknesses can be found in references *26*, *32*, and *35*. Equilibrium concentrations at adiabatic flame temperatures are given in appendix I for the flames of this study. Adiabatic temperatures and expansion ratios may be obtained from references such as *67* and *70*. In instances where the temperature is known and does not correspond to adiabatic combustion, equilibrium composition may be calculated by computer programs (*80*) or by desk computational procedures (*33*, *81*). Equilibrium concentrations as a function of temperature for the nine propane-air flames and for the three methane-air flames used in this study are in given appendixes F and E, respectively.

Concentrations of nitric oxide derived from equation 8 exceed those derived from equation 5; for example, at 2,100° K the concentration of nitric oxide from equation 8 is about 5.3 times the value from equation 5 and 24 times that determined by Zeldovich (*78*). These differences between equations 5 and 8 can be attributed to the fact that within and just above the flame front, the atomic oxygen concentration is more than the equilibrium value. The high reaction rate across the primary flame front is understandable on the basis that the reaction $N_2+O \rightarrow NO+N$ is the rate-controlling step (*18*, *37*, *78*), and that just above the primary flame the atomic oxygen concentration is about seven times the equilibrium value (*48*).

Equations 5 and 8 were tested by using them to predict concentrations of oxides of nitrogen for eight flames. Predicted and experimental values are compared in figures 15–17. Concentrations were predicted only for flames that were not employed in the empirical derivation of the coefficients and activation energies. Whereas equations based on the Zeldovich data (*78*) underpredict concentrations of oxides of nitrogen observed in this study by factors of 3 to 7, equations 5 and 8 generally overpredict concentrations within factors of 2 to 3.5. Figures 15–17 indicate that an improvement has been achieved in the ability to predict concentrations of nitrogen oxides in flames. The eight flames treated in these figures constitute a difficult test of the applicability of equations 5 and 8 because these cases involve flames and zones in flames where temperatures are so low that the fluid temperature is lower than that required for appreciable formation of nitrogen oxides (below 3,050° F) for much of the time available for reaction. Rich flames are included in figures 16 and 17, although only data from lean and stoichiometric flames were used to derive these equations. The predicted curves give concentrations on a secondary-air-free basis, which is physically unreal for rich flames, and the experimental points are not corrected for dilution by secondary air. As a consequence, the experimental points are lower than the predicted curve by a wider margin than would be the case if both were on the same basis with respect to dilution by secondary air. Accordingly, it is expected that the disagreement shown in figures 15–17 is about the worst that will result from the use of equations 5 and 8.

Table 20.—Data for the formation of nitric oxide in the primary combustion zone of hydrocarbon-air flames

Fuel	Corresponding to mixture at sampling site							
	Fraction of stoichiometric of primary mixture	Fraction of stoichiometric	Adiabatic flame temperature, T_a, ° K	Expansion ratio, E_a	Burning velocity, S_u, in/sec	Equilibrium concentrations of $(N_2)(O_2)^{1/2}$, ppm$^{3/2}$	Primary combustion zone thickness, L[1], in	Residence time, t, msec
C_3H_8	0. 85	0. 82	2, 060	7. 26	13. 0	123. 4	0. 0162	0. 172
C_3H_8	1. 00	. 98	2, 250	7. 93	16. 2	54. 7	. 0201	. 156
C_3H_8+B [2]	. 92	. 86	2, 060	7. 35	14. 3	84. 4	. 0177	. 169
CH_4	. 85	. 73	1, 860	6. 82	9. 5	119. 7	. 0162	. 250
CH_4	1. 00	. 87	2, 070	7. 48	12. 6	47. 6	. 0201	. 213

[1] Luminous zone + preluminous reaction zone.

[2] Stoichiometric mixture with flue gas B.

It is interesting to explore possible effects of oxyhydrocarbon radicals in the formation of nitric oxide. As shown in table 21, concentrations of nitrogen oxides at the top of the primary combustion zones of propane-air and methane-air flames are highest for rich flames, although temperatures are below the stoichiometric flame temperatures. Near-equilibrium concentrations of nitric oxide exist in the primary combustion zones of rich flames (appendixes E and F). Concentrations in the secondary combustion zones increase in lean and stoichiometric flames, but not in rich flames. These trends suggest that the formation of nitric oxide is accelerated by some oxygenated hydrocarbon radi-

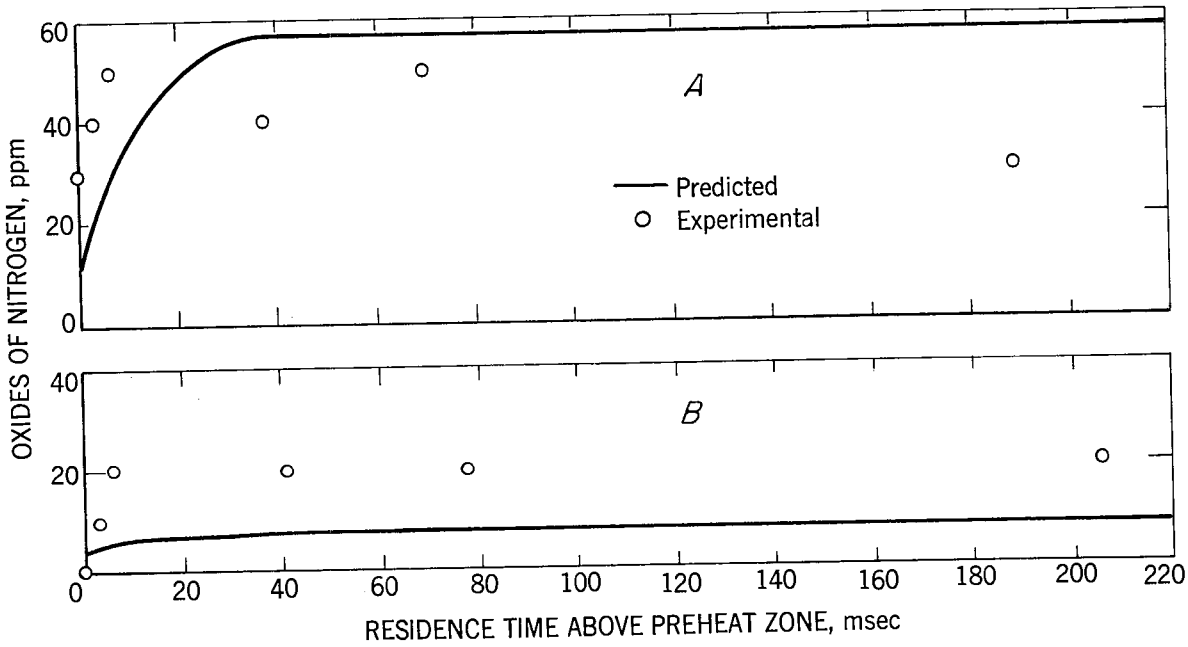

Figure 15.—Comparison of predicted curve and experimental points for nitrogen oxide concentrations in propane-air flames with 15 percent flue gas A added. A. Stoichiometric. B. Lean.

Table 21.—Observed temperatures and concentrations of nitrogen oxides in the core of secondary combustion zones of propane-air and methane-air flames

Distance above primary flame, inches	Fuel	Lean flames		Stoichiometric flames		Rich flames	
		Temp.,[1] ° F	NO_x concentration,[2] ppm	Temp.,[1] ° F	NO_x concentration,[2] ppm	Temp.,[1] ° F	NO_x concentration,[2] ppm
0	C_3H_8	3, 270	30	3, 510	50	3, 350	80
	C_3H_8+A [3]	2, 840	0	3, 150	30	2, 960	40
	C_3H_8+B [4]	2, 810	10	3, 210	30	3, 330	50
	CH_4	2, 950	10	3, 320	40	3, 280	50
0. 5	C_3H_8	3, 170	80	3, 430	120	3, 240	80
	C_3H_8+A [3]	2, 470	10	3, 130	40	2, 920	40
	C_3H_8+B [4]	2, 810	20	3, 180	40	3, 200	60
	CH_4	2, 920	30	3, 220	80	3, 160	50
1. 0	C_3H_8	3, 140	90	3, 400	190	3, 210	80
	C_3H_8+A [3]	2, 770	20	3, 070	50	2, 880	40
	C_3H_8+B [4]	2, 800	20	3, 150	80	3, 190	60
	CH_4	2, 940	30	3, 210	100	3, 120	60

[1] Average of flame temperatures at axis and 0.71 inch from axis.
[2] Average of concentrations at axis and 0.71 inch from axis.
[3] 15 percent flue gas A.
[4] 15 percent flue gas B.

cals, such as CHO, which are unique or in relatively high concentration in the primary combustion zone of rich hydrocarbon flames and which vanish very rapidly in the secondary combustion zone. Concentrations in the secondary combustion zone of lean and stoichiometric flames increase with time, probably because of the reaction of molecular nitrogen with atomic oxygen from molecular primary and secondary oxygen.

KINETICS OF DECAY OF CARBON MONOXIDE IN FLAMES

Past Studies

Several investigators report that concentrations of carbon monoxide in the burned gases close to the primary combustion zone of hydrocarbon flames are considerably above the equilibrium concentration (*20–21, 27–30*). It has also been

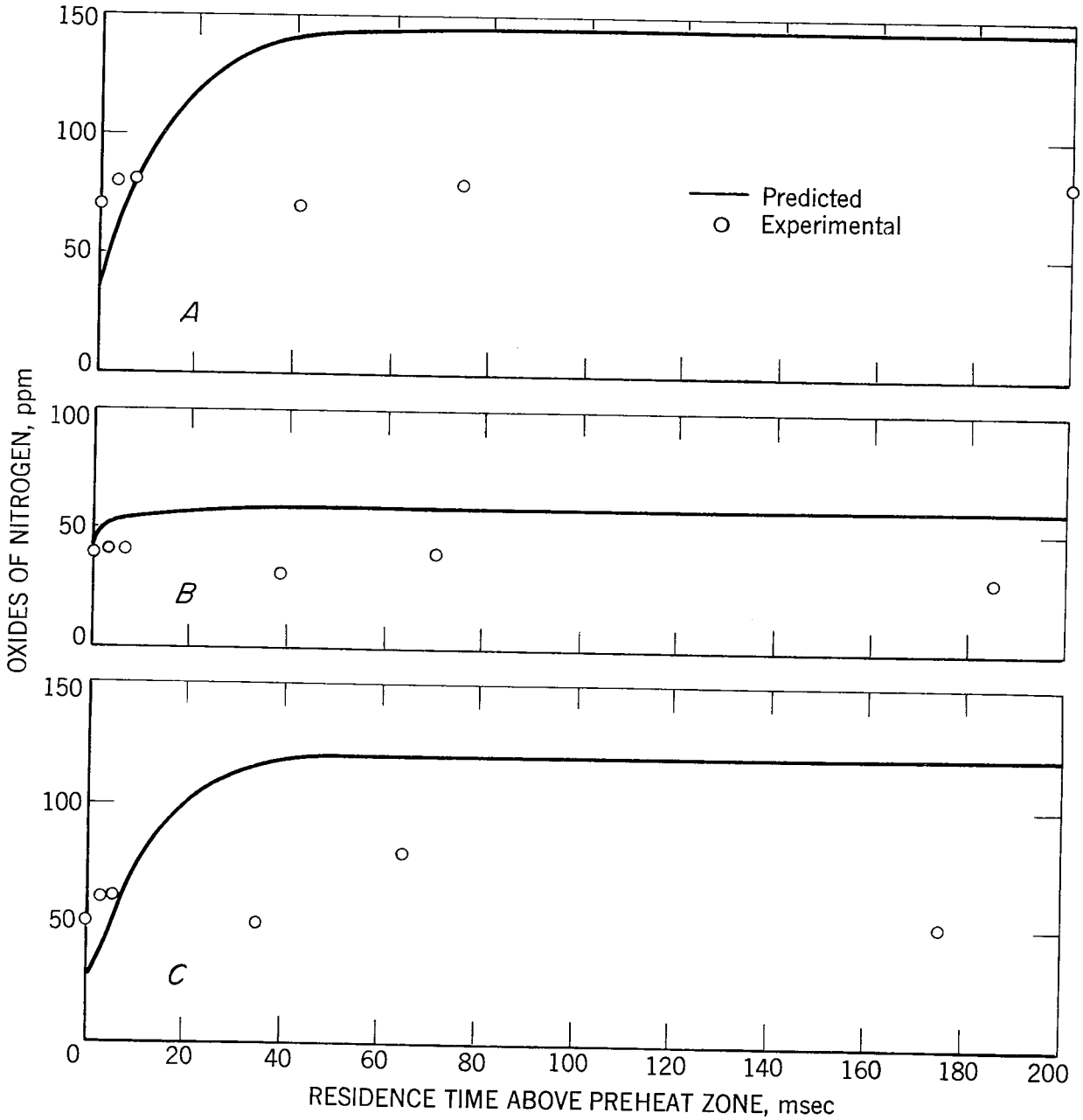

Figure 16.—Comparison of predicted curve and experimental points for nitrogen oxide concentrations in rich propane-air flames. A. No flue gas. B. 15 percent flue gas A added. C. 15 percent flue gas B added.

shown that the logarithm of the concentration is an inverse linear function of distance (*21*, *27*). The supraequilibrium concentration indicates that in hydrocarbon flames the oxidation of the parent hydrocarbon to carbon monoxide is faster than the oxidation of carbon monoxide to carbon dioxide. The oxidation of carbon monoxide to carbon dioxide has been attributed by some investigators to the reaction $OH+CO \rightleftarrows CO_2+H$ (*20–21*, *28*). Others have preferred the direct oxidation reaction

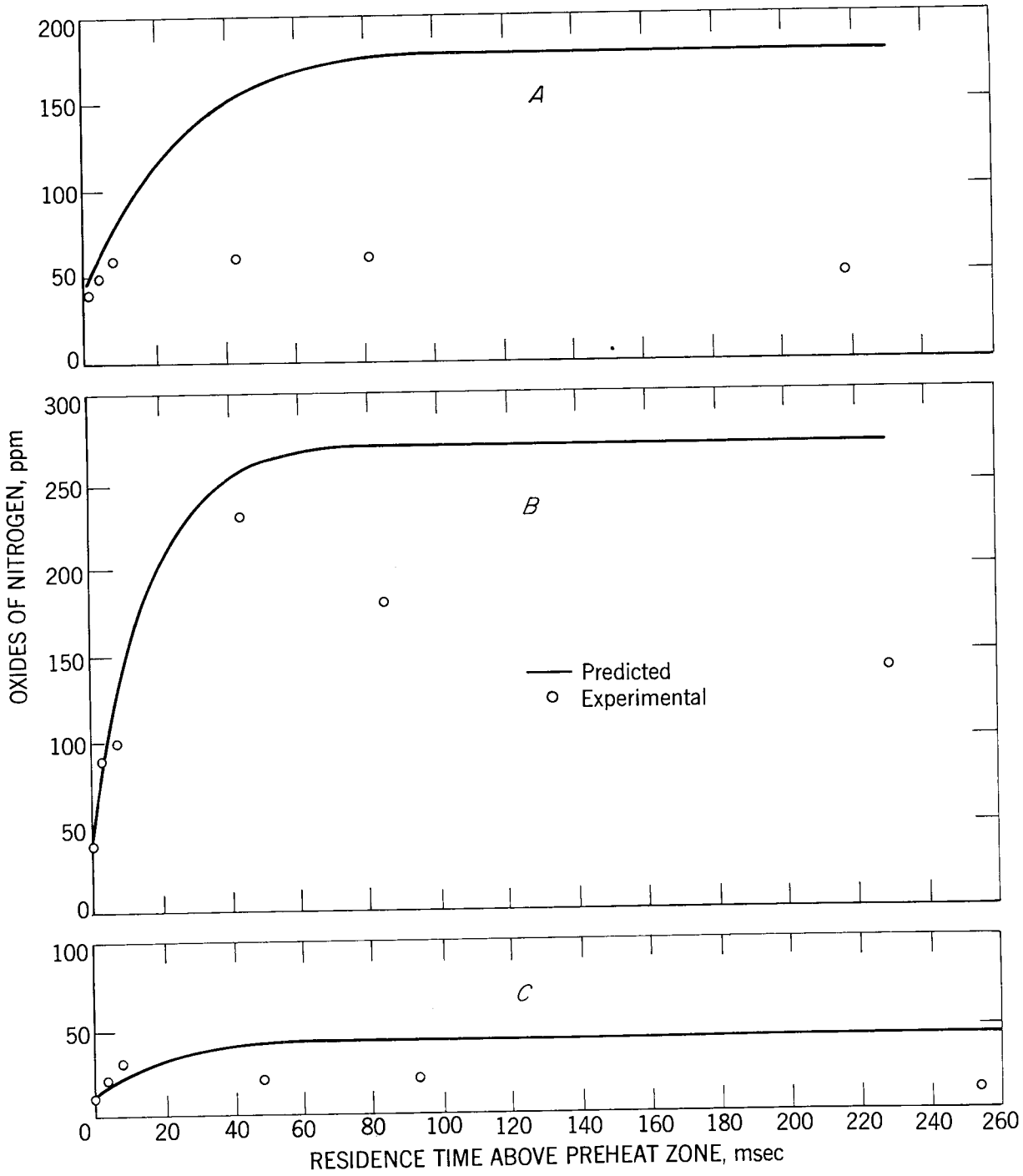

Figure 17.—Comparison of predicted curve and experimental points for nitrogen oxide concentrations in methane-air flames. A. Rich. B. Stoichiometric. C. Lean.

of $2CO+O_2 \rightleftarrows 2CO_2$ (*6, 42, 45*). Most investigators prefer the hydroxyl oxidation mechanism to the direct oxidation mechanism, because it explains the marked increase in the burning rates and other changes in the combustion characteristics of carbon monoxide flames (*63, 73–74*) resulting from the addition of some hydrogen, hydrocarbons, or water vapor.

Most of these kinetic studies have examined carbon monoxide oxidation in the region immediately downstream from the primary combustion zone. Such studies may not be applicable to rates farther downstream in the secondary combustion zone where temperatures may be much lower than near the primary zone. Recently, Dixon-Lewis and coworkers (*14*) have shown that kinetic data for the oxidation of carbon monoxide obtained at different temperatures should not be combined. Because of this problem, in our earlier publication (*66*) extensive use was made of data obtained in regions in the secondary combustion zone considerably downstream from the primary flame front (*12*). Activation energies in the literature further indicate the variation of relevant kinetic parameters with temperature. Activation energies based on studies near the primary combustion zone where temperatures are relatively high (*21–22, 48, 64, 68–69, 79*) are in approximate agreement among themselves and are greater than the values obtained relatively far downstream from the primary zone as in the studies by Dixon-Lewis (*14*) and Hottel (*44*). The data obtained by Fine (*22*) and Kaskan (*48*) support the thesis that reaction rates vary with distance from the primary combustion zone.

This Study

In view of these difficulties, new kinetic relationships were derived from our data by the empirical determination of constants in an Arrhenius-type equation:

$$\frac{-d\ ln\ (CO)}{dt} = A(O_2)(H_2O)^{1/2}\left(1-\frac{(CO_e)}{(CO)}\right)exp(-E/RT). \quad (9)$$

This equation is based on the empirical findings that the oxidation of carbon monoxide varies directly with oxygen concentration when ample water is present (*21, 68*) and with the square root of the water vapor concentration (*44*). Equation 9 does not fit any mechanism which can be specified at this time. If the exponent on oxygen were 0.25 (*44*) instead of the empirical value of unity, equation 9 could be said to be based on the mechanism of $CO+OH \rightarrow CO_2+H$, with the concentration of OH resulting from equilibrium among the species of O_2, H_2O, O, and OH (*44*).

Another empirical step was also taken. No one set of values for A and E would fit the span of experiments in this study. As will be presented shortly, six empirical distinctions were made on the basis of stoichiometry and distance from the primary combustion zone. The details of the mechanism in each of the six zones are not known. It may be that with increasing distance from the primary combustion zone the reaction rate is slowed by the fall in concentration of hydroxyl radicals towards equilibrium values (*48*) and that the initial excess over equilibrium concentration of OH and its rate of decline are a function of stoichiometry; other differences in mechanism may be involved.

