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SOOT FORMATION IN VITIATED-AIR DIFFUSION FLAMES

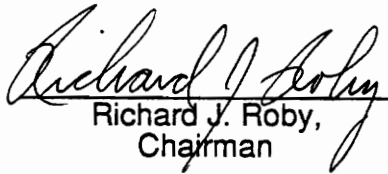
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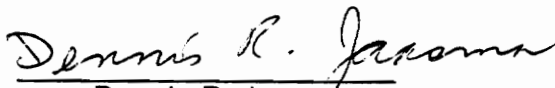
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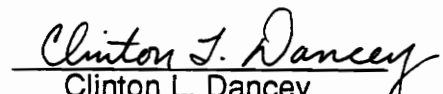
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SOOT FORMATION IN VITIATED-AIR DIFFUSION FLAMES

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(ABSTRACT)

Soot volume fractions have been measured using optical techniques in dual mode diffusion flames. A dual mode flame is defined as a diffusion fuel jet that burns in the wake of a premixed flame. The premixed flame combustion products simulate a vitiated-air environment: the air is preheated, rich in radicals, and depleted in oxygen.

A two stage burner was used to investigate the effects of vitiation on the soot yield in diffusion flames. In the first stage, a fuel-lean premixed methane flame burned. A diffusion fuel jet was injected in the second stage. The effects of vitiation were simulated by varying the premixed flame stoichiometry, diffusion flame injection height above the premixed flame, and premixed flame temperature. The premixed flame stoichiometry affects the oxygen availability. The oxygen availability was varied from an 18% oxygen index to a 23% oxygen index. Different diluent gases (Ar, N₂, and CO₂) were used to alter the premixed flame temperature. The injection height of the diffusion flame (0.0 to 1.0 cm) affects the radical concentrations and temperature field. The soot yield from dual mode combustion was compared to the yield from similar single mode flames. For the single mode flames, air was injected through the first stage.

Experimental results indicate that dual mode combustion increases the soot yield significantly in diffusion flames. Among flames at a 23% oxygen index, the mean

increase in soot levels was 84%. Among flames at an 18% oxygen index, mean soot levels increased by 314%.

In dual mode flames, the effect of injection height is weak, as is the effect of oxygen availability. The effects of the feed air temperature could not be resolved. In single mode flames, the effect of the injection height was weak, but oxygen availability affects soot yield significantly. Single mode flames show an average increase of 180% in soot yield at the 23% oxygen index with respect to the 18% oxygen index. These conclusions are the same for both ethene and propane as the diffusion flame fuels.

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NOMENCLATURE

$F(x,y)$	A property of an attenuating field (extinction coefficient, k_{ext})
a	Spacing between profile points (distance M_i to M_{i+1})
N	Number of equally spaced angular scans
M	Number of points in a profile
$P(r_k, \theta_j)$	Measured extinction profile
ϕ	A filter function
r_k	Distance point is offset from centerline of profile
θ_j	Projection angle
λ	Wavelength of light of probe beam
$E(m)$	$-\text{Im} [(m^2 - 1) / (m^2 + 2)]$
m	The complex index of refraction of soot, assumed to be equal to $1.57 - 0.56i$ [23]
D_{12}	Diffusion coefficient [cm^2/s]
T	Gas temperature [K]
p	Pressure [atm]
T_{12}^*	kT / ϵ_{12}
M_1, M_2	Molecular weight of species 1 and 2
$\sigma_{12}, \epsilon_{12}/k$	Molecular potential energy parameters characteristic of species 1 and 2 interaction [angstroms, K]
$\Omega^{(1,1)*}$	A tabulated correction function
k	Boltzmann constant
η_f	Nondimensional flame height
I	Measured beam intensity
I_o	The original or reference beam intensity
k_{ext}	Extinction coefficient
L	Path length of probe beam through a medium

f_v	Soot volume fraction
T_{ad}	Abbreviation for adiabatic flame temperature
OI	Abbreviation for oxygen index

CHAPTER 1: INTRODUCTION

1.1 BACKGROUND AND MOTIVATION

Soot has long been recognized as a major pollutant which contributes to respiratory disorders and results in environmental degradation when released to the atmosphere [1]. As a result of the deleterious effects of soot, regulations have been proposed or enacted to control the emission of soot from combustion devices including stationary power plants and diesel and gas turbine engines. In addition to the health hazards of soot, the incandescence of soot particles in flames can substantially increase radiant heat transfer in combustion devices. The increased heat load from radiation requires designs capable of withstanding higher temperatures, thus adding to the cost or complexity and reducing the performance of such devices. However, for some devices like industrial boilers, a high rate of radiant heat transfer is desired. The problem in these applications is to ensure sufficient burnout of the soot particles to meet emission standards.

Due to the importance of soot in terms of environmental regulations and mechanical design of various combustors, much research had already been done in this area. Studies have identified several steps in the formation and oxidation of soot in flames [2]. The initial step, called nucleation, occurs when fuel molecules dissociate into smaller fragments upon heating, but subsequently polymerize into much larger hydrocarbons. These soot precursors have a character that is indicative of aromatic rings and polyacetylene structures. The next step, called the growth stage (or growth and agglomeration stage), is where the bulk of the actual soot is formed. Gas phase hydrocarbons condense onto the soot precursors, forming fairly spherical particles. As

the rate of surface growth slows, these particles tend to agglomerate into long chainlike structures. In the final step, oxidation, these soot particles are burned. Whether or not soot is released from a flame depends on the rates of all three of these steps. Therefore, it is important to study the history of the soot particles within the flame in order to understand the overall sooting process.

Recent approaches to soot research have been primarily of two types: burner studies and in situ studies. The advantage of burner studies is that laminar premixed and diffusion flames lend themselves to easy measurement and analysis; the results do much to improve the understanding of the fundamentals of soot formation and oxidation. However, it is evident that purely premixed or purely diffusional flames frequently do not reflect the combustion environment found in practical combustors. Studies of soot formation in diesel and gas turbine engines have focused primarily on the understanding of fuel and engine variables that affect the level of soot emitted by the engine [3]. As such, they lack much of the fundamental understanding obtained from burner studies. However, there is hope that these two approaches can be consolidated. One advancement would be the development of better diagnostics for in situ measurements. Another method would be to use a laboratory burner which more accurately simulates practical combustors. This research focuses on latter approach.

Researchers have studied soot formation in laminar premixed and diffusion flames since these lend themselves to easy measurement and analysis. However, one criticism of laboratory burner studies is that purely premixed or purely diffusional flames are not representative of practical combustors. This is supported by considering two practical examples: diesel engine combustion and gas turbine combustion (turbulent diffusion flames). Each of these examples illustrate a process called dual mode

combustion. The term "dual mode" means that two different types of combustion occur; one mode is similar to premixed flames, and the other mode is similar to diffusion flames. Both modes are readily identified in the following examples.

During diesel engine combustion, some of the fuel premixes with air during the fuel injection. The lighter fuel fractions are vaporized while the heavier fractions remain as droplets. Upon ignition, a lean premixed flame sweeps through the chamber, consuming the vaporized fraction. This depletes some of the available oxygen while producing a rich pool of radical by-products. The fuel droplets subsequently burn in a diffusional mode in the vitiated-air environment [4].

A similar environment would be found in a gas turbine combustor, which uses a turbulent diffusion flame. In turbulent flames, there are regions where the swirling flows create areas of dual mode combustion. Figure 1 illustrates this eddy mixing process. A region of quenched premixed flame (rich in radicals, depleted in oxygen) can combine with unburned fuel in an eddy, leading to diffusional combustion conditions similar to those described above for the diesel engine. It is essential at this point to recognize that the combustion process in either case is neither purely diffusional nor purely premixed - dual mode burning exists.

If dual mode burning is indeed a characteristic of practical flames, then laboratory studies should be taking this into account. The most significant consequence of dual mode combustion is the generation of vitiated feed air. Vitiation means that the feed air is depleted in oxygen, but in dual mode flames the air is also preheated and may be rich in radicals. Previous research into diffusion flames has identified some of the effects of temperature, oxygen availability, and radical species on soot formation, but not in an

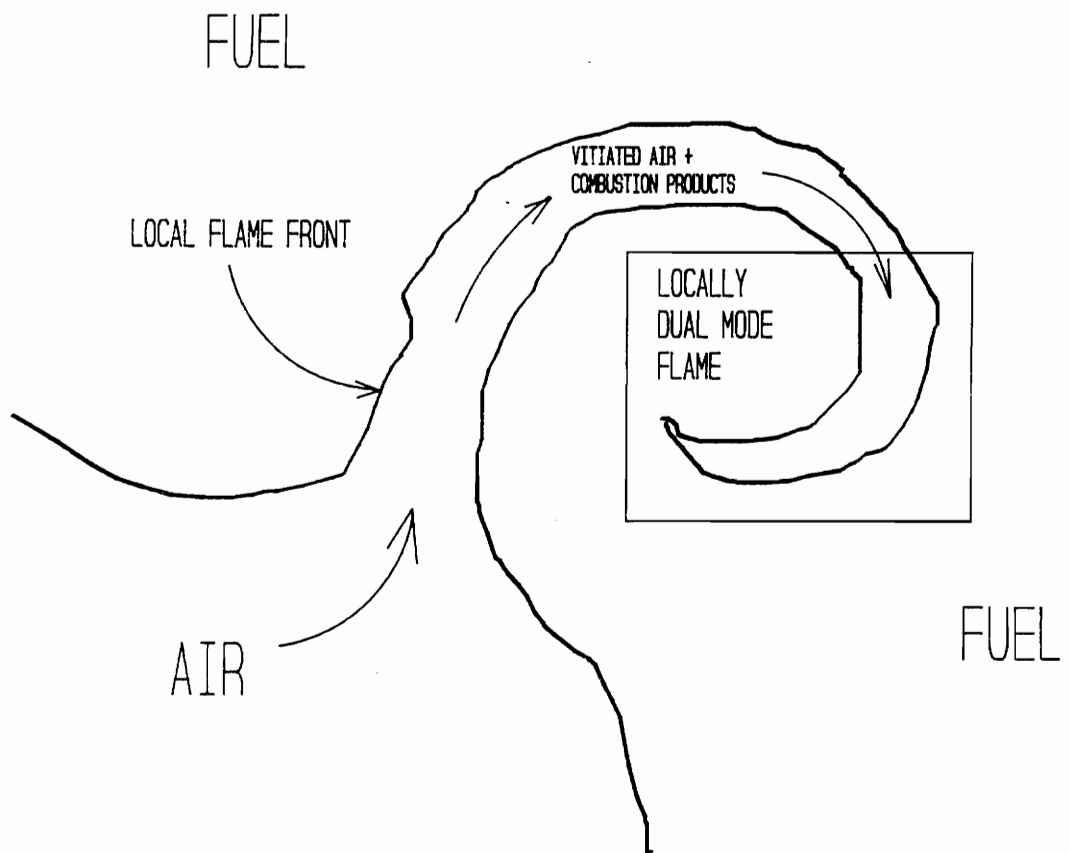


Figure 1. Local Eddy Mixing in Turbulent Diffusion Flames

integrated manner. The following paragraphs summarize the results of these investigations.

Most of research done to date on laboratory-burner diffusion flames has concentrated on the temperature and oxygen availability factors [5-11]. A survey of the results from previous burner studies shows that the rate of soot formation and removal is strongly related to the flame temperature and to the availability of oxygen whether in a premixed or diffusion flame [2,3,5-7,12-17]. However, these rates can vary depending on whether the flame is premixed or diffusional. It is known that the higher the temperature of the diffusion flame, the more soot is formed. Higher temperatures promote pyrolysis on the fuel side of the flame, which encourages the production of more soot precursors. It has also been shown for diffusion flames that increasing the feed air temperature slightly increases the flame temperature (which increases the tendency to soot) [1]. For premixed flames, the opposite is true; higher temperatures decrease the amount of soot formed. Since the fuel and oxidizer are intimately mixed, pyrolysis and oxidative processes can compete. At higher temperatures, oxidation is preferred and less soot precursors are formed.

Fuel structure also plays a role in determining the amount of soot formed. This effect is seen primarily in the soot precursor inception phase, since mature soot from flames is morphologically similar regardless of the fuel burned [2]. Sooting tendency seems to be related to the fuel's readiness to polymerize into polyacetylene and aromatic ring structures. Not surprisingly, acetylene and aromatics like benzene show a high tendency to soot. The stability of these structures permits polymerization to much larger molecules, the soot precursors. Ethene soots readily, since it is fairly similar to acetylene. In general, the alkenes soot more than the alkanes [2].

Recent results suggest that the presence of radicals, particularly OH or O atoms near the fuel pyrolysis zone in diffusion flames, can significantly increase the formation of soot [13-15]. These studies indicate that the primary effect of radicals is seen in the early stages of soot formation: nucleation and surface growth. A diffusion flame generates a super-equilibrium concentration of radicals on its own - it is currently unknown what effect the extra radicals produced by the premixed burning would have. One might expect that the diffusion of radicals to the fuel pyrolysis zone would be enhanced, leading to more sooting. Once again, the burner studies done to date have not addressed this dual mode combustion problem.

More recently the results of Hura and Glassman [18] have shown that a two stage combustion process like the one described above can have a significant effect on soot production. They investigated sooting properties in a counterflow diffusion flame where varying amounts of oxygen were premixed with the fuel flow. For large amounts of oxygen addition, there resulted a sharp increase followed by a sharp decrease in the peak extinction coefficient as the equivalence ratio was lowered in ethene flames. This seemed to coincide with the appearance of a premixed flame on the interior of the diffusion flame zone. The sharp increase was attributed to the generation of radicals and soot precursors by the premixed flame near its rich flammability limit. These radicals/soot precursors, surviving into the diffusion zone, appeared to greatly enhance the soot formation rate in the diffusion flame. They showed that the addition of 10 percent oxygen in ethene flames resulted in an increase in the final soot volume fraction of more than 100 percent. As the equivalence ratio of the premixed zone was reduced further, they surmised that the soot oxidation processes began to dominate the premixed flame so that soot precursors were no longer emitted into the diffusion flame. Additionally, OH radicals were emitted which attack the soot precursors being formed in

the diffusion flame. This influence, along with a shortening of the soot inception time/path length, lead to a greatly reduced amount of soot emission. However, this effect was dependent on the diffusion flame fuel. Hura and Glassman concluded that

... the oxygen effect is strongest in ethene, less so in propene, and negligible in the alkanes, and are in agreement with most of the previous studies. For alkanes the effect of oxygen is extremely weak and quite independent of the oxygen concentration in the fuel.

Unfortunately, their burner geometry allowed only limited measurements of the soot properties so they were unable to resolve many of the observed effects. Nevertheless, these results clearly show that a staged ethene flame has significantly different sooting tendencies than either a premixed or a diffusion flame.

Although in-situ studies are inherently more realistic than laboratory burner studies, they rarely provide information on the critical competition between soot formation and oxidation. A study on the effect of lower cetane number diesel fuel on soot emissions showed that as the cetane number is reduced, the soot emissions increase [21]. The cetane number for a diesel fuel is analogous to the octane rating for gasoline. Since a lower cetane number is associated with a longer ignition delay, there is more time for the volatile fraction of the fuel to premix. The premixed burning of a larger fraction of the fuel may be responsible for the observed increase in emissions. The increase may therefore be attributable to an increase in the number of radicals generated or air vitiation or both. Both of these studies have not identified fundamental mechanisms or revealed the details of the soot formation process. More detailed flame measurements are needed to resolve these questions.

Based on this review, it is clear that there is a need to bridge the gap between the detailed results from burner studies and the basic knowledge of soot emissions from in-

situ studies. There are aspects of dual mode combustion which have not been explained sufficiently by the results of previous burner studies. In the dual mode combustion which occurs in practical combustors, three effects are interrelated. The premixed mode raises the feed air temperature, which should raise the diffusion flame temperature and promote sooting. However, the consumption of oxygen to form inerts like CO_2 and H_2O can lower the temperatures and inhibit sooting in the diffusion flame. Finally, the effect of the radicals is less well understood. Hura and Glassman's results suggest that radicals can increase or decrease the sooting tendency of diffusion flames. The obvious question here is what is the overall effect? A less obvious question is what role did radicals play in the previous studies of temperature and oxygen effects?

1.2 OBJECTIVES AND TECHNICAL APPROACH

The primary focus of this research is to identify the effect of vitiated air on the soot properties of diffusion flames. Single mode and dual mode flames will be compared. Single mode diffusion flames are defined as a diffusion fuel jet issuing into coflowing feed air. Dual mode diffusion flames are defined as a diffusion fuel jet issuing into the products of combustion from a premixed flame. A particular goal is to be able to separate the effects of temperature, oxygen availability, and radicals on the amount of soot formed.

The proposed research is primarily concerned with the role that radical concentrations play in diffusion flames. It is believed that this approach will help make the results of previous burner studies more applicable to practical combustor problems. In order to accomplish these tasks, the research program must meet the following goals:

- 1) The burner must be able to simulate practical combustors, and represent the conditions under which they are operated. For example, the effects of fuel

volatility, ignition delay, and intensity of eddy mixing must have some analog in the laboratory burner.

2) The methods used must be able to separate the effect of the radicals from the effects of the other parameters, such as fuel type, stoichiometry, and feed air temperature.

The following paragraphs describe how the overall research program is intended to achieve these goals. The description emphasizes the versatility of a unique two stage burner, and reflects the long-term expectations of the program. Clearly, some of the measurements were beyond the scope of the research for this thesis. At the conclusion of the overview, the actual scope of the thesis will be defined.

The chief advantage of using a two stage laboratory burner is that there is uninhibited optical access to the steady, laminar flames. This allows measurement of the distribution of soot properties, radical concentrations, and soot precursors by nonintrusive techniques. The soot volume fraction, average particle size and size distribution, and particle number density can be found using Mie-Lorenz theory following the procedures given by D'Alessio [22]. The soot volume fraction is defined as the total volume of soot particles per unit volume of space. Hydroxyl radical concentrations can be determined by absorption or fluorescence measurements using a frequency doubled dye laser system. Hydrogen and oxygen atom concentrations can then be calculated using the partial equilibrium assumption for the $\text{H}_2\text{-O}_2$ system. The wide band fluorescence of polycyclic aromatic hydrocarbons (PAH) can be used to detect soot precursor concentrations. Temperatures can be measured with thermocouples or can be determined from the OH measurements.

Such detailed measurements of the soot formation process should result in a much more fundamental understanding of soot formation in dual mode combustion than is

achievable with in situ measurements. With the two stage burner, the soot particle history can be followed through the diffusion flame. It may be possible that eddy mixing reduces the total soot volume produced in the early stages of the flame, or that the average particle size decreases (promoting better burnout), or both. This question can only be answered if detailed soot measurements can be made, and the literature provides well established optical-based methods for use in laboratory flames [22-25].

The two stage burner allows one to set both the first stage and the overall stoichiometry. Thus, it is possible to study a continuum of combustion regimes from purely premixed to purely diffusional, subject to the stability limits of the burner. If a practical combustor can be characterized by its premixed mode/diffusional mode burning rates, it may be possible to use this type of two stage burner as a diagnostic model. The notion that turbulent diffusion flames are more properly modeled by a dual mode laminar burner flame are supported by the recent work of Flower [19]. In scattering measurements of integrated line-of-sight soot volume fractions in turbulent diffusion flames at various pressures, Flower found that

The flames consist everywhere of alternate soot-laden and soot-free zones, rather than consisting of large mixed regions where soot is found everywhere, as would be expected if substantial premixing occurred before burning. Also, the pressure dependence of the peak soot flux for turbulent diffusion flames with fixed residence time ($p^{1.4}$) is close to the pressure dependence that was observed for laminar diffusion flames ($p^{1.2}$). Both of these observations are consistent with the behavior that would be expected if soot formation occurred in laminar flamelets."

This statement not only supports the notion that diffusional burning with significant eddy mixing is a good model for a turbulent diffusion flame, but also it lends support to the use of a laminar flame system to model this process.

The cetane study indicated that soot production may be affected by the amount of fuel which burns in the premixed mode. The amount of fuel that burns in the premixed mode can be affected by two factors: the percentage and type of light ends in the fuel, and the temperature of the combustion region. In a two stage burner, these factors can be simulated by changing the type of fuel burned in the first stage (use lighter or heavier hydrocarbons), changing the fraction of the total fuel flow that burns in the first stage while keeping the overall stoichiometry constant and by controlling the burner cooling water flow rate. This approach also applies to turbulent diffusion flames, since the degree of eddy mixing is analogous to the relative amount of fuel which is burned in the premixed mode.

One limitation for the premixed stage will be the lean flammability limit, which could limit the maximum concentration of oxygen reaching the diffusion flame. For example, the lean flammability limit of methane in air is about 5%. Normal air contains 21% oxygen; after premixed combustion, there would only be about 10% O_2 left for the diffusion flame. In order to measure the effect of a wider range of oxygen concentrations, the O_2 concentration in the premixed stage will be enriched by using artificial air (O_2 concentrations greater than 21%). The use of artificially enriched air should not detract from the realism of the burner, since some non-vitiated air invariably mixes with the combustion region in actual combustors.

The two stage burner also allows control over the relative input of radicals to the diffusion flame. More importantly, the effect of these radicals can be removed altogether. Preheated "artificial air", composed of oxygen and nitrogen, can be injected through the first stage instead of a fuel-air mix. This preserves the temperature and O_2 depletion character of the feed air, while removing the radical character. If the diffusion flame temperature field is low enough to prevent significant CO_2 dissociation, the

artificial air could be composed of CO_2 and O_2 to better represent the specific heat of vitiated air.

The relative amount of radicals which reach the diffusion flame (second stage) can be varied in several ways. The H/C ratio of the first stage fuel and the first stage equivalence ratio will affect the relative amount of hydrogen-containing radicals which are formed. By varying the injection point of the diffusion flame jet downstream of the first stage, the number of radicals which actually reach the second stage can be controlled. Finally, the burner cooling water flow rate will have some effect on the premixed flame temperature, and therefore the radical concentrations.

Temperatures in the flame regions can be controlled to some extent by varying the type of fuel burned, the burner cooling water flow rate, the diffusion jet injection point, and by dilution with inert gases (either or both stages).

One aspect of practical combustors which has not yet been addressed in this discussion is the role of high pressures in soot formation. Some work in this area, done by Flower and Bowman [26] and Flower [19] shows a significant increase in soot formation with pressure. For this initial study, atmospheric flames will be studied. If the initial results of this study are promising, higher pressure flames would be the next step, following the diagnostic procedures developed by Flower and Bowman [26].

To summarize, the two stage burner allows great flexibility in the combustion conditions. Control of the temperature field, radical inputs, and relative stoichiometries should permit fairly accurate simulation of the environment found in actual combustors. By removing the presence of the radicals, their effect can be isolated from the other combustion parameters. The experimental measurements can be used to globally model the soot reaction rates; these rates can then be compared to the global reaction rates

predicted by studies of combustion in a non-vitiated environment. Thus, one can determine the role that radicals play in the soot formation and oxidation processes in diffusion flames. Furthermore, detailed measurements of soot properties will be obtained from a realistic combustion environment.

