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Measurements of Flame Lengths Under Ceilings

Daniel Gross

U.S. DEPARTMENT OF COMMERCE
National Institute of Standards and Technology
(Formerly National Bureau of Standards)
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August 1988

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75 Years Stimulating America's Progress
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Table of Contents

List of Tables

List of Figures

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Abstract

Measurements of luminous flame extensions beneath ceilings under steady burning conditions are presented. Tests were conducted using both axisymmetric and corner-wall-ceiling configurations for a range of energy supply rates up to 400 kW and burner-to-ceiling heights up to 2.3 m. Flame length observations, which were made both visually and photographically, are expressed in dimensional and in nondimensional terms. Comparisons are made with previous measurements reported in the literature.

Keywords: Fire plumes; flame height; gas burners; luminous flames; ceilings; flame research; crib fires; walls.

1. INTRODUCTION

The extent to which a rising column of flame will deflect and extend along a horizontal ceiling is of critical importance in estimating the spread of fire in building compartments of all sizes and geometries. However, only a limited number of measurements have been reported in the literature [1-5] and the relative importance of geometry, air entrainment, completeness of combustion, and the partitioning of radiative, convective, and conductive heat transfer are not sufficiently established to permit predictions to be made with confidence.

Many experimental and analytical studies have been made of simple fire plumes, i.e., steady-state diffusion flames issuing vertically from a burner supplied with a gas or liquid fuel and situated away from restrictive walls or ceilings. In this simplified configuration, the dimensionless flame height Z/D has been found to be a function, principally of the energy supply rate and the burner size. Here, Z represents the flame height in a free plume and D is the diameter (actual or equivalent) of the burner. If the source velocity is U, a Froude number (= U^2/gD) represents the ratio of fuel momentum to buoyancy. In the regime where the rising flame is controlled almost totally by buoyancy and not fuel momentum, i.e., for Froude numbers of the order of 10^{-6} and below, Z/D becomes of the order of 1, is no longer a strong function of D, and the flame may begin to resemble individual flamelets rather than a single fire plume. In this regime, the definition of the flame tip location becomes very critical and other factors such as the location of the floor relative to the burner may become important. It is not surprising that (a) considerable differences exist among available data and (b) transient effects have been largely ignored.

In previous experimental studies, the instantaneous height of luminous flames during "steady burning" was found to vary considerably, i.e., of the order of ± 25% or more. Fluctuations in the location of the visible limit of flame are accompanied by similar fluctuations in the temperature, in the radiation, and in the chemical composition of gases in the flame tip region. Thus, it may be possible to use a number of instrumental measures to supplement or replace the visual definition of the flame tip location.

In the first part of this limited and exploratory study, a series of measurements were made to obtain flame height data for fire plumes of natural gas issuing from burners of 0.61 and 0.91 m diameter. The natural gas supply range corresponded to energy input rates up to 400 kW. The mean flame tip location was estimated using several techniques: (a) visual (b) 35 mm time-exposure color photography (c) video photography (d) temperature gradients using thermocouples and (e) oxygen and carbon dioxide concentration gradients. A horizontal ceiling was then placed at selected distances above the burner surface and measurements made of the extent of horizontal flame extension. Similar experimental techniques were used to measure the flame tip location. To examine the effect of enclosing surfaces on flame extension, additional measurements were made with a "corner-wall-ceiling" configuration by the addition of two walls adjacent to two edges of a 0.54 m square burner.

2. EXPERIMENTAL DETAILS

The two principal configurations examined were (a) an axisymmetric gas burner flame with and without a horizontal ceiling and (b) a gas burner flame adjacent to a corner-wall and below a confining horizontal ceiling (see Figure 1). In the former case, 0.61 m and 0.91 m diameter burners were used with the burner-to-ceiling distance, designated H, ranging from 0.5 to 1.2 m and the energy supply rate, $\dot{Q}$, ranging from 100 to 414 kW. In the latter case, a

0.54 m square burner was used with burner-to-ceiling distances ranging from 0.2 to 2.3 m and energy supply rates ranging from 50 to 400 kW. In addition, wood cribs weighing 7.5 and 18.6 kg were used in the corner wall configuration. The burner consisted of a sheet steel frame enclosing a thick layer of ceramic fiber blanket through which the natural gas percolated. Calcium silicate ("Marinite") boards 0.0127 m thick, were used for all enclosing wall and ceiling surfaces. A summary listing of the test parameters examined is given in Table 1.

The terms "flame height" and "flame extension" are used to designate the lengths of flame in the vertical and horizontal directions, respectively. These were observed in three ways: (a) visually; (b) by means of video; and (c) from rapid and from extended exposure (typically 1 to 3 sec) 35 mm color transparencies. The video camera was located at a distance of 5 m from the burner and at an elevation of 2 m below the ceiling level; the 35 mm camera was located closer to the burner so as to view the flames on the ceiling from an approximate 30° angle. Distinctions were made between the maximum extent of sustained (i.e., continuous) and of intermittent (i.e., momentary) flames. Defining the location of the flame tip was difficult mainly due to the unsteady, pulsing nature of the flames. In addition, the painted markings (at 10 cm intervals on the walls and ceiling) were sometimes partially obscured by smoke deposits, aerosols and/or heat discoloration.

Instrumental means were also employed in an attempt to supplement the visual definition of the flame tip location. Strings of thermocouples were positioned so as to bracket the anticipated location of the flame tip thus permitting temperature gradients across the visual flame boundary to be plotted. Thermocouple strings were located 20 mm below the ceiling (to indicate flame or gas temperature) and at corresponding points on the ceiling surface. A few measurements of oxygen and carbon dioxide concentrations at selected locations were also made.