As for data from this study, the scatter of experimental points on a semilog plot of $(dCO/dt)(1/O_2)$ versus $(1/T)$ from its root mean square line was least when the exponent on O_2 was unity. A like determination of the exponent for H_2O could not be made because the concentration of H_2O was not directly determined; indirect evaluation of the concentration of water showed it to be nearly constant in the burned gas of each flame. Failing to make our own determination, the exponent on water of 0.5 was chosen on the basis of evidence in the literature (*44*) and the theoretical value of the exponent based on the above stated hydroxyl mechanism.

Experimental values of concentrations of the species in equation 9 were used to derive empirical values of the preexponential coefficient A and the activation energy E.

The initial concentration of carbon monoxide was assumed to form just upstream from the primary combustion zone in the preheat zone and to correspond to all of the carbon in the hydrocarbon being oxidized to carbon monoxide. Equilibrium concentrations of oxygen and water were assumed to correspond to this concentration of carbon monoxide. The following equation was obtained in the same way as for the formation of nitric oxide:

$$ln\frac{(CO)_1}{(CO)_2} = \frac{A(H_2O)^{1/2}}{U_i}\int_{h_1}^{h_2}\left(1-\frac{(CO)_e}{(CO)}\right)(O_2)\left(\frac{T_i}{T}\right)[exp(-E/RT)]dh, \quad (10)$$

in which $(CO)_1$ and $(CO)_2$ are the partial pressures of carbon monoxide in atmospheres at h_1 and h_2, respectively, and the other concentrations are the average partial pressures of these molecules within

this interval in atmospheres. Data were separated into four regions:

1. From the unburned side of the primary combustion zone to the burned side (the reaction zone thickness).
2. From the burned side of the primary combustion zone to 1 inch above the primary combustion zone.
3. From 1 to 6 inches above the primary combustion zone.
4. From 6 to 11 inches above the primary combustion zone.

Data points were located along vertical lines on the axis and one-half radial distance from the axis.

Combustion characteristics and concentrations for the 12 flames used to evaluate the decay rates across the primary combustion zones are listed in tables 22 and 23, respectively. Twelve values of A were computed for each value assumed for E in the primary flame zone. Temperatures at the burned side of the luminous zone ranged from 1,830° to 2,210° K. Equations 11, 12, and 13 represent rates of decay across the primary com-

Table 22.—Combustion characteristics pertaining to the decay of carbon monoxide across the primary combustion zone of hydrocarbon-air flames

Fuel	Fraction of stoichiometric of primary mixture	Corresponding to mixture at sampling site					
		Fraction of stoichiometric	Adiabatic flame temperature, T_a, ° K	Expansion ratio, E_a	Burning velocity, S_u, inches/sec	Primary combustion zone thickness, L[1], inches	Residence time, t, msec
C_3H_8+B [2]	0. 78	0. 76	1, 880	6. 62	11. 5	0. 0150	0. 197
C_3H_8	. 85	. 82	2, 060	7. 26	13. 0	. 0162	. 172
C_3H_8+A [3]	. 85	. 84	1, 900	6. 61	12. 5	. 0162	. 196
CH_4	. 85	. 73	1, 860	6. 82	9. 5	. 0162	. 250
C_3H_8+B [2]	. 92	. 86	2, 060	7. 35	14. 3	. 0177	. 169
C_3H_8	1. 00	. 98	2, 250	7. 93	16. 2	. 0201	. 156
C_3H_8+A [3]	1. 00	. 99	2, 100	7. 30	15. 3	. 0201	. 180
CH_4	1. 00	. 87	2, 070	7. 48	12. 6	. 0201	. 213
C_3H_8+B [2]	1. 10	1. 06	2, 180	7. 70	15. 1	. 0268	. 230
C_3H_8	1. 20	1. 13	2, 250	8. 00	13. 4	. 0303	. 283
C_3H_8+A [3]	1. 20	1. 13	2, 050	7. 19	10. 5	. 0303	. 401
CH_4	1. 20	1. 01	2, 230	7. 34	11. 8	. 0303	. 350

[1] Luminous zone + preluminous reaction zone. [2] 15 percent flue gas B. [3] 15 percent flue gas A.

Table 23.—Concentrations pertaining to the decay of carbon monoxide across the primary combustion zone of hydrocarbon-air flames

Fuel	Fraction of stoichiometric of primary mixture	Upstream concentrations (assuming all carbon oxidized to carbon monoxide), percent			Equilibrium concentrations for adiabatic flame temperature, percent		Carbon monoxide observed [1] immediately downstream, percent
		(CO)	(H_2O)	(O_2)	$(H_2O)_e$	$(O_2)_e$	
C_3H_8+B [2]	0. 78	9. 00	11. 0	8. 18	11. 5	3. 84	0. 156
C_3H_8	. 85	9. 50	12. 4	7. 40	13. 0	2. 90	. 410
C_3H_8+A [3]	. 85	10. 92	10. 9	7. 28	11. 5	2. 55	. 435
CH_4	. 85	7. 80	15. 4	6. 70	16. 0	3. 00	. 127
C_3H_8+B [2]	. 92	10. 37	12. 6	6. 30	13. 3	1. 33	. 560
C_3H_8	1. 00	10. 94	14. 1	5. 44	14. 8	. 59	1. 41
C_3H_8+A [3]	1. 00	11. 10	12. 5	5. 52	13. 2	. 29	1. 16
CH_4	1. 00	16. 70	17. 6	4. 52	18. 3	. 45	. 534
C_3H_8+B [2]	1. 10	11. 84	14. 0	4. 45	14. 65	. 017	3. 72
C_3H_8	1. 20	12. 80	14. 9	3. 73	15. 46	. 006	5. 39
C_3H_8+A [3]	1. 20	12. 70	13. 2	3. 97	13. 70	. 004	4. 49
CH_4	1. 20	10. 60	18. 2	2. 92	18. 77	. 001	3. 30

[1] Adjusted for $(H_2O)_e$ in the mixture. [2] 15 percent flue gas B. [3] 15 percent flue gas A.

bustion zone of lean, stoichiometric, and rich mixtures, respectively:

$$\frac{-d\ ln\ (CO)}{dt} = (O_2)(H_2O)^{1/2} exp(-O/RT + 13.89)$$
$$= 1.07 \times 10^6 (O_2)(H_2O)^{1/2}. \quad (11)$$

$$\frac{-d\ ln\ (CO)}{dt} = (O_2)(H_2O)^{1/2} exp(-O/RT + 14.06)$$
$$= 1.27 \times 10^6 (O_2)(H_2O)^{1/2}. \quad (12)$$

$$\frac{-d\ ln\ (CO)}{dt} = (O_2)(H_2O)^{1/2} exp(-O/RT + 13.10)$$
$$= 4.89 \times 10^5 (O_2)(H_2O)^{1/2}. \quad (13)$$

The probable errors in the above equations are 8.7, 9.6, and 9.6, respectively.

According to equations 11–13, decay rates across the primary combustion zone are independent of the temperature, the fuel used, and the addition of flue gas. They vary strongly with fuel-air stoichiometry. Rates computed by means of these equations for propane-air flames at 2,100° K are about 300, 240, and 110 times faster, respectively, than the rates previously derived from kinetic data (*66*). These earlier calculations were based on decay rates in a region far downstream from the primary combustion zone (*12*).

For the secondary combustion zones, values of A and E were evaluated using the data obtained with lean and stoichiometric propane-air flames and stoichiometric propane-air flame with flue gas B added. Twelve values of A were computed in the 0- to 1-inch region; six values of A were computed in the other two regions. That value of E was taken which gave the minimum standard error of the mean of A; the uncertainty in E was within 15 kcal. The decay rate across the 0- to 1-inch interval from the primary combustion zone, where temperatures ranged from 1,900° to 2,210° K, is given by

$$\frac{-d\ ln\ (CO)}{dt} = (O_2)(H_2O)_e^{1/2} exp(-20/RT + 15.77). \quad (14)$$

The decay rate from 1 to 6 inches from the primary combustion zone, where temperatures ranged from 1,840° to 2,140° K, is given by

$$\frac{-d\ ln\ (CO)}{dt} = (O_2)(H_2O)_e^{1/2} exp(-25/RT + 15.74). \quad (15)$$

The decay rate from 6 to 11 inches from the primary combustion zone, where temperatures ranged from 1,420° to 2,000° K is given by

$$\frac{-d\ ln\ (CO)}{dt} = (O_2)(H_2O)_e^{1/2} exp(-25/RT + 14.67). \quad (16)$$

The probable errors in the carbon monoxide concentrations resulting from equations 14, 15, and 16 are 32.5, 46.5, and 48.0 percent, respectively.

The rates computed by means of equation 14 for propane-air flames at 2,100° K are about 3 and 10 times faster than those from equations 15 and 16, respectively. Equation 14 predicts a decay rate that is about 8.5 times faster than the rate derived from previous research (*66*). The activation energies in equations 14, 15, and 16 are between the values of 37 to 49 kcal/mole for the dry reaction between carbon monoxide with molecular oxygen and the activation energy of 0 to 2 kcal/mole for the reaction between carbon monoxide and hydroxyl radicals (*55*).

The decay rate of equation 14, which is for the region close to the downstream side of the primary combustion zone, agrees well with rates reported by other investigators for the same region (*21–22*, *48*, *68*). The decay rate of equation 16, which represents rates in a region far downstream from the primary combustion zone, where radical concentrations are lower, agrees well with the rates based on our analysis of an investigation probing far downstream (*12*, *66*). The decrease in decay rate with distance from the primary combustion zone indicates that the decay rate of carbon monoxide depends greatly on the decay rate of the hydroxyl radicals from supraequilibrium to equilibrium concentrations (*48*).

Concentrations of carbon monoxide for four flames were predicted by means of equations 11–16 and compared with experimental values (figs. 18–21). Flames were used that were not employed in the empirical derivation of the coefficients and activation energies of these equations. The computations were made with experimentally determined concentrations of molecular oxygen, which included secondary oxygen as well as residual primary oxygen. Equilibrium concentrations of carbon monoxide were adjusted to correspond with observations of the overall stoichiometry and temperature; corresponding curves of equilibrium concentrations of carbon monoxide are included in figures 18–21. Agreement is good between predicted and observed concentrations for lean and stoichiometric methane-air flames, but only fair for lean and stoichiometric flames of propane-air with added flue gas. These comparisons show a considerable improvement over earlier correlations of carbon monoxide concentrations (*66*).

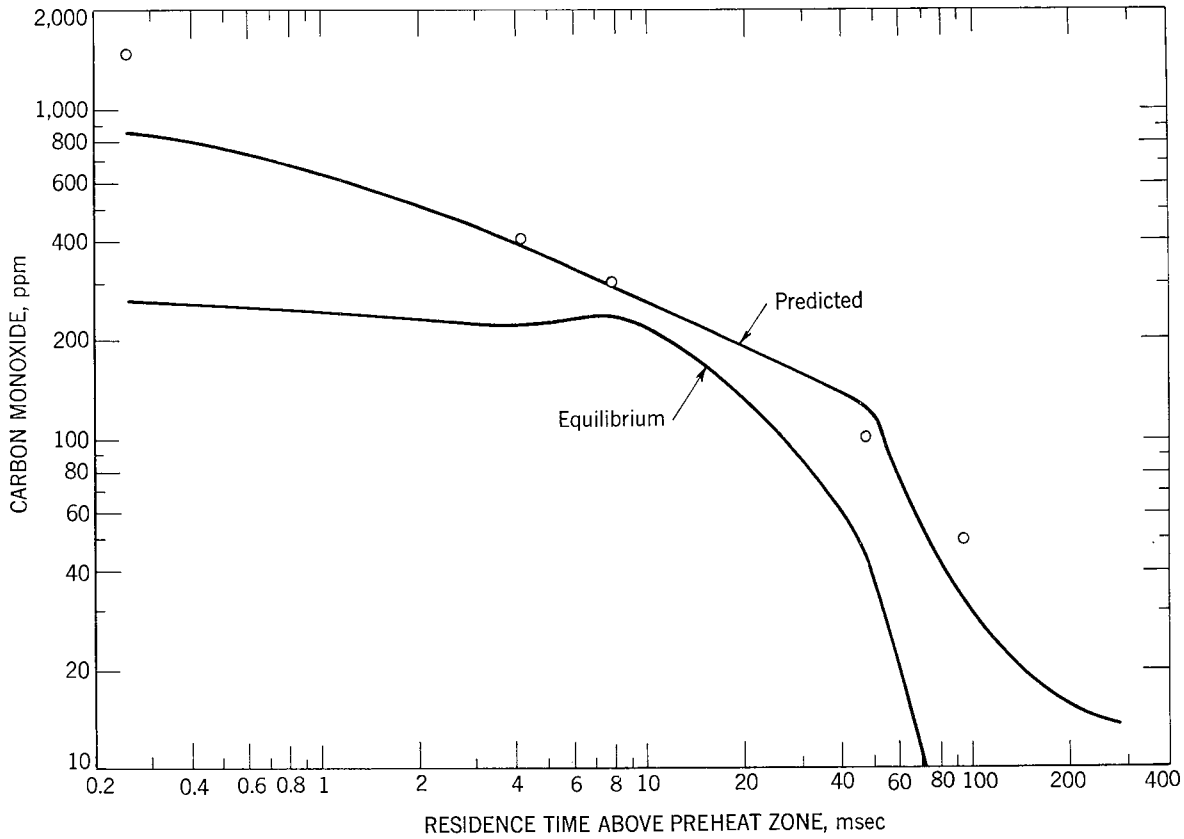

Figure 18.—Comparison of predicted curve and experimental points for carbon monoxide concentrations in a lean methane-air flame.

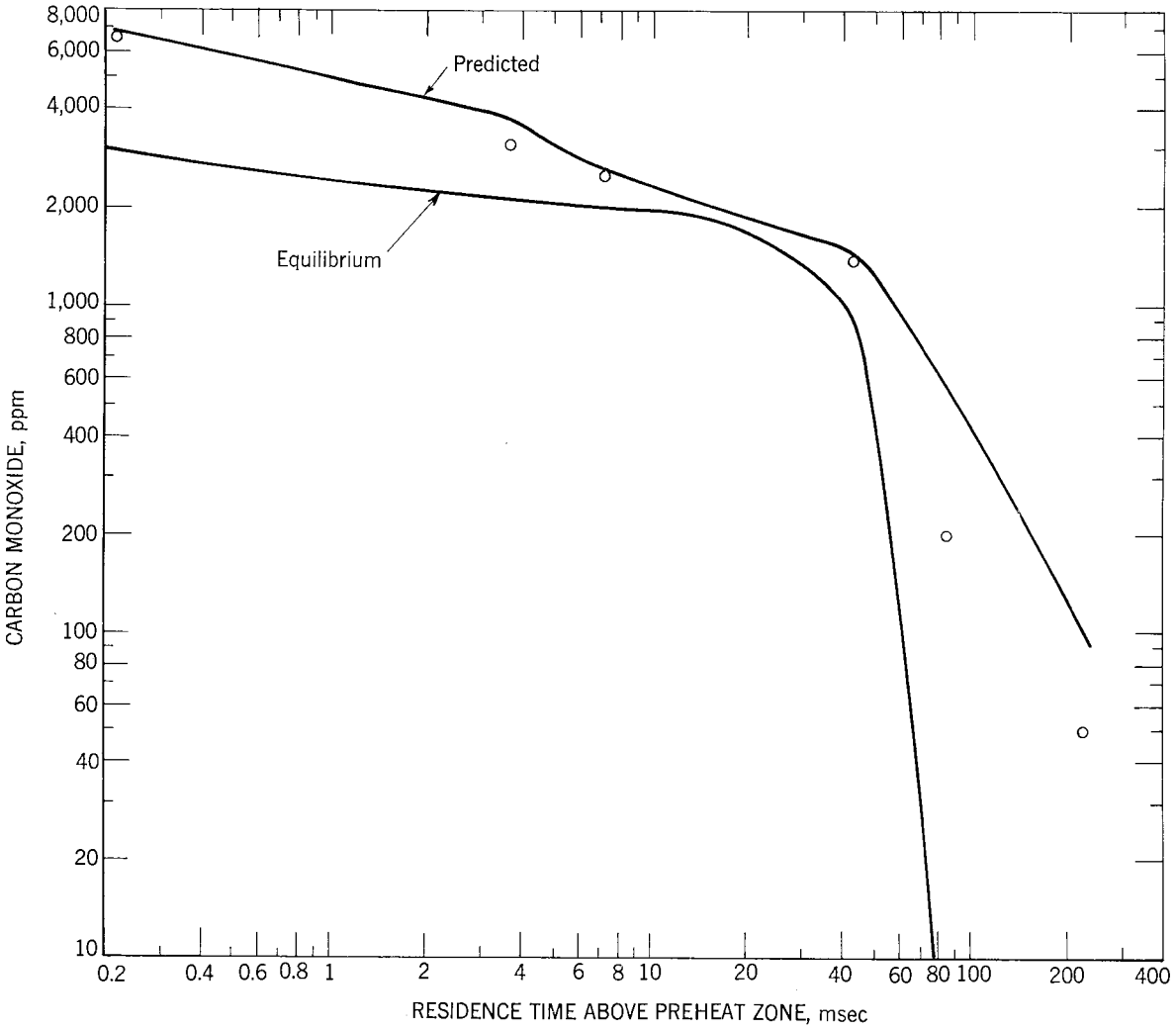

Figure 19.—Comparison of predicted curve and experimental points for carbon monoxide concentrations in a stoichiometric methane-air flame.

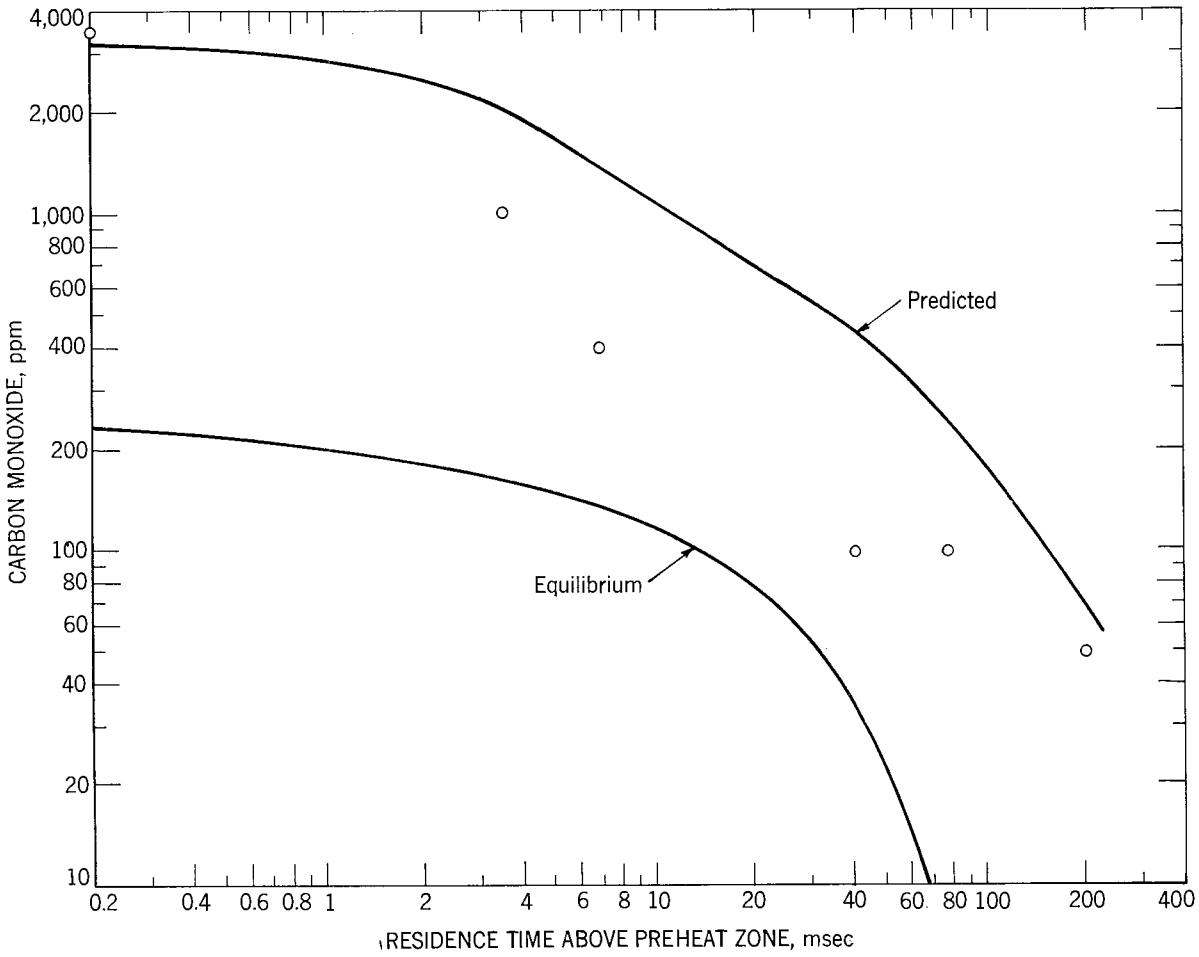

Figure 20.—Comparison of predicted curve and experimental points for carbon monoxide concentrations in a lean propane-air flame with 15 percent flue gas A added.