1.3 SCOPE OF THESIS

The scope of the current research had to be limited to accommodate time restrictions and the expectations for a Master's thesis. The current research primarily investigated the following topics:

- 1) The operation of the burner was tested to check its actual capabilities and operating limits.
- 2) The optical system necessary for extinction measurements was designed and tested. Optical hardware was tested and refined, and the software required for data acquisition and analysis was written and debugged.
- 3) Soot volume fractions were measured in a variety of flames. These flames investigated the effects of combustion mode (single vs. dual), diffusion fuel, diffusion flame injection height, temperature, and oxygen availability. Spatial resolution of the soot volume fractions was achieved across the flame cross section at selected elevations of the flames.

One purpose for this thesis is to document the development of the experimental system and data acquisition procedure. The development was greatly influenced by several unexpected problems; the system and procedure evolved to overcome most of these problems. It is important to recognize these problems for several reasons. First, some of these problems limit the measurement capabilities of the current system. Second, there is room for much improvement in the current system. This improvement

should be guided by identifying the unresolved problems which have the greatest impact on the measurements. A third reason is that the system will have to be expanded at some time to increase its capabilities (scattering measurements, for example). Many of the problems that have already been identified may affect the development of these new capabilities.

Of course, the primary reason for this thesis is to present the findings of the research completed to date, and to offer suggestions for further research. These topics are covered in the Results, Discussion of Results, and Conclusions and Recommendations sections.

CHAPTER 2: THEORETICAL CONSIDERATIONS

This purpose of this chapter is to outline the theory of optical diagnostics pertinent to these experiments. The first section defines extinction measurements and how they are made. The second section describes the methods used to calculate local soot volume fractions from the extinction measurements.

2.1 EXTINCTION MEASUREMENTS

The relationship between the attenuation of a probe beam and the attenuation properties of a medium are described by Beer's Law:

$$I / I_o = \exp [- k_{\text{ext}} * L]$$

I = The measured beam intensity

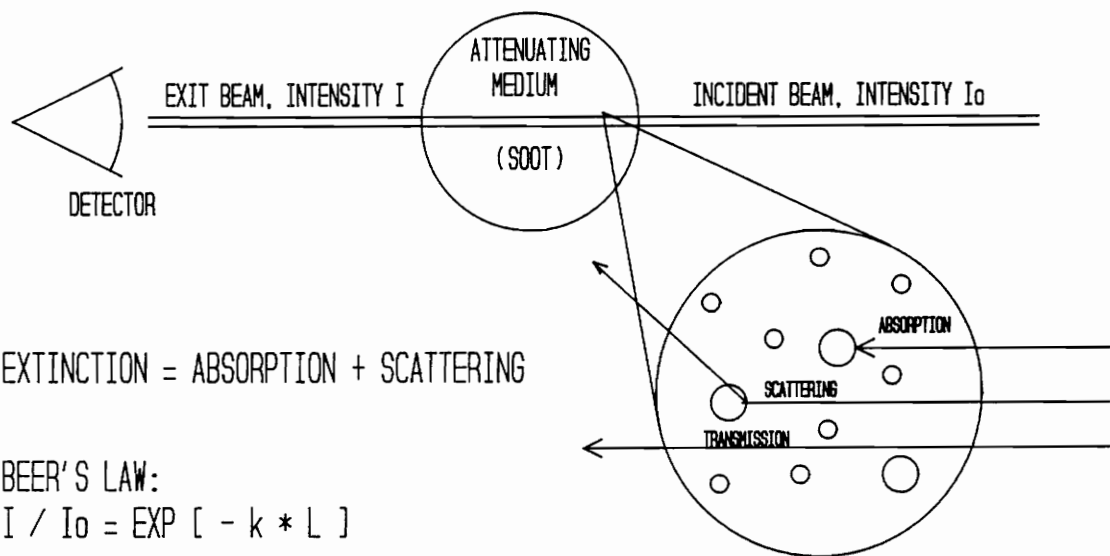
I_o = The original beam intensity

k_{ext} = The extinction coefficient of the medium

L = The path length of the beam through the medium

Figure 2 illustrates this type of measurement. Extinction of the beam intensity is determined by the relative strength of the absorption, scattering, and transmission properties of the medium. The experimentalist measures the original and transmitted beam intensities, and tries to infer information about the attenuating medium from this data. For soot particles that are assumed to be spherical and much smaller than the wavelength of the probe beam, Rayleigh theory applies and the relationship between the absorption and scattering properties are known. Therefore, extinction measurements are sufficient to estimate the soot volume fraction. However, if the particles are not much smaller than the probe beam wavelength, Mie theory applies and the scattering properties of the soot particles must be measured as well.

EXTINCTION THEORY: BEER'S LAW



I = EXIT BEAM INTENSITY (MEASURED)
 I_0 = INCIDENT BEAM INTENSITY (MEASURED)
 L = PATH LENGTH THROUGH ATTENUATING MEDIUM (KNOWN)
 k = EXTINCTION COEFFICIENT, PROPORTIONAL TO THE VOLUME FRACTION OF SOOT IN THE FLAME

Figure 2. Extinction Theory and Beer's Law

Unfortunately, extinction measurements of this sort provide an integrated line of sight measure of the extinction coefficient. In order to get spatial resolution of the extinction coefficient, a procedure called optical tomography is necessary.

2.2 OPTICAL TOMOGRAPHY

The tomography method used for these experiments is a back convolution technique [30-35]. This technique uses the integrated line-of-sight information contained in the extinction profiles to back out the local soot volume fractions in the attenuating field (i.e. the flame zone). Figure 3 illustrates the relationship between the local extinction coefficient ($F(x,y)$) and the measured extinction profile ($P(r,\theta)$). A profile is obtained by measuring the extinction of the probe beam at M equally-spaced intervals across the flame. Ordinarily, profiles would have to be obtained at some N equally-spaced angular orientations. If the flame zone is assumed to be symmetric, the extinction profile at every angle θ would be identical. This has been assumed for these experiments, therefore only one set of profiles is obtained for each flame.

The local extinction coefficient (which leads to soot volume fraction) is calculated using the equation (for more detail/development see references 30 through 35):

$$F(x,y) = (a/2N) \sum_{j=1}^N \sum_{k=1}^M P(r_k, \theta_j) \phi(x \cos \theta_j + y \sin \theta_j - r_k)$$

where

$F(x,y)$ = The property of the attenuating field (extinction coefficient, k_{ext})

a = Spacing between profile points (distance M_i to M_{i+1})

N = Number of equally spaced angular scans

M = Number of points in a profile

$P(r_k, \theta_j)$ = Measured extinction profile

$\phi(x \cos \theta_j + y \sin \theta_j - r_k)$ = A filter function

$r_k = ka$ = Distance point is offset from centerline of profile

$\theta_j = (j-1)\pi/N$ = The projection angle

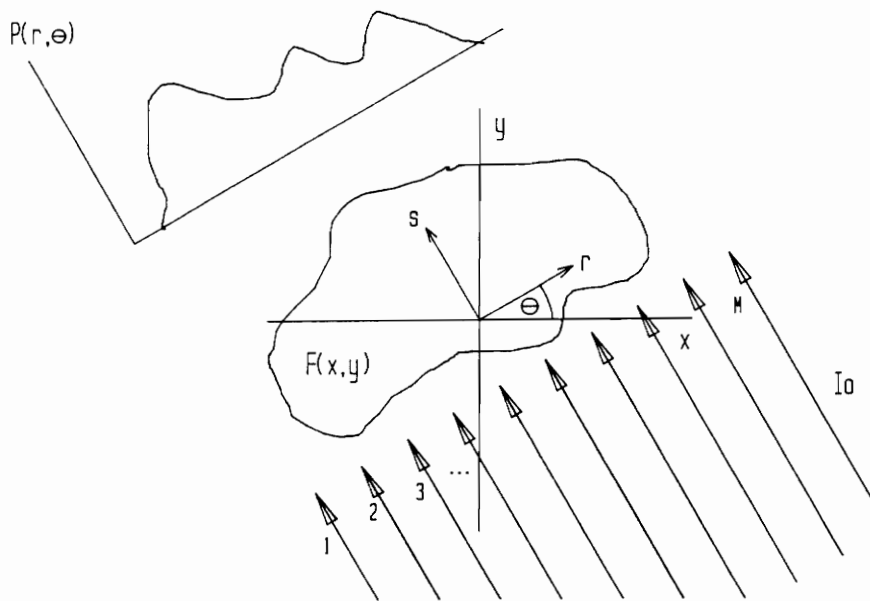


Figure 3. Extinction Profile Measurements

The Shepp-Logan filter function was used [34,35]. The filter function attenuates some noise in the extinction profile. It has the form:

$$\begin{aligned}\phi_0 &= -4 / (\pi a^2) & k &= 0 \\ \phi_k &= -4 / (\pi a^2 (4k^2 - 1)) & k &= \pm 1, \pm 2, \dots\end{aligned}$$

If one assumes that Rayleigh theory applies for these measurements, the local soot volume fraction $f_v(x,y)$ is related to the extinction coefficients ($F(x,y)$) by the equation [23]:

$$f_v = \lambda k_{ext} / (6 \pi E(m))$$

where

λ = Wavelength of light of probe beam

$E(m) = -\text{Im} [(m^2 - 1) / (m^2 + 2)]$

m = The complex index of refraction of soot,
assumed to be equal to $1.57 - 0.56i$ [23]

Appendix C lists the computer program which was used to perform the convolution operation on extinction profiles. This program was tested by constructing a known field with two dimensional Gaussian extinction properties. The Gaussian field is represented by the equation:

$$f(x,y) = 20 \exp [-(x^2 + y^2)]$$

Extinction profiles were calculated by integrating the area under cross sections of this gaussian field. This profile simulates the result that would be obtained by making extinction measurements of the Gaussian field. Figure 4 shows the original function and the reconstruction based on the test profile. The reconstruction accuracy is good in all regions except for the rise and dip along one axis at the base. The agreement indicates that the program operates correctly.

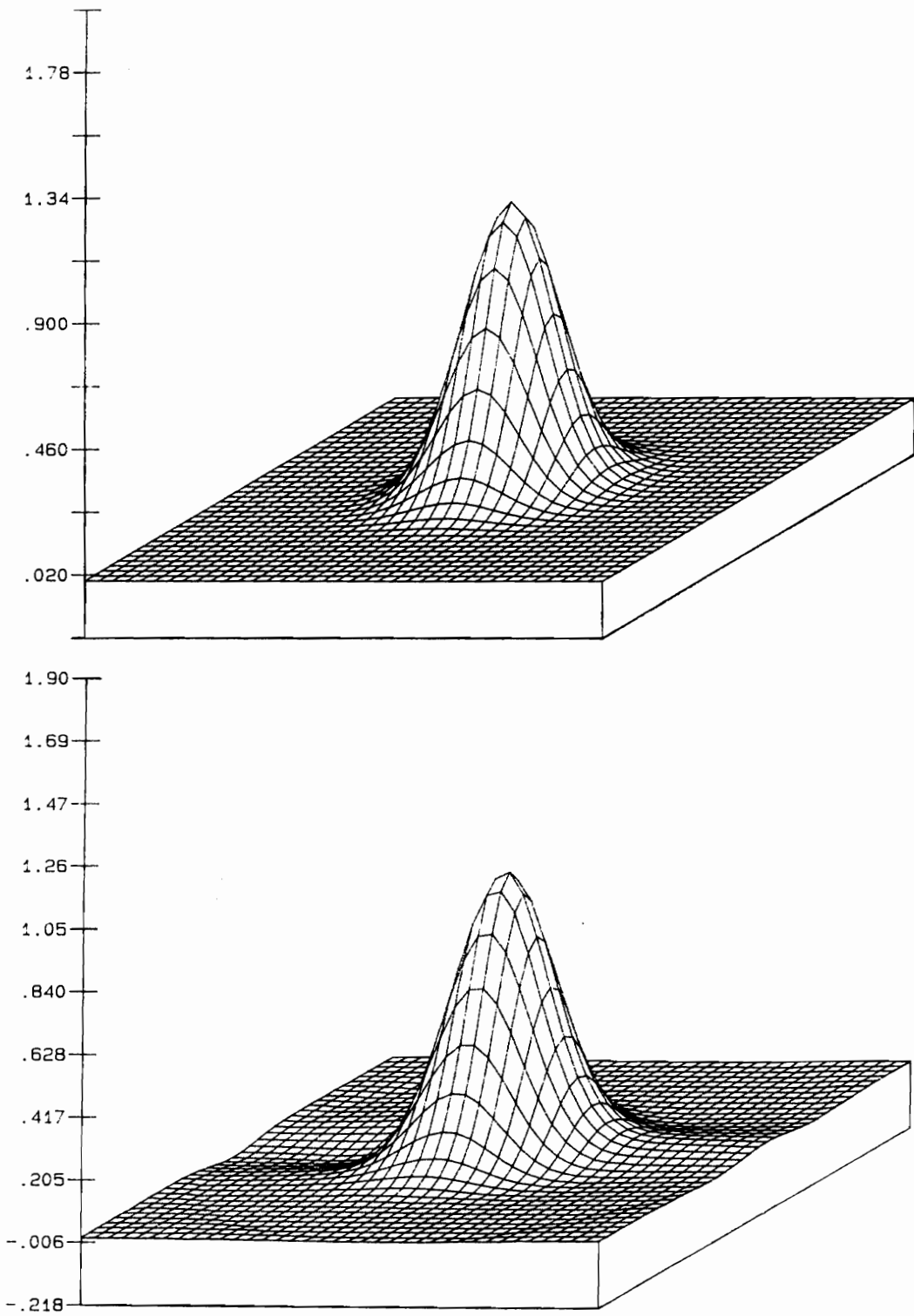


Figure 4 Reconstruction Accuracy of a Gaussian Profile
Top: Original Function
Bottom: Reconstructed Function

The accuracy of the reconstruction is sensitive to several problems. Most of these problems occur if a single measured extinction profile is used to represent many angular scans of a presumed symmetrical profile. Suppose that the measured profile shape is symmetric, but it has been shifted/offset by about 5 percent. This could occur if the scan were not centered about the axis of symmetry of the measured field. The Gaussian extinction profile was shifted so that the axis of symmetry of the profile was offset by two increments (0.050 mm). Figure 5 shows the reconstructed field based on this shifted profile. The reconstruction shows strong distortion in the plane of the cross section. Figure 6 compares cross sections taken into the plane of the page. The solid line represents the original gaussian distribution. The short dashed line shows that the reconstruction based on the centered profile agrees well with the original function, but shows about a 10% error in reproducing the peak height. The other dashed lines show that the errors are large if the profile is shifted by 5 or 10% (2 or 4 increments, respectively).

Suppose that the measured profile is centered properly, but the profile has an asymmetric shape. This is a problem that occurred occasionally in the measured flame profiles: a double-peaked extinction profile where one peak was larger than the other. Figure 7 shows symmetric and asymmetric double-peaked extinction profiles. The height of the asymmetric peaks are -5% and +5% with respect to the symmetric profile. Figure 8 shows the effect of this type of asymmetry on the accuracy of the reconstruction. While the symmetric profile yields an even-topped field, the asymmetric profile produces a tilted field. Figure 9 compares cross sections from the reconstructed fields. The cross sections are taken from the middle of each field, but the "slices" were taken in different directions. The cross sections shown at the top of Figure 9 were cut in the direction approximately perpendicular to the page, whereas those in the bottom of the figure were

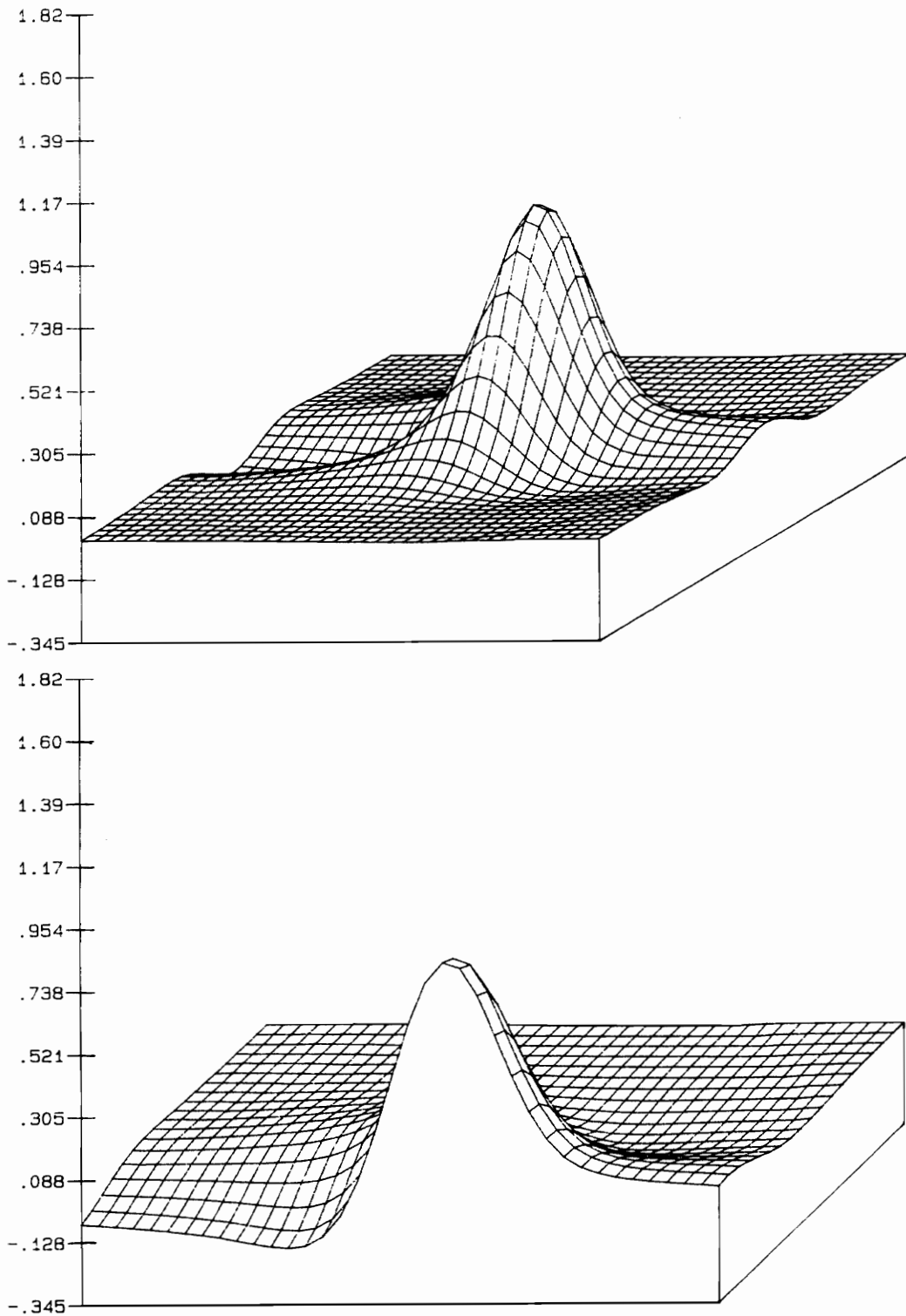


Figure 5 Reconstruction Accuracy of a 5% Shifted Gaussian Profile
Top: Reconstructed Function
Bottom: Cross Section of Reconstructed Function

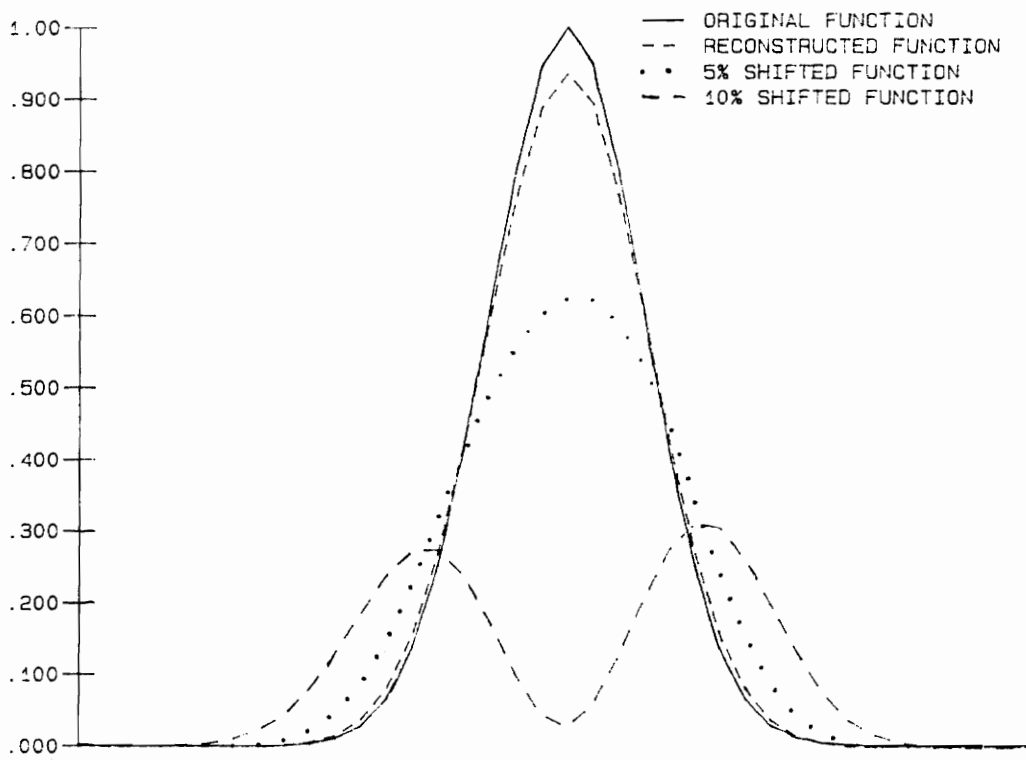


Figure 6 Comparison of Gaussian Profile Reconstruction Accuracies

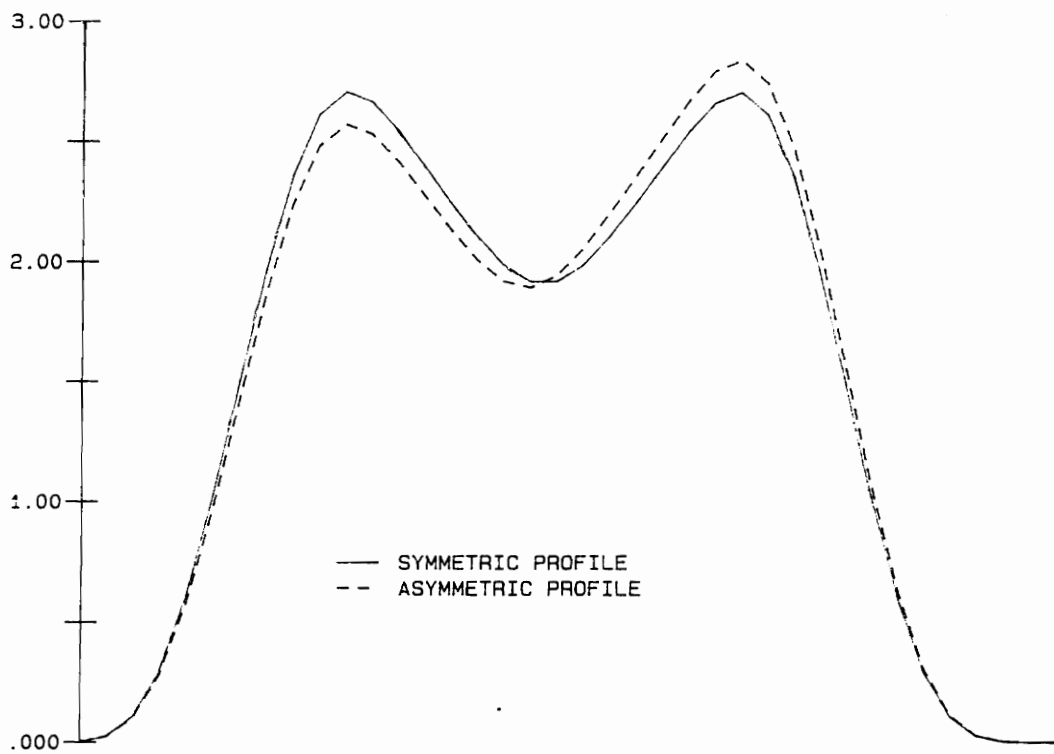


Figure 7. Reconstruction Accuracy of an Asymmetric Profile:
Symmetric and Asymmetric Extinction Profiles