3. RESULTS

3.1 Axisymmetric Gas Burner

Visually observed flame heights in the absence of a ceiling increased with energy supply rate over the range 100 to 414 kW but at a decreasing rate. Here, a distinction was made between the highest level at which flames were observed to exist continuously ("sustained") and the highest level at which momentary excursions of flame were observed over an extended observation period ("intermittent"). The intermittent flame tips were observed to be approximately 75 ± 25 percent higher than the sustained flame tips. In terms of nondimensional height and energy supply rate, the data shown in Figure 2 bracket the "eye-averaged (intermittency approaches zero)" values assembled by Zukoski [1] from a number of sources. Since this observer's eye tended to focus on the location of the maximum, i.e., intermittent, flame tip and since the location of the sustained flame tips (intermittency = 100 %) was equally difficult to estimate, most observations are reported here in terms of the intermittent flame tip position.

In the presence of a ceiling, the maximum flame extension, i.e., the combined vertical and horizontal extension of the intermittent flame tip was noticeably less than for the corresponding energy supply rate without a ceiling. This was particularly evident for the larger (0.91 m dia) burner and for the smallest burner-to-ceiling distances. For example, with $\dot{Q}$ = 206 kW, the observed intermittent flame tips above the 0.61 m and 0.91 m diameter burners in the absence of a ceiling were 1.8 and 1.6 m high respectively. When a ceiling was placed 0.5 m above the burners, the corresponding maximum extension of the flame tips (0.5 m plus horizontal) was 1.5 and 1.3 m. In simple geometrical terms, this is not surprising since a relatively small cone-shaped volume of vertical flames within the intermittent flame region will be re-shaped into a disk (or very flat cone) of horizontal flames spreading in a 360° circle. This is also in qualitative agreement with the results of You and Faeth [5] for smaller liquid hydrocarbon pools. They found that radial extension of an axisymmetric flame under an unconfined ceiling was significantly less that the corresponding flame height in the absence of a ceiling. Accompanying the apparent 20% reduction in flame extension in this study was a significant increase in the gas (and surface) temperatures at the corresponding distance from the burner. There was also a corresponding increase in the carbon dioxide concentration and a decrease in the oxygen concentration, supporting a model of more complete burning.

3.2 Corner-Wall Gas Burner

Special attention was given to the corner-wall-ceiling configuration in view of its unique and critical nature. Using a 0.54 m square burner (area equivalent to 0.61 m dia), visual observations were made of the maximum extent of sustained and of intermittent flames. The intermittent flame tips were observed to extend approximately 40 to 70 percent beyond the sustained flame level; however, these are the observations of a single individual and would be expected to vary somewhat between observers. The maximum horizontal extension of the intermittent flame tip as a function of energy supply rate for different burner-to-ceiling distances is shown in Figure 3. The horizontal extensions are measured from the corner intersection, no correction having been made for the burner axis displacement. The horizontal flame extension was found to increase at less than a proportionate rate. For the two closest spacings (H = 0.20 and 0.23 m), the nature of the flames on the ceiling changed, becoming an orderly series of cellular flame pockets. Such flames have been extensively studied and characterized [6]. In these close-spacing tests, the horizontal flame extensions were greatest and the maximum amount of smoke was generated and deposited on the ceiling.

Considering now the maximum combined vertical and horizontal extension of the intermittent flame tips, the data are shown in Figure 4 plotted in terms of nondimensional total flame length versus energy supply rate. The data for the closest spacing (0.2 m) demonstrates the significantly longer flame extension compared to burner spacings of 0.5 m and above.

3.3 Corner-Wall Wood Crib

A wood crib is an idealized but more realistic flame source since its instantaneous rate of burning is determined by the chemistry and physics of thermal decomposition rather than by a gas valve setting. In addition, the effects of flame radiation and smoke are considered more representative of the burning of typical solid combustibles. One crib consisted of 28 sticks (each 3.8 by 3.8 by 35 cm) arranged in 7 layers with 4 sticks per layer and weighed approximately 7.5 kg. The second crib consisted of 50 sticks (each 3.8 by 3.8 by 50 cm) arranged in 10 layers with 5 sticks per layer and weighing 18.6 kg. When placed with the top surface 0.5 m below the ceiling at the corner-wall intersection, the 7.5 and 18.6 kg wood cribs released energy at the measured rates of 95 kW and 240 kW respectively during the steady maximum burning periods. The corresponding observed flame extensions on the ceiling are shown in Figure 5. Using these values, two points have been placed on the nondimensional plot of Figure 4, in reasonably close agreement with the gas burner data.

3.4 Flame Extension Comparisons

Comparisons were made among the directly observed ceiling flame extensions, those determined from continuous video recordings, and from "instantaneous" and extended exposure 35 mm transparencies. The extended exposures were typically of 1 second duration with f8 to f16 apertures using ASA 50 film and appropriate neutral density filters. A summary of measurements and estimates for selected tests (Nos. 6, 16 and 25), is given in Table 2. In general, it was found that the location of the intermittent flame tips determined visually was the same as those from the video record but greater than that determined from exposed transparencies, typically of the order of 20 to 40 percent greater. For time exposures of one second (and greater), the extended exposure recording of flame extension was typically slightly shorter than the instantaneously recorded flame extension. No attempt was made to estimate the "average flame extension", defined as the 50 % intermittency point, although the video recordings are available for future analysis by digitizing techniques.

3.5 Temperature and Gas Concentrations

The observed position of the intermittent flame tip along the ceiling for each selected energy supply rate served as the reference point for temperature gradient comparisons. It was hypothesized that a noticeable temperature step could occur at this point since flames would occasionally reach this point but would not extend beyond. In a typical example for the axisymmetric burner configuration (see Figure 6), the gas temperature measured 20 mm below the ceiling varied in a regular fashion both below and above the intermittent flame tip but no noticeable step was observed. It is interesting to note that (a) the temperature profiles were relatively unchanged over the range in energy supply rate investigated (104 to 283 kW), and (b) the temperature at the observed intermittent flame tip was approximately 340 °C in good agreement with the value of $\Delta T = 320$ °C obtained by McCaffrey [7] from a correlation of temperature rise data at the intersection of the intermittent flame and plume regions of buoyant gas diffusion flames. Although it was difficult to visually estimate the length of the sustained part of the horizontal flame extension, it appears that its average location is approximately 70 cm from the intermittent flame tip, corresponding to a temperature of 740 ± 40 °C. Temperature profile data for the corner-wall-ceiling configuration were less regular, in part due to the limited number of measuring points and to the three-dimensional effects at the wall-ceiling intersections.