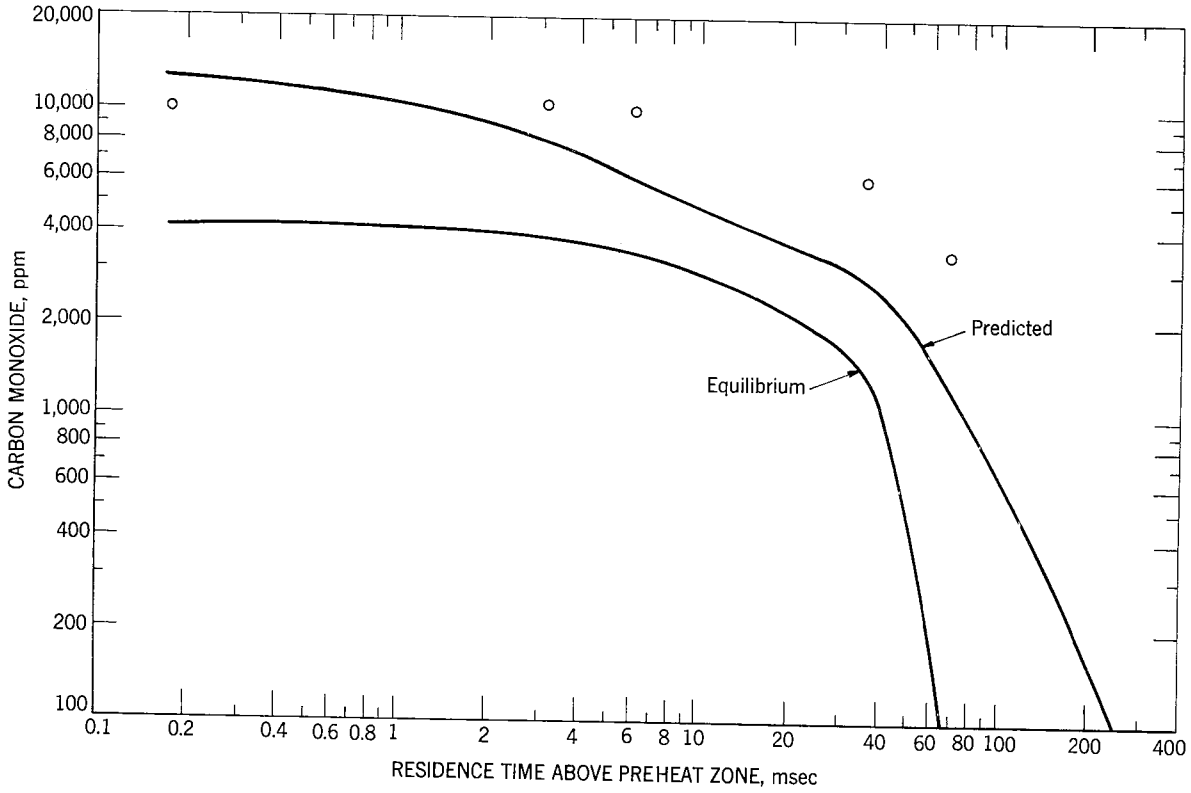

Figure 21.—Comparison of predicted curve and experimental points for carbon monoxide concentrations in a stoichiometric propane-air flame with 15 percent flue gas A added.

SUMMARY

The prime purpose of this investigation was to develop principles for the design of gas appliances which would reduce significantly or practically eliminate oxides of nitrogen, carbon monoxide, and residual hydrocarbons in the effluent from these appliances. Four such design principles were established:

1. Depress peak temperatures of flames below 3,050° F.
2. If peak temperatures are above 3,050° F, initiate rapid cooling to temperatures below 3,050° F.
3. The rapid induction of secondary air into the primary and secondary combustion zones of flames will speed up the oxidation of carbon monoxide and simultaneously oppose the formation of more nitrogen oxides by lowering local temperatures.
4. Hydrocarbons can be prevented from escaping by designing for flames that are well within the stable flame region for the particular fuel used.

The first two principles are useful in significantly reducing concentrations of nitrogen oxides from gas burner appliances. The third principle is useful in reducing concentrations of carbon monoxide. The fourth design principle pertains to avoiding the emission of residual hydrocarbons. To the extent that effluent gases from combustion systems employing liquid and solid fuels resemble those employing gaseous fuels, the principles are pertinent to liquid and solid fuel combustors.

It became apparent as the work progressed that the concentrations being obtained and those computed by means of kinetic information in the literature did not agree. It appears that these discrepancies exist because earlier studies did not examine the homogeneous primary combustion of gases closely enough. Therefore, the data obtained in this experimental study were analyzed to obtain reaction rates for the formation of nitrogen oxides and the oxidation of carbon monoxide under the conditions of gas appliance flames; this study did not yield data that could be used to derive corresponding information on the oxidation of hydrocarbons.

ACKNOWLEDGMENTS

The authors wish to thank Sanford Gordon and Mrs. Bonnie McBride of the National Aeronautics and Space Administration (NASA) Lewis Research Center, Cleveland, Ohio, and David Saul, formerly of the Bureau of Mines, Pittsburgh, Pa., for the thermodynamic computations of equilibrium compositions of gases from propane-air flames (appendix F). A 7094 version of the computer program presented in reference *80* was employed. The authors also wish to thank Leon F. Miller of the Bureau of Mines, Pittsburgh, Pa., who made many of the chromatographic analyses of the flame gases.

BIBLIOGRAPHY[4]

1. Austin, H. C., and P. Sedor. Combustion Scheme Cuts Power Plant Smog Component. Electrical World, v. 157, No. 8, 1962, pp. 51–53.
2. Bacon, T. S. Production of Noncorrosive Inert Gas by the Combustion of Fuel Gas. Petrol. Eng., v. 11, No. 13, 1940, pp. 51–56.
3. ———. Inert Gas Suitable for Mixing With Fuel Gas. U.S. Pat. 2,051,125, Aug. 18, 1936.
4. Bahn, G. S. Chemical Kinetics. Reactions Involving N_2, O_2, N and O. Pyrodynamics, v. 1, Nos. 1–2, 1964, reaction 5, p. 149.
5. Barnhart, Donald H., and Erle K. Diehl. Control of Nitrogen Oxides in Boiler Flue Gases by Two-Stage Combustion. J. Air Pollution Control Assoc., v. 10, No. 5, 1960, pp. 397–406.
6. Batchelder, Howard R., Robert M. Busche, and Willard P. Armstrong. Kinetics of Coal Gasification. Proposed Mechanism of Gasification. Ind. and Eng. Chem., v. 45, No. 9, 1953, pp. 1856–1878.
7. Beatty, Robert L., L. B. Berger, and H. H. Schrenk. Determination of the Oxides of Nitrogen by the Phenoldisulfonic Acid Method. BuMines Rept. of Inv. 3687, 1943, 14 pp.
8. Bienstock, Daniel, Robert L. Amsler, and Edgar R. Bauer, Jr. Formation of Oxides of Nitrogen in Pulverized Coal Combustion. J. Air Pollution Control Assoc., v. 16, No. 8, 1966, pp. 442–445.
9. Camac, Morton, and Robert M. Feinberg. Formation of NO in Shock-Heated Air. 11th Symp. (Internat.) on Combustion, The Combustion Institute, Pittsburgh, Pa., 1967, pp. 137–145.
10. Chironis, Nicholas P. Smog: The Deadly Poisons Peril Life in All City Areas. Products Eng., Special Rept., Dec. 19, 1966, 10 pp.
11. Connolly, T. J., and K. Nobe. Formation of Oxides of Nitrogen in Gas Fired Heaters. First Report of Air Pollution Studies, Rept. No. 55–27, Dept. Engineering, Univ. California (Los Angeles), July 1955, 25 pp.
12. Cubbage, P. A., and K. C. Ling. The Composition of Combustion Products. The Gas Council Research Communication GC 100 (London), November 1963, 21 pp.
13. Davidson, Norman. Rates of Selected Reactions Involving Nitrogen and Oxygen. AVCO Corp., Research and Advanced Development Division, Wilmington, Mass., Res. Rept. 32, June 1958, p. 4.
14. Dixon-Lewis, G., M. M. Sutton, and A. Willams. Reactions Contributing to the Establishment of the Water Gas Equilibrium When Carbon Dioxide Is Added to a Hydrogen-Oxygen Flame. Trans. Faraday Soc., v. 61, February 1965, pp. 255–262.
15. Faith, W. L. Nitrogen Oxides. A Challenge to Chemical Engineers. Chem. Eng. Prog., v. 52, No. 8, 1956, pp. 342–344.
16. Fenimore, C. P., and G. W. Jones. The Decomposition of Ethylene and Ethane in Premixed Hydrocarbon-Oxygen-Hydrogen Flames. 9th Symp. (Internat.) on Combustion, Academic Press Inc., New York, 1963, pp. 597–606.
17. ———. Formation of Carbon Monoxide in Methane Flames by Reaction of Oxygen Atoms With Methyl Radicals. J. Phys. Chem., v. 65, September 1961, pp. 1532–1536.
18. ———. Nitric Oxide Decomposition at 2,200°–2,400° K. J. Phys. Chem., v. 61, May 1957, pp. 654–657.
19. ———. Rate of Reaction of Methane With H Atoms and OH Radicals in Flames. J. Phys. Chem., v. 65, December 1961, pp. 2200–2203.
20. ———. The Reaction of Hydrogen Atoms With Carbon Dioxide at 1200°–1350° K. J. Phys. Chem., v. 62, December 1958, pp. 1578–1581.
21. ———. The Water-Catalyzed Oxidation of Carbon Monoxide by Oxygen at High Temperature. J. Phys. Chem., v. 61, May 1957, pp. 651–654.
22. Fine, Burton D. Chemical Sampling Downstream of Lean, Flat Hydrogen and Propane Flames. NASA TN D–198, December 1959, pp. 15–18.
23. Freedman, E., and J. W. Daiber. Decomposition Rate of Nitric Oxide Between 3,000° and 4,300° K. J. Chem. Phys., v. 34, No. 4, 1961, pp. 1271–1278.
24. Freeze, Paul D. Review of Recent Developments of High-Temperature Thermocouples. ASME paper 63–WA–212, 1963, 16 pp.
25. Friedman, R. Analysis of Flame-Traverse Studies With Gas-Sampling Probes. J. Chem. Phys., v. 24, No. 6, 1956, p. 1268.
26. ———. Measurement of the Temperature Profile in a Laminar Flame. 4th Symp. (Internat.) on Combustion, The Williams & Wilkins Co., Baltimore, Md., 1953, pp. 259–263.
27. Friedman, Raymond, and Joseph A. Cyphers. Flame Structure Studies. III. Gas Sampling in a Low-Pressure Propane-Air Flame. J. Chem. Phys., v. 23, No. 10, 1955, pp. 1875–1880.
28. Friedman, R., and R. G. Nugent. Flame Structure Studies. IV. Premixed Carbon Monoxide Combustion. 7th Symp. (Internat.) on Combustion, Butterworths Scientific Publications, London, 1959, pp. 311–316.
29. Fristrom, Robert M. The Structure of Laminar Flames. 6th Symp. (Internat.) on Combustion, Rheinhold Publishing Corp., New York, 1957, pp. 96–110.
30. ———. The Mechanism of Combustion in Flames. Chem. and Eng. News, v. 41, Oct. 14, 1963, pp. 150–160.
31. Fristrom, R. M., W. H. Avery, and C. Grunfelder. Reactions of Simple Hydrocarbons in Flame Fronts—Microstructure of C_2 Hydrocarbon-Oxygen Flames. 7th Symp. (Internat.) on Combustion, Butterworths Scientific Publications, London, 1959, pp. 304–310.
32. Fristrom, R. M., R. Prescott, R. K. Neumann, and W. H. Avery. Temperature Profiles in Propane-Air Flame Fronts. 4th Symp (Internat.) on Combustion, The Williams & Wilkins Co., Baltimore, Md., 1953, pp. 267–274.
33. Gaydon, A. G., and H. G. Wolfhard. Flames. Their Structure, Radiation and Temperature. Chapman & Hall Ltd., London, 2d ed., 1960, pp. 283–296.
34. George, Ralph E., and Robert L. Chass. Control of Contaminant Emissions From Fossil Fuel-Fired Boilers. J. Air Pollution Control Assoc., v. 17, No. 6, 1967, pp. 392–395.
35. Gibbs, G. J., and H. F. Calcote. Effect of Molecular Structure on Burning Velocity. J. Chem. and Eng. Data, v. 4, July 1959, pp. 226–237.
36. Gilbert, Nathan, and Farrington Daniels. Fixation of Atmospheric Nitrogen in a Gas Heated Furnace. Ind. and Eng. Chem., v. 40, No. 9, 1948, pp. 1719–1723.
37. Glick, H. S., J. J. Klein, and W. Squire. Single-Pulse Shock Tube Studies of the Kinetics of the Reaction $N_2+O_2 \leftrightarrows 2NO$ Between 2,000°–3,000° K. J. Chem. Phys., v. 27, No. 4, 1957, pp. 850–857.

[4] Titles enclosed in parentheses are translations from the language in which the item was originally published.

38. Grumer, J., Margaret E. Harris, and Valeria R. Rowe. Fundamental Flashback, Blowoff, and Yellow-Tip Limits of Fuel Gas-Air Mixtures. BuMines Rept. of Inv. 5225, 1956, 199 pp.
39. Hall, Edwin L. Products of Combustion of Gaseous Fuels. Proc. 2d National Air Pollution Symp., Pasadena, Calif., March 1952, pp. 84–89.
40. Halperin, C., and F. W. Ruegg. A Study of Sampling of Flame Gases. J. Res. National Bureau of Standards, v. 60, No. 1, 1958, pp. 29–37 (Research Paper 2818).
41. Hangebrauck, R. P., D. J. von Lehmden, and J. E. Meeker. Emissions of Polynuclear Hydrocarbons and Other Pollutants From Heat-Generation and Incineration Processes. J. Air Pollution Control Assoc., v. 14, No. 7, 1964, pp. 267–278.
42. Haslam, R. T. The Simultaneous Combustion of Hydrogen and Carbon Monoxide. Ind. and Eng. Chem., v. 15, No. 7, 1923, pp. 679–681.
43. Hirschfelder, Joseph O. Semi-Empirical Calculations of Activation Energies. J. Chem. Phys., v. 9, August 1941, pp. 645–653.
44. Hottel, H. C., G. C. Williams, N. M. Nerheim, and G. R. Schneider. Kinetic Studies in Stirred Reactors: Combustion of Carbon Monoxide and Propane. 10th Symp. (Internat.) on Combustion, The Combustion Institute, Pittsburgh, Pa., 1965, pp. 111–121.
45. Hougen, Olaf A., and Kenneth M. Watson. Chemical Process Principles. Part 3. Kinetics and Catalysis. John Wiley & Sons, Inc., New York, 1947, p. 1069.
46. Industrial Hygiene Digest. Threshold Limit Values for 1968 Adopted at the 30th Annual Meeting of the American Conference of Governmental Industrial Hygienists. V. 32, No. 10, 1968, pp. 3–11.
47. Jellinek, K. Über Zersetzungsgeschwindigkeit von Stickoxyd und Abhängigkeit derselben von der Temperatur (On the Rate of Decomposition of Nitric Oxide and Its Temperature Dependence). Z. Anorg. Chem., v. 49, 1906, pp. 229–247.
48. Kaskan, W. E. Excess Radical Concentration and the Disappearance of Carbon Monoxide in Flame Gases From Some Lean Flames. Combustion and Flame, v. 3, 1959, pp. 49–60.
49. Kaufman, F., and L. J. Decker. Effect of Oxygen on Thermal Decomposition of Nitric Oxide at High Temperatures. 7th Symp. (Internat.) on Combustion, Butterworths Scientific Publications, London, 1959, pp. 57–60.
50. Knox, Joseph. Fixation of Atmospheric Nitrogen. Chemical Monographs, D. Van Nostrand Co., New York, 1914, p. 14.
51. Kopa, Richard D., and Hiroshi Kimura. Exhaust Gas Recirculation as a Method of Nitrogen Oxides Control in an Internal Combustion Engine. 53d Annual Meeting, Air Pollution Control Assoc., Paper 60–72, May 1960, 53 pp.
52. Kydd, P. H. Hydrocarbon Products From Rich Hydrocarbon Flames. Combustion and Flame, v. 3, 1959, pp. 133–145.
53. Laboratory Management. V. 5, No. 4, 1967, p. 42.
54. Marrone, P. V. Nonequilibrium Flow Field Analysis. Anti-Missile Research Advisory Council Proc., Univ. Michigan Inst. Sci. and Tech. (Ann Arbor), v. 4, part 1, 1961, pp. 353–362.
55. Mayer, S. W. Computed Activation Energies for Bimolecular Reactions of O_2, N_2, NO, N_2O, NO_2 and CO_2. J. Phys. Chem., v. 71, No. 12, 1967, pp. 4159–4161.
56. Nernst, W. Über die Bildung von Stickoxyd bei hohen Temperaturen (On the Formation of Nitric Oxide at High Temperatures). Z. Anorg. Chem., v. 49, 1906, pp. 213–228.
57. Perry, H., and J. H. Field. Air Pollution and the Coal Industry. Trans. AIME., v. 238, December 1967, pp. 337–345.
58. Richter, G. N., H. H. Reimer, and E. H. Sage. Oxides of Nitrogen in Combustion. Investigations in a Premixed Flame. Chem. Eng. Sci., v. 17, November 1962, pp. 813–823.
59. Rider, B. F., with M. G. Mellon. Colorimetric Determination of Nitrites. Ind. and Eng. Chem. (Anal. Ed.), v. 18, No. 2, 1946, pp. 96–99.
60. Rosenberg, R. B., and D. S. Hacker. Formation of Nitrogen Oxides in Aerated Methane Flames. Preprints, Div. Fuel Chemistry, Am. Chem. Soc., v. 10, No. 3, 1966, pp. 91–104.
61. Saltzman, Bernard E. Colorimetric Microdetermination of Nitrogen Dioxide in the Atmosphere. Anal. Chem., v. 26, No. 12, 1954, pp. 1949–1955.
62. ———. Modified Nitrogen Dioxide Reagent for Recording Air Analyzers. Anal. Chem., v. 32, No. 1, 1960, pp. 135–136.
63. Scholte, T. G., and P. B. Vaggs. The Influence of Small Quantities of Hydrogen and Hydrogen Compounds on the Burning Velocity of Carbon Monoxide-Air Flames. Combustion and Flame, v. 3, No. 4, 1959, pp. 503–510.
64. Semenov, N.N. Thermal Theory of Combustion and Explosion. III. Theory of Normal Flame Propagation. National Advisory Committee for Aeronautics TM 1026, September 1942, p. 63.
65. Singer, J. M., and J. Grumer. Carbon Formation in Very Rich Hydrocarbon-Air Flames. BuMines Rept. of Inv. 6007, 1962, 80 pp.
66. Singer, J. M., E. B. Cook, Margaret E. Harris, Valeria R. Rowe, and J. Grumer. Flame Characteristics Causing Air Pollution: Production of Oxides of Nitrogen and Carbon Monoxide. BuMines Rept. of Inv. 6958, 1967, 34 pp.
67. Smith, Robert W., Jr., and Edwin B. Cook. The Thermodynamics of Combustion Gases. Computed Compositions of Methane-Air, Propane-Air, and Ethylene-Air Flames. BuMines Rept. of Inv. 6672, 1965, 30 pp.
68. Sobolev, G. K. High-Temperature Oxidation and Burning of Carbon Monoxide. 7th Symp. (Internat.) on Combustion, Butterworths Scientific Publications, London, 1959, pp. 386–391.
69. Sokolik, A. S. Self-Ignition, Flame and Detonation in Gases. U.S. Dept. Commerce, OTS 63–11179, 1963, pp. 213–215.
70. Steffensen, R. J., J. T. Agnew, and R. A. Olsen. Tables for Adiabatic Gas Temperature and Equilibrium Composition of Six Hydrocarbons. Engineering Bulletin of Purdue Univ. (Lafayette, Ind.), No. 122, Eng. Ext. Ser., May 1966, 98 pp.
71. Vogely, W. A., and W. E. Morrison. Pattern of Energy Consumption in the United States 1947 to 1965 and 1980 Projected. World Power Conf. (Tokyo), Paper 83, October 1966, 23 pp.
72. Walker, J. D., and B. J. Stocks. Thermocouple Errors in Forest Fire Research. Fire Technol., v. 4, No. 1, 1968, pp. 59–62.
73. Walker, P. L., Jr., and C. C. Wright. Stability of Burner Flames for Binary and Tertiary Mixtures of Methane, Carbon Monoxide and Water Vapour. Fuel (London), v. 31, No. 1, 1952, pp. 37–44.
74. Watermeier, Leland A. Influence of Hydrogen and Deuterium on Flame Velocities of Dry Carbon Monoxide-Oxygen Mixtures. J. Chem. Phys., v. 47, No. 5, 1957, pp. 1118–1126.
75. Wise, Henry, and Maurice F. Frech. Kinetics of Decomposition of Nitric Oxide at Elevated Temperatures. I. Rate Measurements in a Quartz Vessel. J. Chem. Phys., v. 20, No. 1, 1952, pp. 22–24.
76. Yee, Y. S., and W. Linville. The Effect of Exhaust Gas Recirculation on Oxides of Nitrogen. 53d Ann. Meeting Air Pollution Control Assoc., Paper 60–71, May 1960, 11 pp.
77. Yuan, Edward L., John I. Slaughter, William E. Koerner, and Farrington Daniels. Kinetics of the Decomposition of Nitric Oxide in the Range 700°–1,800° C. J. Phys. Chem., v. 63, June 1959, pp. 952–956.