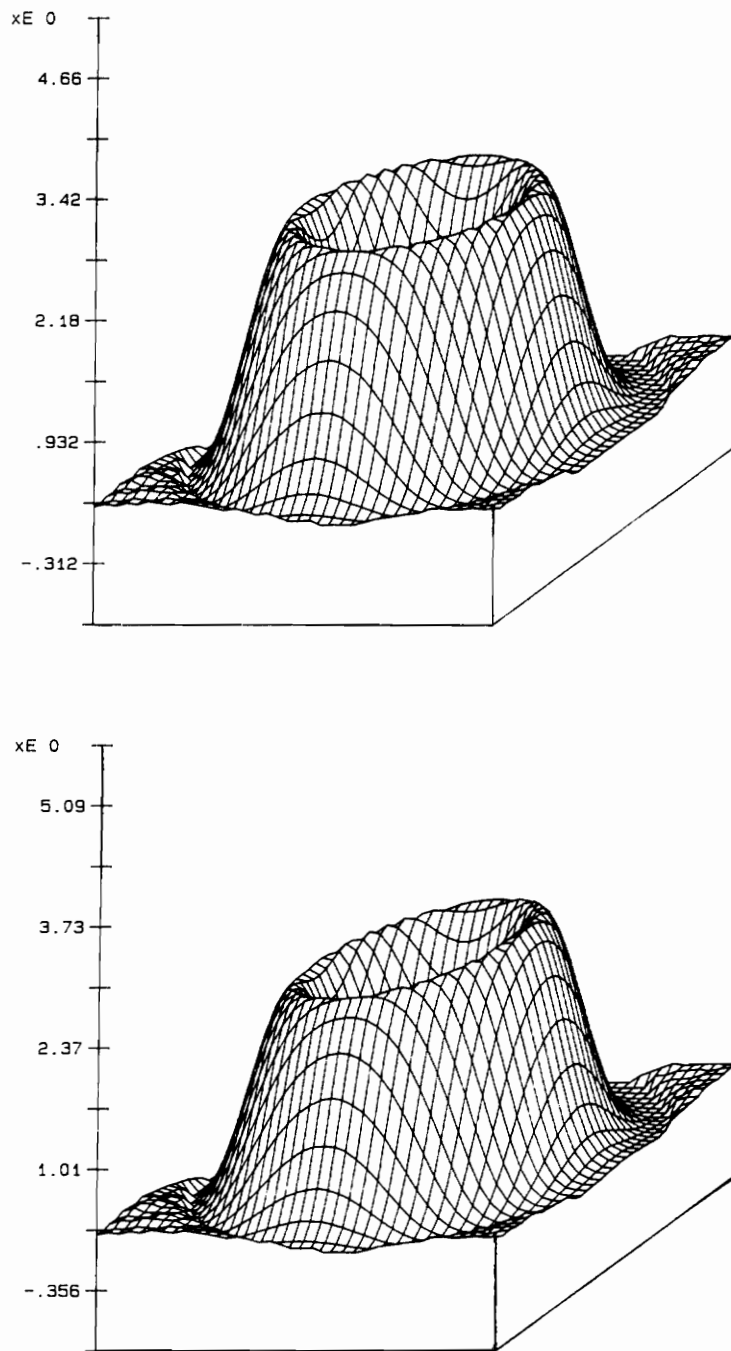
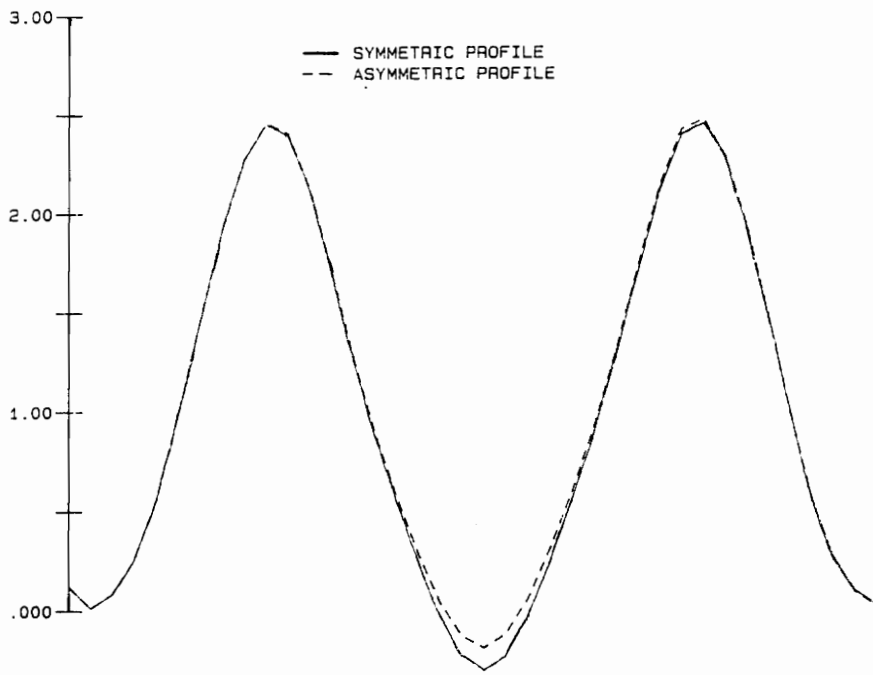
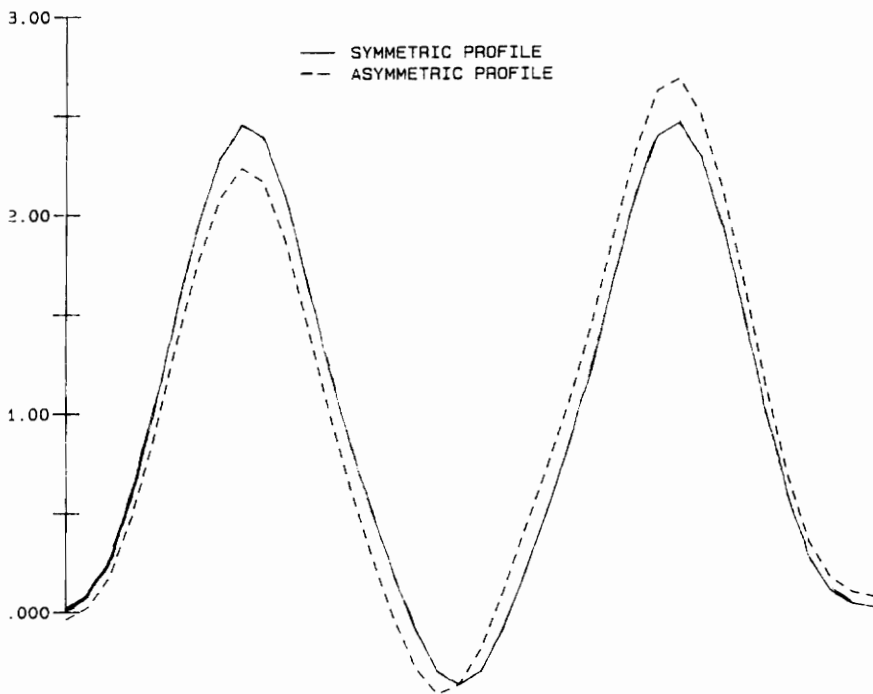


Figure 8. Reconstruction Accuracy of an Asymmetric Profile:
Top: Reconstruction of Symmetric Profile
Bottom: Reconstruction of Asymmetric Profile



CROSS SECTIONS PERPENDICULAR TO PAGE



CROSS SECTIONS THROUGH PLANE OF PAGE

Figure 9. Cross Sections of Reconstruction of Asymmetric Profile:
Top: Cross Section Taken into Page
Bottom: Cross Section Taken in Plane of Page

cut in the plane of the page. This shows that the reconstruction error depends on the orientation of the cross section. The perpendicular cross sections match closely, but the asymmetry is still visible in the plane-of-the-page cross sections.

Finally, consider the extinction field suggested at the top of Figure 10. Although this shape is symmetrical, it still produces large reconstruction errors due to its sharp discontinuities. The extinction profile was calculated by integrating "slices" through this shape, and the reconstructed shape is shown in Figure 10. This convolution illustrates two points. First, the convolution program has difficulty reconstructing sharp features. Sharp discontinuities of this sort would be unusual for diffusion-controlled phenomena, and fortunately this is the case for diffusion flames. Secondly, the reconstruction shows large errors at the edge of the field if the profile does not tend to approach zero smoothly at the edges. This can be avoided by assuring that the width of the extinction profile exceeds the width of the attenuating field.

All three of these extinction profile problems occurred during the experiments. Most profiles were shifted, and some showed asymmetry and/or discontinuities. The shifted profiles were corrected by centering them. Discontinuities occurred because some of the soot volume fraction gradients are quite sharp, and any perturbation of the flame would result in jagged profiles. A curve-smoothing procedure was used to minimize the effect of these excursions. Figure 11 is an example of a measured extinction profile which shows sharp discontinuities due to flame instability, and the effect of the smoothing routine on the profile. The inversion between the 5th and 6th points in the profile has produced a sharp discontinuity, but the smoothed curve effectively removes it. The oscillations between the 10th and 26th points are due to the measurement technique, which is explained in section 3.3.1. The smoothing process minimizes these smaller discontinuities as well. Asymmetrical profiles are still a

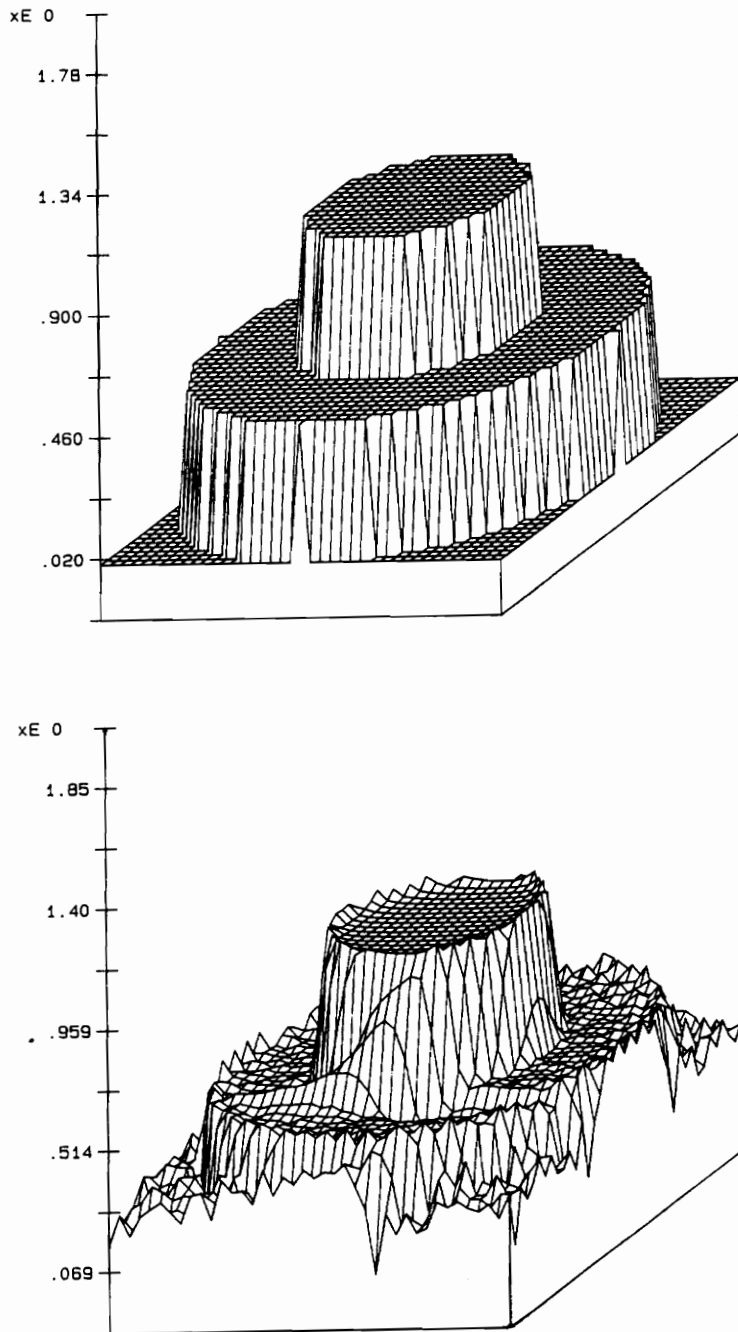


Figure 10. Reconstruction Accuracy of Profile with Sharp Discontinuities
Top: Original Function
Bottom: Reconstructed Function

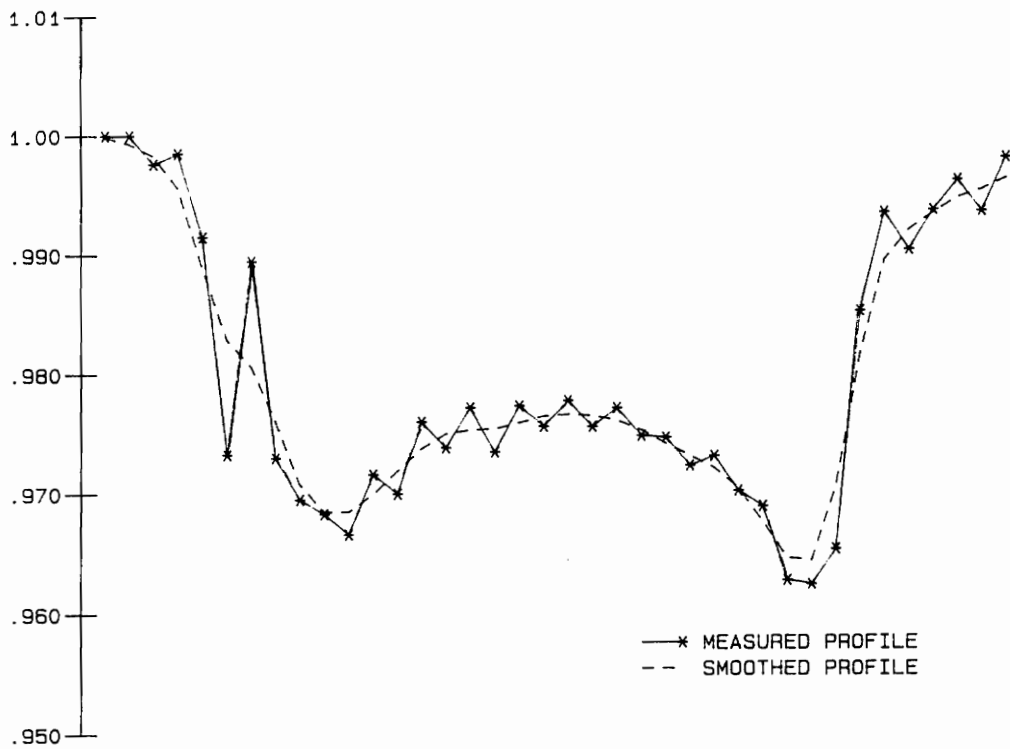


Figure 11. Example Extinction Profile Showing Discontinuities and Smoothed Profile

problem because not much can be done about them. Fortunately, the reconstruction errors do not seem to be as large as for the other profile shape problems. When cross sections of the reconstructed soot volume fractions were required, these were taken in the direction that minimizes the error.

CHAPTER 3: EXPERIMENTAL

3.1 OVERVIEW

The primary purpose of this chapter is to describe the experimental hardware, software, and procedures used for the optical measurements. An equally important part of this documentation is the description of the problems that were encountered and overcome during the development of this system. The chapter begins with a description of the hardware and the software developed for the extinction measurements. The next section explains the evolution of the optical system and the procedures for aligning it. The final sections describe the flames that were studied and the temperature measurements.

3.2 HARDWARE

3.2.1 Dual Mode Burner

The burner consists of a sintered bronze burner plate with a coaxial fuel feed tube shown schematically in Figure 12. The first stage consists of a flat flame (for dual mode flames) stabilized on a porous sintered bronze surface. In the second stage a diffusion flame forms around a fuel jet injected downstream of the flat flame through the center tube. The height of this tube above the flat flame region can be varied by moving the tube higher or lower. In this way, the radical concentrations and the temperature field in which the diffusion flame burns can be varied. An inert shield gas is injected through the outermost ring to isolate the flame from room air.

The center tube is made of 6 mm O.D. quartz glass tubing. This tubing has an inner diameter of 3.8 mm and is L-shaped; the shorter leg is about 7.5 cm long and the

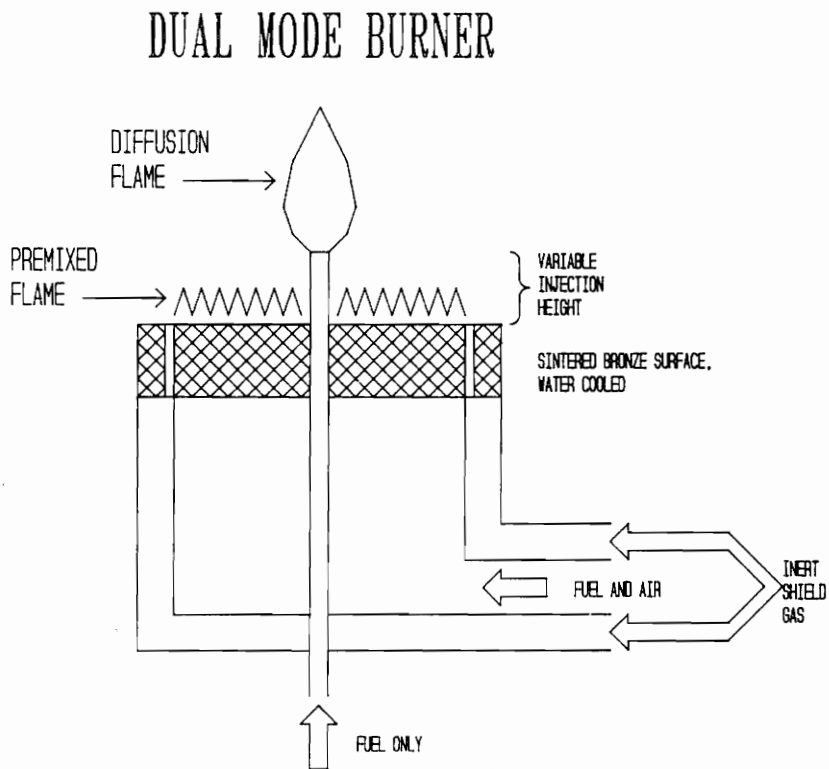


Figure 12. Schematic of Dual Mode Burner

longer leg measures about 20 cm. This center tube is held in place by a Cajon Ultra-Torr fitting, which also eliminates air infiltration through the access hole. The inner ring of the sintered bronze plate has an inner diameter of 9.53 mm and an outer diameter of 60.3 mm. Cooling water is supplied to the inner ring through an internal copper coil. The outer ring of the sintered bronze plate has an inner diameter of 62.6 mm and an outer diameter of 73.0 mm.

The burner was mounted on a two-axis translator. Each full turn of the translator screws displaces the burner by 1mm. A mounting bracket allows access for the gas supply and cooling water lines. The bracket tolerances allow the burner to slide ± 0.5 mm in any direction; for all tests, the burner was pushed as close to the vertical arm of the translator as possible.

Figure 13 is a schematic of the gas supply system for the burner. The gas flow rates were measured with Matheson rotameters in the 601 through 605 tube sizes. These rotameters were calibrated with an American Meter Company model 802 gas flow meter. The calibration curves are given in Appendix F. The shield gas was nitrogen, and this was supplied to the outer ring of the burner. Ethene and propane were used as the diffusion fuels, and these were supplied to the center tube of the burner. For the single mode flames, either normal air or nitrogen-diluted air was supplied through the inner ring of the burner. For the dual mode flames, the premixed flame gases were supplied to the inner ring of the burner. The premixed flame gases were methane as the fuel, oxygen, and a diluent (nitrogen, argon, or carbon dioxide).