The existence of distinctive changes in the oxygen and/or carbon dioxide concentrations at the intermittent flame tip location was also explored. For several tests, plots of oxygen and carbon dioxide concentrations exhibited regular, i.e., gradual, changes across the region separating intermittent and sustained flames. From this, it does not appear feasible to use gas concentrations to define the location of the flame tip. Also, no conclusion could be drawn as to any "characteristic" oxygen or carbon dioxide concentration at the intersection of the intermittent flame and hot gas (plume) regions.

4. SUMMARY AND DISCUSSION

In this limited study of flame lengths under ceilings, the following general conclusions may be noted:

A. Visual Observations of Flame Location

Visual observations of flames are very observer-dependent; since the location of sustained flames was not always clearly evident, this observer was more inclined to estimate the maximum excursion of the intermittent (momentary) flame tip. The visually observed heights of the intermittent portions of natural gas diffusion flames in the absence of a ceiling were between 1.5 and 2.0 times the sustained flame heights.

This covers the range of values mentioned by Zukoski [1] in his survey encompassing a wide range of burner sizes. Based on detailed analysis of individual motion picture frames from a 0.3 m square gas burner, McCaffrey [7] reported this value to be approximately 2.5.

B. Photographic and Video Observations

An individual observer is likely to define the location of flame tips from video recordings in the same way as direct "live" observation of the flames. However, flame extension measurements made visually may be significantly greater than those recorded photographically with either short or extended time (1 second or more) exposures.

C. Instrumental Measurements of Flame Location

No distinctive shift in temperature or gas concentration (oxygen or carbon dioxide) was observed at the intermittent flame tip location. Using such alternate ways for defining flame tip location does not appear feasible. There may be value in determining the "average flame extension" defined as the 50% intermittency point; although not explored, video digitizing techniques may be feasible.

D. Effect of Ceiling

The combined vertical and horizontal extension of the intermittent flame tip in the presence of a ceiling was less (approximately 20%) than the vertical flame height for the corresponding energy supply rate without a ceiling. The accompanying temperature and gas concentration measurements suggest that this is the result of higher temperatures and therefore more complete burning.

E. Corner-Wall-Ceiling Configuration

Horizontal flame extensions from the corner intersection increased with energy supply rate, but at less than a proportionate amount.

F. Cellular Flames

Horizontal flame extensions were greatest at the shortest burner-to-ceiling spacings (0.2 and 0.23 m). Under these conditions, cellular flame pockets similar to those described by Kokkala and Rinkinen [6] were obtained.

G. Additional Research

Suggestions for follow-on research include the following experimental parameters and analytical studies:

1. Presence of restrictive floor at burner level
2. Different thermal properties of enclosing surfaces
3. Configuration representative of long, narrow corridor

4. Analysis of air entrainment, completeness of combustion and overall heat balance.

5. ACKNOWLEDGEMENT

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Table 1. Summary of Test Parameters and Results

Configuration	Test No.	Burner Size Dia. m	Energy Supply Rate kW	Burner-Ceiling Distance m	Maximum Flame Height(V) Sust. m	Maximum Flame Height(V) Interm. m	Maximum Flame Extension(H) Sust. m	Maximum Flame Extension(H) Interm. m
AXISYMMETRIC	01	0.91	100-414	∞	1.6	2.6		
	02	0.61	100-283	∞	1.3	2.1		
	03	0.61	100-283	1.2	>1.2	>1.2		0.8
	04	"	"	1.0	>1.0	>1.0		0.8
	05	"	"	0.8	>0.8	>0.8		1.0
	06	"	"	0.5	>0.5	>0.5		1.2
	07	0.91	"	1.0	>1.0	>1.0		0.6
	08	"	"	1.0	>1.0	>1.0		0.1
	09	"	"	0.5	>0.5	>0.5		0.9
	10	Crib		0.65	>0.65	>0.65		0.6
CORNER-WALL-CEILING	11	0.54sq	104-283	1.0	>1.0	>1.0		1.6
	12	"	104-231	0.5	>0.5	>0.5		1.8
	13	"	104-283	0.8	>0.8	>0.8		1.8
	14	"	50-200	0.23	>0.23	>0.23	2.0	2.7
	15	"	50-400	1.2				2.2
	16	"	"	0.5			2.0	2.8
	17	Crib	7.5kg	0.31			1.3	1.8
	18	"	"	0.5			1.0	1.5
	19	"	7.3kg	0.2			1.2	1.6
	20	"	6.9kg	2.0	1.8	>2.0		0.6
	21	0.54sq	50-400	2.3	2.3	>2.3		1.5
	22	"	"	0.2			2.5	>3.2
	23	"	"	0.35			2.4	>3.2
	24	Crib	18.6kg	2.0			0.5	1.4
	25	"	"	0.5			1.8	2.7

Table 2. Comparison of Ceiling Flame Extension Observations

Maximum Extension of Intermittent Flame Tips, m

Axisymmetric Burner 0.61 m dia H=0.5 m					Corner-Wall Burner 0.54 m sq H=0.5 m					Corner-Wall Wood Crib 18.6 kg wood crib				
$\dot{Q}$ kW	Visual	35 mm Inst	35 mm Time	Video	$\dot{Q}$ kW	Visual	35 mm Inst	35 mm Time	Video	Time min	Visual	35 mm Inst	35 mm Time	Video
104	0.75	0.4	0.4	0.7	50	0.2	0	0	0.5	3	0.9	0.7	0.8	0.8
126	0.8	0.7	0.6	0.8	100	1.0	0.6	0.8	1.0	5	2.3	1.4	1.3	1.8
146	0.8	0.6	0.6	0.9	150	1.5	1.7	1.1	1.5	8	2.6	-	1.5	2.5
163	0.9	0.7	0.7	0.9	200	1.9	1.5	1.3	1.8	10	2.6	1.6	1.5	2.5
179	0.9	0.7	0.7	1.0	250	2.2	1.7	1.7	2.0	12	2.6	1.5	1.5	2.2
206	1.0	0.8	0.8	1.1	300	2.5	-	1.5	2.2	14	2.5	-	1.4	2.2
231	1.1	0.9	0.8	1.1	400	2.8	2.2	2.0	-	16	2.3	-	1.2	2.0
253	1.2	0.9	0.8	1.1						18	1.2	-	0.8	1.2
283	1.2	0.9	0.8	1.1										