78. Zeldovich, IA. B. The Oxidation of Nitrogen in Combustion and Explosions. Acta Physicochimica U.R.S.S., v. 21, No. 4, 1946, pp. 577–628.
79. Zeldovich, IA. B., and N. N. Semenov. (Kinetics of Chemical Reaction in Flames.) Zh. Eksperim. i Teor. Fiz., v. 10, No. 9–10, 1940, pp. 1116–1136; No. 12, 1940, pp. 1427–1440.
80. Zeleznik, Frank J., and Sanford Gordon. A General IBM 704 or 7090 Computer Program for Computation of Chemical Equilibrium Compositions, Rocket Performance, and Chapman-Jouguet Detonations. NASA TN D–1454, October 1962, 149 pp.
81. ———. Calculation of Complex Chemical Equilibria. Ind. and Eng. Chem., v. 60, No. 6, 1968, pp. 27–57.

APPENDIX A.—PRODUCTS OF COMBUSTION IN PROPANE-AIR FLAMES ON A FLAT-FLAME BURNER

Table A–1.—Lean propane-air flames [1]

Distance, inches		Flue gas addition	NO_x,[2] ppm	CO,[3] ppm	Total HC,[4] ppm	H_2,[3] pct	N_2+Ar,[3] pct	CO_2,[3] pct	O_2,[3] pct	Secondary O_2,[3] pct	Temp.,[2] T, ° F	Residence time,[2] t, msec
Vertical	Radial											
0	0	None	20	4,200	0	0	84.4	10.8	4.4	0.7	3,270	0.172
0	0	[5] A	0	3,500	4,185	0	84.4	10.4	4.4	.4	2,840	.200
0	0	[6] B	0	900	[7] 5	0	84.3	10.4	5.2	.6	2,850	.201
0	0.71	None	30	5,200	0	0	84.4	10.7	4.5	.9	3,260	.172
0	.71	A	0	6,500	13,095	0.1	82.0	6.9	9.2	.8	2,830	.200
0	.71	B	10	2,600	0	0	84.4	10.2	5.2	.9	2,760	.203
0	1.42	None	20	18,800	10,825	.5	81.0	6.1	9.4	4.4	3,260	.172
0	1.42	A	0	1,900	26,940	0	78.9	2.6	15.7	5.6	130	.333
0	1.42	B	0	11,100	5,675	.3	81.7	6.6	9.3	1.2	2,240	.221
0	1.78	None	[8]	100	0	0	79.1	.1	20.7	[9]	410	2.44
0	1.78	A	[8]	0	[7] 145	0	79.3	.1	20.7	[9]	210	2.85
0	1.78	B	[8]	0	2,380	0	79.1	.1	20.6	[9]	210	2.64
0.5	0	None	80	1,600	0	0	84.7	11.1	3.9	.3	3,170	3.63
.5	0	A	10	1,000	0	0	85.1	11.4	3.5	.3	2,790	3.52
.5	0	B	20	500	0	0	84.8	10.4	4.8	.3	2,830	3.50
.5	.71	None	80	2,300	0	0	84.5	11.0	4.3	.4	3,160	3.64
.5	.71	A	0	1,300	0	0	85.1	11.3	3.4	.4	2,140	3.94
.5	.71	B	20	500	0	0	84.7	10.4	4.7	.5	2,790	3.56
.5	1.42	None	70	2,200	0	0	84.1	10.9	4.8	1.3	3,150	3.65
.5	1.42	A	0	6,900	18,145	.3	79.9	4.6	12.8	3.1	840	13.9
.5	1.42	B	10	600	0	0	84.3	10.3	5.6	.1	2,710	3.93
.5	1.78	None	[8]	100	0	0	79.3	.5	20.2	[9]	1,290	43.0
.5	1.78	A	[8]	0	[7] 1,430	0	79.0	.1	20.8	[9]	180	84.5
.5	1.78	B	[8]	2,300	11,195	0	79.0	1.4	18.3	[9]	1,300	47.7
1.0	0	None	90	1,100	[7] 45	0	84.2	11.1	4.6	.8	3,140	7.11
1.0	0	A	20	400	0	0	85.3	11.4	3.3	.3	2,760	6.85
1.0	0	B	20	300	0	0	84.7	10.4	4.8	.7	2,810	6.76
1.0	.71	None	90	1,500	0	0	84.2	11.1	4.6	.6	3,130	7.12
1.0	.71	A	10	900	0	0	85.1	11.3	3.5	.2	2,780	7.16
1.0	.71	B	20	200	0	0	84.6	10.4	4.9	.5	2,780	6.93
1.0	1.42	None	70	900	0	0	84.6	11.1	4.2	2.7	3,060	7.17
1.0	1.42	A	10	3,700	1,910	0	83.2	8.8	7.0	1.6	2,660	20.0
1.0	1.42	B	20	200	0	0	84.5	10.5	5.1	1.5	2,700	7.65
1.0	1.78	None	[8]	0	0	0	79.4	.6	20.0	[9]	1,410	82.2
1.0	1.78	A	[8]	2,400	9,105	0	80.0	2.6	16.2	[9]	420	154
1.0	1.78	B	[8]	1,700	1,335	0	82.4	7.1	10.3	[9]	2,290	81.8
6.0	0	None	110	400	0	0	84.4	11.2	4.3	.3	2,900	43.1
6.0	0	A	20	100	[7] 10	0	84.7	11.4	3.8	.3	2,530	41.5
6.0	0	B	10	100	[7] 5	0	84.6	10.5	4.9	.5	2,570	41.1
6.0	.71	None	80	400	0	0	84.0	11.1	4.9	.6	2,860	43.3
6.0	.71	A	20	100	0	0	84.8	11.4	3.8	.4	2,500	40.9
6.0	.71	B	10	100	0	0	84.2	10.4	5.4	.4	2,530	42.0
6.0	1.42	None	50	200	0	0	83.4	11.0	5.6	7.8	2,100	47.9
6.0	1.42	A	10	700	485	0	84.8	11.3	3.9	4.7	2,080	87.9
6.0	1.42	B	20	900	550	0	83.8	10.2	5.9	8.1	2,090	49.0
6.0	1.78	None	[8]	0	0	0	81.2	4.7	14.1	[9]	1,740	273
6.0	1.78	A	[8]	1,000	1,520	0	82.0	6.1	11.7	[9]	1,560	393
6.0	1.78	B	[8]	1,000	1,200	0	80.8	3.5	15.5	[9]	1,570	298
11.0	0	None	100	100	0	0	84.4	11.2	4.4	4.0	2,220	83.1
11.0	0	A	20	100	[7] 10	0	84.7	11.4	4.0	.4	2,230	77.9
11.0	0	B	20	100	0	0	84.0	10.4	5.5	.4	2,190	77.8
11.0	.71	None	90	0	0	0	83.8	11.0	5.1	6.7	2,090	83.5
11.0	.71	A	20	400	60	0	84.8	11.4	3.9	2.3	2,200	76.3
11.0	.71	B	10	200	[7] 5	0	84.0	10.4	5.6	1.7	2,170	79.2
11.0	1.42	None	90	0	0	0	83.3	10.9	5.7	9.1	1,830	90.9
11.0	1.42	A	20	1,600	1,155	0	84.2	10.9	4.6	8.0	1,800	160
11.0	1.42	B	20	1,100	440	0	83.8	10.1	6.0	7.7	1,810	92.7
11.0	1.78	None	[8]	0	0	0	81.6	5.8	12.5	[9]	1,770	473
11.0	1.78	A	[8]	1,400	1,240	0	81.5	5.2	13.1	[9]	1,620	629
11.0	1.78	B	[8]	900	475	0	81.5	5.0	13.4	[9]	1,630	513
26.0	0	None	80	0	0	0	83.6	11.0	5.4	8.8	1,390	225
26.0	0	A	20	300	0	0	84.7	11.4	4.0	7.2	1,450	206
26.0	0	B	20	200	0	0	83.9	10.3	5.8	7.4	1,410	207
26.0	.71	None	80	0	0	0	83.5	11.0	5.5	8.8	1,390	223
26.0	.71	A	20	200	0	0	84.5	11.3	4.2	7.1	1,450	200
26.0	.71	B	20	200	0	0	83.6	10.3	6.3	7.5	1,390	205
26.0	1.42	None	80	0	0	0	84.1	11.0	5.0	9.3	1,370	234
26.0	1.42	A	20	300	0	0	84.6	11.3	4.2	7.7	1,420	396
26.0	1.42	B	20	200	0	0	83.3	10.3	6.4	7.4	1,390	237
26.0	1.78	None	[8]	0	0	[8]	[8]	[8]	[8]	[9]	1,350	1,140
26.0	1.78	A	[8]	500	[7] 5	0	82.2	7.0	10.9	[9]	1,400	1,380
26.0	1.78	B	[8]	200	0	0	81.9	6.5	11.6	[9]	1,390	1,200

[1] Corrected for dilution by secondary air at 0-, 0.71- and 1.42- inch radial positions.
[2] Average of 2 replicates.
[3] Average of 3 replicates.
[4] Total hydrocarbons, average of 2 replicates.
[5] Flue gas A: 12.4 percent CO_2, 87.6 percent N_2.
[6] Flue gas B: 6.3 percent CO_2, 10.5 percent O_2, 83.2 percent N_2.
[7] Propane.
[8] Not experimentally determined.
[9] Not relevant.

Table A–2.—Stoichiometric propane-air flames [1]

Distance, inches		Flue gas addition	NO_x,[2] ppm	CO,[3] ppm	Total HC,[4] ppm	H_2,[3] pct	N_2+Ar,[3] pct	CO_2,[3] pct	O_2,[3] pct	Secondary O_2,[3] pct	Temp.,[2] T, °F	Residence time,[2] t, msec
Vertical	Radial											
0	0	None	50	15,600	[5] 10	0.4	84.7	11.8	1.5	0.5	3,510	0.159
0	0	[6] A	30	10,400	[5] 10	.2	85.5	12.2	1.1	.3	3,160	.184
0	0	[7] B	30	5,100	0	0	85.5	11.8	2.1	1.5	3,230	.171
0	0.71	None	50	18,300	[5] 5	.4	84.7	11.5	1.5	1.2	3,500	.159
0	.71	A	30	16,400	0	.4	85.0	11.5	1.5	.8	3,140	.185
0	.71	B	30	8,500	0	0	85.4	11.5	2.3	.8	3,180	.172
0	1.42	None	50	15,100	[5] 85	.1	84.9	11.8	1.7	3.3	3,510	.159
0	1.42	A	0	6,000	30,075	.1	79.2	3.1	14.2	7.4	770	.266
0	1.42	B	20	10,400	25,310	.4	79.1	3.4	13.7	5.9	3,120	.173
0	1.78	None	[8]	0	[5] 5	0	79.2	.1	20.8	[9]	340	3.19
0	1.78	A	[8]	400	1,365	0	79.4	.2	20.2	[9]	490	2.86
0	1.78	B	[8]	1,400	1,230	0	79.5	3.0	17.4	[9]	1,410	1.56
0.5	0	None	110	13,200	[5] 10	.4	84.8	12.1	1.5	.5	3,440	3.36
.5	0	A	40	10,500	[5] 5	.2	85.5	12.2	1.1	.8	3,130	3.18
.5	0	B	40	3,000	0	0	85.2	12.0	2.5	.5	3,180	3.12
.5	.71	None	130	16,800	[5] 5	.4	84.6	11.6	1.7	.6	3,420	3.38
.5	.71	A	30	12,700	[5] 70	.3	85.5	12.0	1.8	.2	3,120	3.20
.5	.71	B	40	4,200	0	0	85.2	11.9	2.5	.9	3,170	3.14
.5	1.42	None	110	5,300	0	0	85.2	12.9	1.4	3.1	3,400	3.38
.5	1.42	A	10	11,900	[5] 10	.2	85.4	12.0	1.3	1.1	3,110	4.77
.5	1.42	B	50	6,800	0	0	85.4	11.7	2.2	.6	3,130	3.19
.5	1.78	None	[8]	0	0	0	78.5	1.2	20.3	[9]	750	56.2
.5	1.78	A	[8]	4,800	1,480	0	83.2	8.0	8.3	[9]	2,360	31.1
.5	1.78	B	[8]	1,200	175	0	82.5	6.5	10.9	[9]	2,690	22.7
1.0	0	None	200	13,200	0	.4	84.8	12.0	1.5	1.6	3,400	6.58
1.0	0	A	50	10,300	0	.3	85.3	12.1	1.3	3.1	3,080	6.20
1.0	0	B	70	2,200	0	0	85.6	12.1	2.0	1.3	3,150	6.08
1.0	.71	None	170	13,400	0	.3	84.5	12.0	1.9	.5	3,400	6.61
1.0	.71	A	50	10,100	0	.3	85.2	12.2	1.3	.3	3,060	6.23
1.0	.71	B	80	3,000	0	0	85.6	12.1	2.1	.9	3,140	6.12
1.0	1.42	None	130	3,000	0	0	85.2	13.1	1.4	4.7	3,200	6.69
1.0	1.42	A	40	7,100	0	0	85.8	12.5	1.0	1.1	3,040	9.23
1.0	1.42	B	70	2,800	0	0	85.4	12.0	2.3	.9	3,080	6.22
1.0	1.78	None	[8]	0	0	0	79.5	.4	20.1	[9]	1,040	104
1.0	1.78	A	[8]	7,500	0	0	83.8	10.6	4.9	[9]	2,830	57.0
1.0	1.78	B	[8]	400	95	0	80.5	4.9	14.5	[9]	2,400	44.8
6.0	0	None	310	9,500	0	.3	85.5	12.5	.7	.5	3,140	39.9
6.0	0	A	40	5,900	0	.2	85.2	12.6	1.4	.4	2,820	37.5
6.0	0	B	70	800	[5] 5	0	84.7	12.2	3.1	.8	2,920	36.7
6.0	.71	None	280	6,400	0	.2	85.6	12.8	.8	1.0	3,020	40.6
6.0	.71	A	30	4,700	0	.2	85.3	12.7	1.4	.5	2,780	37.8
6.0	.71	B	80	900	0	0	85.2	12.3	2.5	.3	2,870	37.1
6.0	1.42	None	140	1,400	0	0	84.9	13.1	1.9	8.6	2,150	45.3
6.0	1.42	A	50	300	0	0	85.9	13.2	1.0	6.9	2,440	58.9
6.0	1.42	B	60	100	0	0	84.8	12.2	2.9	6.7	2,310	40.3
6.0	1.78	None	[8]	100	0	0	81.6	5.5	12.9	[9]	1,820	311
6.0	1.78	A	[8]	200	[5] 20	0	82.0	5.9	12.2	[9]	1,870	234
6.0	1.78	B	[8]	100	[5] 10	0	81.2	4.0	15.0	[9]	1,690	188
11.0	0	None	260	1,500	0	0	85.3	13.3	1.2	4.7	2,490	76.6
11.0	0	A	50	3,400	0	.1	86.2	12.9	.4	.7	2,570	70.1
11.0	0	B	90	300	0	0	84.8	12.2	3.0	1.1	2,500	69.3
11.0	.71	None	240	800	0	0	85.0	13.2	1.7	7.1	2,310	78.4
11.0	.71	A	50	2,900	0	0	85.7	12.9	1.1	2.1	2,490	70.9
11.0	.71	B	90	300	0	0	85.6	12.3	2.0	4.4	2,390	70.6
11.0	1.42	None	230	200	0	0	84.7	13.3	2.0	9.5	2,010	85.0
11.0	1.42	A	30	400	0	0	85.6	13.1	1.3	8.7	2,050	112
11.0	1.42	B	70	200	0	0	85.2	12.2	2.6	8.5	2,010	76.2
11.0	1.78	None	[8]	0	0	0	82.0	6.7	11.3	[9]	1,890	515
11.0	1.78	A	[8]	100	0	0	82.3	6.6	11.2	[9]	1,810	414
11.0	1.78	B	[8]	100	0	0	81.8	6.4	11.8	[9]	1,820	329
26.0	0	None	230	0	0	0	84.6	13.3	2.2	9.0	1,460	210
26.0	0	A	30	0	0	0	85.2	13.1	1.8	7.2	1,490	189
26.0	0	B	60	0	0	0	84.5	12.2	3.4	7.6	1,470	188
26.0	.71	None	230	0	0	0	85.0	13.4	1.8	9.5	1,460	212
26.0	.71	A	40	0	0	0	85.3	13.1	1.7	7.4	1,490	190
26.0	.71	B	80	0	0	0	84.6	12.2	3.2	7.5	1,470	190
26.0	1.42	None	250	0	0	0	84.8	13.3	2.0	9.3	1,450	219
26.0	1.42	A	40	0	0	0	85.2	13.1	1.8	7.5	1,490	292
26.0	1.42	B	70	0	0	0	84.7	12.1	3.2	7.6	1,470	197
26.0	1.78	None	[8]	0	0	[8]	[8]	[8]	[8]	[9]	1,430	1,200
26.0	1.78	A	[8]	0	0	[8]	[8]	[8]	[8]	[9]	1,470	1,000
26.0	1.78	B	[8]	0	0	[8]	[8]	[8]	[8]	[9]	1,450	791

[1] Corrected for dilution by secondary air at 0-, 0.71-, and 1.42-inch radial positions.
[2] Average of 2 replicates.
[3] Average of 3 replicates.
[4] Total hydrocarbons, average of 2 replicates.
[5] Propane.
[6] Flue gas A: 12.4 percent CO_2, 87.6 percent N_2.
[7] Flue gas B: 6.3 percent CO_2, 10.5 percent O_2, 83.2 percent N_2.
[8] Not experimentally determined.
[9] Not relevant.