3.2.2 Optics

Soot properties were measured using optical (extinction) techniques. The schematic arrangement of the test hardware is shown in Figure 14. The oscilloscope

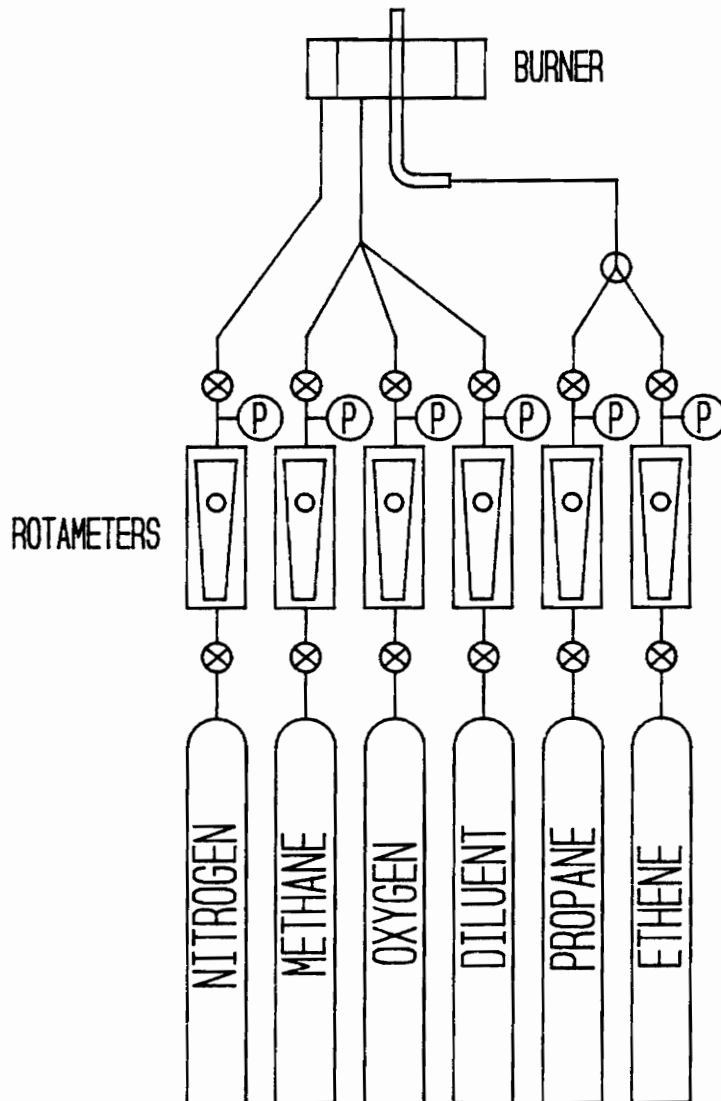


Figure 13. Schematic of Gas Supply System

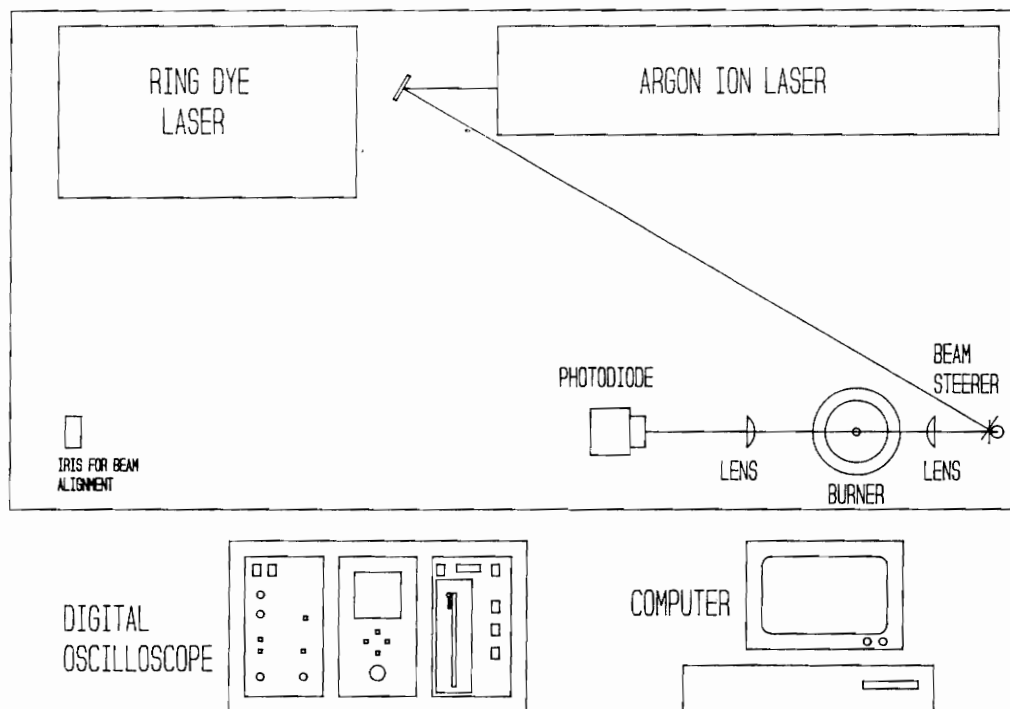


Figure 14. Setup of Data Acquisition Hardware and Optics

monitored the photodiode output, primarily as an indicator of stable operation of the laser. A personal computer recorded the experimental data through its data acquisition board. A Spectra-Physics 5 watt argon ion laser was used for the extinction measurements in the single-line mode at the 514.5 nm wavelength. The laser power was about 0.2 W. This power level seemed to avoid output power stability problems. The laser power was unstable at significantly higher or lower power levels, particularly during the burn-in time of the tube. The laser output was directed with mirrors to the beamsteerer, where the beam was raised to a height of about 25 cm above the table. A pair of irises were used to align the beam over the burner. The lenses reduce the beam diameter over the burner and minimize thermal beamsteering effects. A silicon photodiode was used to measure the intensity of the laser beam (photodiode details follow).

Figure 15 shows the optical path in greater detail. The first iris has a diameter of about 1mm when closed; the second iris has a minimum diameter of about 2mm. The first iris was located about 12.7 cm from the upper beamsteerer mirror; the second was located at the far end of the table, about 2.06 m away from the first iris. The initial alignment directed the beam through both of these irises. A lens was used to focus the beam down to a small diameter over the burner. The focussing lens was a 25.4 mm diameter crown glass plano-convex lens with a focal length of 250 mm (Oriel model number 41390). It was located approximately 12.7 cm from the center of the burner. This lens was placed so that the planar surface faced the burner. A second 25.4 mm diameter lens was used on the opposite (downbeam) side of the burner. This was a fused silica plano-convex lens with a 200 mm focal length (Oriel model number 41380). This lens collected the laser beam exiting the flame and directed it to the photodiode. It was

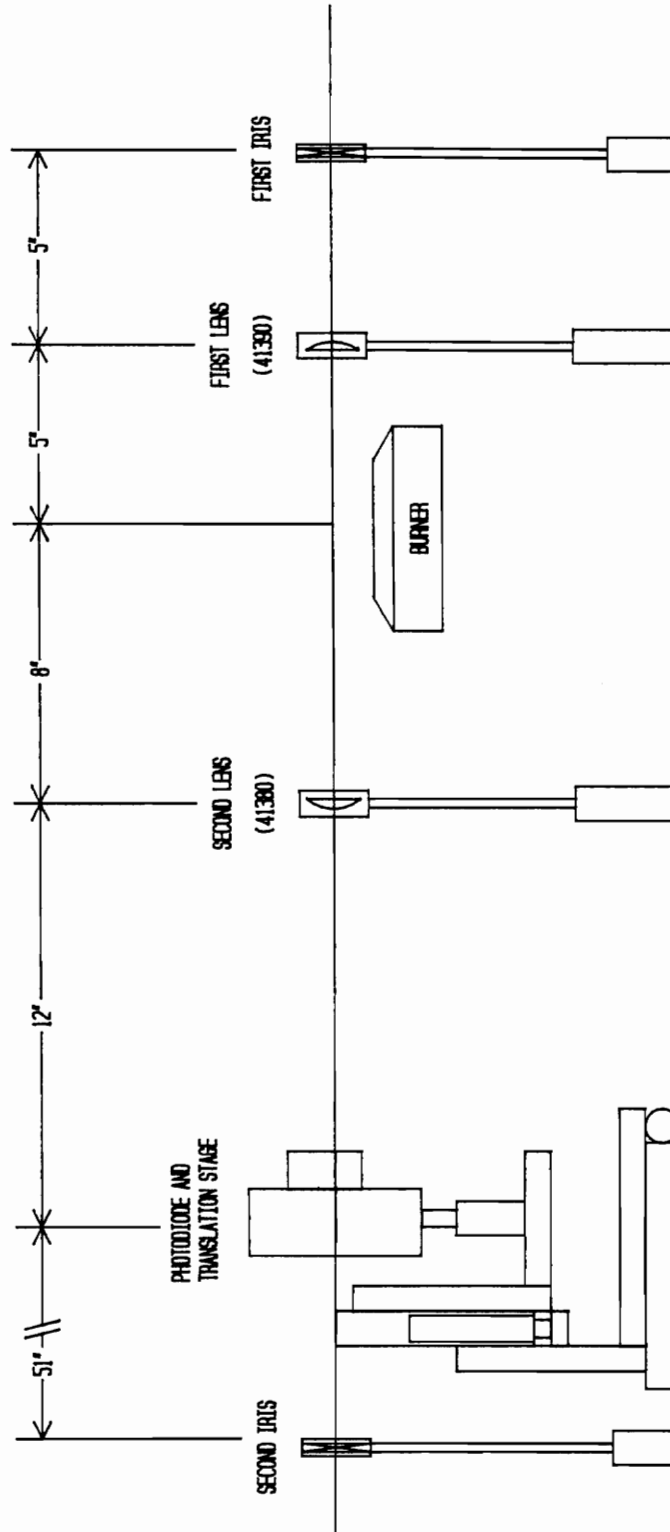


Figure 15. Detail of Optical Path

placed about 20.3 cm from the center of the burner, with its plane surface facing the burner.

The transmitted beam intensity was measured with a photodiode. The photodiode box was mounted on an x-y translation stage so that it could be positioned accurately horizontally and vertically with respect to the beam. The photodiode was placed in the optical path about 30.5 cm from the second lens. Note that this is not precisely at the lens' focal length - the beam spot diameter was approximately 1.5 mm.

3.2.3 Photodiode

An EG&G model HUV-2000 photoconductive photodiode was used. Figure 16 shows a schematic of the electrical circuit. The box shows the internal circuitry of the photodiode. This type of photodiode has an integral operational amplifier; the feedback resistance R_f is fixed at 200 kilo-ohms. The pin connections are labelled where they connect with the external circuit. Two separate power supplies are required to supply +15V and -15V to the photodiode. The positive voltage was supplied by a Hewlett Packard model 721A power supply, and a Hewlett Packard model 6200B supplied the negative voltage. The photodiode output was about 14.7 volts at saturation (i.e. if the light input was too intense). Neutral density filters were used to attenuate the beam strength enough to prevent saturation. At this point, the photodiode output would still exceed 5 volts, the upper limit for the data acquisition board on the computer. A 10 kilo-ohm potentiometer was used as an output voltage attenuator; the photodiode output was usually lowered to about 4.3 volts by adjusting this potentiometer.

The photodiode was mounted on a piece of breadboard, and placed inside an electrical chassis box. Figure 17 shows the details of this box. This box held the potentiometer and the terminals for the power and output signal connections, and allowed

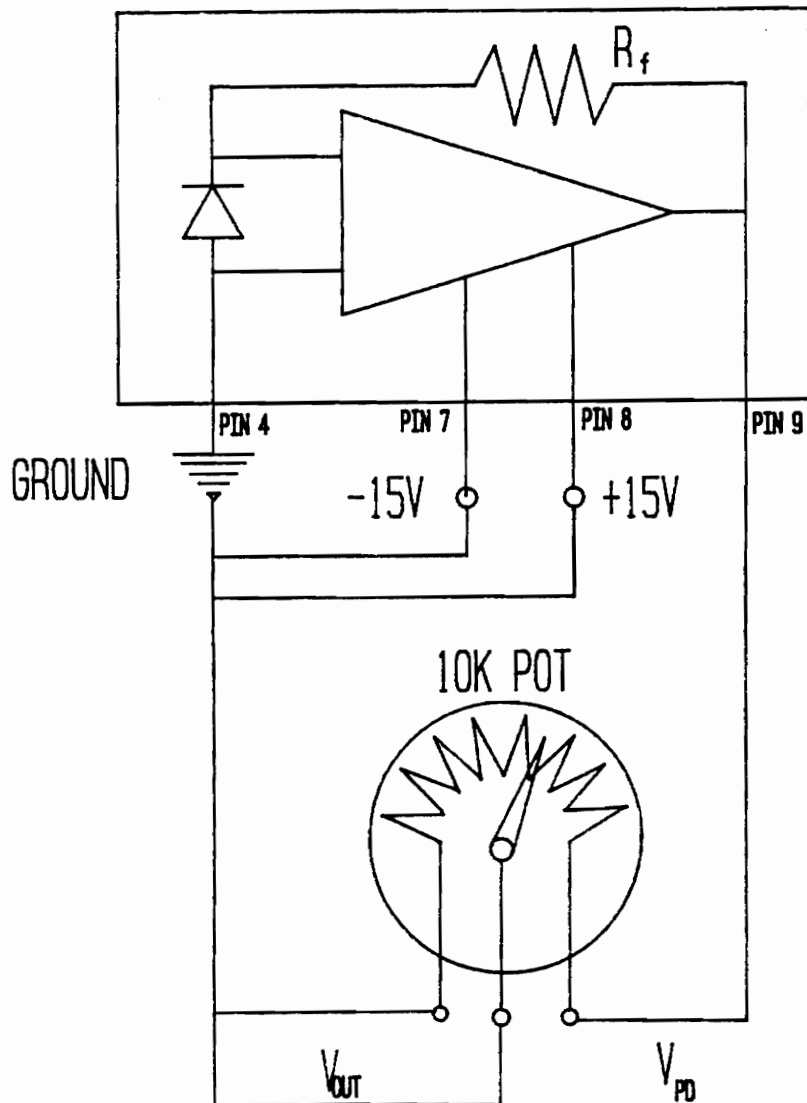


Figure 16. Photodiode Circuit Diagram

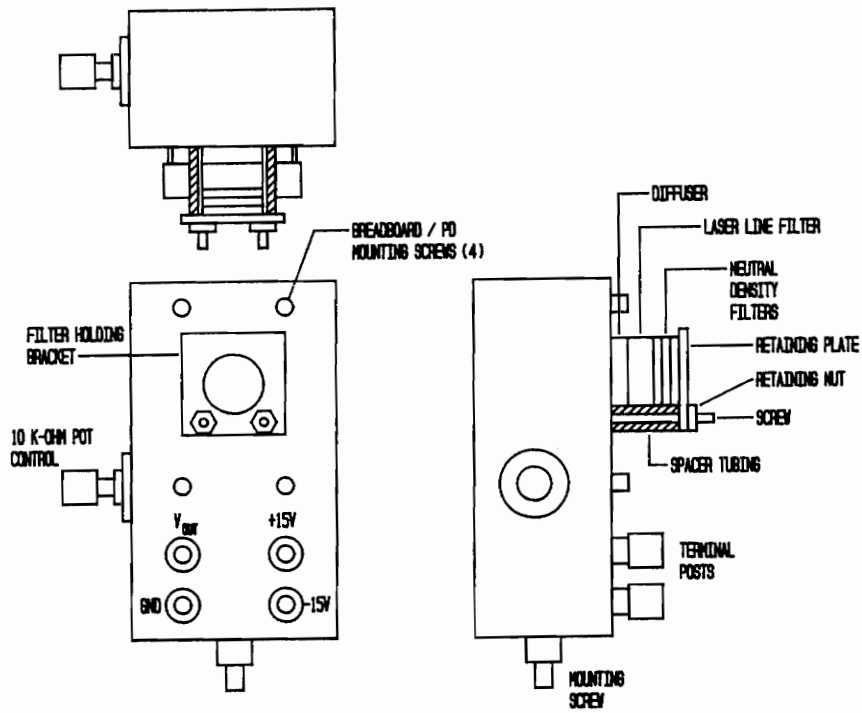
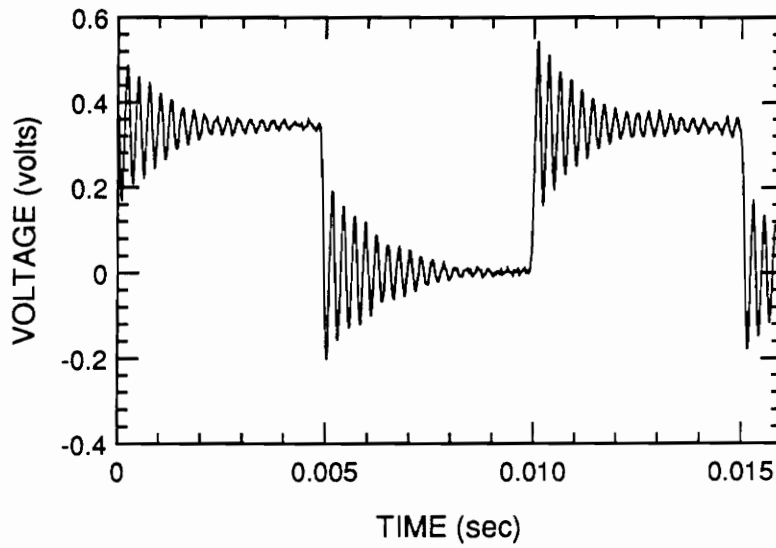


Figure 17. Details of Photodiode Chassis Box

the box to be held in place by a vertical rod. A bracket held the neutral density filters, laser line filter, and diffuser over the access port to the photodiode. Four neutral density filters were used, with a total neutral density of 3.8. A 514.5 nm laser line filter was placed after the neutral density filters in the optical path; an Oriel model 52670 3-nm bandwidth filter was used. A diffuser was the last component in the optical path before the photodiode; this attenuated the beam further and helped to minimize the effect of the spot location on the photodiode output. The edges of the box were covered with electrical tape and the filter bracket was surrounded with a cardboard screen (not shown) to keep out any stray light. It was necessary to make all of the electrical connections to the box using multistrand copper wire; the stiffness of the single-strand copper wire or the weight of a coaxial cable connection was sufficient to distort the shape of the box and therefore deflect the photodiode.

The following paragraphs explain why the photodiode response to a chopped beam is important even though a chopped beam system was not used for these experiments. Originally, the photodiode was mounted on a piece of perfboard, and the circuit wires were soldered directly to the pins of the photodiode. The top of Figure 18 shows the response of this configuration to a chopped laser beam. This response could be attenuated but not eliminated by soldering the wires to a special socket, then plugging the photodiode pins into the socket (again through the perfboard). While experimenting with the photodiode plugged into an electrical breadboard, the oscillatory response failed to occur. On this board, there were no soldered connections. The photodiode response to a chopped beam for this configuration is shown on the bottom of Figure 18. The breadboard was a necessary part of the photodiode box design to eliminate the peculiar oscillatory response of the photodiode to a chopped laser beam.

OSCILLATING CIRCUIT



STABLE CIRCUIT

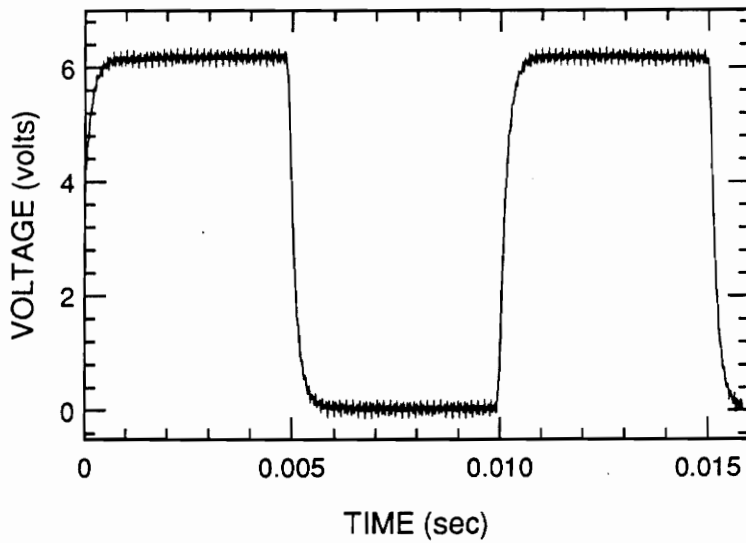


Figure 18. Photodiode Response to a Chopped Beam
Top: Perfboard Configuration
Bottom: Breadboard Configuration

Although a chopper and lock-in amplifier were available, the lock-in technique could not be used during these experiments. The use of a lock-in amplifier should improve the signal to noise ratio of the extinction measurements dramatically. However, the photodiode was incompatible with this system. The photodiode has a rise time of about 1 ms, as a result of the fixed feedback resistor. The product literature stated that at chopping frequencies lower than 1 kHz, the photovoltaic photodiode is preferred over the photoconductive photodiode due to its greater output stability and better signal to noise ratio. Unfortunately, the effects of the rise time seemed to have a definite deleterious effect on the measured signal. Figure 19 shows the photodiode output at two chop frequencies. Ideally, the photodiode output should be a square wave at the same frequency as the chopped laser beam. At 200 Hz, the response does approximate a square wave. At 800 Hz, the photodiode output barely reaches a steady state value and significant information is lost. The chopping system was not used since it did not seem to improve the extinction measurements significantly. However, the breadboard design feature may still prove necessary if further work is done using a faster photodiode and the lock-in amplifier.