Table A1. Test Data for Axisymmetric Burner Configuration
Visual Observations

WITHOUT CEILING

Test 01 0.61 m Dia Burner			Test 02 0.91 m Dia Burner		
Energy Supply Rate	Flame Height		Energy Supply Rate	Flame Height	
	Sustained	Intermittent		Sustained	Intermittent
kW	m	m	kW	m	m
104	0.6	1.0	104	0.9	1.6
160	0.9	1.5	146	1.1	1.7
207	1.0	1.6	179	1.2	2.0
262	1.2	2.2	231	1.2	2.0
293	1.3	2.2	283	1.3	2.1
359	1.5	2.6			
414	1.6	2.6			

WITH CEILING

0.61 m Dia Burner

Energy Supply Rate	Test 03 H = 1.2 m		Test 04 H = 1.0 m		Test 05 H = 0.8 m		Test 06 H = 0.5 m	
	Flame Height	Flame Extens.	Flame Height	Flame Extens.	Flame Height	Flame Extens.	Flame Height	Flame Extens.
kW	m	m	m	m	m	m	m	m
104	>1.2	0.2	1.0	0.0	>0.8	0.6	>0.5	0.75
126	>1.2	0.4	>1.0	0.1	>0.8	0.6	>0.5	0.8
146	>1.2	0.4	>1.0	0.4	>0.8	0.7	>0.5	0.8
163	>1.2	0.6	>1.0	0.4	>0.8	0.7	>0.5	0.9
179	>1.2	0.6	>1.0	0.5	>0.8	0.7	>0.5	0.95
206	>1.2	0.6	>1.0	0.6	>0.8	0.7	>0.5	1.0
231	>1.2	0.7	>1.0	0.7	>0.8	0.8	>0.5	1.1
253	>1.2	0.7	>1.0	0.7	>0.8	0.8	>0.5	1.2
283	>1.2	0.8	>1.0	0.8	>0.8	1.0	>0.5	1.2

0.91 m Dia Burner

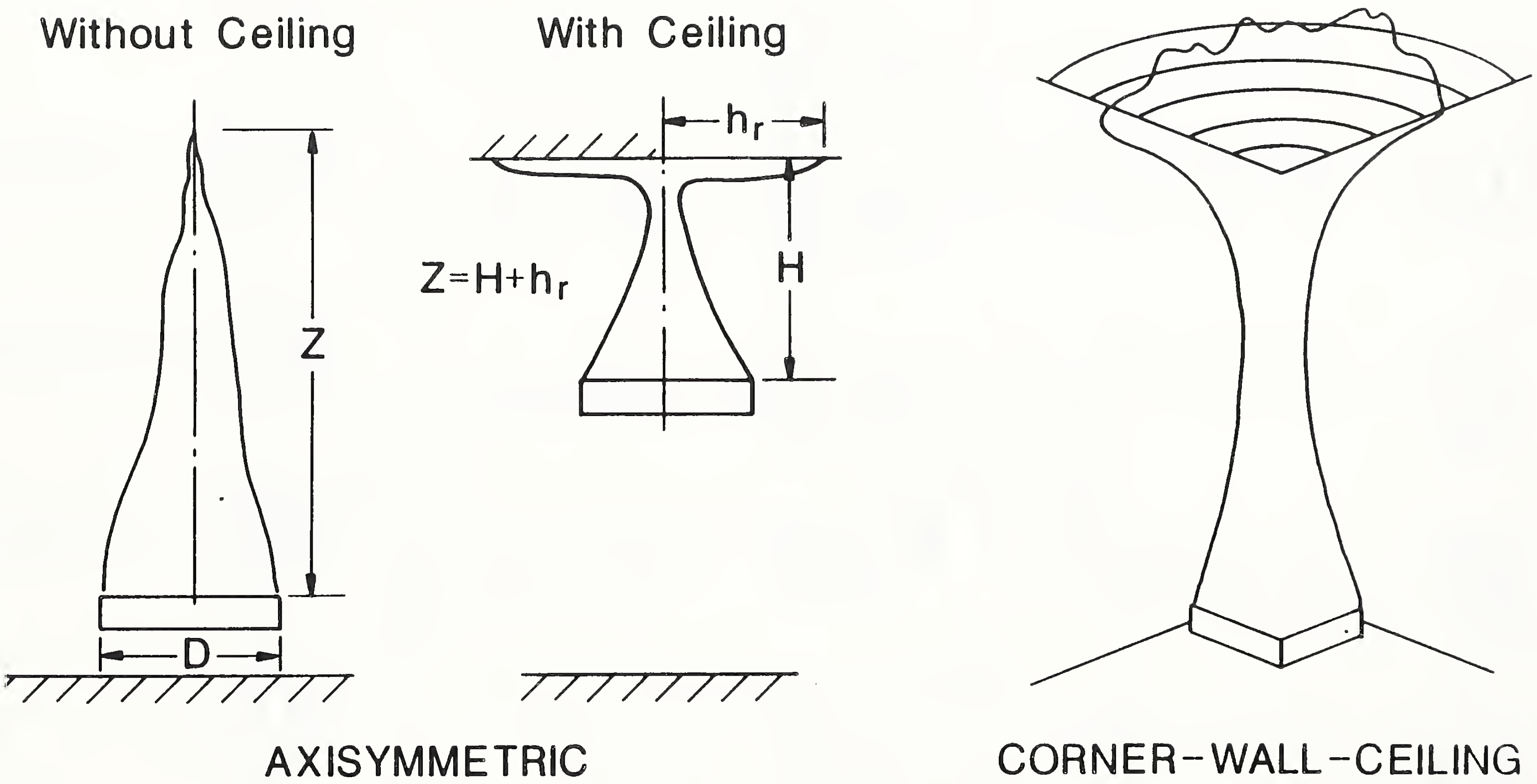
Energy Supply Rate	Test 07 H = 1.0 m		Test 08 H = 1.0 m		Test 09 H = 0.5 m	
	Flame Height	Flame Extension	Flame Height	Flame Extension	Flame Height	Flame Extension
kW	m	m	m	m	m	m
104	1.0	0.0	1.0	0.0	>0.5	0.5
126	1.0	0.0	"	"	>0.5	0.5
146	>1.0	0.2	"	"	>0.5	0.6
163	>1.0	0.2	"	"	>0.5	0.7
179	>1.0	0.4	"	"	>0.5	0.7
206	>1.0	0.5	"	"	>0.5	0.8
231	>1.0	0.5	"	"	>0.5	0.8
253	>1.0	0.6	"	"	>0.5	0.8
283	>1.0	0.6	"	"	>0.5	0.9