Table A–3.—Rich propane-air flames

Distance, inches		Flue gas addition	NO_x,[1] ppm	CO,[2] ppm	Total HC,[3] ppm	H_2,[2] pct	N_2+Ar,[2] pct	CO_2,[2] pct	O_2,[2] pct	Secondary O_2,[2] pct	Temp.,[1] T, °F	Residence time,[1] t, msec
Vertical	Radial											
0	0	None	70	63,400	0	2.8	80.8	8.2	1.9	1.2	3,360	0.287
0	0	[4] A	40	51,400	0	2.2	82.2	9.1	1.4	1.3	2,970	.410
0	0	[5] B	50	44,200	[6] 5	1.3	83.2	9.4	1.6	.9	3,340	.233
0	0.71	None	80	64,100	0	3.0	80.8	8.4	1.5	1.0	3,340	.287
0	.71	A	40	52,600	[6] 10	2.2	82.3	9.0	1.2	1.0	2,940	.411
0	.71	B	40	43,000	[6] 10	1.3	83.6	9.9	.9	.8	3,320	.234
0	1.42	None	70	31,600	[6] 5	1.0	83.7	10.6	1.5	2.8	3,250	.291
0	1.42	A	20	35,600	18,020	2.2	79.8	5.4	7.9	3.0	3,010	.407
0	1.42	B	30	19,700	11,220	.6	82.3	8.0	6.4	3.2	3,350	.233
0	1.78	None	[7]	0	0	0	79.1	.2	20.7	[8]	370	4.71
0	1.78	A	[7]	600	[6] 5	0	82.1	5.6	12.3	[8]	2,340	1.92
0	1.78	B	[7]	100	0	0	79.3	.2	20.5	[8]	700	3.34
0.5	0	None	80	62,600	0	2.9	81.0	8.4	1.4	1.1	3,240	3.61
.5	0	A	40	53,800	0	2.3	82.2	9.0	2.7	.8	2,930	3.46
.5	0	B	60	35,800	0	1.3	83.6	10.2	1.4	.8	3,200	3.05
.5	.71	None	80	65,300	[6] 5	3.0	81.0	8.6	.8	.4	3,230	3.52
.5	.71	A	40	54,800	0	2.3	82.5	9.1	.6	.7	2,910	3.48
.5	.71	B	60	35,700	0	1.2	83.8	10.7	.8	.4	3,200	3.06
.5	1.42	None	80	10,100	0	.2	84.8	10.8	3.2	5.8	3,240	3.56
.5	1.42	A	50	61,500	0	2.8	81.5	8.6	.9	.4	2,900	3.45
.5	1.42	B	70	31,400	0	1.0	83.8	10.8	1.2	.7	3,150	3.07
.5	1.78	None	[7]	0	0	.1	79.2	.2	20.5	[8]	890	5.35
.5	1.78	A	[7]	2,200	0	0	83.1	7.4	9.3	[8]	3,020	18.8
.5	1.78	B	[7]	100	0	0	80.1	1.5	18.4	[8]	1,980	32.8
1.0	0	None	80	63,000	0	3.3	80.5	8.2	1.6	1.0	3,210	6.84
1.0	0	A	40	54,100	0	2.3	82.6	9.1	1.0	1.0	2,880	6.53
1.0	0	B	60	33,000	0	1.3	83.5	10.3	1.6	1.0	3,190	5.87
1.0	.71	None	80	60,900	[6] 10	3.2	80.6	8.5	1.6	1.0	3,200	6.76
1.0	.71	A	40	53,900	[6] 5	2.5	82.2	8.7	1.3	1.2	2,870	6.57
1.0	.71	B	60	36,100	[6] 15	1.3	83.3	10.2	1.5	1.1	3,180	5.90
1.0	1.42	None	90	9,200	0	.2	84.2	10.0	4.7	6.7	3,260	6.81
1.0	1.42	A	40	52,600	[6] 5	2.2	82.0	9.0	1.7	1.1	2,850	6.52
1.0	1.42	B	50	14,600	0	.4	84.8	11.6	1.6	2.1	3,160	5.90
1.0	1.78	None	[7]	100	[6] 5	0	79.6	6.9	19.7	[8]	1,220	97.0
1.0	1.78	A	[7]	1,800	[6] 5	0	83.6	9.2	7.0	[8]	2,800	36.3
1.0	1.78	B	[7]	100	0	0	80.6	2.4	17.1	[8]	2,130	61.4
6.0	0	None	70	59,400	[6] 5	2.9	81.2	8.6	1.5	1.2	2,900	40.5
6.0	0	A	30	51,900	0	2.2	82.3	9.3	1.1	.7	2,680	38.2
6.0	0	B	50	34,000	0	1.4	83.8	10.8	.6	.3	2,970	35.0
6.0	.71	None	50	55,800	0	2.4	81.6	9.5	.8	.6	3,010	40.1
6.0	.71	A	40	51,800	0	2.4	82.3	9.5	.6	.4	2,670	38.4
6.0	.71	B	60	30,900	0	1.2	83.5	10.9	1.3	.5	2,960	35.1
6.0	1.42	None	80	6,700	0	.2	82.8	7.9	8.4	9.6	2,400	48.1
6.0	1.42	A	30	5,100	0	.1	84.1	10.2	5.0	6.4	2,550	38.6
6.0	1.42	B	40	2,400	0	0	83.5	8.9	7.4	7.8	2,460	37.3
6.0	1.78	None	[7]	500	0	0	81.7	5.5	12.8	[8]	1,940	297
6.0	1.78	A	[7]	200	0	0	82.1	5.7	12.2	[8]	1,940	153
6.0	1.78	B	[7]	500	0	0	82.4	7.5	10.1	[8]	2,160	219
11.0	0	None	80	31,300	0	1.3	83.1	10.5	1.8	2.8	2,810	74.7
11.0	0	A	40	42,500	0	1.9	82.6	10.1	1.1	.9	2,490	70.9
11.0	0	B	80	21,300	0	.8	84.1	11.6	2.4	1.0	2,700	65.3
11.0	.71	None	80	13,400	0	.6	83.4	9.8	4.9	6.4	2,690	75.0
11.0	.71	A	40	28,200	0	1.2	83.6	10.4	1.9	2.9	2,470	71.4
11.0	.71	B	70	8,100	0	.3	84.3	10.4	4.2	4.9	2,580	66.1
11.0	1.42	None	80	1,300	0	0	82.9	8.0	9.0	10.4	2,340	85.3
11.0	1.42	A	40	4,200	0	.1	83.8	8.8	6.8	8.6	2,200	72.7
11.0	1.42	B	50	1,000	0	0	83.5	8.1	8.2	9.1	2,220	69.9
11.0	1.78	None	[7]	300	0	0	82.3	7.3	10.4	[8]	2,120	488
11.0	1.78	A	[7]	1,100	0	0	82.7	7.6	9.7	[8]	2,020	269
11.0	1.78	B	[7]	500	0	0	82.8	8.0	9.3	[8]	2,080	380
26.0	0	None	80	0	0	0	82.8	9.0	8.3	9.1	1,650	199
26.0	0	A	30	0	0	0	83.9	10.1	6.1	7.3	1,660	185
26.0	0	B	50	0	0	0	82.4	9.3	7.4	7.5	1,610	175
26.0	.71	None	70	0	0	0	82.7	8.9	8.5	9.1	1,650	201
26.0	.71	A	40	0	0	0	83.8	10.0	6.3	7.5	1,660	186
26.0	.71	B	40	0	0	0	83.3	9.2	7.7	7.6	1,610	177
26.0	1.42	None	70	0	0	0	82.8	9.1	8.3	8.9	1,620	213
26.0	1.42	A	30	0	0	0	83.5	10.0	6.6	7.3	1,660	187
26.0	1.42	B	40	0	0	0	83.4	9.0	7.7	7.8	1,580	181
26.0	1.78	None	[7]	0	0	[7]	[7]	[7]	[7]	[8]	1,620	1,130
26.0	1.78	A	[7]	0	0	[7]	[7]	[7]	[7]	[8]	1,630	648
26.0	1.78	B	[7]	0	0	[7]	[7]	[7]	[7]	[8]	1,550	919

[1] Average of 2 replicates.
[2] Average of 3 replicates.
[3] Total hydrocarbons, average of 2 replicates.
[4] Flue gas A: 12.4 percent CO_2, 87.6 percent N_2.
[5] Flue gas B: 6.3 percent CO_2, 10.5 percent O_2, 83.2 percent N_2.
[6] Propane.
[7] Not experimentally determined.
[8] Not relevant.

APPENDIX B.—HYDROCARBONS IN PRODUCTS OF COMBUSTION IN PROPANE-AIR FLAMES ON A FLAT-FLAME BURNER

Distance, inches		Flue gas addition	CH_4, ppm [1]	C_2H_6, ppm [1]	C_2H_4, ppm [1]	C_3H_8, ppm [1]	C_3H_6, ppm [1]	n-C_4H_{10}, ppm [1]	C_2H_2, ppm [1]	1-Butene, ppm [1]	Propadiene, ppm [1]	3-Methyl-1-Butene, ppm [1]	1,3-Butadiene, ppm [1]	Methyl acetylene, ppm [1]
Vertical	Radial													
LEAN PROPANE-AIR FLAMES [2]														
0	0	A	1,945	70	710	1,180	180	----------	75	15	5	----------	5	----------
0	0.71	A	130	70	355	12,360	100	----------	55	5	5	10	----------	5
0	1.42	None	520	360	2,225	6,580	835	15	250	30	5	----------	5	----------
0	1.42	A	20	25	110	26,700	50	----------	15	----------	----------	20	----------	----------
0	1.42	B	260	165	1,045	3,710	340	5	130	10	5	----------	5	----------
0	1.78	B	----------	5	5	2,365	5	----------	----------	----------	----------	----------	----------	----------
0.5	1.42	A	110	85	470	17,200	190	5	70	5	5	5	----------	----------
.5	1.78	B	45	45	235	10,720	110	----------	25	5	----------	----------	10	----------
1.0	1.42	A	65	30	165	1,570	50	----------	25	5	----------	----------	----------	----------
1.0	1.78	A	75	55	370	8,380	170	5	35	5	----------	10	----------	----------
1.0	1.78	B	35	30	180	1,000	70	----------	15	5	----------	----------	----------	----------
6.0	1.42	A	20	20	100	300	40	----------	5	----------	----------	----------	----------	----------
6.0	1.42	B	10	10	90	400	40	----------	----------	----------	----------	----------	----------	----------
6.0	1.78	A	25	15	130	1,285	60	----------	5	----------	----------	----------	----------	----------
6.0	1.78	B	20	10	105	1,010	50	----------	5	----------	----------	----------	----------	----------
11.0	.71	A	5	5	30	10	5	----------	5	----------	----------	----------	----------	----------
11.0	1.42	A	45	15	200	795	85	----------	10	5	----------	----------	----------	----------
11.0	1.42	B	25	10	115	250	40	----------	----------	----------	----------	----------	----------	----------
11.0	1.78	A	45	10	175	920	80	----------	5	5	----------	----------	----------	----------
11.0	1.78	B	25	5	105	285	50	----------	5	----------	----------	----------	----------	----------
STOICHIOMETRIC PROPANE-AIR FLAMES [2]														
0	1.42	A	120	95	425	29,150	160	5	85	5	----------	30	----------	----------
0	1.42	B	310	200	1,260	22,820	470	15	195	15	5	20	----------	----------
0	1.78	A	----------	10	50	1,280	20	----------	5	----------	----------	----------	----------	----------
0	1.78	B	10	10	100	1,050	45	----------	10	5	----------	----------	----------	----------
0.5	1.78	A	75	50	300	900	110	----------	40	5	----------	----------	----------	----------
.5	1.78	B	5	5	65	75	20	----------	5	----------	----------	----------	----------	----------
1.0	1.78	B	----------	----------	30	55	10	----------	----------	----------	----------	----------	----------	----------
RICH PROPANE-AIR FLAMES														
0	1.42	A	1,965	680	4,165	8,570	970	5	1,520	50	30	----------	10	55
0	1.42	B	520	300	1,745	7,580	530	10	485	25	10	----------	5	10

[1] Average of 2 replicates.
[2] Corrected for dilution by secondary air at 0-, 0.71-, and 1.42-inch radial positions.

371-272 O - 70 - 3

APPENDIX C.—PRODUCTS OF COMBUSTION IN METHANE-AIR FLAMES ON A FLAT-FLAME BURNER

Table C–1.—Lean methane-air flames [1]

Distance, inches		NO_x,[2] ppm	CO,[2] ppm	Total HC,[3] ppm	H_2,[2] pct	N_2+Ar,[2] pct	CO_2,[2] pct	O_2,[2] pct	Secondary O_2,[2] pct	Temp.,[4] T, °F	Residence time,[4] t, msec
Vertical	Radial										
0	0	10	1,500	0	0	86.5	9.4	4.0	3.5	2,950	0.257
0	0.71	10	2,100	0	0	86.6	9.3	3.9	3.0	2,950	.257
0	1.42	10	3,300	72,900	0	74.2	.5	17.7	3.5	2,770	.263
0	[5] 1.78	(6)	400	1,935	0	79.2	.1	20.4	(7)	1,280	1.51
0.5	0	20	400	0	0	86.6	9.4	3.9	3.3	2,920	4.13
.5	.71	30	600	0	0	86.6	9.5	3.9	3.0	2,910	4.14
.5	1.42	10	600	0	0	86.3	9.4	4.2	3.3	2,870	4.28
.5	[5] 1.78	(6)	1,400	2,345	0	80.3	1.8	17.5	(7)	1,960	27.2
1.0	0	30	300	0	0	86.4	9.5	4.2	3.1	2,940	7.99
1.0	.71	30	400	0	0	86.4	9.4	4.1	2.9	2,930	8.01
1.0	1.42	10	300	0	0	86.6	9.5	3.9	4.0	2,830	8.31
1.0	[5] 1.78	(6)	600	845	0	80.8	2.2	16.9	(7)	1,660	54.5
6.0	0	20	100	0	0	86.5	9.5	4.0	2.7	2,630	48.4
6.0	.71	30	100	0	0	86.3	9.5	4.2	3.5	2,510	49.3
6.0	[5] 1.42	10	100	[8] 30	0	82.0	3.8	14.3	11.6	1,470	59.2
6.0	[5] 1.78	(6)	100	[8] 10	0	81.3	2.6	16.1	(7)	1,270	229
11.0	0	20	0	[8] 5	0	86.1	9.4	4.5	7.8	1,990	93.6
11.0	[5] .71	10	0	[8] 5	0	81.9	3.7	14.4	11.9	1,790	96.2
11.0	[5] 1.42	10	0	[8] 5	0	81.7	3.5	14.7	12.1	1,590	109
11.0	[5] 1.78	(6)	0	[8] 5	0	81.3	2.8	15.9	(7)	1,520	393
26.0	[5] 0	10	0	0	0	82.5	4.3	13.2	10.6	1,220	254
26.0	[5] .71	10	0	0	0	82.2	4.3	13.5	10.6	1,180	259
26.0	[5] 1.42	10	0	0	0	82.2	4.2	13.6	10.9	1,150	275
26.0	[5] 1.78	(6)	100	0	0	82.3	4.2	13.5	(7)	1,110	943

[1] Corrected for dilution by secondary air.
[2] Average of 3 replicates.
[3] Total hydrocarbons, average of 3 replicates.
[4] Average of 2 replicates.
[5] Not corrected for dilution by secondary air.
[6] Not experimentally determined.
[7] Not relevant.
[8] Methane.

Table C–2.—Stoichiometric methane-air flames [1]

Distance, inches		NO_x,[2] ppm	CO,[2] ppm	Total HC,[3] ppm	H_2,[2] pct	N_2+Ar,[2] pct	CO_2,[2] pct	O_2,[2] pct	Secondary O_2,[2] pct	Temp.,[4] T, °F	Residence time,[4] t, msec
Vertical	Radial										
0	0	40	6,800	0	0	87.6	10.8	1.0	3.0	3,320	0.220
0	0.71	30	8,700	0	0.1	87.8	10.6	.6	3.1	3,320	.220
0	1.42	10	23,500	22,660	1.4	82.4	6.0	5.6	4.6	3,380	.218
0	[5] 1.78	(6)	0	0	0	79.3	.2	20.5	(7)	990	2.18
0.5	0	90	3,100	0	0	87.9	11.1	.6	3.4	3,220	3.74
.5	.71	70	4,400	0	0	87.7	11.0	.9	2.8	3,220	3.74
.5	1.42	50	2,700	0	0	87.7	11.1	.9	3.8	3,180	3.73
.5	[5] 1.78	(6)	100	0	0	79.5	.4	20.0	(7)	1,260	35.7
1.0	0	100	2,500	0	0	87.6	11.2	1.0	2.3	3,210	7.27
1.0	.71	100	3,100	0	0	87.6	11.2	.9	2.3	3,200	7.28
1.0	1.42	70	1,000	0	0	87.6	11.3	1.0	5.2	3,080	7.30
1.0	[5] 1.78	(6)	0	0	0	79.8	.7	19.5	(7)	1,250	69.3
6.0	0	230	1,400	0	0	87.9	11.3	.7	2.2	3,000	43.6
6.0	.71	210	1,100	0	0	87.7	11.3	.9	2.8	2,870	44.3
6.0	[5] 1.42	30	0	0	0	81.6	3.1	15.3	14.1	1,580	52.5
6.0	[5] 1.78	(6)	0	0	0	81.1	2.6	16.3	(7)	1,480	249
11.0	0	180	200	0	0	87.7	11.3	.9	8.6	2,200	84.7
11.0	[5] .71	60	0	0	0	81.7	3.4	14.9	13.6	1,920	87.4
11.0	[5] 1.42	40	0	0	0	81.6	3.1	15.2	14.1	1,640	97.1
11.0	[5] 1.78	(6)	0	0	0	81.7	3.2	15.1	(7)	1,550	426
26.0	0	140	0	0	0	87.8	11.3	1.4	10.3	1,380	230
26.0	[5] .71	60	0	0	0	82.9	5.1	12.1	10.7	1,330	235
26.0	[5] 1.42	60	0	0	0	82.9	5.1	12.0	10.7	1,300	243
26.0	[5] 1.78	(6)	0	0	0	82.8	5.1	12.1	(7)	1,270	998

[1] Corrected for dilution by secondary air.
[2] Average of 3 replicates.
[3] Total hydrocarbons, average of 3 replicates.
[4] Average of 2 replicates.
[5] Not corrected for dilution by secondary air.
[6] Not experimentally determined.
[7] Not relevant.