3.2.4 Gas Sampling System

A gas sampling system was used periodically to check the oxygen index of various gas mixtures. Figure 20 shows a schematic of the gas sampling system. For "hot" samples, the premixed flame gases were drawn through the probe, cooling coils, and filter by a vacuum pump and then discharged into a teflon bag. The sampling probe was a spare quartz glass center tube for the burner. For "cold" samples ("artificial air" mixtures used to feed the single mode flames), the sample bag was filled via a line directly from the rotameters. The samples were analyzed off-line with a Horiba model OPE-325 oxygen analyzer. Room air was sampled for several minutes to determine if

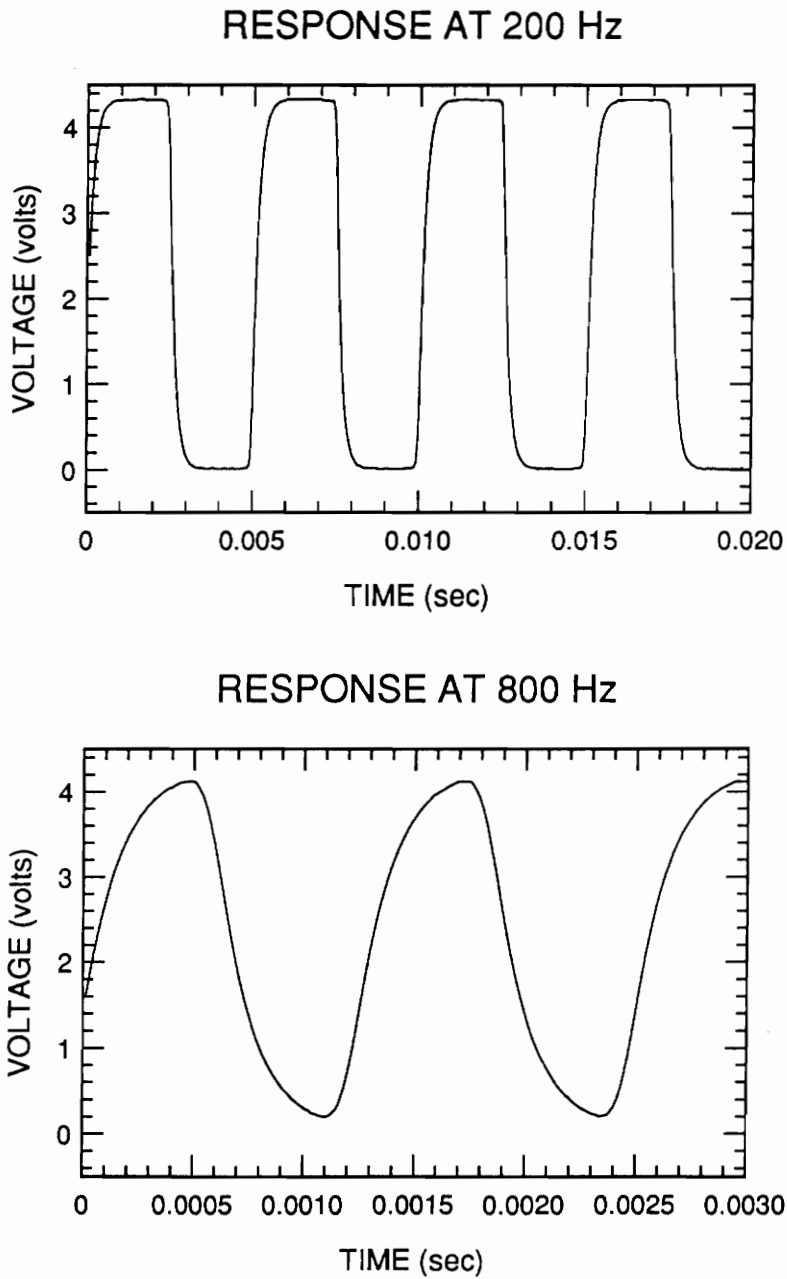


Figure 19. Photodiode Response to Laser Beam Chopped at Different Frequencies
Top: Beam Chopped at 200 Hz
Bottom: Beam Chopped at 800 Hz

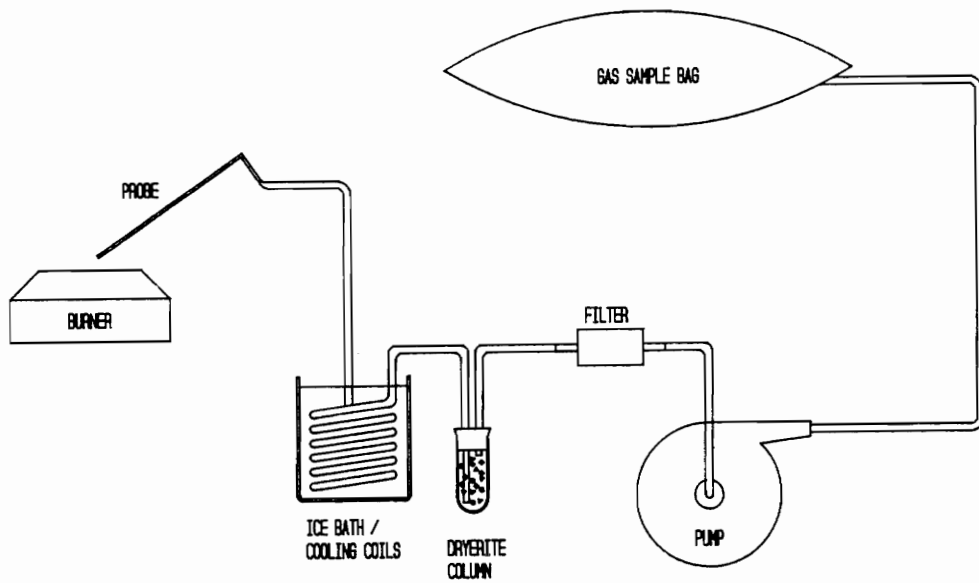


Figure 20. Schematic of Gas Sampling System

recalibration of the analyzer was necessary. Then, the sample bag was connected to the analyzer intake line. The oxygen analyzer took a few minutes to settle out at a steady reading. After recording this reading, room air was sampled again to check that the analyzer had returned to proper operation.

3.2.5 Thermocouple Probe

Figure 21 shows the construction of the thermocouple probe. The thermocouple was a type S (Platinum / Platinum - 10% Rhodium) using wires of 76 μm diameter. The diameter of the thermocouple bead was assumed to be 200 μm , based on measurements by another researcher of similar thermocouples [36]. The thermocouple wires were welded to sturdier support leads of 0.25 mm diameter (also platinum and platinum/10% rhodium wire). These support leads pass through two holes of a ceramic tube. The ceramic tube is protected by a stainless steel sleeve. The leads are connected to the base of the probe, which plugs into an electronic artificial ice point compensator. This compensator is an Omega model MCJ-S, specifically designed for Pt/Pt-10%Rh thermocouples. The thermocouple output voltage was measured by a Keithley model 179 TRMS digital voltmeter.

3.3 SOFTWARE

The raw extinction data was measured and stored on a personal computer, using a BASIC program and driver software for the data acquisition boards. All subsequent manipulations of the data were made using the ASYST software package (version 2.0). Section 3.3.1 describes the data acquisition procedure and construction of the extinction profiles. Section 3.3.2 describes the ASYST manipulations of the profiles and their subsequent convolution.

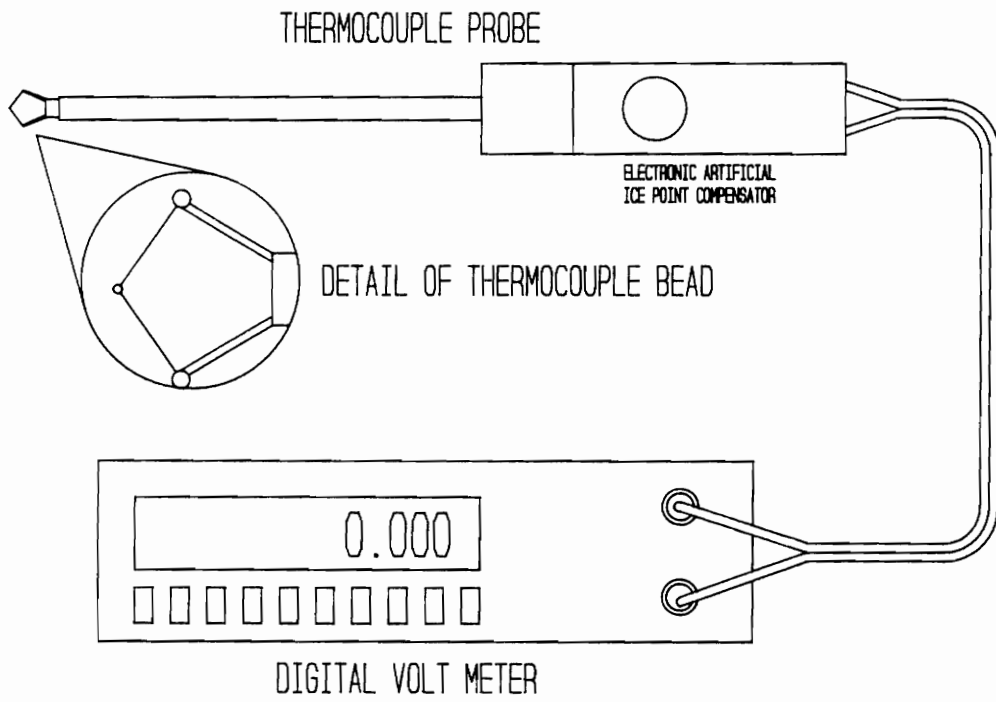


Figure 21. Schematic of Thermocouple Measurement System

3.3.1 Data Acquisition / Extinction Profiles

The extinction profiles were obtained using the BASIC program in Appendix C. This program allowed 20 data points to be sampled during a scan of the flame. The first sampled point was a reference voltage: this was the photodiode output when the flame was off. This point was kept as a check of the laser stability between repeated experiments. The next 19 points were obtained as the flame was traversed across the laser beam and were used to calculate the extinction profile.

For each extinction measurement, 100 samples were taken at a sampling rate of 30 Hz. The program stores the 100 voltage values and the mean voltage for each point. The sampling rate of 30 Hz assures that there should be no aliasing effects due to undersampling a flickering flame. Since all of these flames seemed to flicker at about 10 Hz or less, the program samples at about 3 points per cycle. The recommended minimum is two samples per cycle [39].

Individual scans revealed that the photodiode box was not entirely lightproofed. When the dual mode flame was ignited, the photodiode voltage would jump by up to 3.5%. The first data point (flame-off reference) was therefore unsuitable to represent the reference intensity I_0 and was dropped from the scan. The extinction profiles were calculated by dividing the remaining 19 data points by the voltage at the first point (I_0) of the scan. The scan started and ended outside the visible flame zone, so this first point should be free of extinction effects.

Any single extinction profile actually consists of two consecutive scans of the same flame. Figure 22 shows a sample extinction profile composed of two scans. The top figure shows the extinction profiles from the first and second scans. The bottom figure shows the combined extinction profile and the smoothed curve. The first scan

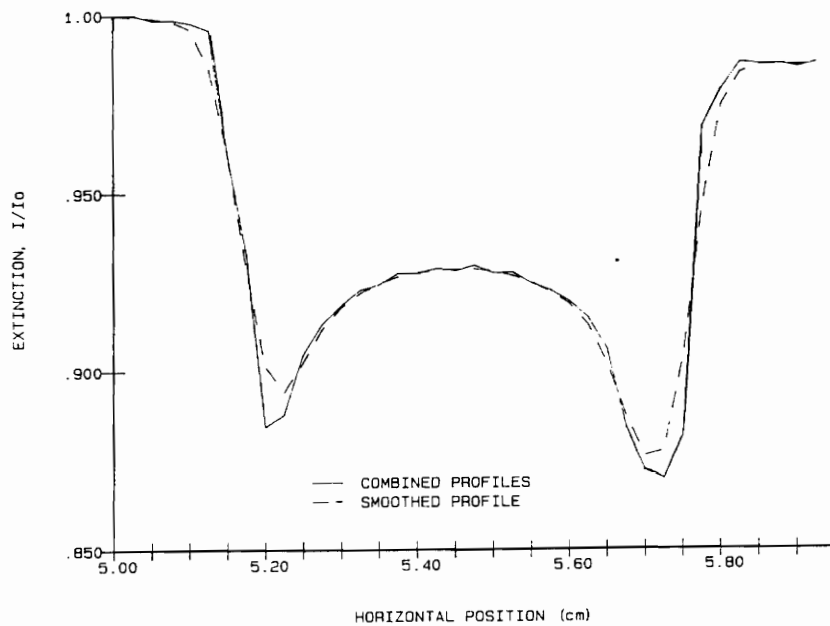
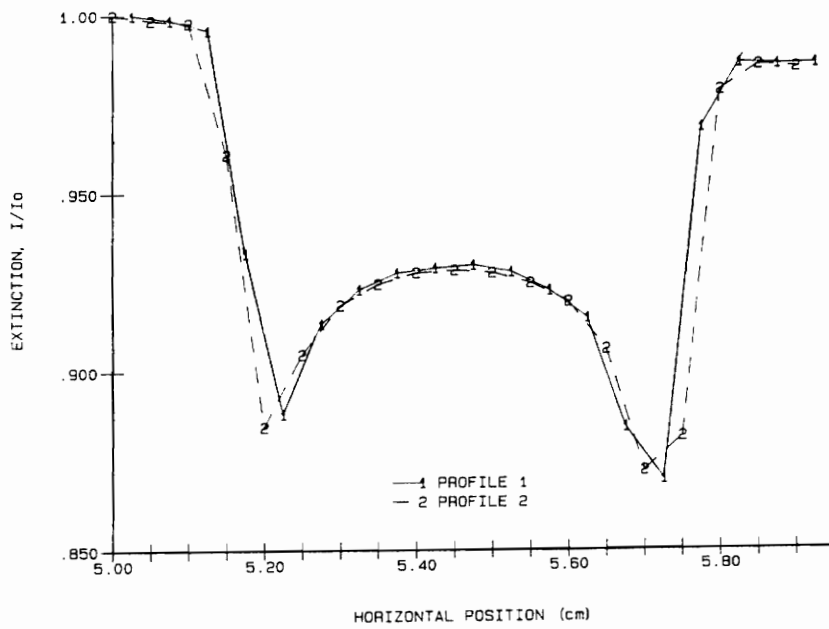


Figure 22. Construction of Extinction Profiles

started at a horizontal position of 5.00 cm, and was traversed to 5.90 cm in 0.05 cm increments. The second scan started at 5.025 cm and went to 5.925 cm by 0.05 cm increments. Both scans cover the full width of the flame, but superposition of the two scans improves the resolution of the measurement. When two scans are superimposed, the extinction profile consists of 38 data points spaced at 0.025 cm increments. One advantage of this method is that two separate scans of the same flame gives some indication of the repeatability of the measurements. In most cases, the two scans superimposed well - if they did not, it was an indication that something (laser stability, usually) had changed during one of the scans and the experiment would be repeated.

3.3.2 Data Reduction / Convolutions

The first operation performed on the raw extinction profiles was fitting a smooth curve through the data. Figure 10 (in section 2.2) is an example of the improvement of a poor profile with smoothing. ASYST's smoothing routine performs a fourier transform analysis of the raw data. The cutoff frequency parameter of this routine was variable and it had an effect on the curve fit. A low cutoff frequency would smooth out discontinuities effectively but it would attenuate the peaks of the profiles excessively. A high cutoff frequency could represent the peaks adequately but would not dampen discontinuities / oscillations sufficiently. A cutoff frequency of 0.5 was visually judged to achieve the closest fit to the raw data while smoothing out the discontinuities.

The measured extinction profiles only provide line-of-sight information about the soot properties. The local soot volume fractions were calculated using a convolution integral technique [30-35], which was outlined in section 2.2. For this study, measurements were only obtained at one angle θ . It was assumed that the flame was symmetrical, thus the profiles at all angles should be identical. Some asymmetry was

observed in the profiles, but scans repeated at different angles failed to result in significantly different profiles. It seems likely that the asymmetry is due primarily to some beamsteering effects.

The measured profiles were shifted if necessary to improve the symmetry around the center of the scan. The amount of shift required to improve the scans was somewhat subjective; profiles were shifted enough to make them "look right." A shift would delete part of the tail on one side of the profile, and these gaps were filled in by assuming I/I_0 was unity at those points. This should not have affected the information, since most of the points were outside the flame zone and the deleted points had a value very close to unity themselves. Appendix A contains a table which lists the amount each extinction profile was shifted prior to convolution.

Appendix C contains a listing of the ASYST convolution program. The output of this program is the local extinction coefficient distribution. The local soot volume fractions were obtained by multiplying k_{ext} by an appropriate constant. This assumption requires that the soot particles were in the Rayleigh regime, i.e. their diameter was much smaller than the wavelength of the light used. An estimate of the particle mean diameter cannot be directly made with extinction measurements only. Santoro's scattering measurements indicated that his mean soot particle diameters were on the same order as the wavelength (514.5 nm), so the Rayleigh assumption was not strictly valid [23]. He estimated the error due to this assumption to be 10 to 25%. Without scattering measurements and the use of Mie theory, it should be noted that the results of this study cannot be expected to be any more accurate than Santoro's.

Other miscellaneous ASYST programs are listed in Appendix E. These programs were used to read the data storage files, shift the profiles, and manipulate the soot volume fraction information.

3.4 DEVELOPMENT OF PROCEDURES

3.4.1 Optical Alignments

The laser beam was aligned through the optics according to the following procedure. The beam was aligned through the two irises first (no lenses or photodiode present). The centerline through the irises was parallel to the edge of the optical table. This centerline was about 25 cm higher than the table surface. The irises were closed to their smallest diameter and the beam was directed through both apertures by adjustments of the beamsteerer mirrors. The first lens was placed in the beam path; its height and orientation were adjusted to minimize any deflection of the beam from the second iris. The beam was out of focus at this distance, so that the spot size was larger than the maximum iris aperture. Minimal corrections were made with the beamsteering mirrors so that the spot was centered on the second iris holding bracket. The second lens was then placed in its holder and its height and orientation were adjusted. Again, the beamsteerer mirrors were adjusted for fine corrections to the alignment. The photodiode was the last element placed in the beam path.

Accurate positioning of the photodiode was critical to the symmetry of the measured extinction profiles. Once the photodiode was roughly in position, its location with respect to the beam was "tuned" to find the spot where the maximum output voltage occurred. Figure 23 shows the photodiode's output voltage sensitivity to the location of the laser spot on the photodiode surface. With the flame off and the laser on, the photodiode output was measured at various vertical increments of the translation stage.

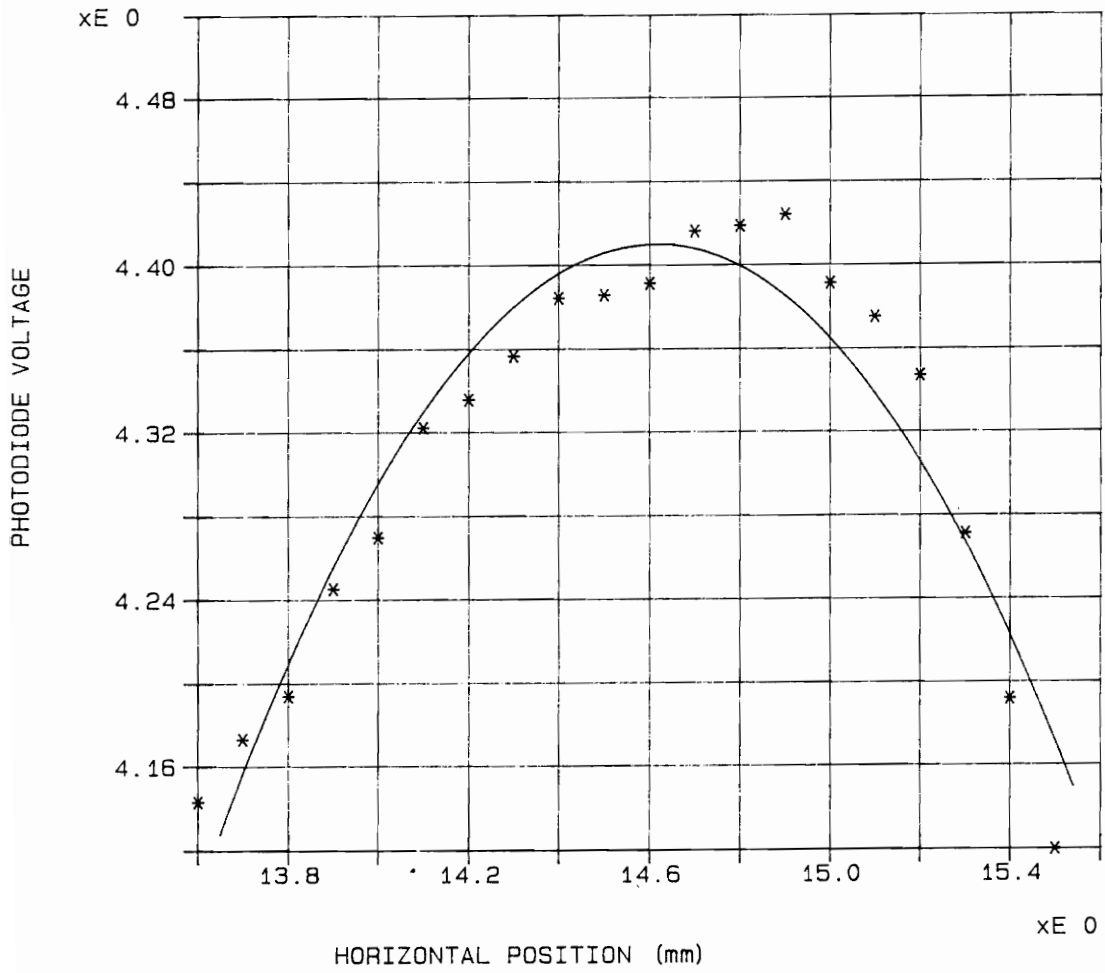


Figure 23. Photodiode Voltage Output Sensitivity to Beam Spot Location

The optimal height of the photodiode occurred where the photodiode output voltage peaked. The photodiode was set to this optimum height, and then the procedure was repeated as the photodiode was translated horizontally.

3.4.2 Thermal Beamsteering Corrections

The photodiode tuning procedure is necessary to reduce the effects of thermal beamsteering. Thermal beamsteering occurs while the beam is outside the visible flame zone, as it passes through heated air. The density variations in this air cause changes in the index of refraction, and the beam is deviated from its original path. As the laser spot traverses the photodiode surface, the output voltage changes. This can cause either an increase or a decrease with respect to the measured reference voltage, depending on the spot's original location. However, there can only be a decrease in the measured voltage if the photodiode is at its "optimal" position before the flame is ignited.

Thermal beamsteering can still cause a kind of phantom extinction, where the measured voltage decreases even though there is no soot to attenuate the beam. Originally, the photodiode was placed at the far end of the optical table from the burner, about 12.7 cm beyond the second iris. Although the photodiode had been "tuned" to its optimal position, a strong extinction still occurred just outside the visible flame zone. These troughs were due to thermal beamsteering rather than extinction, since the full reference voltage I_0 could be regained by a slight horizontal translation of the photodiode.

This thermal beamsteering problem was reduced by two changes. First, the photodiode was moved much closer to the flame. This reduced the "moment arm," so that for a given angular deflection of the beam, its horizontal displacement was reduced. Second, the lens placed between the burner and the photodiode seems to reduce the

angular deflection of the beam. Despite these changes, the beamsteering effect interacts with the attenuation due to soot and produces some asymmetry in the measured profiles.

3.5 EXPERIMENTAL MEASUREMENTS

3.5.1 Nondimensional Flame Heights

In an attempt to make the results of this study compatible with the work of Santoro et al, the single mode flames were scaled to be similar to their published results [23]. A nondimensional flame height is defined by the equation

$$\eta_f = (\text{Flame height}) (\text{Diffusivity}) / (\text{Fuel flow rate})$$

Santoro et al. measured extinction profiles and soot volume fractions in a non-sooting flame where $\eta_f = 0.36$. This flame was 88 mm high. The diameter of their fuel jet was roughly 3 times the diameter of the center tube of our burner, and in the current study it was not possible to obtain a flame that was exactly similar. The most similar single mode flame used for this study had a height of about 45 mm, which resulted in $\eta_f = 0.35$.

The diffusivity of different gas pairs were calculated using molecular theory. The diffusivity was calculated for a binary gas mixture consisting of the diffusion fuel and the particular diluent used (N_2 , Ar, or CO_2). For single mode flames, the diffusivity was evaluated at a temperature of 298 K. For the dual mode flames, the diffusivity was evaluated at an effective temperature of 75% of the maximum measured temperature of the premixed flame. Molecular theory states that the diffusivity can be approximated by the equation [37]:

$$D_{12} = \frac{0.0026280 [T^3 (M_1 + M_2) / 2M_1M_2]^{0.5}}{p \sigma_{12}^2 \Omega^{(1,1)*}(T_{12}^*)}$$

D_{12} = Diffusion coefficient [cm²/s]

T = Gas temperature [K]

p = Pressure [atm]

$T_{12}^* = kT / \epsilon_{12}$

M_1, M_2 = Molecular weight of species 1 and 2

$\sigma_{12}, \epsilon_{12}/k$ = Molecular potential energy parameters characteristic of 1,2 interaction [angstroms,K]

$\Omega^{(1,1)*}$ = A tabulated correction function

k = Boltzmann constant

Table 1 shows the diffusivities and the nondimensional flame heights for the flames studied. The characteristics of these flames are defined in the next section.