Table A2. Test Data for Corner-Wall-Ceiling Configuration
0.54 m Square Gas Burner
Visual Observations

Energy Supply Rate kW	Test 11 H = 1.0 m Flame Height Interm. m	Flame Extension Interm. m	Test 12 H = 0.5 m Flame Height Interm. m	Flame Extension Interm. m	Test 13 H = 0.8 m Flame Height Interm. m	Flame Extension Interm. m
104	>1.0	0.6	>0.5	1.4	>0.8	0.9
126	>1.0	0.9	>0.5	1.4	>0.8	1.1
146	>1.0	0.8	>0.5	1.6	>0.8	1.1
163	>1.0	1.0	>0.5	1.5	>0.8	1.2
179	>1.0	0.9	>0.5	1.7	>0.8	1.4
206	>1.0	1.2	>0.5	1.8	>0.8	1.6
231	>1.0	1.4	>0.5	1.8	>0.8	1.6
253	>1.0	1.4			>0.8	1.7
283	>1.0	1.6			>0.8	1.8

Energy Supply Rate kW	Test 14 H = 0.23 m Flame Extension Sustained m	Flame Extension Interm. m	Test 15 H = 1.2 m Flame Height Interm. m	Flame Extension Interm. m	Test 16 H = 0.5 m Flame Extension Sustained m	Flame Extension Interm. m
50	1.0	1.1	0.7	-	-	0.2
100	1.2	1.7	>1.2	0.2	0.5	1.0
150	1.6	2.2	>1.2	0.8	1.0	1.5
200	2.0	2.7	>1.2	1.2	1.2	1.9
250			>1.2	1.5	1.3	2.2
300			>1.2	1.6	1.8	2.5
400			>1.2	2.2	2.0	2.8

Energy Supply Rate kW	Test 21 H = 2.3 m Flame Height Sustained m	Flame Height Interm. m	Flame Extension Interm. m	Test 22 H = 0.2 m Flame Extension Sustained m	Flame Extension Interm. m	Test 23 H = 0.35 m Flame Extension Sustained m	Flame Extension Interm. m
50	0.4	0.6	-	0.7	1.2	0.4	0.7
100	0.5	1.0	-	1.2	1.8	0.8	1.4
150	0.7	1.8	-	1.4	2.4	1.2	1.7
200	1.0	2.2	-	2.0	2.8	1.5	2.2
250	1.2	>2.3	0.5	2.2	3.0	1.7	2.6
300	1.8	>2.3	0.8	2.5	>3.2	1.8	2.8
400	2.3	>2.3	1.5			2.4	>3.2



$$\dot{Q} = \text{Energy Supply Rate} \quad \text{kW}$$

$$\dot{Q}^{*} = \frac{\dot{Q}}{\rho_\infty C_{p\infty} T_\infty \sqrt{gD}\, D^2} = \frac{\dot{Q}}{1116\ D^{5/2}}$$