Table C–3.—Rich methane-air flames

Distance, inches		NO_x,[1] ppm	CO,[1] ppm	Total HC,[2] ppm	H_2,[1] pct	N_2+Ar,[1] pct	CO_2,[1] pct	O_2,[1] pct	Secondary O_2,[1] pct	Temp.,[3] T, °F	Residence time,[3] t, msec
Vertical	Radial										
0	0	40	40,200	0	2.6	83.7	6.9	2.7	3.8	3,280	0.344
0	0.71	50	41,100	0	2.6	83.5	7.3	2.4	3.1	3,280	.344
0	1.42	10	27,900	42,415	2.1	77.8	3.5	9.5	2.7	3,320	.343
0	1.78	(4)	100	0	0	79.6	.2	20.2	(5)	830	3.55
0.5	0	50	37,500	0	2.5	83.8	7.3	2.7	3.6	3,160	3.79
.5	.71	50	36,900	0	2.4	84.1	7.6	2.2	3.3	3,160	3.78
.5	1.42	60	26,100	0	1.4	85.2	8.7	2.1	3.7	3,180	3.76
.5	1.78	(4)	100	0	0	80.2	1.1	18.7	(5)	1,930	32.8
1.0	0	60	39,100	0	2.5	83.1	7.6	3.0	2.9	3,120	7.25
1.0	.71	50	37,700	0	2.4	84.0	7.8	2.1	2.9	3,120	7.24
1.0	1.42	80	13,300	0	.5	86.5	9.9	1.7	4.0	3,150	7.18
1.0	1.78	(4)	0	0	0	80.3	1.5	18.1	(5)	1,880	62.3
6.0	0	60	38,700	0	2.7	83.6	7.8	2.0	2.6	2,940	42.7
6.0	.71	60	28,700	0	1.8	84.7	8.8	1.8	2.9	2,950	42.7
6.0	1.42	50	1,100	0	0	82.5	4.3	13.0	13.5	1,910	48.6
6.0	1.78	(4)	100	0	0	81.2	3.3	15.5	(5)	1,550	241
11.0	0	60	9,000	0	.5	83.4	6.2	8.9	9.6	2,490	80.7
11.0	.71	50	5,200	0	.3	83.2	5.7	10.3	10.8	2,400	81.2
11.0	1.42	30	1,400	0	0	82.5	4.4	13.0	13.3	2,070	88.6
11.0	1.78	(4)	400	0	0	82.2	3.8	14.0	(5)	1,970	404
26.0	0	50	0	0	0	84.0	6.6	9.4	10.4	1,480	218
26.0	.71	40	0	0	0	83.8	6.3	9.9	10.8	1,430	220
26.0	1.42	40	0	0	0	83.7	6.3	9.9	10.7	1,390	227
26.0	1.78	(4)	0	0	0	83.8	6.3	9.8	(5)	1,380	961

[1] Average of 3 replicates.
[2] Total hydrocarbons, average of 3 replicates.
[3] Average of 2 replicates.
[4] Not experimentally determined.
[5] Not relevant.

APPENDIX D.—HYDROCARBONS IN PRODUCTS OF COMBUSTION IN METHANE-AIR FLAMES ON A FLAT-FLAME BURNER

Distance, inches		Hydrocarbons, ppm [1]					
Vertical	Radial	CH_4	C_2H_6	C_2H_4	C_3H_8	C_3H_6	C_2H_2
		LEAN METHANE-AIR FLAMES [2]					
0	1.42	72,510	260	100	25	----------	5
0	1.78	1,915	15	5	----------	----------	----------
0.5	1.78	2,315	20	10	----------	----------	----------
1.0	1.78	830	10	5	----------	----------	----------
		STOICHIOMETRIC METHANE-AIR FLAMES [2]					
0	1.42	21,085	830	595	20	5	125
		RICH METHANE-AIR FLAMES					
0	1.42	40,280	1,060	750	25	10	290

[1] Average of 3 replicates.
[2] Corrected for dilution by secondary air at the 1.42-inch radial position.

APPENDIX E.—THERMODYNAMIC EQUILIBRIUM CONCENTRATIONS OF PRODUCTS IN LEAN, STOICHIOMETRIC, AND RICH METHANE-AIR FLAMES

Temp., °F	Concentration, mole fraction											
	Ar	CO	CO_2	H	H_2	H_2O	NO	N_2	N	O	OH	O_2
	FRACTION OF STOICHIOMETRIC=0.832											
2,420	0.00859	0.00001	0.07920	----------	0.00001	0.15780	0.00080	0.71881	----------	0.00000	0.00012	0.03465
2,780	.00859	.00009	.07910	0.00000	.00005	.15756	.00169	.71825	----------	.00002	.00046	.03417
3,140	.00858	.00059	.07856	.00003	.00025	.15678	.00307	.71709	0.00000	.00013	.00139	.03353
3,500	.00856	.00261	.07636	.00018	.00100	.15460	.00501	.71453	.00001	.00054	.00341	.03320
3,860	.00851	.00831	.07018	.00087	.00301	.14941	.00764	.70893	.00003	.00173	.00719	.03416
	FRACTION OF STOICHIOMETRIC=1.00											
2,420	0.00844	0.00018	0.09490	0.00000	0.00012	0.18947	0.00005	0.70672	----------	----------	0.00003	0.00012
2,780	.00843	.00088	.09414	.00001	.00045	.18895	.00021	.70623	----------	0.00000	.00018	.00052
3,140	.00842	.00306	.09180	.00006	.00135	.18743	.00068	.70477	0.00000	.00003	.00072	.00168
3,500	.00838	.00821	.08625	.00032	.00330	.18380	.00178	.70125	.00001	.00019	.00223	.00429
3,860	.00831	.01765	.07599	.00133	.00697	.17633	.00386	.69414	.00003	.00088	.00558	.00888
	FRACTION OF STOICHIOMETRIC=1.20											
2,420	0.00794	0.04226	0.06699	0.00001	0.03699	0.18099	----------	0.66482	----------	----------	0.00000	----------
2,780	.00794	.04552	.06373	.00007	.03371	.18423	0.00000	.66479	----------	----------	.00002	----------
3,140	.00794	.04786	.06136	.00029	.03132	.18640	.00003	.66465	0.00000	0.00000	.00015	0.00000
3,500	.00793	.04979	.05935	.00097	.02961	.18729	.00020	.66402	.00001	.00002	.00076	.00006
3,860	.00791	.05221	.05660	.00271	.02909	.18523	.00095	.66164	.00003	.00022	.00287	.00056

Source: Smith (*67*).

APPENDIX F.—THERMODYNAMIC EQUILIBRIUM CONCENTRATIONS OF PRODUCTS IN PROPANE-AIR FLAMES

Table F–1.—0.85 stoichiometric propane-air flame [1]

Temp., °F	Concentration, mole fraction										
	Ar	CO	CO_2	H	H_2	H_2O	NO	N_2	O	OH	O_2
4,310	0.00847	0.02801	0.06870	0.00392	0.00706	0.11195	0.01200	0.70357	0.00546	0.01525	0.03559
4,220	.00851	.02389	.07326	.00294	.00592	.11513	.01094	.70734	.00429	.01331	.03445
4,130	.00855	.02003	.07752	.00217	.00490	.11795	.00994	.71071	.00335	.01153	.03335
4,040	.00858	.01648	.08142	.00158	.00400	.12040	.00901	.71369	.00259	.00991	.03234
3,950	.00860	.01330	.08489	.00114	.00323	.12252	.00815	.71629	.00198	.00846	.03143
3,860	.00862	.01052	.08792	.00080	.00256	.12434	.00735	.71854	.00151	.00717	.03067
3,770	.00864	.00815	.09050	.00056	.00200	.12587	.00661	.72045	.00114	.00604	.03004
3,680	.00866	.00618	.09264	.00038	.00154	.12714	.00594	.72206	.00085	.00504	.02957
3,590	.00867	.00459	.09437	.00025	.00116	.12820	.00532	.72339	.00063	.00418	.02923
3,500	.00868	.00334	.09573	.00016	.00087	.12906	.00475	.72448	.00046	.00343	.02902
3,410	.00869	.00238	.09678	.00011	.00063	.12976	.00423	.72537	.00033	.00280	.02892
3,320	.00869	.00166	.09757	.00007	.00045	.13031	.00375	.72610	.00023	.00225	.02890
3,230	.00870	.00113	.09814	.00004	.00032	.13075	.00331	.72668	.00016	.00180	.02895
3,140	.00870	.00075	.09856	.00002	.00022	.13110	.00291	.72716	.00011	.00142	.02905
3,050	.00870	.00049	.09885	.00001	.00015	.13137	.00253	.72754	.00008	.00111	.02917
2,960	.00870	.00031	.09905	.00001	.00010	.13158	.00219	.72785	.00005	.00085	.02930
2,870	.00871	.00019	.09918	.00000	.00006	.13173	.00188	.72811	.00003	.00064	.02945
2,780	.00871	.00012	.09927	------	.00004	.13185	.00160	.72832	.00002	.00048	.02959
2,690	.00871	.00007	.09932	------	.00003	.13194	.00135	.72850	.00001	.00035	.02972
2,600	.00871	.00004	.09935	------	.00002	.13201	.00113	.72864	.00001	.00025	.02984
2,510	.00871	.00002	.09938	------	.00001	.13206	.00093	.72877	.00000	.00018	.02995
2,420	.00871	.00001	.09939	------	.00001	.13209	.00076	.72887	------	.00012	.03004
2,330	.00871	.00001	.09939	------	.00000	.13212	.00061	.72895	------	.00008	.03012
2,240	.00871	.00000	.09940	------	------	.13213	.00048	.72902	------	.00005	.03019
2,150	.00871	------	.09940	------	------	.13214	.00038	.72908	------	.00003	.03025
2,060	.00871	------	.09940	------	------	.13215	.00029	.72913	------	.00002	.03030
1,970	.00871	------	.09940	------	------	.13216	.00022	.72917	------	.00001	.03033
1,880	.00871	------	.09940	------	------	.13216	.00016	.72920	------	.00001	.03036
1,790	.00871	------	.09940	------	------	.13216	.00011	.72922	------	.00000	.03039
1,700	.00871	------	.09940	------	------	.13216	.00008	.72924	------	------	.03041
1,610	.00871	------	.09940	------	------	.13216	.00005	.72925	------	------	.03042
1,520	.00871	------	.09940	------	------	.13216	.00003	.72926	------	------	.03043
1,430	.00871	------	.09940	------	------	.13216	.00002	.72927	------	------	.03044
1,340	.00871	------	.09940	------	------	.13216	.00001	.72927	------	------	.03044
1,250	.00871	------	.09940	------	------	.13216	.00001	.72927	------	------	.03044
1,160	.00871	------	.09940	------	------	.13216	.00000	.72928	------	------	.03044
1,070	.00871	------	.09940	------	------	.13216	------	.72928	------	------	.03045
980	.00871	------	.09940	------	------	.13216	------	.72928	------	------	.03045
890	.00871	------	.09940	------	------	.13216	------	.72928	------	------	.03045

[1] Additional products which were considered but whose mole fractions were less than 0.000005 for all assigned conditions were

C(G)	CH(G)	CH_2(G)	CH_3(G)	CH_4(G)	CN(G)	CN_2(G)	C_2(G)	C_2H(G)	C_2H_2(G)
C_2H_4(G)	C_2N_2(G)	C_2O(G)	C_3(G)	HCN(G)	HCO(G)	HO_2(G)	N(G)	NH(G)	NH_2(G)
NH_3(G)	NO_2(G)	N_2C(G)	N_2H_4(G)	N_2O(G)	N_2O_4(G)	H_2O(S)	H_2O(L)	C(S).	

Table F–2.—0.85 stoichiometric propane-air flame plus 15 percent flue gas A [1]

Temp., ° F	Concentration, mole fraction										
	Ar	CO	CO_2	H	H_2	H_2O	NO	N_2	O	OH	O_2
4,310	0.00740	0.02971	0.07005	0.00372	0.00637	0.09712	0.01169	0.72187	0.00524	0.01393	0.03289
4,220	.00743	.02543	.07477	.00280	.00536	.09998	.01063	.72566	.00411	.01214	.03167
4,130	.00746	.02140	.07920	.00207	.00446	.10252	.00963	.72906	.00320	.01051	.03049
4,040	.00749	.01768	.08327	.00151	.00365	.10473	.00870	.73208	.00247	.00903	.02938
3,950	.00751	.01433	.08693	.00109	.00295	.10665	.00784	.73473	.00189	.00770	.02838
3,860	.00753	.01138	.09013	.00077	.00235	.10830	.00705	.73702	.00143	.00652	.02752
3,770	.00755	.00886	.09288	.00053	.00185	.10969	.00633	.73897	.00107	.00548	.02680
3,680	.00756	.00675	.09517	.00036	.00142	.11085	.00567	.74062	.00080	.00457	.02623
3,590	.00757	.00503	.09703	.00024	.00108	.11181	.00506	.74198	.00059	.00378	.02581
3,500	.00758	.00367	.09851	.00016	.00081	.11260	.00452	.74310	.00043	.00311	.02553
3,410	.00759	.00262	.09965	.00010	.00059	.11323	.00401	.74401	.00031	.00253	.02536
3,320	.00759	.00183	.10051	.00006	.00042	.11374	.00356	.74474	.00022	.00204	.02528
3,230	.00760	.00125	.10114	.00004	.00030	.11414	.00314	.74533	.00015	.00163	.02529
3,140	.00760	.00083	.10159	.00002	.00021	.11446	.00275	.74581	.00011	.00128	.02534
3,050	.00760	.00054	.10191	.00001	.00014	.11470	.00240	.74619	.00007	.00100	.02543
2,960	.00760	.00035	.10213	.00001	.00009	.11489	.00207	.74650	.00005	.00077	.02555
2,870	.00760	.00021	.10227	.00000	.00006	.11503	.00178	.74675	.00003	.00058	.02567
2,780	.00760	.00013	.10237	----------	.00004	.11514	.00152	.74695	.00002	.00043	.02579
2,690	.00760	.00008	.10243	----------	.00002	.11522	.00128	.74712	.00001	.00032	.02591
2,600	.00760	.00004	.10247	----------	.00001	.11528	.00107	.74726	.00001	.00023	.02602
2,510	.00760	.00002	.10249	----------	.00001	.11533	.00088	.74738	.00000	.00016	.02612
2,420	.00760	.00001	.10250	----------	.00000	.11536	.00072	.74748	----------	.00011	.02621
2,330	.00760	.00001	.10251	----------	----------	.11538	.00058	.74756	----------	.00008	.02628
2,240	.00760	.00000	.10251	----------	----------	.11539	.00046	.74762	----------	.00005	.02635
2,150	.00760	----------	.10252	----------	----------	.11541	.00036	.74768	----------	.00003	.02640
2,060	.00760	----------	.10252	----------	----------	.11541	.00027	.74772	----------	.00002	.02645
1,970	.00760	----------	.10252	----------	----------	.11542	.00020	.74776	----------	.00001	.02648
1,880	.00760	----------	.10252	----------	----------	.11542	.00015	.74779	----------	.00001	.02651
1,790	.00760	----------	.10252	----------	----------	.11542	.00011	.74781	----------	.00000	.02653
1,700	.00760	----------	.10252	----------	----------	.11542	.00007	.74783	----------	----------	.02655
1,610	.00760	----------	.10252	----------	----------	.11542	.00005	.74784	----------	----------	.02656
1,520	.00760	----------	.10252	----------	----------	.11542	.00003	.74785	----------	----------	.02657
1,430	.00760	----------	.10252	----------	----------	.11542	.00002	.74785	----------	----------	.02658
1,340	.00760	----------	.10252	----------	----------	.11542	.00001	.74786	----------	----------	.02658
1,250	.00760	----------	.10252	----------	----------	.11542	.00001	.74786	----------	----------	.02659
1,160	.00760	----------	.10252	----------	----------	.11542	.00000	.74786	----------	----------	.02659
1,070	.00760	----------	.10252	----------	----------	.11542	----------	.74786	----------	----------	.02659
980	.00760	----------	.10252	----------	----------	.11542	----------	.74786	----------	----------	.02659
890	.00760	----------	.10252	----------	----------	.11542	----------	.74786	----------	----------	.02659

[1] Additional products which were considered but whose mole fractions were less than 0.000005 for all assigned conditions were

C(G)	CH(G)	CH_2(G)	CH_3(G)	CH_4(G)	CN(G)	CN_2(G)	C_2(G)	C_2H(G)	C_2H_2(G)
C_2H_4(G)	C_2N_2(G)	C_2O(G)	C_3(G)	HCN(G)	HCO(G)	HO_2(G)	N(G)	NH(G)	NH_2(G)
NH_3(G)	NO_2(G)	N_2C(G)	N_2H_4(G)	N_2O(G)	N_2O_4(G)	H_2O(S)	H_2O(L)	C(S).	

Table F–3.—0.85 stoichiometric propane-air flame plus 15 percent flue gas B [1]

(Overall stoichiometry equals 0.78)

Temp., ° F	Concentration, mole fraction										
	Ar	CO	CO	H	H_2	H_2O	NO	N_2	O	OH	O_2
4,310	0.00742	0.02524	0.06721	0.00351	0.00568	0.09771	0.01316	0.71733	0.00592	0.01485	0.04198
4,220	.00745	.02134	.07150	.00263	.00473	.10050	.01207	.72096	.00469	.01300	.04113
4,130	.00748	.01773	.07546	.00194	.00389	.10296	.01104	.72421	.00368	.01129	.04032
4,040	.00750	.01445	.07904	.00141	.00316	.10510	.01006	.72707	.00286	.00974	.03960
3,950	.00752	.01156	.08219	.00101	.00253	.10695	.00915	.72956	.00221	.00834	.03898
3,860	.00754	.00907	.08490	.00071	.00199	.10852	.00830	.73169	.00169	.00709	.03848
3,770	.00755	.00697	.08718	.00049	.00155	.10985	.00751	.73351	.00128	.00599	.03810
3,680	.00757	.00525	.08905	.00033	.00119	.11096	.00678	.73504	.00096	.00501	.03786
3,590	.00757	.00388	.09054	.00022	.00089	.11188	.00610	.73631	.00071	.00416	.03773
3,500	.00758	.00281	.09170	.00014	.00066	.11263	.00547	.73736	.00052	.00342	.03769
3,410	.00759	.00199	.09259	.00009	.00048	.11324	.00488	.73822	.00038	.00279	.03774
3,320	.00759	.00139	.09325	.00006	.00035	.11373	.00433	.73893	.00027	.00225	.03784
3,230	.00760	.00094	.09374	.00004	.00024	.11413	.00383	.73951	.00019	.00180	.03799
3,140	.00760	.00063	.09408	.00002	.00017	.11444	.00336	.73999	.00013	.00142	.03816
3,050	.00760	.00041	.09433	.00001	.00011	.11468	.00293	.74038	.00009	.00111	.03834
2,960	.00760	.00026	.09449	.00001	.00008	.11487	.00254	.74071	.00006	.00085	.03853
2,870	.00760	.00016	.09460	.00000	.00005	.11502	.00218	.74099	.00004	.00065	.03871
2,780	.00760	.00010	.09468	----------	.00003	.11513	.00185	.74122	.00002	.00048	.03889
2,690	.00760	.00006	.09472	----------	.00002	.11521	.00156	.74141	.00001	.00035	.03904
2,600	.00760	.00003	.09475	----------	.00001	.11527	.00130	.74157	.00001	.00025	.03919
2,510	.00760	.00002	.09477	----------	.00001	.11532	.00108	.74171	.00001	.00018	.03931
2,420	.00760	.00001	.09478	----------	.00000	.11535	.00088	.74182	.00000	.00012	.03942
2,330	.00760	.00000	.09479	----------	----------	.11538	.00071	.74192	----------	.00008	.03952
2,240	.00760	----------	.09479	----------	----------	.11539	.00056	.74200	----------	.00005	.03960
2,150	.00760	----------	.09479	----------	----------	.11540	.00044	.74207	----------	.00003	.03966
2,060	.00760	----------	.09479	----------	----------	.11541	.00033	.74212	----------	.00002	.03972
1,970	.00760	----------	.09479	----------	----------	.11542	.00025	.74216	----------	.00001	.03976
1,880	.00760	----------	.09479	----------	----------	.11542	.00018	.74220	----------	.00001	.03980
1,790	.00760	----------	.09479	----------	----------	.11542	.00013	.74222	----------	.00000	.03982
1,700	.00760	----------	.09479	----------	----------	.11542	.00009	.74224	----------	----------	.03984
1,610	.00760	----------	.09479	----------	----------	.11542	.00006	.74226	----------	----------	.03986
1,520	.00760	----------	.09479	----------	----------	.11542	.00004	.74227	----------	----------	.03987
1,430	.00760	----------	.09479	----------	----------	.11542	.00003	.74228	----------	----------	.03988
1,340	.00760	----------	.09479	----------	----------	.11542	.00001	.74228	----------	----------	.03988
1,250	.00760	----------	.09479	----------	----------	.11542	.00001	.74229	----------	----------	.03989
1,160	.00760	----------	.09479	----------	----------	.11542	.00000	.74229	----------	----------	.03989
1,070	.00760	----------	.09479	----------	----------	.11542	----------	.74229	----------	----------	.03989
980	.00760	----------	.09479	----------	----------	.11542	----------	.74229	----------	----------	.03989
890	.00760	----------	.09479	----------	----------	.11542	----------	.74229	----------	----------	.03989

[1] Additional products which were considered but whose mole fractions were less than 0.000005 for all assigned conditions were

C(G)	CH(G)	CH_2(G)	CH_3(G)	CH_4(G)	CN(G)	CN_2(G)	C_2(G)	C_2H(G)	C_2H_2(G)
C_2H_4(G)	C_2N_2(G)	C_2O(G)	C_3(G)	HCN(G)	HCO(G)	HO_2(G)	N(G)	NH(G)	NH_2(G)
NH_3(G)	NO_2(G)	N_2C(G)	N_2H_4(G)	N_2O(G)	N_2O_4(G)	H_2O(S)	H_2O(L)	C(S).	