3.5.2 Flame Parameters

A number of different flames were studied. For all flames, the visible flame height of the diffusion flame was kept at 45 millimeters. The variables that were altered were:

- 1) Diffusion fuel (methane or ethene or propane)
- 2) Dual mode flame or single mode flame
- 3) Oxygen index of the products of combustion from the premixed flame for dual mode flames or the feed air for single mode flames. The oxygen index is defined as the volume fraction of oxygen among all of the gases in the mixture.
- 4) Injection height of the diffusion flame above the sintered bronze surface.
- 5) Effect of different diluent gases (Nitrogen, Argon, and Carbon dioxide)

Table 2 summarizes the parameters of the flames studied.

The original intention for flames 1 and 2 (the first two studied) was to have a post-premixed combustion oxygen index of 21%, the same as normal air. When the actual products of combustion were sampled and tested with an oxygen analyzer, they had a dry (water vapor removed) oxygen content of 26%. Assuming that the methane

TABLE 1
DIFFUSIVITIES AND NONDIMENSIONAL FLAME HEIGHTS FOR THE
FLAMES STUDIED

FLAME NUMBER	EFFECTIVE TEMP. (K)	DIFFUSIVITY (cm ² /s)	NONDIMENSIONAL FLAME HEIGHT (η_f)
1	298	0.16	0.35
2	1367	2.16	3.21
3	298	0.16	0.35
4	1367	2.16	3.21
5	298	0.16	0.42
6	1334	2.08	4.35
7	298	0.16	0.42
8	1334	2.08	4.35
13	1427	2.23	3.56
15	1427	2.23	3.56
17	1392	2.14	4.32
19	1392	2.14	4.32
21	1404	1.78	3.38
23	1404	1.78	3.38
25	1418	1.80	4.17
27	1418	1.80	4.17
28	298	0.11	0.30
29	298	0.11	0.30
30	298	0.11	0.41
31	298	0.11	0.41
32	1367	1.57	3.17
33	1367	1.57	3.17
34	1334	1.57	4.12
35	1334	1.57	4.12

TABLE 2
CHARACTERISTICS OF THE FLAMES STUDIED:

FLAME NUMBER	MODE TYPE	OXYGEN INDEX	INJECTION HEIGHT (cm)	DIFFUSION FUEL	DILUENT GAS
1	SINGLE	0.23	0.0	ETHENE	NITROGEN
2	DUAL	0.23	0.0	ETHENE	NITROGEN
3	SINGLE	0.23	1.0	ETHENE	NITROGEN
4	DUAL	0.23	1.0	ETHENE	NITROGEN
5	SINGLE	0.18	0.0	ETHENE	NITROGEN
6	DUAL	0.18	0.0	ETHENE	NITROGEN
7	SINGLE	0.18	1.0	ETHENE	NITROGEN
8	DUAL	0.18	1.0	ETHENE	NITROGEN
9	SINGLE	0.23	0.0	METHANE	NITROGEN
10	DUAL	0.23	0.0	METHANE	NITROGEN
11	SINGLE	0.23	0.1	ETHENE	NITROGEN
12	SINGLE	0.23	0.0	ETHENE	ARGON
13	DUAL	0.23	0.0	ETHENE	ARGON
14	SINGLE	0.23	1.0	ETHENE	ARGON
15	DUAL	0.23	1.0	ETHENE	ARGON
16	SINGLE	0.18	0.0	ETHENE	ARGON
17	DUAL	0.18	0.0	ETHENE	ARGON
18	SINGLE	0.18	1.0	ETHENE	ARGON
19	DUAL	0.18	1.0	ETHENE	ARGON
20	SINGLE	0.23	0.0	ETHENE	CO ₂
21	DUAL	0.23	0.0	ETHENE	CO ₂
22	SINGLE	0.23	1.0	ETHENE	CO ₂
23	DUAL	0.23	1.0	ETHENE	CO ₂
24	SINGLE	0.18	0.0	ETHENE	CO ₂
25	DUAL	0.18	0.0	ETHENE	CO ₂
26	SINGLE	0.18	1.0	ETHENE	CO ₂
27	DUAL	0.18	1.0	ETHENE	CO ₂
28	SINGLE	0.23	0.0	PROPANE	NITROGEN
29	SINGLE	0.23	1.0	PROPANE	NITROGEN
30	SINGLE	0.18	0.0	PROPANE	NITROGEN
31	SINGLE	0.18	1.0	PROPANE	NITROGEN
32	DUAL	0.23	0.0	PROPANE	NITROGEN
33	DUAL	0.23	1.0	PROPANE	NITROGEN
34	DUAL	0.18	0.0	PROPANE	NITROGEN
35	DUAL	0.18	1.0	PROPANE	NITROGEN

flow rate was accurate, and therefore accounting for the amount of water vapor condensed out from the sampled gases, the products of combustion actually had an oxygen index near 22.5%. The primary source of this error was not in the rotameter calibrations, but in the "air" supplied by the vendor. A sample of air from the current tank had a measured oxygen index of 23%, not 21% as had been assumed. The supplier makes up their air not from compressed atmospheric air, but from a blend of pure oxygen and nitrogen. The high oxygen index of their air is probably due to a metering error on their part. For subsequent flame studies, all air tanks were analyzed prior to use to determine their oxygen index. Most were very close to 23% (23.0%, 29.9%, and 29.9%).

After the discovery of this fact, all of the "21%" oxygen index flames were then known to be 23% oxygen index flames. The premixed flame stoichiometries were calculated to produce a post-combustion oxygen index of 22.5% for all subsequent flames to maintain compatibility with the flames that had already been measured.

The height of the diffusion flames were estimated visually. A scale was marked with 1 mm gradations; this scale was held next to the flame to estimate the flame height. The stable flames could be estimated to about ± 1 mm. The flickering flames were more difficult to judge. The visible flame height was assumed to correspond to the minimum position of the tip of the flame (i.e. the highest point at which the laser beam would continually see soot). The flickering flame heights could be measured to perhaps ± 2 mm. The scale was also used to verify the height of the beam over the surface of the burner. When held in the beam at the focal point of the lens, a tiny hole was burned through the scale; the elevation of the hole confirmed the elevation of the beam over the burner.

Extinction profiles were measured at elevations of 10, 15, 20, 25, and 35 millimeters above the diffusion flame injection point, in flames with a visible flame height of 45 mm. This was done so that the measured profiles could be compared to extinction profiles published by Santoro [23]. He made measurements in an 88 mm high nonsooting flame at 20, 30, 40, 50, and 70 mm. The ratios of the flame elevation to the visible flame height are therefore approximately equal for the published and our measured profiles.

The dual mode flames were achieved by burning a fuel lean premixed flame flat on the sintered bronze inner ring of the burner. There were six such flames: one for each combination of oxygen index (18 and 23%) and diluent gas (argon, nitrogen, and carbon dioxide). A general equation for premixed methane flames is

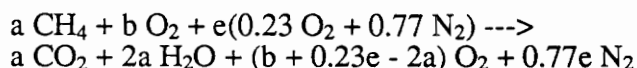


where D is the diluent species

This equation is applicable for the argon and carbon dioxide- diluted flames, since the diluent was regulated through a separate rotameter. For this equation, the post-combustion oxygen index is

$$\text{OI} = (b - 2a) / (a + b + c)$$

This equation had to be modified slightly for the nitrogen-diluted flames. Although it was possible to mix oxygen and nitrogen in the correct proportions, this required more rotameters and limited the maximum shield gas flow rate. The nitrogen-diluted flames were fed with bottled air; this air tended to have an oxygen index close to 23%. In order to achieve the desired post-premixed-flame oxygen index, the air flow was supplemented with pure oxygen. The general equation is:



which gives an oxygen index of

$$\text{OI} = (b + 0.23e - 2a) / (a + b + e)$$

Table 3 shows the gas flow rates used for the various premixed flames. It should be noted that the nitrogen- and argon-diluted flames have the same stoichiometry, but the carbon dioxide-diluted flames are different. This occurred because the carbon dioxide-diluted flame was too lean to burn at this stoichiometry. The mixture was made richer until it would attach to the sintered bronze surface without "puckering." Puckering would occur if the mixture was only marginally stable; it would attach to the burner at many points but would be lifted as much as 1 cm off the burner in other places. The nitrogen and carbon-dioxide flames represent the leanest flames that would burn without puckering at the given post-combustion oxygen index.

In most cases, higher soot volume fractions were observed in the dual mode flames than in the corresponding single mode flames. This could be expected based on the knowledge that higher temperatures increase the tendency to soot in diffusion flames. In order to investigate this argument, three different diluents were used in the premixed flames. The specific heat capacity of the diluent affects the premixed flame temperature. Argon was used in some flames to increase the combustion temperatures. Carbon dioxide was used in other flames to decrease the combustion temperatures. Table 4 shows the predicted adiabatic flame temperatures for the premixed flames. The effect of argon dilution is to raise the adiabatic flame temperature by about 300K, and the carbon dioxide dilution decreases the adiabatic flame temperature by about 100K with respect to the 23% OI nitrogen-diluted flames. At the 18% oxygen index, argon dilution still raises

TABLE 3
CHARACTERISTICS OF THE PREMIXED FLAMES:

FLAME IDENT.	DILUENT GAS	OXYGEN INDEX	FLOW RATES (cc/s)		DILUENT
			METHANE	OXYGEN	
A	NITROGEN	0.23	32	159	231
B	NITROGEN	0.18	25	113	212
C	ARGON	0.23	32	159	231
D	ARGON	0.18	25	113	212
E	CO ₂	0.23	32	144	177
F	CO ₂	0.18	32	125	180

TABLE 4: CALCULATED ADIABATIC FLAME TEMPERATURES FOR
THE PREMIXED FLAMES

DILUENT GAS	OXYGEN INDEX	ADIABATIC FLAME TEMPERATURE (K)
NITROGEN	0.23	1951
	0.18	1877
ARGON	0.23	2251
	0.18	2211
CARBON DIOXIDE	0.23	1846
	0.18	1887

the adiabatic flame temperature by about 300 K with respect to nitrogen dilution. For carbon dioxide dilution, the difference is only 10 K and the nitrogen-diluted flame is the coolest flame. The original temperature predictions for the carbon dioxide-diluted flames were much lower (200 - 300 K), but these were based on the same stoichiometry as the argon- and nitrogen-diluted flames. At the richer stoichiometry required for stable combustion, the temperature of the CO₂-diluted flame now approximates that of the leaner nitrogen-diluted flame.

3.5.3 Temperature Measurements

Temperatures profiles were measured above the six premixed flames. Fig. 24 shows the orientation of the thermocouple above the burner. The fine thermocouple leads were parallel to the burner. This makes the leads nearly isothermal and minimizes conduction losses from the thermocouple bead.

The measured voltages were converted to their corresponding temperatures using tables in the Omega Temperature Measurement Handbook [38]. A correction was made to these measured temperatures to account for radiation and convection losses from the thermocouple bead. The program was obtained from Sandia National Laboratories and is listed in Appendix C [36]. The temperature correction was about 100 K for all of the measured temperatures.

The six different premixed flames were modeled using the CHEMKIN chemical kinetics code [36]. CHEMKIN predicts gas species mole fractions as a function of distance downstream from the premixed flame reaction zone. Program inputs are the total gas mass flux, the relative proportions of the reactants, and a fixed temperature profile. The assumed temperature profiles were based on the thermocouple measurements. The temperature at the burner surface was extrapolated from the

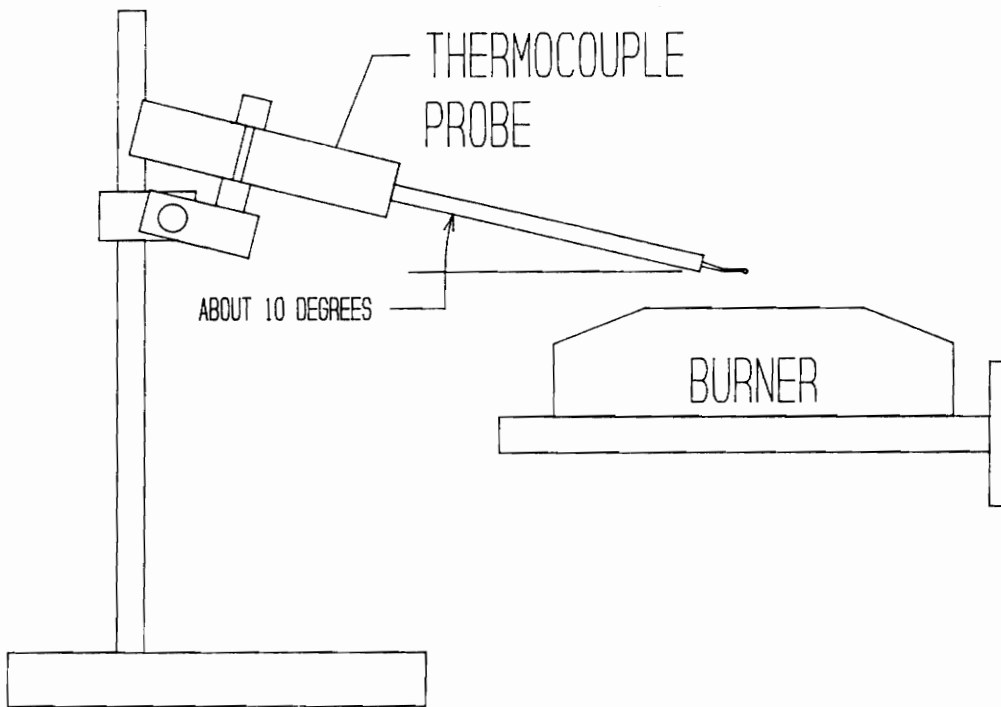


Figure 24. Orientation of Thermocouple Probe During Temperature Measurements

measured temperatures 0.5 and 1.0 mm above the burner. The code was used to obtain OH radical mole fractions as a function of distance from the burner surface.

CHAPTER 4: RESULTS

This chapter presents the results obtained for 24 of the 35 flames listed in Table 2. The first section describes the measured extinction profiles. The second section provides a qualitative comparison of the single and dual mode flames based on their local soot volume fraction distributions. The third section makes quantitative comparisons based on the local soot volume fractions. The fourth makes comparisons based on the average amount of soot measured at each flame elevation (integrated soot volume fractions). The fifth section compares the overall sootiness of the flames. In the final section, the results of the thermocouple measurements are presented. The following paragraphs briefly explain the absence of the other 11 flames from the results.

Three of the 11 flames were actually measured. Flames 9 and 10 were an attempt to measure the soot volume fractions in methane diffusion flames. These flames did not produce sufficient amounts of soot to be measured reliably (i.e. system noise was about equal to magnitude of extinction). Flame 11 was measured to determine whether the diffusion flame stabilization point had an effect on the flame sooting properties. The elevated flames stabilized on the rim of the glass center tube, but the flush-injected flames seemed to attach to the burner itself. Flame 11 was injected at a height of 1 mm, so that the diffusion flame was anchored to the glass tube but the temperature and radical species concentrations would not be significantly different from the similar flush-injected flame. The measured extinction profile matched that of flame 1 closely, so the flame stabilization point was not considered an important factor.

However, eight of these 11 flames could not be measured. These were the single mode argon- and carbon dioxide-diluted flames (the even flame numbers between 14 and 26, inclusive). The argon-diluted flames flickered greatly and their flame heights could

not be estimated accurately. Appendix B is a discussion of flickering in laminar diffusion flames. It was also difficult to ensure that these flames were not emitting soot, since soot was observed intermittently. The carbon dioxide-diluted flames at the 23% oxygen index also flickered considerably, but did not appear to emit soot. The carbon dioxide-diluted flame at the 18% oxygen index would not stabilize on the centertube of the burner.

4.1 EXTINCTION PROFILES

Figure 25 shows the measured extinction profiles for flame 1, along with the smoothed curves used for the reconstruction. The extinction profiles for all of the other flames are given in Appendix A. Since all the measured profiles were qualitatively similar, the following description applies to all of the profiles. The highest peak extinction is found in the 20 mm to 25 mm range, and the lowest at the 10 mm elevations. The extinction profiles at 10 mm and 15 mm are double-peaked. Some of the profiles at 20 mm or even 25 mm show remnants of the double peaks as well. However, these profiles are more often similar to a single broad flat-topped hump. The profile at 35 mm shows a more rounded single peak. This figure displays two additional features. One of these is the fact that the superimposed profiles do not always match up exactly, but that the curve fitting routine generally does a good job of smoothing out these irregularities. The other significant feature is that the noisiness of the raw extinction data seems to increase with the flame elevation. The spread of the data points about the smoothed curves is much greater at the 35 mm elevation than at the 10 mm elevation. Much of this is due to the lateral instability of the diffusion flame; it wavers with the room air currents more at the flame tip than at the base.

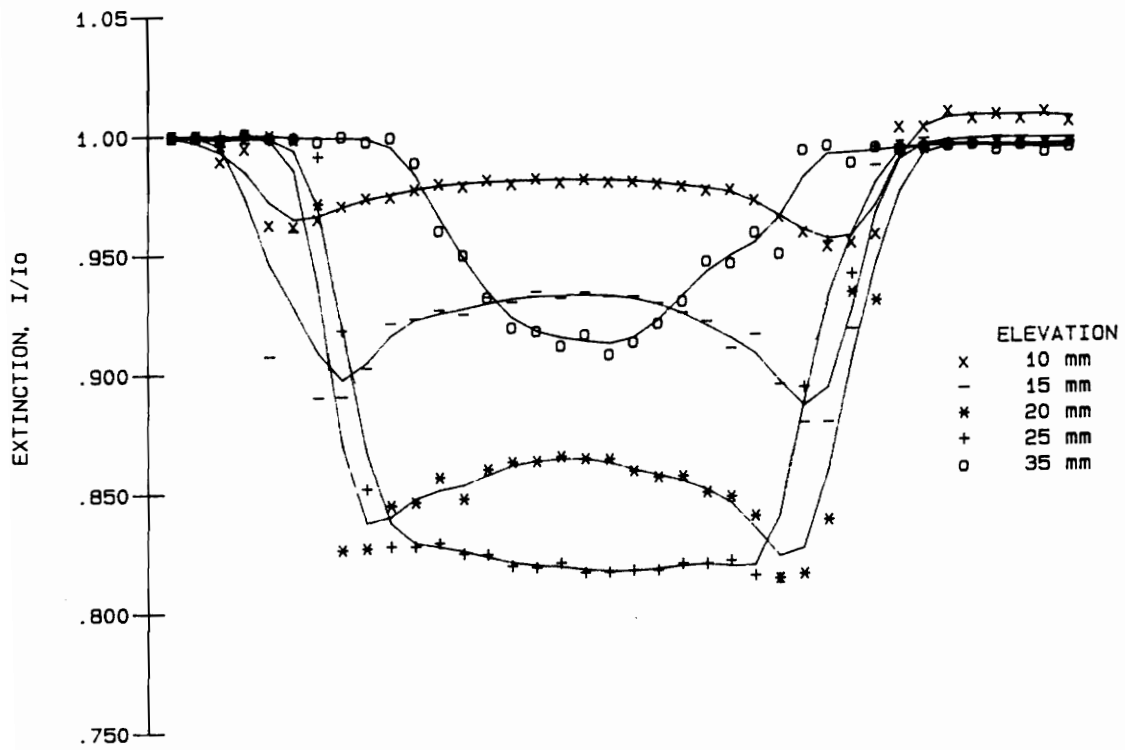


Figure 25. Flame 1 Extinction Profiles

The smoothed profiles were shifted to improve their symmetry about the centerline prior to convolution. For instance, the left-hand tail of the extinction profile at 10 mm is longer than the right-hand tail. This profile was centered by shifting it three increments (0.750 mm) to the right. Appendix A tabulates the amount of shift that was applied to each profile. The results of the convolutions can be viewed four ways. The local soot volume fraction distribution can be plotted axonometrically, or a 2-D cross section of this distribution can be plotted. The local soot volume fraction can be integrated and normalized to show the average amount of soot present at a given flame elevation. Finally, the integrated soot volume fractions can be incorporated into a total soot factor, which represents the overall sootiness of a flame. The following sections present these four ways of showing the soot volume fraction information.

4.2 LOCAL SOOT VOLUME FRACTION DISTRIBUTIONS

Figure 26 shows axonometric plots of the soot volume fraction from flames 7 and 8. This type of plot shows the shape of the local soot volume fraction distribution. Figure 26 compares flames 7 and 8 at different flame elevations, and show the overall soot volume fraction distributions. Figure 27 shows the same distributions, but as cross sections so that the interior shape is more visible. At low elevations in the flames, the soot is found in an annular ring (10 to 15 mm). At higher elevations, the amount of soot along the axis of the flame tends to increase. Finally, at the tip of the flame (35 mm), there is significant soot across the whole flame.