Figure 1. Geometrical arrangement and nomenclature for flame length measurements

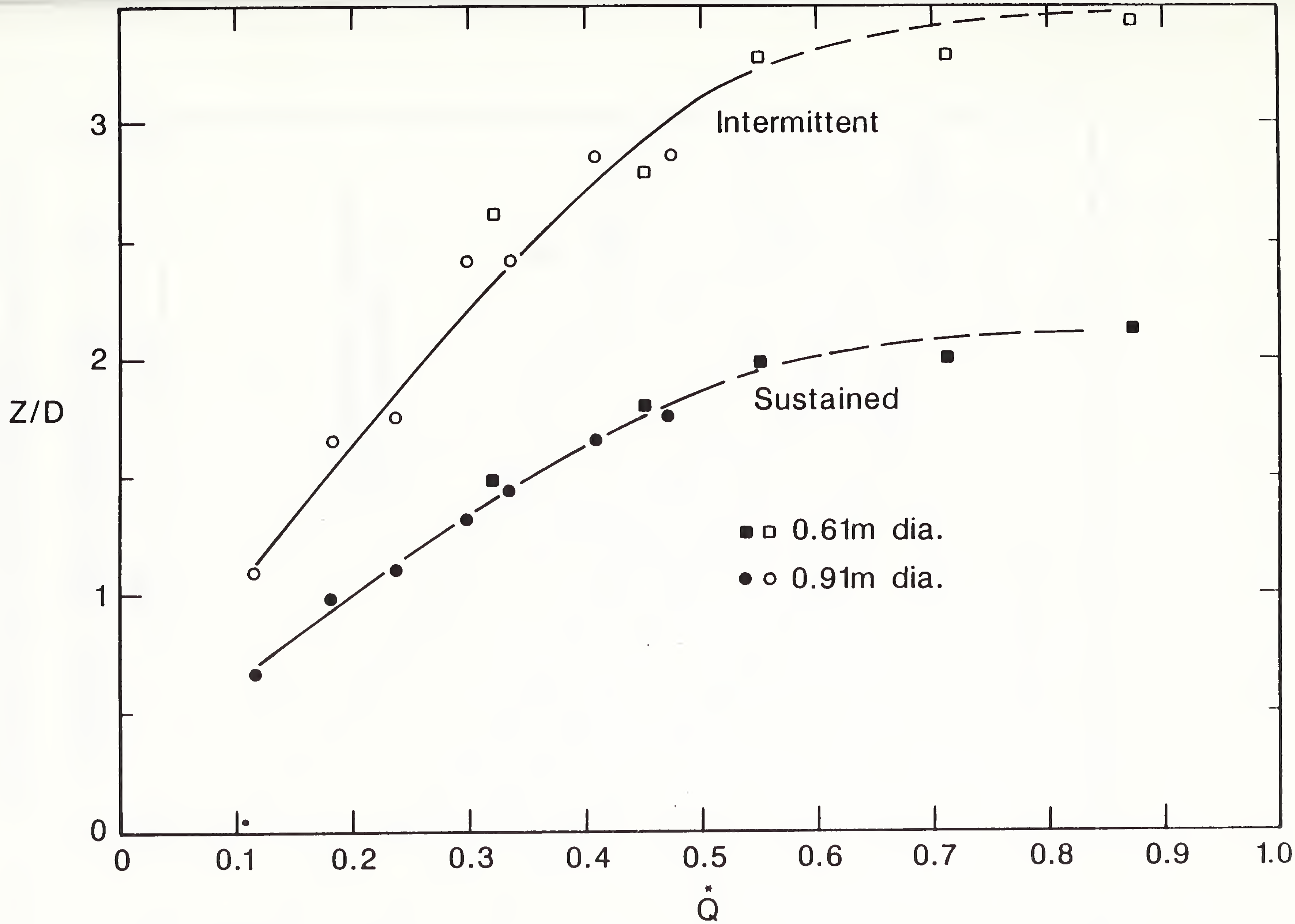


Figure 2. Height of visible flames above an axisymmetric burner (no ceiling)

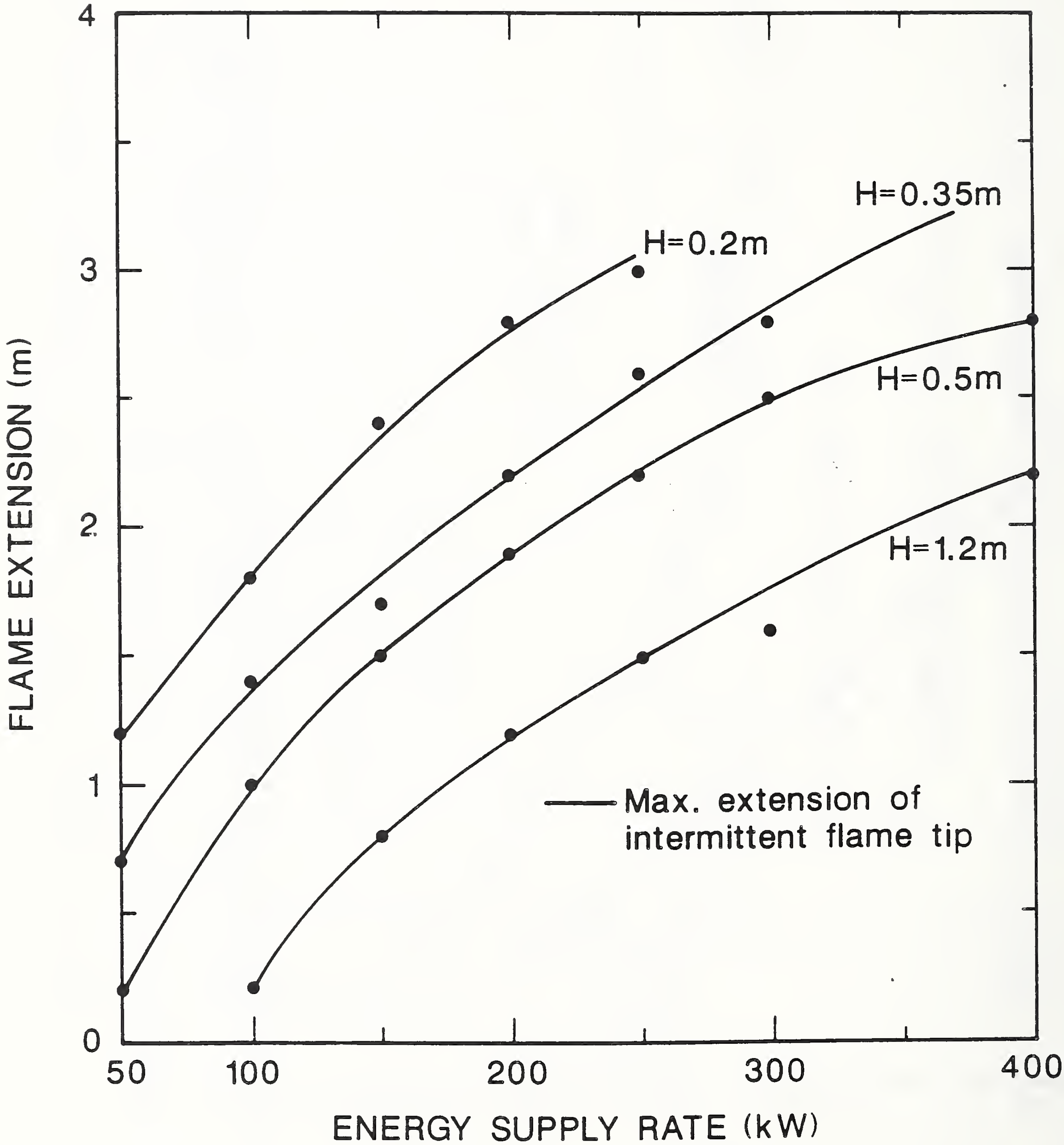


Figure 3. Horizontal flame extension in corner-wall-ceiling configuration 0.54 m sq. gas burner