Table F–4.—Stoichiometric propane-air flame [1]

Temp., °F	Concentration, mole fraction										
	Ar	CO	CO_2	H	H_2	H_2O	NO	N_2	O	OH	O_2
4,310	0.00830	0.04093	0.07118	0.00498	0.01142	0.12835	0.00843	0.69088	0.00387	0.01375	0.01790
4,220	.00834	.03641	.07627	.00381	.00995	.13214	.00741	.69488	.00293	.01178	.01608
4,130	.00838	.03203	.08115	.00288	.00861	.13551	.00645	.69851	.00219	.01000	.01428
4,040	.00841	.02787	.08578	.00215	.00739	.13850	.00557	.70178	.00161	.00839	.01255
3,950	.00844	.02396	.09008	.00159	.00631	.14111	.00476	.70470	.00117	.00697	.01090
3,860	.00847	.02037	.09404	.00116	.00535	.14339	.00403	.70729	.00083	.00573	.00935
3,770	.00849	.01710	.09762	.00083	.00450	.14536	.00337	.70956	.00058	.00465	.00793
3,680	.00851	.01419	.10080	.00059	.00375	.14704	.00280	.71153	.00040	.00373	.00665
3,590	.00853	.01162	.10360	.00041	.00310	.14847	.00229	.71322	.00027	.00296	.00551
3,500	.00854	.00939	.10603	.00028	.00255	.14968	.00186	.71466	.00018	.00232	.00451
3,410	.00856	.00749	.10810	.00019	.00207	.15068	.00149	.71586	.00012	.00180	.00364
3,320	.00857	.00589	.10983	.00013	.00167	.15151	.00118	.71687	.00007	.00137	.00291
3,230	.00858	.00456	.11127	.00008	.00133	.15220	.00093	.71769	.00005	.00103	.00229
3,140	.00858	.00348	.11245	.00005	.00104	.15275	.00072	.71836	.00003	.00076	.00178
3,050	.00859	.00261	.11339	.00003	.00081	.15319	.00055	.71890	.00002	.00056	.90137
2,960	.00859	.00192	.11414	.00002	.00062	.15354	.00041	.71932	.00001	.00040	.00104
2,870	.00859	.00139	.11471	.00001	.00047	.15382	.00030	.71965	.00001	.00028	.00077
2,780	.00860	.00098	.11516	.00001	.00035	.15403	.00022	.71990	.00000	.00019	.00057
2,690	.00860	.00067	.11549	.00000	.00025	.15419	.00016	.72009	------	.00013	.00042
2,600	.00860	.00045	.11573	------	.00018	.15431	.00011	.72022	------	.00009	.00031
2,510	.00860	.00029	.11590	------	.00012	.15440	.00008	.72033	------	.00006	.00022
2,420	.00860	.00018	.11602	------	.00008	.15447	.00006	.72040	------	.00004	.00016
2,330	.00860	.00010	.11610	------	.00005	.15451	.00004	.72044	------	.00002	.00012
2,240	.00860	.00006	.11615	------	.00003	.15454	.00003	.72048	------	.00001	.00010
2,150	.00860	.00003	.11618	------	.00002	.15456	.00002	.72050	------	.00001	.00008
2,060	.00860	.00001	.11620	------	.00001	.15457	.00001	.72051	------	.00001	.00007
1,970	.00860	.00001	.11621	------	.00000	.15458	.00001	.72052	------	.00000	.00007
1,880	.00860	.00000	.11621	------	------	.15458	.00001	.72052	------	------	.00007
1,790	.00860	------	.11622	------	------	.15459	.00001	.72052	------	------	.00007
1,700	.00860	------	.11622	------	------	.15459	.00000	.72052	------	------	.00007
1,610	.00860	------	.11622	------	------	.15459	------	.72052	------	------	.00007
1,520	.00860	------	.11622	------	------	.15459	------	.72052	------	------	.00007
1,430	.00860	------	.11622	------	------	.15459	------	.72052	------	------	.00007
1,340	.00860	------	.11622	------	------	.15459	------	.72052	------	------	.00007
1,250	.00860	------	.11622	------	------	.15459	------	.72052	------	------	.00007
1,160	.00860	------	.11622	------	------	.15459	------	.72052	------	------	.00007
1,070	.00860	------	.11622	------	------	.15459	------	.72052	------	------	.00007
980	.00860	------	.11622	------	------	.15459	------	.72052	------	------	.00007
890	.00860	------	.11622	------	------	.15459	------	.72052	------	------	.00007

[1] Additional products which were considered but whose mole fractions were less than 0.000005 for all assigned conditions were

C(G)	CH(G)	CH_2(G)	CH_3(G)	CH_4(G)	CN(G)	CN_2(G)	C_2(G)	C_2H(G)	C_2H_2(G)
C_2H_4(G)	C_2N_2(G)	C_2O(G)	C_3(G)	HCN(G)	HCO(G)	HO_2(G)	N(G)	NH(G)	NH_2(G)
NH_3(G)	NO_2(G)	N_2C(G)	N_2H_4(G)	N_2O(G)	N_2O_4(G)	H_2O(S)	H_2O(L)	C(S).	

Table F–5.—Stoichiometric propane-air flame plus 15 percent flue gas A [1]

Temp., °F	Concentration, mole fraction										
	Ar	CO	CO_2	H	H_2	H_2O	NO	N_2	O	OH	O_2
4,310	0.00726	0.04151	0.07165	0.00467	0.01001	0.11172	0.00849	0.71043	0.00384	0.01278	0.01763
4,220	.00730	.03692	.07679	.00357	.00873	.11510	.00746	.71441	.00291	.01096	.01585
4,130	.00733	.03248	.08173	.00270	.00755	.11811	.00650	.71803	.00218	.00930	.01409
4,040	.00736	.02826	.08640	.00202	.00649	.12077	.00561	.72130	.00160	.00781	.01238
3,950	.00738	.02430	.09076	.00149	.00554	.12311	.00479	.72422	.00116	.00649	.01075
3,860	.00740	.02066	.09476	.00108	.00470	.12514	.00405	.72681	.00083	.00533	.00923
3,770	.00742	.01735	.09837	.00078	.00395	.12689	.00340	.72909	.00058	.00433	.00783
3,680	.00744	.01439	.10159	.00055	.00330	.12840	.00282	.73107	.00040	.00348	.00657
3,590	.00746	.01179	.10443	.00039	.00273	.12967	.00231	.73277	.00027	.00276	.00544
3,500	.00747	.00953	.10688	.00027	.00224	.13074	.00187	.73421	.00018	.00216	.00445
3,410	.00748	.00760	.10897	.00018	.00182	.13164	.00150	.73543	.00012	.00167	.00359
3,320	.00749	.00598	.11073	.00012	.00147	.13238	.00119	.73644	.00007	.00128	.00286
3,230	.00749	.00464	.11218	.00008	.00117	.13298	.00093	.73727	.00005	.00096	.00225
3,140	.00750	.00354	.11337	.00005	.00092	.13347	.00072	.73794	.00003	.00071	.00175
3,050	.00751	.00265	.11433	.00003	.00071	.13387	.00055	.73848	.00002	.00052	.00134
2,960	.00751	.00196	.11508	.00002	.00055	.13418	.00041	.73890	.00001	.00037	.00101
2,870	.00751	.00141	.11567	.00001	.00041	.13442	.00030	.73923	.00001	.00026	.00076
2,780	.00751	.00100	.11612	.00001	.00031	.13461	.00022	.73949	.00000	.00018	.00056
2,690	.00752	.00069	.11645	.00000	.00022	.13475	.00016	.73968	----------	.00012	.00041
2,600	.00752	.00046	.11670	----------	.00016	.13486	.00011	.73982	----------	.00008	.00029
2,510	.00752	.00030	.11687	----------	.00011	.13494	.00008	.73992	----------	.00005	.00021
2,420	.00752	.00019	.11700	----------	.00007	.13500	.00005	.73999	----------	.00003	.00015
2,330	.00752	.00011	.11708	----------	.00005	.13504	.00004	.74004	----------	.00002	.00011
2,240	.00752	.00006	.11713	----------	.00003	.13506	.00003	.74007	----------	.00001	.00009
2,150	.00752	.00003	.11716	----------	.00001	.13508	.00002	.74009	----------	.00001	.00007
2,060	.00752	.00001	.11718	----------	.00001	.13509	.00001	.74010	----------	.00000	.00006
1,970	.00752	.00001	.11719	----------	.00000	.13510	.00001	.74011	----------	----------	.00006
1,880	.00752	.00000	.11719	----------	----------	.13510	.00001	.74011	----------	----------	.00006
1,790	.00752	----------	.11720	----------	----------	.13510	.00001	.74011	----------	----------	.00006
1,700	.00752	----------	.11720	----------	----------	.13510	.00000	.74012	----------	----------	.00006
1,610	.00752	----------	.11720	----------	----------	.13510	----------	.74012	----------	----------	.00006
1,520	.00752	----------	.11720	----------	----------	.13510	----------	.74012	----------	----------	.00006
1,430	.00752	----------	.11720	----------	----------	.13510	----------	.74012	----------	----------	.00006
1,340	.00752	----------	.11720	----------	----------	.13510	----------	.74012	----------	----------	.00006
1,250	.00752	----------	.11720	----------	----------	.13510	----------	.74012	----------	----------	.00006
1,160	.00752	----------	.11720	----------	----------	.13510	----------	.74012	----------	----------	.00006
1,070	.00752	----------	.11720	----------	----------	.13510	----------	.74012	----------	----------	.00006
980	.00752	----------	.11720	----------	----------	.13510	----------	.74012	----------	----------	.00006
890	.00752	----------	.11720	----------	----------	.13510	----------	.74012	----------	----------	.00006

[1] Additional products which were considered but whose mole fractions were less than 0.000005 for all assigned conditions were

C(G)	CH(G)	CH_2(G)	CH_3(G)	CH_4(G)	CN(G)	CN_2(G)	C_2(G)	C_2H(G)	C_2H_2(G)
C_2H_4(G)	C_2N_2(G)	C_2O(G)	C_3(G)	HCN(G)	HCO(G)	HO_2(G)	N(G)	NH(G)	NH_2(G)
NH_3(G)	NO_2(G)	N_2C(G)	N_2H_4(G)	N_2O(G)	N_2O_4(G)	H_2O(S)	H_2O(L)	C(S).	

Table F–6.—Stoichiometric propane-air flame plus 15 percent flue gas B [1]

(Overall stoichiometry equals 0.92)

Temp., °F	Concentration, mole fraction										
	Ar	CO	CO_2	H	H_2	H_2O	NO	N_2	O	OH	O_2
4,310	0.00729	0.03482	0.07133	0.00431	0.00855	0.11324	0.01005	0.70699	0.00456	0.01402	0.02484
4,220	.00732	.03031	.07635	.00326	.00730	.11659	.00901	.71093	.00353	.01214	.02326
4,130	.00735	.02598	.08114	.00244	.00616	.11956	.00804	.71450	.00270	.01043	.02170
4,040	.00738	.02191	.08561	.00179	.00514	.12218	.00714	.71769	.00205	.00888	.02021
3,950	.00741	.01816	.08972	.00130	.00424	.12446	.00632	.72053	.00154	.00750	.01882
3,860	.00743	.01478	.09343	.00093	.00344	.12644	.00557	.72301	.00114	.00629	.01754
3,770	.00745	.01178	.09669	.00065	.00275	.12812	.00490	.72515	.00084	.00524	.01642
3,680	.00746	.00919	.09951	.00045	.00217	.12955	.00431	.72698	.00061	.00433	.01544
3,590	.00748	.00701	.10188	.00030	.00168	.13073	.00378	.72851	.00044	.00355	.01464
3,500	.00749	.00522	.10382	.00020	.00127	.13171	.00331	.72977	.00032	.00289	.01399
3,410	.00750	.00379	.10537	.00013	.00095	.13250	.00290	.73080	.00023	.00234	.01350
3,320	.00750	.00269	.10657	.00008	.00069	.13313	.00254	.73162	.00016	.00187	.01315
3,230	.00751	.00186	.10747	.00005	.00049	.13362	.00222	.73226	.00011	.00149	.01292
3,140	.00751	.00125	.10814	.00003	.00034	.13401	.00194	.73276	.00008	.00117	.01278
3,050	.00751	.00082	.10860	.00002	.00023	.13430	.00168	.73315	.00005	.00091	.01272
2,960	.00752	.00052	.10893	.00001	.00016	.13452	.00145	.73345	.00003	.00070	.01271
2,870	.00752	.00033	.10914	.00001	.00010	.13469	.00124	.73369	.00002	.00053	.01274
2,780	.00752	.00020	.10929	.00000	.00006	.13481	.00106	.73387	.00001	.00039	.01279
2,690	.00752	.00012	.10938	------	.00004	.13490	.00089	.73401	.00001	.00029	.01285
2,600	.00752	.00007	.10943	------	.00002	.13496	.00075	.73413	.00001	.00021	.01291
2,510	.00752	.00004	.10947	------	.00001	.13501	.00062	.73422	.00000	.00015	.01297
2,420	.00752	.00002	.10949	------	.00001	.13504	.00050	.73429	------	.00010	.01303
2,330	.00752	.00001	.10950	------	.00000	.13506	.00040	.73435	------	.00007	.01308
2,240	.00752	.00000	.10950	------	------	.13508	.00032	.73440	------	.00004	.01313
2,150	.00752	------	.10951	------	------	.13509	.00025	.73444	------	.00003	.01316
2,060	.00752	------	.10951	------	------	.13509	.00019	.73447	------	.00002	.01320
1,970	.00752	------	.10951	------	------	.13510	.00014	.73450	------	.00001	.01322
1,880	.00752	------	.10951	------	------	.13510	.00011	.73452	------	.00001	.01324
1,790	.00752	------	.10951	------	------	.13510	.00008	.73453	------	.00000	.01326
1,700	.00752	------	.10951	------	------	.13510	.00005	.73455	------	------	.01327
1,610	.00752	------	.10951	------	------	.13510	.00004	.73456	------	------	.01328
1,520	.00752	------	.10951	------	------	.13510	.00002	.73456	------	------	.01328
1,430	.00752	------	.10951	------	------	.13510	.00001	.73457	------	------	.01329
1,340	.00752	------	.10951	------	------	.13510	.00001	.73457	------	------	.01329
1,250	.00752	------	.10951	------	------	.13510	.00000	.73457	------	------	.01329
1,160	.00752	------	.10951	------	------	.13510	------	.73457	------	------	.01329
1,070	.00752	------	.10951	------	------	.13510	------	.73457	------	------	.01329
980	.00752	------	.10951	------	------	.13510	------	.73457	------	------	.01329
890	.00752	------	.10951	------	------	.13510	------	.73457	------	------	.01329

[1] Additional products which were considered but whose mole fractions were less than 0.000005 for all assigned conditions were

C(G)	CH(G)	CH_2(G)	CH_3(G)	CH_4(G)	CN(G)	CN_2(G)	C_2(G)	C_2H(G)	C_2H_2(G)
C_2H_4(G)	C_2N_2(G)	C_2O(G)	C_3(G)	HCN(G)	HCO(G)	HO_2(G)	N(G)	NH(G)	NH_2(G)
NH_3(G)	NO_2(G)	N_2C(G)	N_2H_4(G)	N_2O(G)	N_2O_4(G)	H_2O(S)	H_2O(L)	C(S).	

Table F–7.—1.20 stoichiometric propane-air flame [1]

Temp., °F	Concentration, mole fraction												
	Ar	CO	CO_2	H	H_2	H_2O	NO	N_2	O	OH	O_2	CH_4	NH_3
4,310	0.00800	0.06869	0.06197	0.00725	0.02416	0.14090	0.00430	0.66753	0.00201	0.01038	0.00482		
4,220	.00803	.06595	.06523	.00580	.02302	.14442	.00344	.67067	.00138	.00847	.00358	------	------
4,130	.00806	.06356	.06807	.00462	.02213	.14733	.00268	.67330	.00093	.00678	.00255	------	------
4,040	.00808	.06155	.07044	.00367	.02149	.14965	.00203	.67545	.00060	.00532	.00173	------	------
3,950	.00809	.05991	.07235	.00290	.02108	.15143	.00150	.67715	.00038	.00409	.00112	------	------
3,860	.00811	.05862	.07385	.00229	.02087	.15273	.00108	.67845	.00023	.00309	.00070	------	------
3,770	.00812	.05762	.07502	.00179	.02083	.15363	.00075	.67942	.00013	.00228	.00041	------	------
3,680	.00812	.05682	.07592	.00139	.02092	.15420	.00051	.68013	.00008	.00166	.00024	------	------
3,590	.00813	.05618	.07665	.00107	.02112	.15451	.00034	.68064	.00004	.00118	.00013	------	------
3,500	.00813	.05563	.07726	.00082	.02139	.15462	.00022	.68100	.00002	.00083	.00007	------	------
3,410	.00814	.05513	.07780	.00062	.02172	.15458	.00014	.68126	.00001	.00057	.00003	------	------
3,320	.00814	.05466	.07830	.00046	.02211	.15440	.00009	.68144	.00001	.00038	.00002	------	------
3,230	.00814	.05419	.07880	.00034	.02253	.15413	.00005	.68156	.00000	.00025	.00001	------	------
3,140	.00814	.05370	.07930	.00025	.02300	.15378	.00003	.68164	------	.00016	.00000	------	------
3,050	.00814	.05318	.07982	.00017	.02350	.15335	.00002	.68170	------	.00010	------	------	------
2,960	.00814	.05264	.08038	.00012	.02405	.15286	.00001	.68174	------	.00006	------	------	------
2,870	.00814	.05205	.08097	.00008	.02464	.15231	.00001	.68177	------	.00004	------	------	------
2,780	.00814	.05142	.08160	.00006	.02528	.15169	.00000	.68178	------	.00002	------	------	------
2,690	.00814	.05073	.08229	.00004	.02597	.15102	------	.68179	------	.00001	------	------	------
2,600	.00814	.04998	.08304	.00002	.02672	.15028	------	.68180	------	.00001	------	------	------
2,510	.00814	.04917	.08385	.00002	.02754	.14947	------	.68181	------	.00000	------	------	------
2,420	.00814	.04829	.08474	.00001	.02842	.14859	------	.68181	------	------	------	------	------
2,330	.00814	.04732	.08570	.00001	.02939	.14763	------	.68181	------	------	------	------	------
2,240	.00814	.04626	.08676	.00000	.03045	.14657	------	.68181	------	------	------	------	------
2,150	.00814	.04511	.08792	------	.03161	.14541	------	.68181	------	------	------	------	------
2,060	.00814	.04384	.08919	------	.03288	.14414	------	.68181	------	------	------	------	------
1,970	.00814	.04244	.09059	------	.03428	.14274	------	.68181	------	------	------	------	------
1,880	.00814	.04090	.09213	------	.03581	.14121	------	.68181	------	------	------	------	------
1,790	.00814	.03921	.09382	------	.03751	.13951	------	.68181	------	------	------	------	------
1,700	.00814	.03734	.09569	------	.03937	.13764	------	.68181	------	------	------	------	------
1,610	.00814	.03528	.09775	------	.04143	.13559	------	.68181	------	------	------	------	------
1,520	.00814	.03302	.10001	------	.04370	.13332	------	.68181	------	------	------	------	------
1,430	.00814	.03053	.10250	------	.04618	.13083	------	.68181	------	------	------	------	------
1,340	.00814	.02781	.10522	------	.04889	.12812	------	.68182	------	------	------	------	0.00000
1,250	.00814	.02485	.10817	------	.05183	.12517	------	.68182	------	------	------	------	0.00001
1,160	.00814	.02167	.11134	------	.05494	.12203	------	.68185	------	------	------	0.00000	0.00001
1,070	.00814	.01822	.11471	------	.05792	.11882	------	.68200	------	------	------	0.00002	0.00001
980	.00816	.01419	.11823	------	.05924	.11635	------	.68297	------	------	------	0.00014	0.00002
890	.00820	.00901	.12135	------	.05362	.11734	------	.68679	------	------	------	0.00084	0.00004
												0.00364	0.00005

[1] Additional products which were considered but whose mole fractions were less than 0.000005 for all assigned conditions were

C(G)	CH(G)	CH_2(G)	CH_3(G)	CN(G)	CN_2(G)	C_2(G)	C_2H(G)	C_2H_2(G)
C_2H_4(G)	C_2N_2(G)	C_2O(G)	C_3(G)	HCN(G)	HCO(G)	HO_2(G)	N(G)	NH(G)
NH_2(G)	NO_2(G)	N_2C(G)	N_2H_4(G)	N_2O(G)	N_2O_4(G)	H_2O(S)	H_2O(L)	C(S).