These figures show that the dual mode flame appears to mature sooner than the single mode flame. The maturity of the flames can be judged by comparing the relative amount of soot found at the centerline with respect to the annulus of the flame. The cross-sectional views at 15 mm and 20 mm show that the growth of soot along the

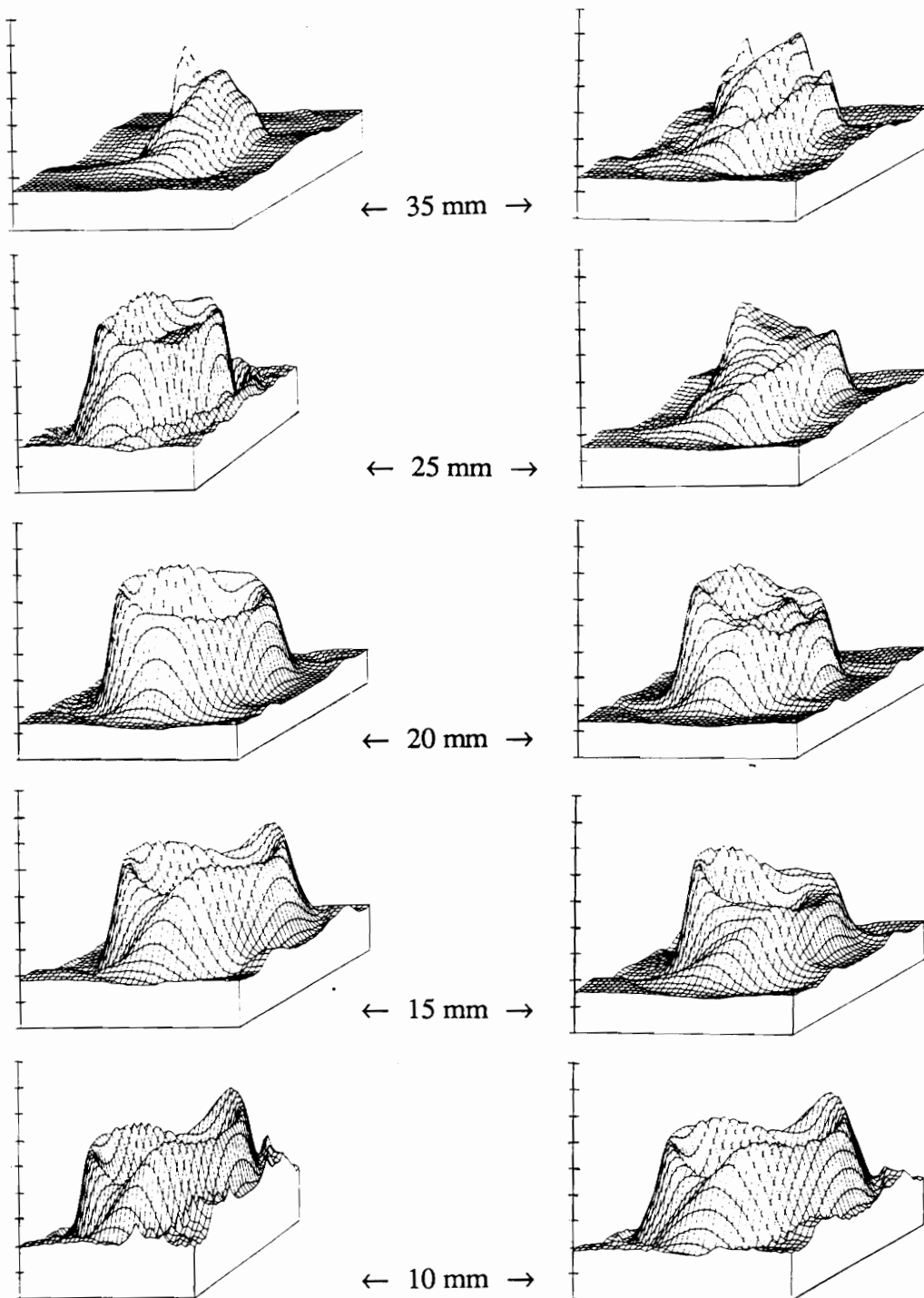


Figure 26. Local Soot Volume Fraction Distributions
Left: Flame 7 (Single Mode)
Right: Flame 8 (Dual Mode)
(Vertical Scales Arbitrary)

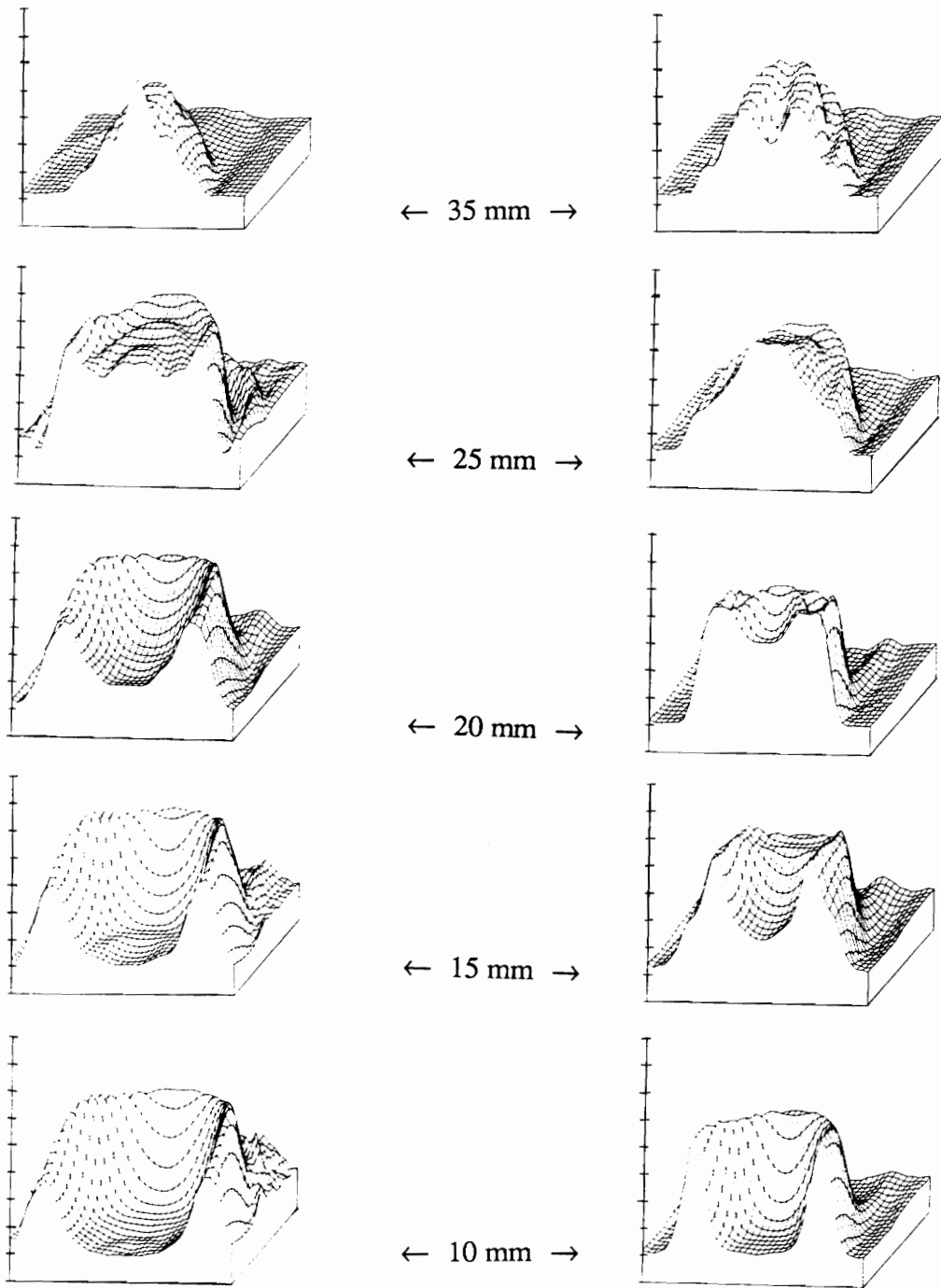


Figure 27. Cross Sections of Local Soot Volume Fraction Distributions
 Left: Flame 7 (Single Mode)
 Right: Flame 8 (Dual Mode)
 (Vertical Scales Arbitrary)

centerline is more advanced in the dual mode flame. In the views at 25 mm, the flames are very different. The amount of soot along the centerline of the single mode flame is still lower than that at the edges, whereas the dual mode flame has already achieved the inversion of the relative centerline/annulus soot volume fractions.

4.3 LOCAL SOOT VOLUME FRACTION CROSS SECTIONS

Quantitative comparisons between flames are more easily visualized by considering cross sections of the local soot volume fraction distributions. In Figures 28 through 39, these cross sections have been plotted to the same scale. In Figures 28 through 31 and 36 through 39, the single mode flames are plotted next to their most similar dual mode flame (same oxygen index, diffusion fuel, and injection height). Figures 32 through 35 are for dual mode flames only, and the difference between the flames on each figure is the injection height. Figures 28 to 31 (ethene diffusion flames) show an increase in the soot volume fractions for dual mode combustion at all elevations below 35 mm. In Figures 36 through 39 (propane diffusion flames), the increases are larger, and there is a significant difference even at the 35 mm elevation.

Figures 32 through 35 illustrate that the soot volume fractions increase when the diffusion flame injection height is increased. Comparisons between various figures show that this is the case for all of the similar flame pairs (compare flames 1 and 3, or flames 2 and 4, for example).

All of these figures support the observations of the previous section. The soot forms an annular ring at the lower elevations, and eventually soot fills in at the centerline. Furthermore, the relative centerline-to-annular soot growth rate is greater for the dual mode flames than the single mode flames.

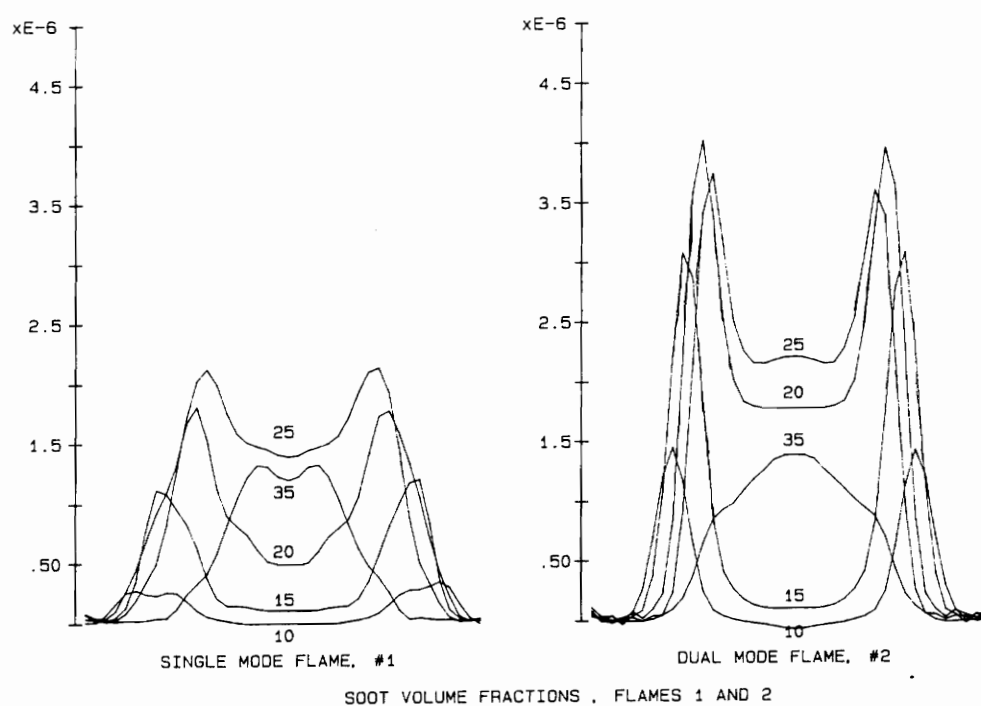


Figure 28. Soot Volume Fraction Cross Sections, Flames 1 and 2
(Both at 23% OI, 0.0 cm Injection Height)

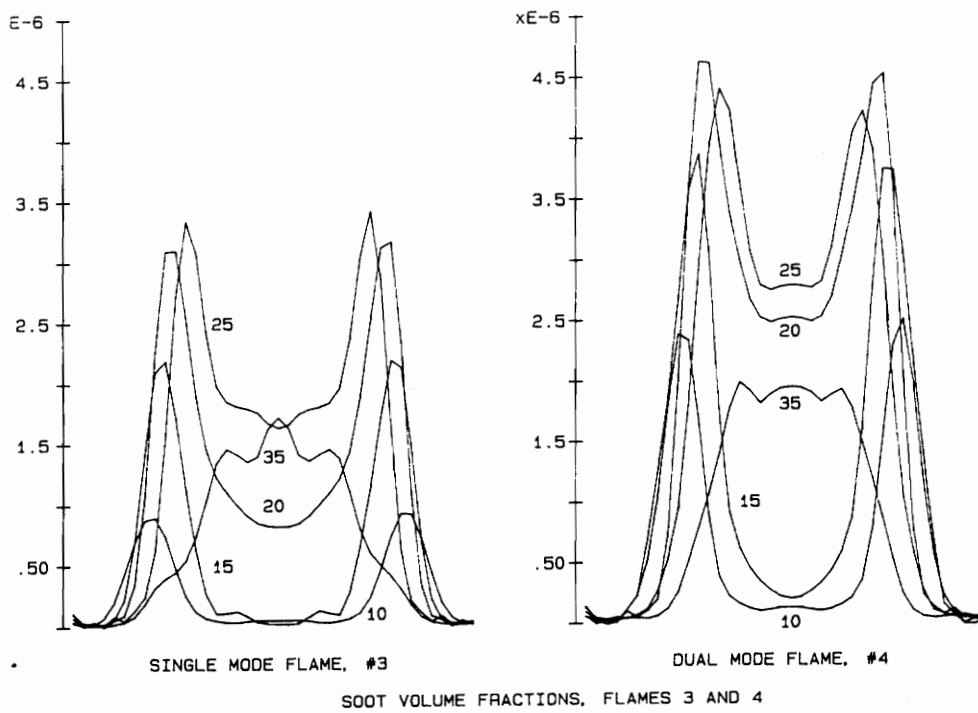


Figure 29. Soot Volume Fraction Cross Sections, Flames 3 and 4
(Both at 23% OI, 1.0 cm Injection Height)

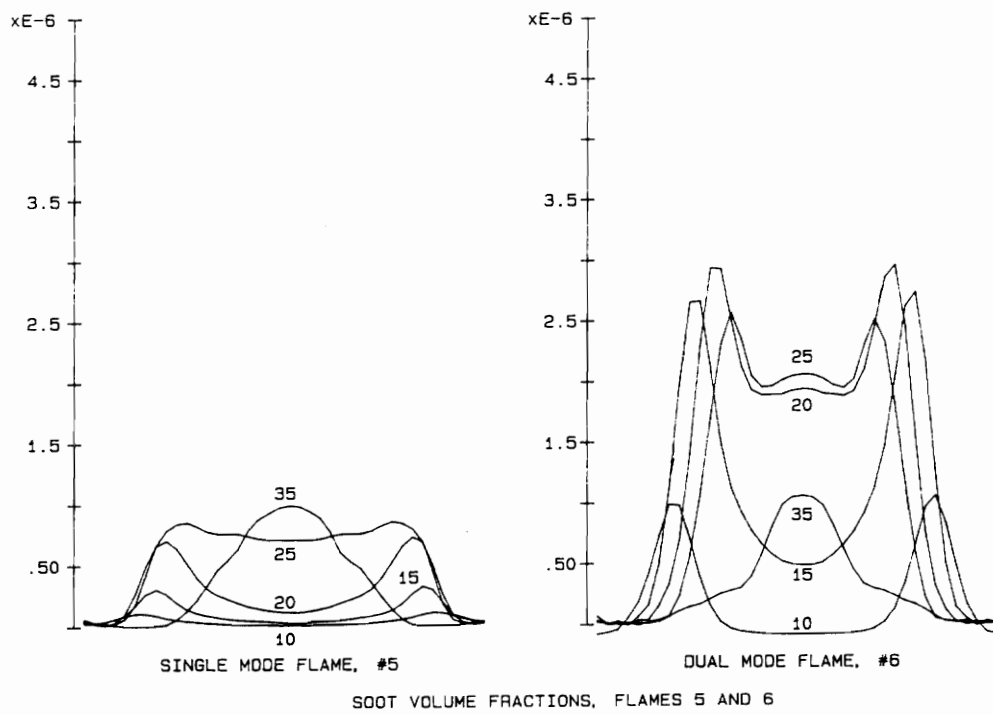


Figure 30. Soot Volume Fraction Cross Sections, Flames 5 and 6
(Both at 18% OI, 0.0 cm Injection Height)

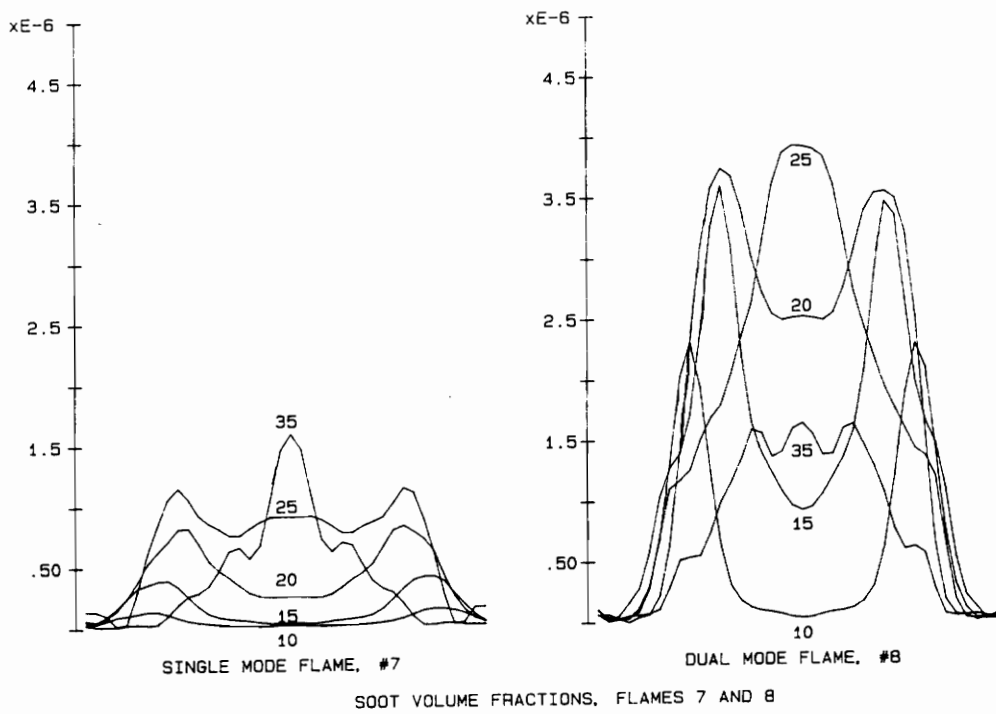


Figure 31. Soot Volume Fraction Cross Sections, Flames 7 and 8
(Both at 18% OI, 1.0 cm Injection Height)

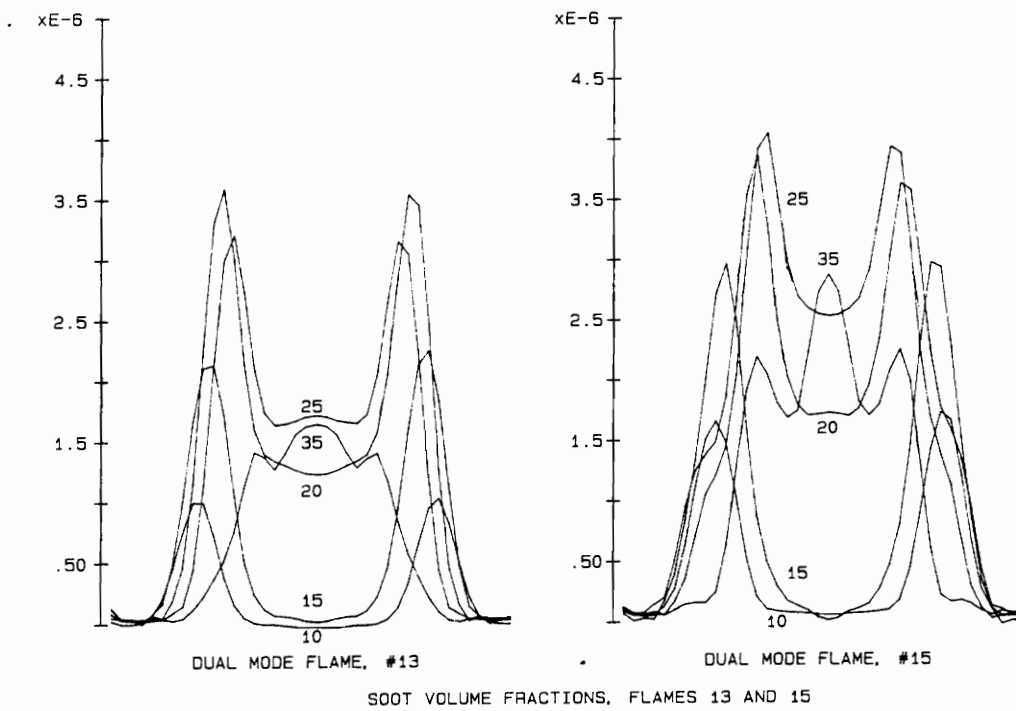


Figure 32. Soot Volume Fraction Cross Sections, Flames 13 and 15
(Both at 23% OI, 0.0 cm and 1.0 cm Injection Height, Argon Dilution)

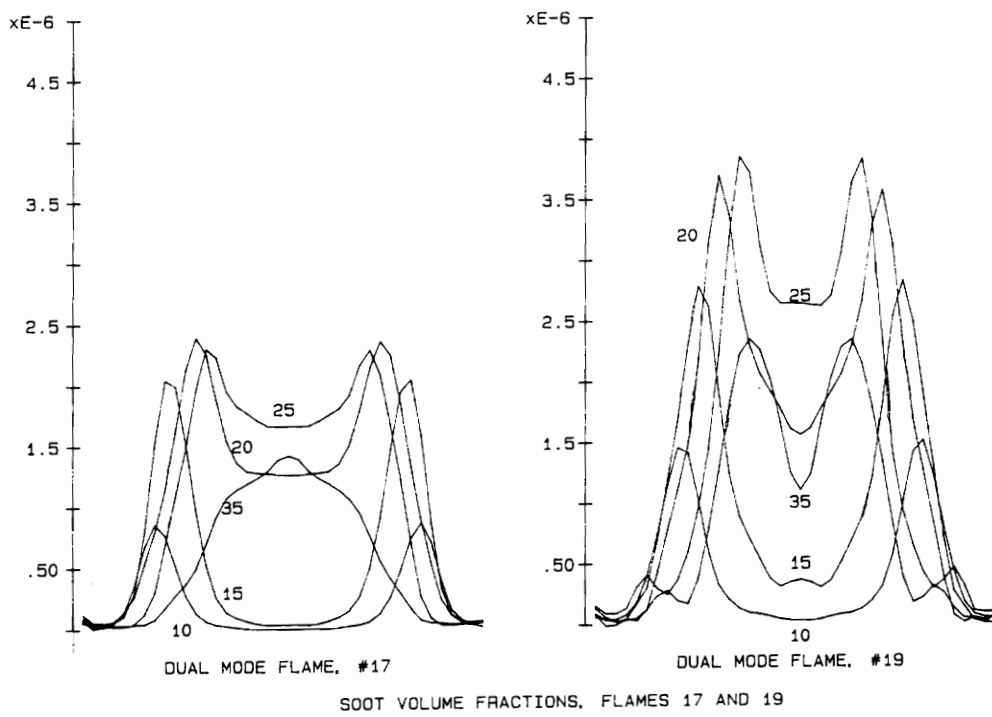


Figure 33. Soot Volume Fraction Cross Sections, Flames 17 and 19
(Both at 18% OI, 0.0 cm and 1.0 cm Injection Height, Argon Dilution)