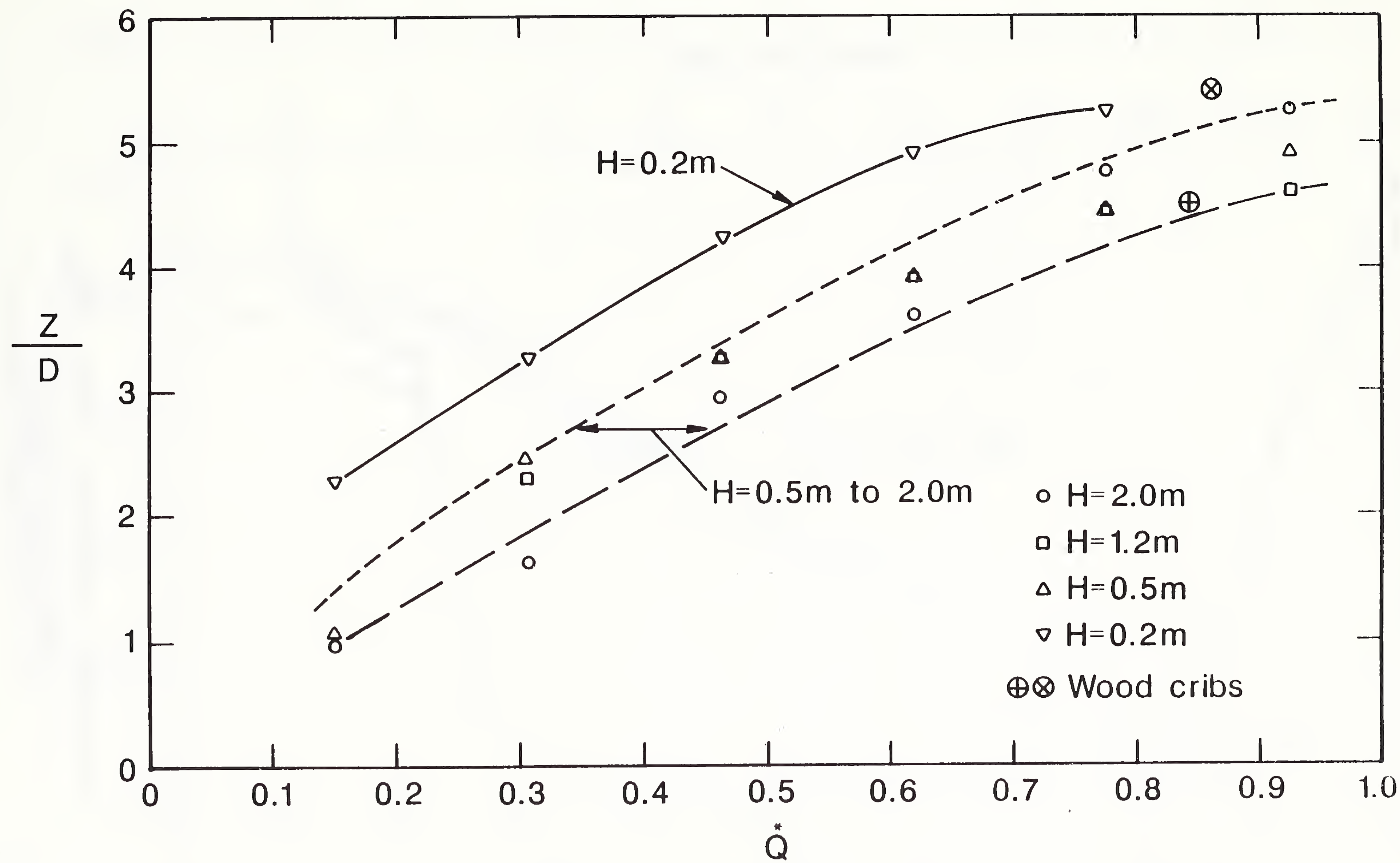


Figure 4. Maximum total flame extension in corner-wall-ceiling configuration 0.54 m sq. gas burner