Table F–8.—1.20 stoichiometric propane-air flame plus 15 percent flue gas A [1]

Temp., °F	Concentration, mole fraction												
	Ar	CO	CO_2	H	H_2	H_2O	NO	N_2	O	OH	O_2	CH_4	NH_3
4,310	0.00703	0.06588	0.06363	0.00659	0.01994	0.12448	0.00468	0.69002	0.00215	0.01009	0.00552		
4,220	.00705	.06282	.06722	.00524	.01883	.12778	.00378	.69329	.00150	.00828	.00419		
4,130	.00708	.06011	.07038	.00416	.01794	.13055	.00298	.69608	.00101	.00667	.00305		
4,040	.00710	.05779	.07307	.00329	.01726	.13279	.00228	.69838	.00066	.00527	.00212		
3,950	.00711	.05589	.07525	.00259	.01680	.13455	.00170	.70022	.00042	.00407	.00140		
3,860	.00713	.05439	.07698	.00204	.01652	.13585	.00123	.70165	.00026	.00309	.00088		
3,770	.00713	.05323	.07830	.00159	.01641	.13678	.00087	.70272	.00015	.00229	.00053		
3,680	.00714	.05235	.07930	.00124	.01644	.13738	.00059	.70350	.00009	.00167	.00030		
3,590	.00715	.05166	.08008	.00095	.01657	.13774	.00040	.70406	.00005	.00119	.00017		
3,500	.00715	.05110	.08070	.00073	.01678	.13789	.00026	.70445	.00003	.00083	.00009		
3,410	.00715	.05062	.08122	.00055	.01704	.13789	.00016	.70473	.00001	.00057	.00005		
3,320	.00715	.05018	.08169	.00041	.01736	.13778	.00010	.70491	.00001	.00039	.00002		
3,230	.00715	.04976	.08213	.00030	.01772	.13756	.00006	.70504	.00000	.00025	.00001		
3,140	.00715	.04933	.08258	.00022	.01811	.13727	.00004	.70513	----------	.00016	.00000		
3,050	.00716	.04888	.08303	.00016	.01854	.13691	.00002	.70519	----------	.00010			
2,960	.00716	.04841	.08351	.00011	.01901	.13650	.00001	.70523	----------	.00006			
2,870	.00716	.04790	.08402	.00007	.01952	.13602	.00001	.70526	----------	.00004			
2,780	.00716	.04735	.08457	.00005	.02007	.13550	.00000	.70527	----------	.00002			
2,690	.00716	.04676	.08517	.00003	.02066	.13492	----------	.70528	----------	.00001			
2,600	.00716	.04611	.08582	.00002	.02131	.13428	----------	.70529	----------	.00001			
2,510	.00716	.04541	.08653	.00001	.02202	.13358	----------	.70530	----------	.00000			
2,420	.00716	.04464	.08730	.00001	.02279	.13281	----------	.70530					
2,330	.00716	.04379	.08814	.00000	.02364	.13196	----------	.70530					
2,240	.00716	.04287	.08907	----------	.02457	.13104	----------	.70530					
2,150	.00716	.04185	.09009	----------	.02559	.13002	----------	.70530					
2,060	.00716	.04072	.09121	----------	.02671	.12890	----------	.70530					
1,970	.00716	.03949	.09245	----------	.02795	.12766	----------	.70530					
1,880	.00716	.03812	.09382	----------	.02931	.12629	----------	.70530					
1,790	.00716	.03661	.09533	----------	.03083	.12478	----------	.70530					
1,700	.00716	.03493	.09700	----------	.03250	.12311	----------	.70530					
1,610	.00716	.03308	.09885	----------	.03435	.12125	----------	.70530					
1,520	.00716	.03103	.10090	----------	.03640	.11921	----------	.70530					
1,430	.00716	.02877	.10316	----------	.03866	.11695	----------	.70530					
1,340	.00716	.02629	.10564	----------	.04113	.11447	----------	.70530					0.00000
1,250	.00716	.02358	.10835	----------	.04383	.11176	----------	.70531				0.00000	.00001
1,160	.00716	.02064	.11128	----------	.04672	.10885	----------	.70533				.00002	.00001
1,070	.00716	.01746	.11441	----------	.04959	.10583	----------	.70544				.00009	.00002
980	.00717	.01378	.11771	----------	.05130	.10326	----------	.70615				.00060	.00003
890	.00720	.00900	.12084	----------	.04737	.10337	----------	.70933				.00285	.00004

[1] Additional products which were considered but whose mole fractions were less than 0.000005 for all assigned conditions were

C(G)	CH(G)	CH_2(G)	CH_3(G)	CN(G)	CN_2(G)	C_2(G)	C_2H(G)	C_2H_2(G)
C_2H_4(G)	C_2N_2(G)	C_2O(G)	C_3(G)	HCN(G)	HCO(G)	HO_2(G)	N(G)	NH(G)
NH_2(G)	NO_2(G)	N_2C(G)	N_2H_4(G)	N_2O(G)	N_2O_4(G)	H_2O(S)	H_2O(L)	C(S).

Table F–9.—1.20 stoichiometric propane-air flame plus 15 percent flue gas B [1]

(Overall stoichiometry equals 1.1)

Temp., ° F	Concentration, mole fraction												
	Ar	CO	CO_2	H	H_2	H_2O	NO	N_2	O	OH	O_2	CH_4	NH_3
4,310	0.00708	0.05509	0.06809	0.00593	0.01614	0.12898	0.00599	0.68929	0.00275	0.01162	0.00904		
4,220	.00711	.05122	.07254	.00464	.01477	.13267	.00500	.69300	.00198	.00971	.00735		
4,130	.00714	.04759	.07667	.00362	.01357	.13587	.00410	.69629	.00139	.00798	.00578		
4,040	.00716	.04430	.08040	.00280	.01255	.13861	.00328	.69914	.00095	.00645	.00436		
3,950	.00719	.04142	.08365	.00217	.01172	.14088	.00255	.70155	.00063	.00510	.00315		
3,860	.00720	.03899	.08637	.00167	.01109	.14271	.00193	.70354	.00040	.00396	.00215		
3,770	.00722	.03704	.08855	.00128	.01064	.14412	.00141	.70510	.00024	.00300	.00139		
3,680	.00723	.03554	.09023	.00098	.01036	.14516	.00100	.70630	.00014	.00222	.00085		
3,590	.00723	.03442	.09148	.00075	.01023	.14587	.00068	.70717	.00008	.00160	.00049		
3,500	.00724	.03360	.09238	.00057	.01022	.14632	.00045	.70778	.00004	.00113	.00027		
3,410	.00724	.03300	.09305	.00043	.01031	.14655	.00029	.70819	.00002	.00078	.00014		
3,320	.00724	.03253	.09356	.00032	.01046	.14663	.00018	.70847	.00001	.00053	.00007		
3,230	.00725	.03214	.09397	.00023	.01066	.14660	.00011	.70866	.00001	.00035	.00003		
3,140	.00725	.03179	.09434	.00017	.01090	.14647	.00007	.70878	.00000	.00023	.00002		
3,050	.00725	.03145	.09469	.00012	.01118	.14627	.00004	.70885	----------	.00014	.00001		
2,960	.00725	.03111	.09503	.00008	.01149	.14602	.00002	.70890	----------	.00009	.00000		
2,870	.00725	.03076	.09539	.00006	.01182	.14572	.00001	.70893	----------	.00005			
2,780	.00725	.03038	.09578	.00004	.01220	.14537	.00001	.70895	----------	.00003			
2,690	.00725	.02997	.09619	.00003	.01260	.14498	.00000	.70897	----------	.00002			
2,600	.00725	.02952	.09663	.00002	.01305	.14455	----------	.70897	----------	.00001			
2,510	.00725	.02904	.09712	.00001	.01353	.14407	----------	.70898	----------	.00001			
2,420	.00725	.02851	.09765	.00001	.01406	.14354	----------	.70898	----------	.00000			
2,330	.00725	.02792	.09824	.00000	.01465	.14296	----------	.70898					
2,240	.00725	.02728	.09888	----------	.01529	.14231	----------	.70898					
2,150	.00725	.02657	.09959	----------	.01600	.14160	----------	.70898					
2,060	.00725	.02578	.10037	----------	.01679	.14082	----------	.78098					
1,970	.00725	.02492	.10124	----------	.11766	.13995	----------	.70898					
1,880	.00725	.02396	.10220	----------	.01861	.13899	----------	.70898					
1,790	.00725	.02290	.10326	----------	.01968	.13793	----------	.70898					
1,700	.00725	.02172	.10444	----------	.02085	.13676	----------	.70898					
1,610	.00725	.02042	.10574	----------	.02215	.13546	----------	.70898					
1,520	.00725	.01899	.10717	----------	.02358	.13403	----------	.70898					
1,430	.00725	.01742	.10874	----------	.02515	.13246	----------	.70899					
1,340	.00725	.01571	.11045	----------	.02686	.13075	----------	.70899					0.00000
1,250	.00725	.01387	.11229	----------	.02870	.12891	----------	.70899				0.00000	.00001
1,160	.00725	.01192	.11424	----------	.03064	.12696	----------	.70899				.00001	.00001
1,070	.00725	.00989	.11626	----------	.03262	.12495	----------	.70900				.00009	.00002
980	.00725	.00780	.11830	----------	.03441	.12303	----------	.70911				.00059	.00003
890	.00726	.00556	.12017	----------	.03468	.12190	----------	.70982					

[1] Additional products which were considered but whose mole fractions were less than 0.000005 for all assigned conditions were

C(G)	CH(G)	CH_2(G)	CH_3(G)	CN(G)	CN_2(G)	C_2(G)	C_2H(G)	C_2H_2(G)
C_2H_4(G)	C_2N_2(G)	C_2O(G)	C_3(G)	HCN(G)	HCO(G)	HO_2(G)	N(G)	NH(G)
NH_2(G)	NO_2(G)	N_2C(G)	N_2H_4(G)	N_2O(G)	N_2O_4(G)	H_2O(S)	H_2O(L)	C(S).

APPENDIX G.—PRODUCTS OF COMBUSTION IN METHANE-AIR FLAMES ON A MULTIPORT-RING BURNER

Vertical distance, inch	Fraction of stoichiometric	NO_x,[1] ppm	CO,[1] ppm	Total HC,[2] ppm	H_2,[1] pct	N_2+Ar,[1] pct	CO_2,[1] pct	O_2,[1] pct	Secondary O_2,[1] pct	Temperature,[1] °F
0	1.0	[3] 10	[3] 3,800	0	0	[3] 86.4	[3] 10.9	[3] 2.9	10.0	2,940
0	1.2	30	5,000	0	0	83.7	6.5	9.3	10.2	3,170
0	1.5	30	5,800	0	0	84.4	7.9	7.2	11.0	3,200
0	2.0	40	5,200	0	0	84.6	7.9	7.1	14.3	3,150
0.5	1.0	[3] 40	[3] 0	0	0	[3] 86.7	[3] 11.0	[3] 2.3	15.4	1,390
.5	1.2	10	0	0	0	81.1	3.3	15.6	15.5	1,540
.5	1.5	10	0	0	0	81.2	3.5	15.3	16.4	1,860
.5	2.0	20	0	0	0	81.6	4.2	14.3	17.2	1,970

[1] Average of 2 replicates.
[2] Total hydrocarbons, average of 2 replicates.
[3] Corrected for dilution by secondary air.

APPENDIX H.—PRODUCTS OF COMBUSTION IN METHANE-AIR FLAMES ON A CERAMIC INFRARED FLAT-FLAME BURNER

Distance, inches		NO_x,[1] ppm	CO,[1] ppm	Total[2] HC, ppm	H_2,[1] pct	N_2+Ar,[1] pct	CO_2,[1] pct	O_2,[1] pct	Secondary O_2,[1] pct	Temp.,[1] °F
Above flame	From midline									
LEAN FLAMES[3]										
0	0.09	0	300	0	0	85.6	9.3	5.0	4.3	2,010
0	.84	10	800	0	0	85.7	9.3	5.0	4.2	2,560
0	1.59	10	1,100	0	0	85.5	9.2	5.3	3.6	2,590
0	2.09	0	1,400	0	0	85.7	9.2	4.9	3.7	2,590
0	2.84	10	1,800	0	0	85.7	9.2	4.9	3.2	2,650
0	[4] 3.59	10	2,600	750	0.1	81.4	3.7	14.5	11.7	2,260
1.0	.09	0	0	0	0	85.8	9.4	4.9	3.8	2,150
1.0	.84	10	0	0	0	85.8	9.4	4.8	3.4	2,340
1.0	1.59	10	0	0	0	86.0	9.4	4.6	3.2	2,360
1.0	2.09	0	0	0	0	85.6	9.3	5.1	4.8	2,410
1.0	2.84	10	0	0	0	85.4	9.3	5.4	9.2	2,320
1.0	[4] 3.59	0	0	0	0	78.9	.2	20.9	20.1	330
STOICHIOMETRIC FLAMES[3]										
0	.09	10	1,700	0	0.1	87.1	11.2	1.4	4.8	2,140
0	.84	10	5,000	0	.1	87.1	10.9	1.4	4.8	2,780
0	1.59	10	5,400	0	.1	87.1	10.8	1.5	4.3	2,820
0	2.09	10	6,300	0	.1	86.8	10.7	1.7	4.5	2,830
0	2.84	10	6,700	0	.1	87.0	10.7	1.5	3.6	2,930
0	[4] 3.59	10	3,100	370	.1	82.0	4.5	13.0	11.7	2,390
1.0	.09	10	300	0	0	87.6	11.4	1.0	4.7	2,270
1.0	.84	10	700	0	0	87.6	11.4	1.0	4.2	2,510
1.0	1.59	10	600	0	0	87.3	11.4	1.4	3.6	2,510
1.0	2.09	10	700	0	0	87.3	11.3	1.4	3.9	2,580
1.0	2.84	20	300	0	0	87.0	11.3	1.8	8.4	2,480
1.0	[4] 3.59	0	0	0	0	78.9	.2	20.8	20.2	360
RICH FLAMES[4]										
0	.09	10	32,000	310	2.9	82.0	6.8	5.1	5.0	2,080
0	.84	20	34,600	0	2.8	82.0	6.4	5.3	5.5	2,660
0	1.59	20	35,300	0	2.8	82.3	6.7	4.7	4.8	2,680
0	2.09	20	35,700	0	2.8	82.3	6.8	4.6	4.7	2,730
0	2.84	30	36,500	0	2.7	82.5	7.1	3.9	4.0	2,790
0	3.59	10	3,700	25	.1	83.2	5.8	10.5	11.7	2,580
1.0	.09	20	30,700	0	2.7	82.2	6.8	5.1	5.6	2,230
1.0	.84	20	33,600	0	2.7	82.2	6.7	5.0	5.2	2,420
1.0	1.59	20	34,000	0	2.9	82.3	7.1	4.3	4.4	2,430
1.0	2.09	20	32,600	0	2.6	82.7	7.3	4.1	4.4	2,490
1.0	2.84	30	9,700	0	.6	84.0	7.6	6.8	8.0	2,720
1.0	3.59	0	0	0	0	79.3	.4	20.2	20.1	410

[1] Average of 3 replicates.
[2] Total hydrocarbons, average of 2 replicates.
[3] Corrected for dilution by secondary air.
[4] Not corrected for dilution by secondary air.

APPENDIX I.—THERMODYNAMIC EQUILIBRIUM CONCENTRATIONS OF PRODUCTS IN LEAN, STOICHIOMETRIC, AND RICH PROPANE-AIR AND METHANE-AIR FLAMES AT ADIABATIC FLAME TEMPERATURES

Fuel	Adiabatic temp., °F	Concentration, mole fraction										
		Ar	CO	CO_2	H	H_2	H_2O	NO	N_2	O	OH	O_2
LEAN FLAMES												
C_3H_8	3,340	0.00869	0.00176	0.09745	0.00007	0.00048	0.13023	0.00383	0.72599	0.00025	0.00234	0.02890
C_3H_8+A[1]	3,000	.00760	.00043	.10204	.00001	.00011	.11481	.00222	.74636	.00006	.00087	.02549
C_3H_8+B[2]	3,010	.00760	.00033	.09441	.00001	.00010	.11477	.00275	.74054	.00007	.00098	.03843
CH_4	3,220	.00858	.00073	.07841	.00004	.00030	.15661	.00328	.71687	.00016	.00157	.03346
STOICHIOMETRIC FLAMES												
C_3H_8	3,620	0.00852	0.01248	0.10267	0.00047	0.00332	0.14800	0.00246	0.71266	0.00031	0.00322	0.00589
C_3H_8+A[1]	3,330	.00749	.00609	.11060	.00012	.00149	.13233	.00121	.73637	.00008	.00130	.00292
C_3H_8+B[2]	3,370	.00750	.00323	.10598	.00010	.00082	.13281	.00273	.73121	.00019	.00211	.01332
CH_4	3,550	.00837	.00921	.08517	.00040	.00368	.18306	.00200	.70054	.00024	.00255	.00478
RICH FLAMES												
C_3H_8	3,490	0.00813	0.05558	0.07732	0.00080	0.02142	0.15463	0.00021	0.68103	0.00002	0.00080	0.00006
C_3H_8+A[1]	3,140	.00715	.04932	.08259	.00022	.01812	.13726	.00004	.70513	.00000	.00016	.00000
C_3H_8+B[2]	3,430	.00724	.03314	.09289	.00046	.01028	.14651	.00033	.70810	.00003	.00086	.00017
CH_4	3,360	.00794	.04903	.06016	.00061	.03019	.18716	.00010	.66439	.00000	.00041	.00001

[1] 15 percent flue gas A. [2] 15 percent flue gas B.

U.S. GOVERNMENT PRINTING OFFICE: 1969 O—371-272

RECEIVED
NATIONAL TECHNICAL
APR 12 1971
INFORMATION SERVICE