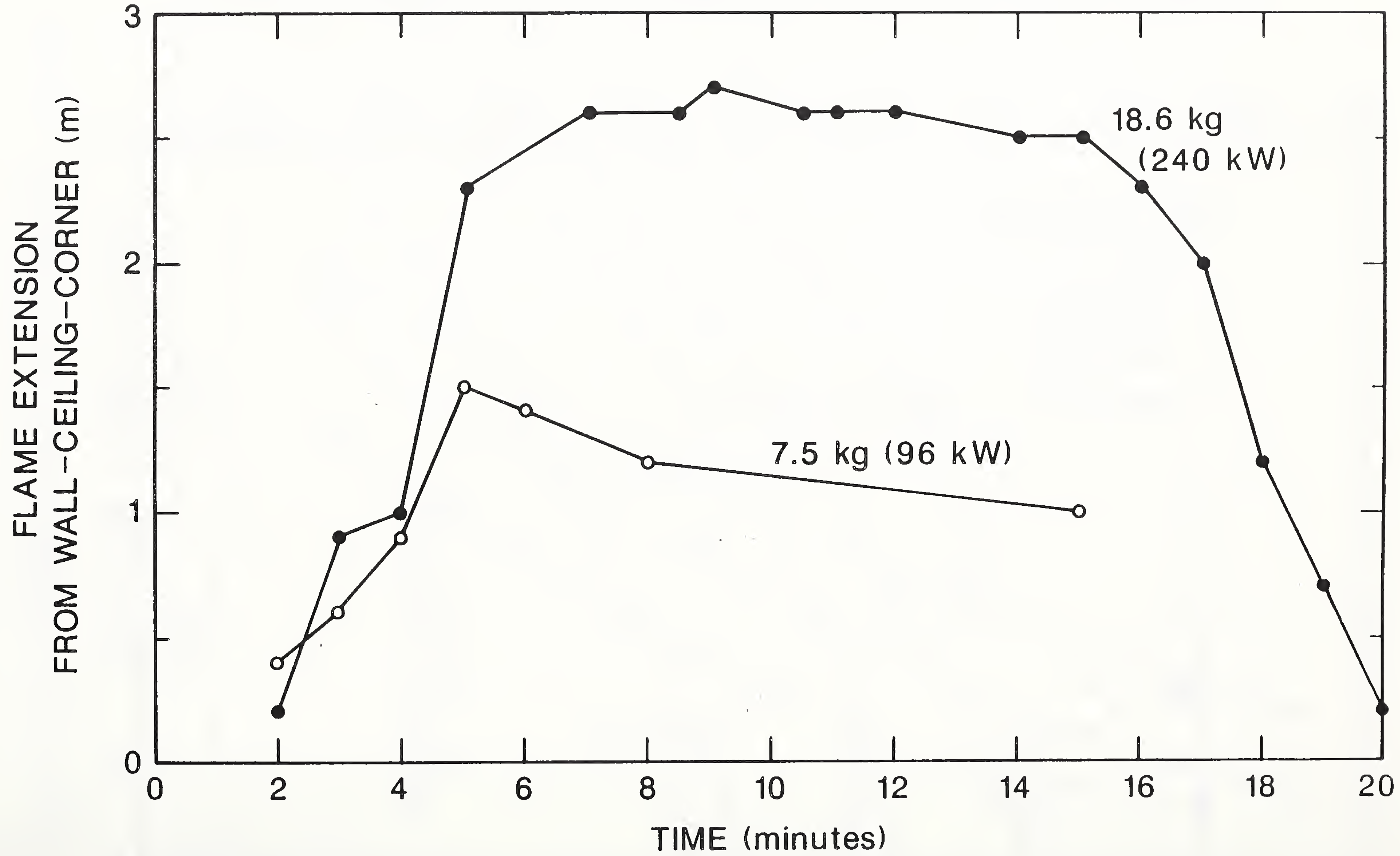


Figure 5. Horizontal (ceiling) flame extension for wood cribs H=0.5 m

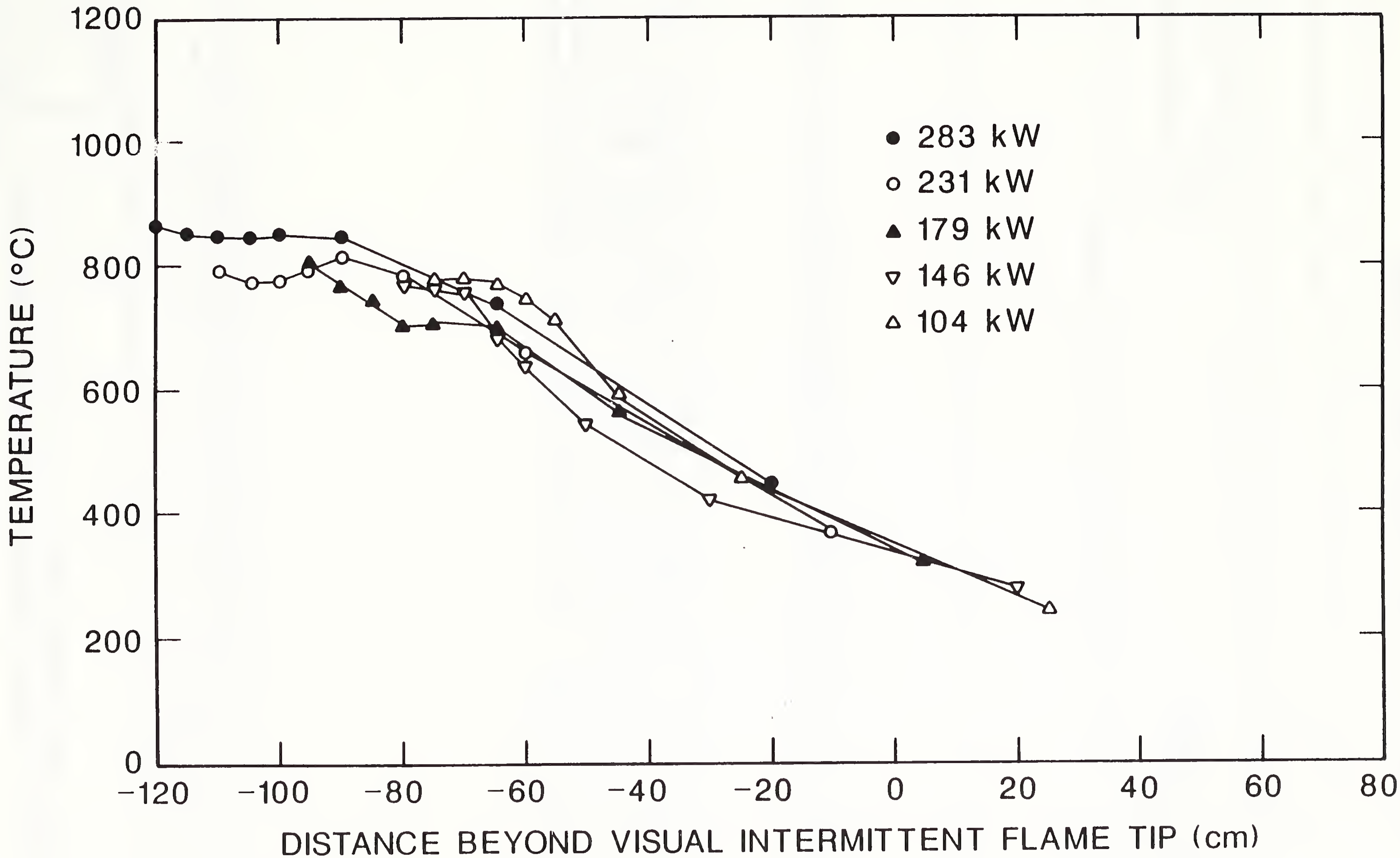


Figure 6. Temperature profile along ceiling for axisymmetric gas burner C=0.61 m H=0.5 m

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☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

Measurements of luminous flame extensions beneath ceilings under steady burning conditions are presented. Tests were conducted using both axisymmetric and corner-wall-ceiling configurations for a range of energy supply rates up to 400 kW and burner-to-ceiling heights up to 2.3 m. Flame length observations, which were made both visually and photographically, are expressed in dimensional and in nondimensional terms. Comparisons are made with previous measurements reported in the literature.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

Fire plumes; flame height; gas burners; luminous flames; ceilings; flame research; crib fires; walls.

13. AVAILABILITY

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