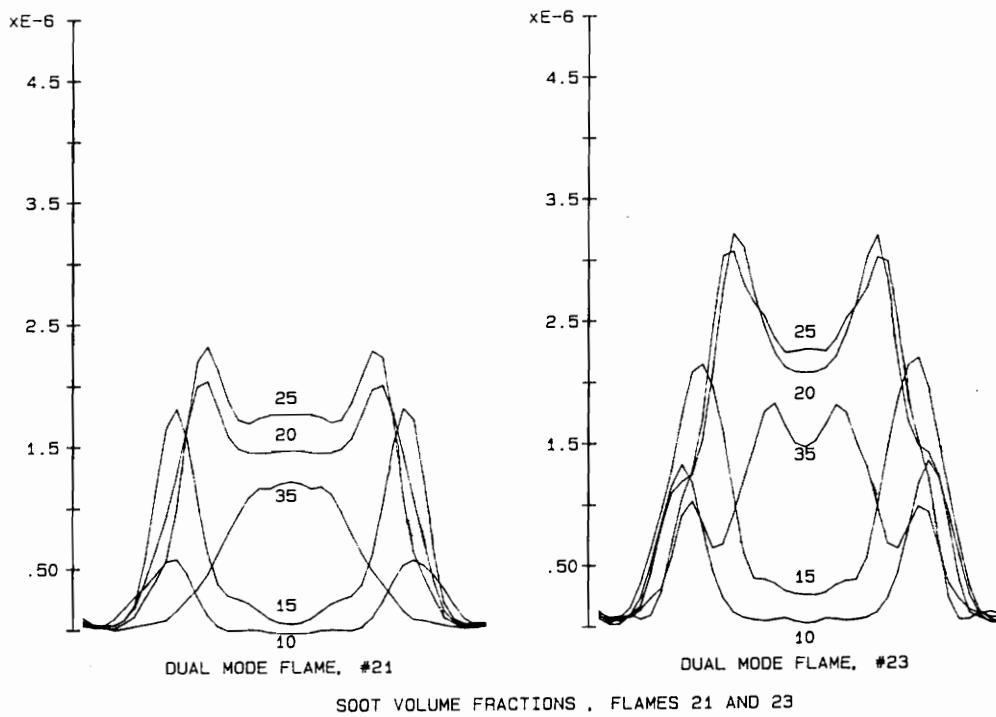


Figure 34. Soot Volume Fraction Cross Sections, Flames 21 and 23
(Both at 23% OI, 0.0 cm and 1.0 cm Injection Height, CO₂ Dilution)

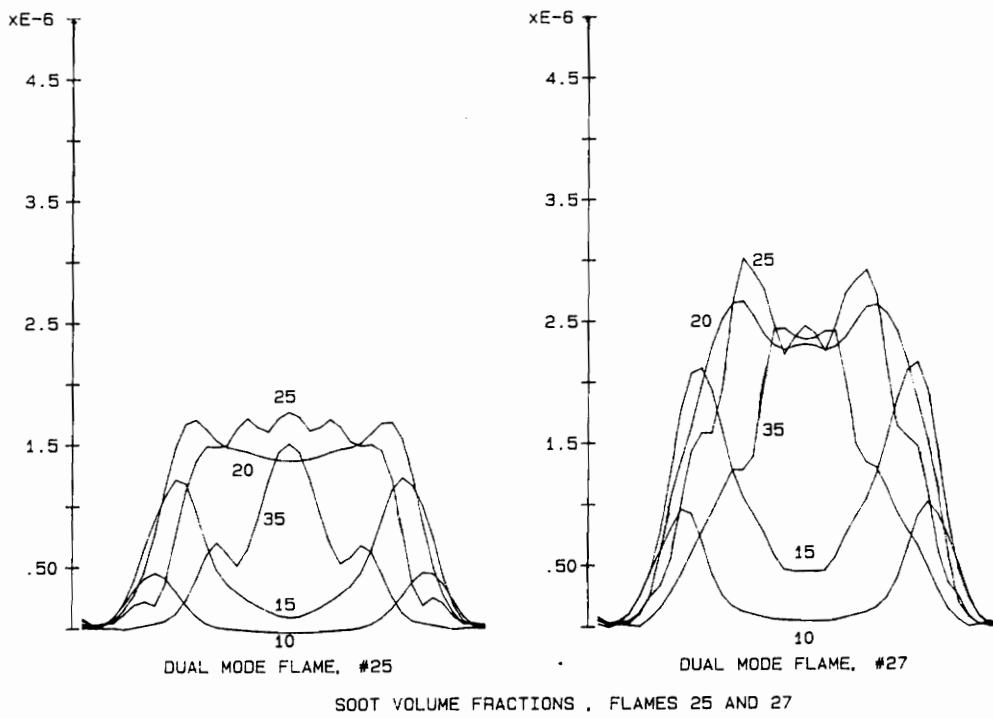


Figure 35. Soot Volume Fraction Cross Sections, Flames 25 and 27
(Both at 18% OI, 0.0 cm and 1.0 cm Injection Height, CO₂ Dilution)

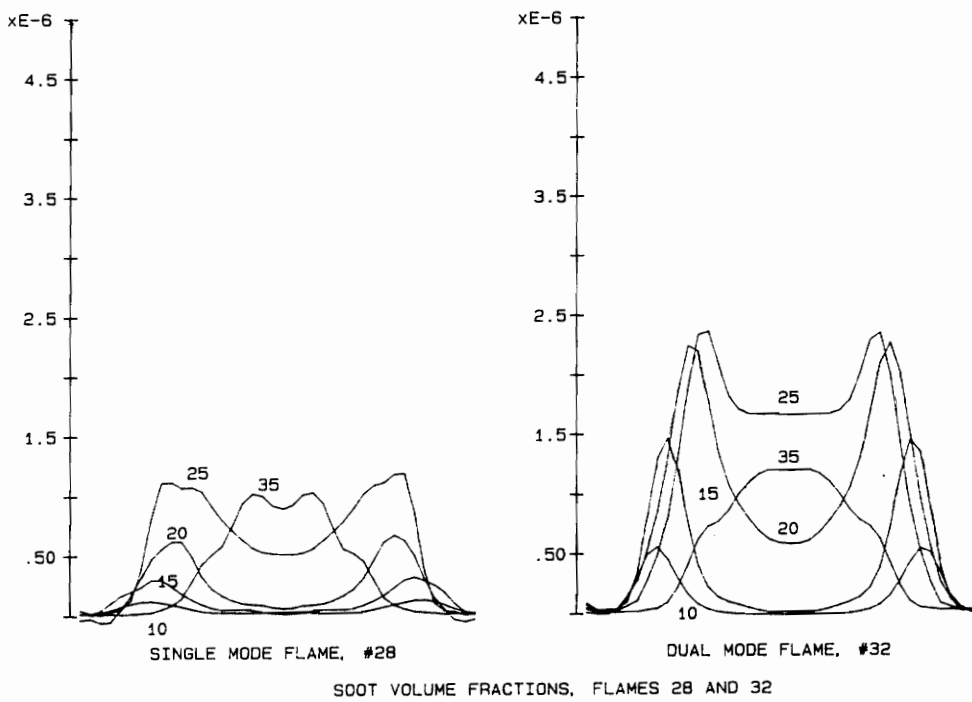


Figure 36. Soot Volume Fraction Cross Sections, Flames 28 and 32
(Both at 23% OI, 0.0 cm Injection Height, Propane Diffusion Fuel)

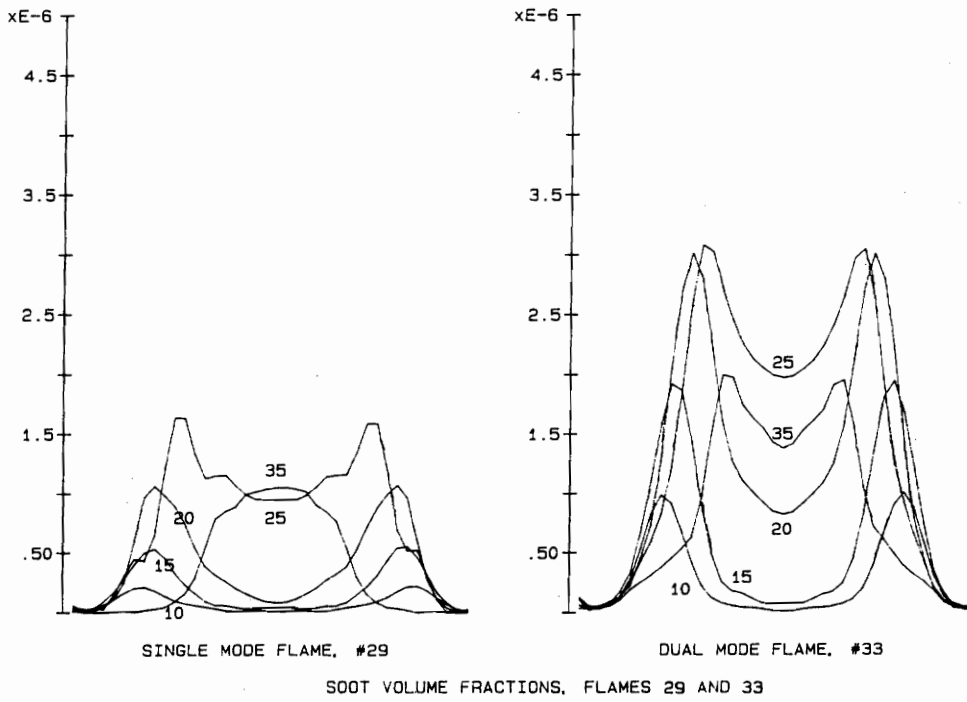


Figure 37. Soot Volume Fraction Cross Sections, Flames 29 and 33
(Both at 23% OI, 1.0 cm Injection Height, Propane Diffusion Fuel)

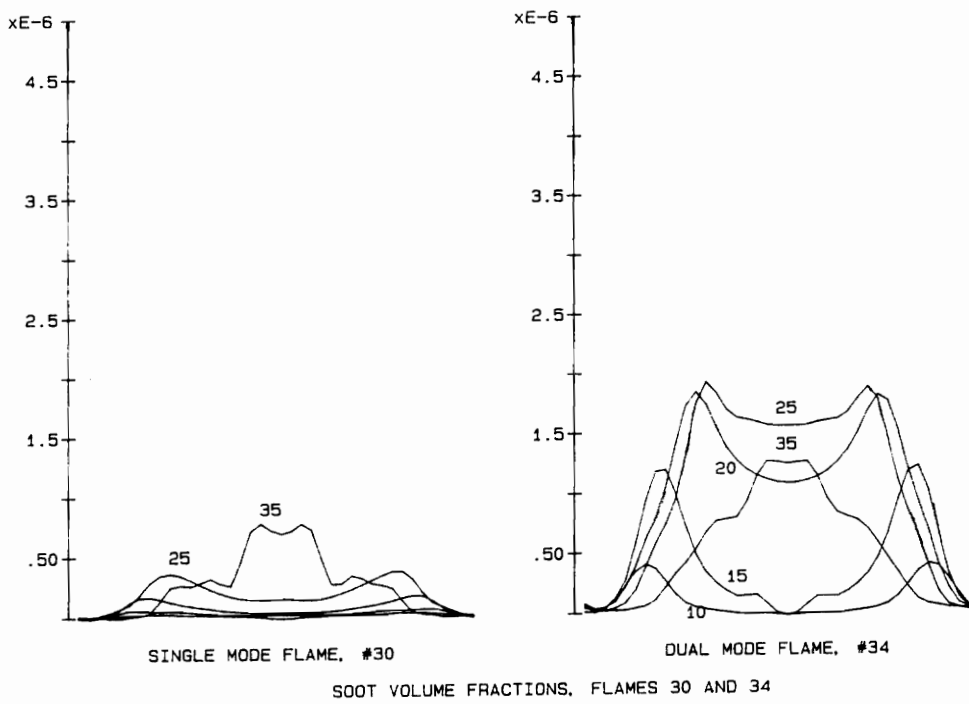


Figure 38. Soot Volume Fraction Cross Sections, Flames 30 and 34
(Both at 18% OI, 0.0 cm Injection Height, Propane Diffusion Fuel)

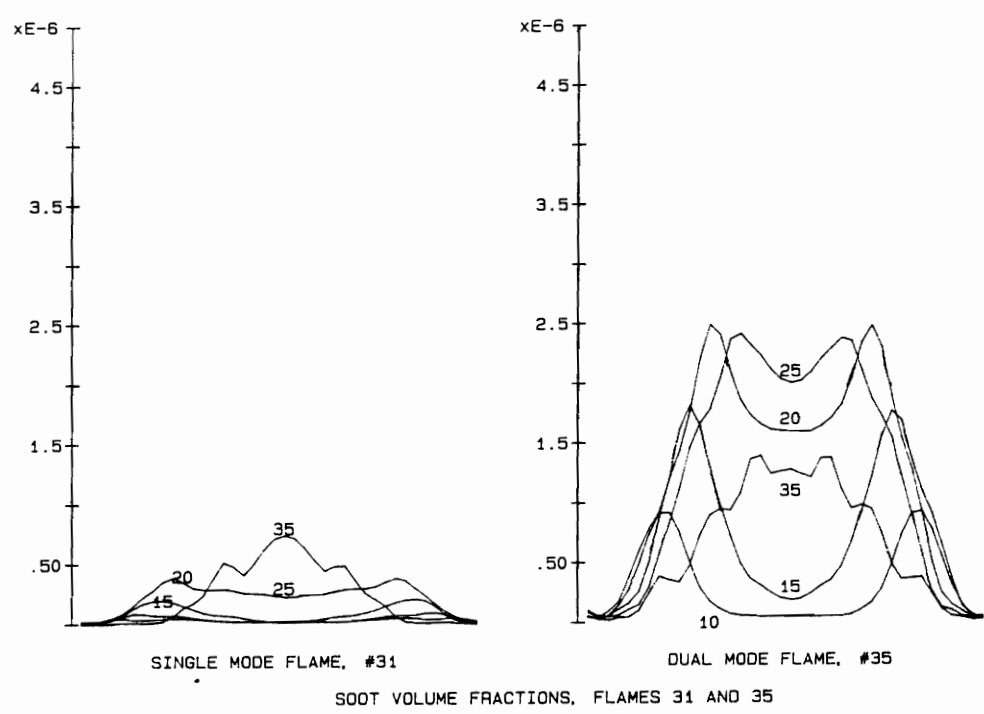


Figure 39. Soot Volume Fraction Cross Sections, Flames 34 and 35
(Both at 18% OI, 1.0 cm Injection Height, Propane Diffusion Fuel)

4.4 INTEGRATED SOOT VOLUME FRACTIONS

In this section, another measure of the soot volume fraction is presented. The integrated soot volume fraction represents an average amount of soot measured at a flame elevation. The integrated soot volume fraction calculation is based on the soot volume fraction cross sections shown in Figures 28 through 39. The integration procedure ignored all data smaller than 5% of the maximum soot volume fraction (usually the "tails" of each distribution). The volume under the distribution curve was calculated according to

$$2 \pi \int_0^R r f_v(r) dr$$

The upper and lower limits of the integration were defined by the 5% cutoff points described above. This integrated value was normalized by the circular area defined within the cutoff radius.

Figures 40 through 42 show the integrated soot volume fractions at the five flame elevations for the various flames. The magnitude of the integrated soot volume fraction is proportional to the total amount of soot at the given elevation in the flame. The slope of the line segments represents an average rate of soot growth or decay.

The top of Figure 40 shows the integrated soot volume fraction distribution for the single mode ethene flames. The distributions show that the elevated-injection height flames (3 and 7) produce more soot than the flush-injected flames (1 and 5). Both of the flames at the 23% oxygen index (1 and 3) produce more soot than the flames at the 18% oxygen index (5 and 7). The greatest amount of soot is found at the 25 mm elevation.

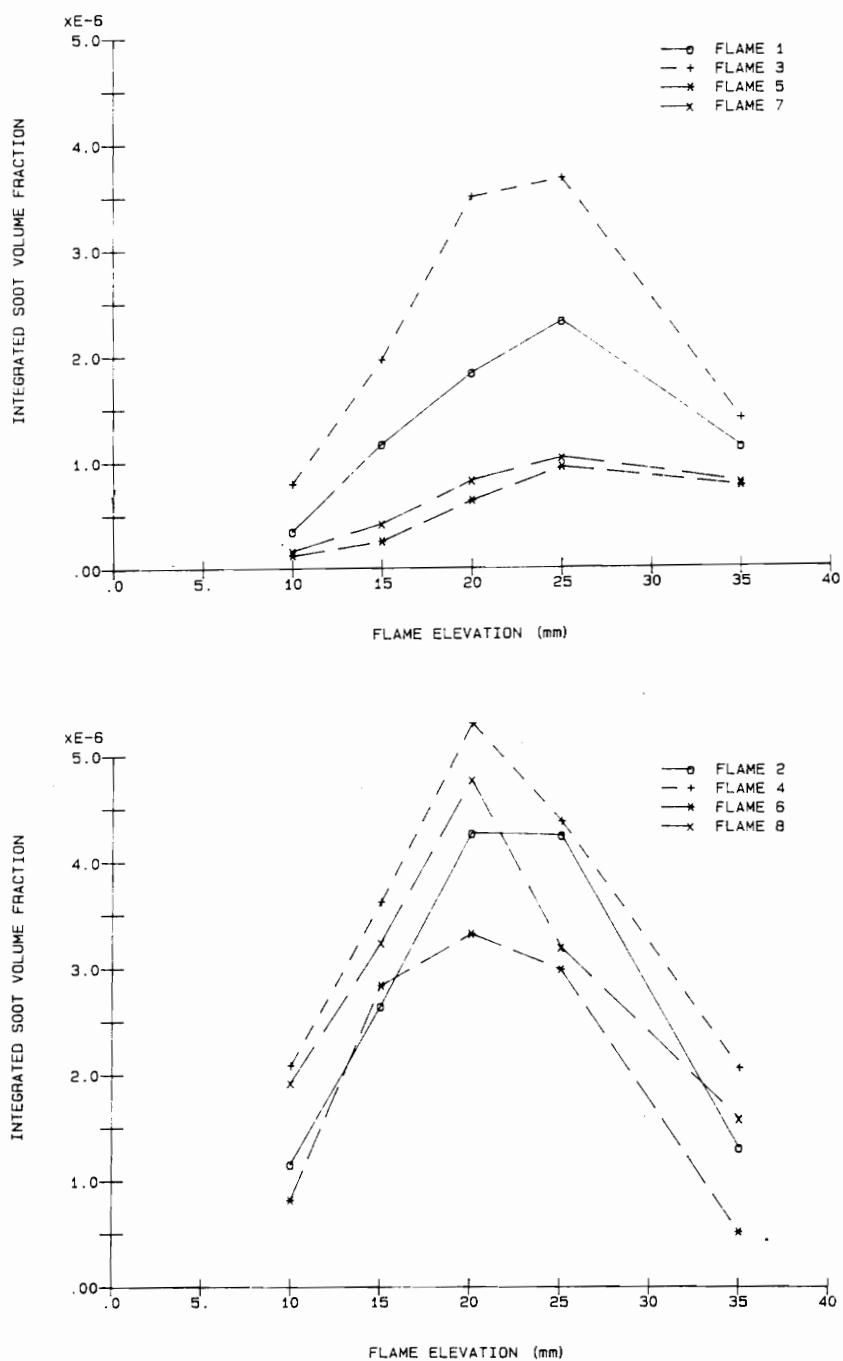


Figure 40. Integrated Soot Volume Fractions
 Top: Nitrogen-Diluted Single Mode Ethene Flames
 Bottom: Nitrogen-Diluted Dual Mode Ethene Flames

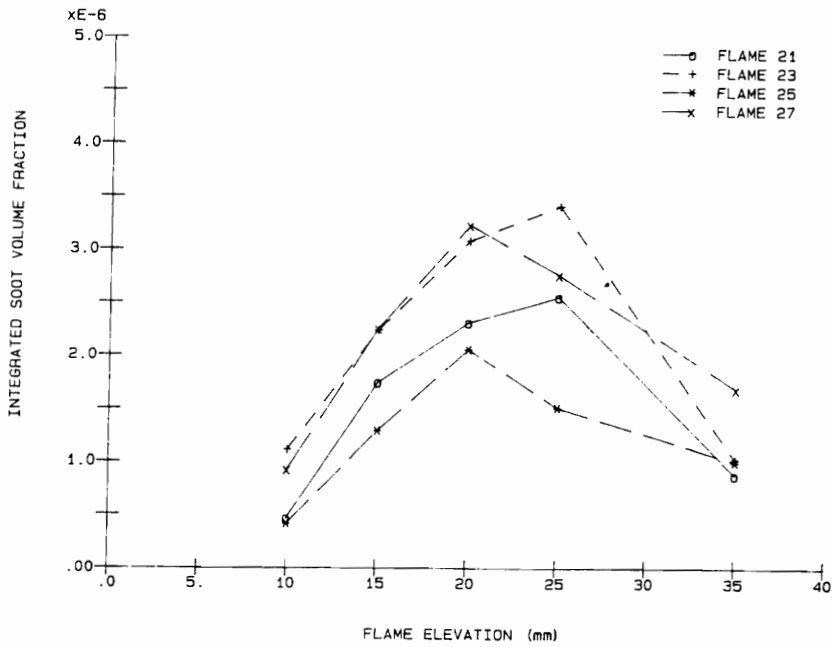
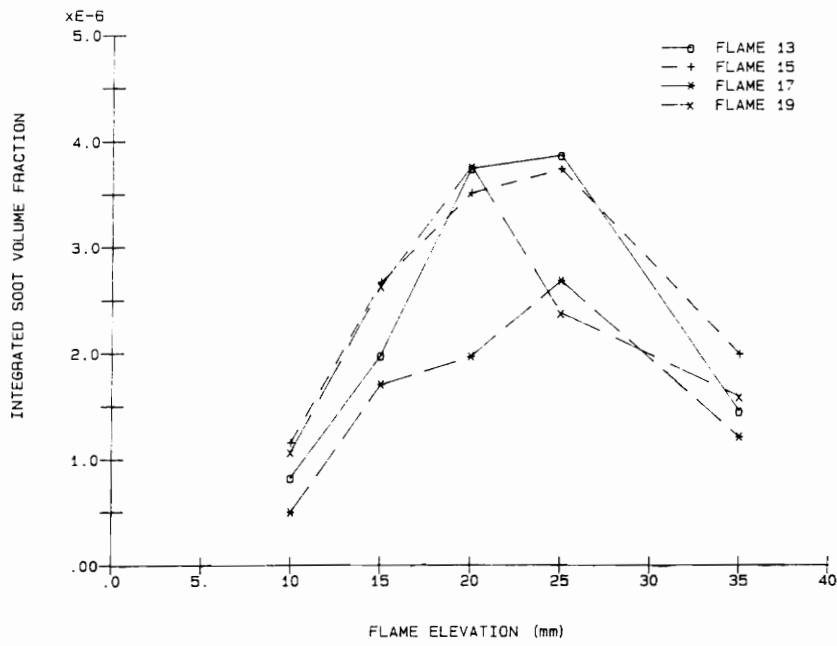


Figure 41. Integrated Soot Volume Fractions
 Top: Argon-Diluted Dual Mode Ethene Flames
 Bottom: Carbon Dioxide-Diluted Dual Mode Ethene Flames

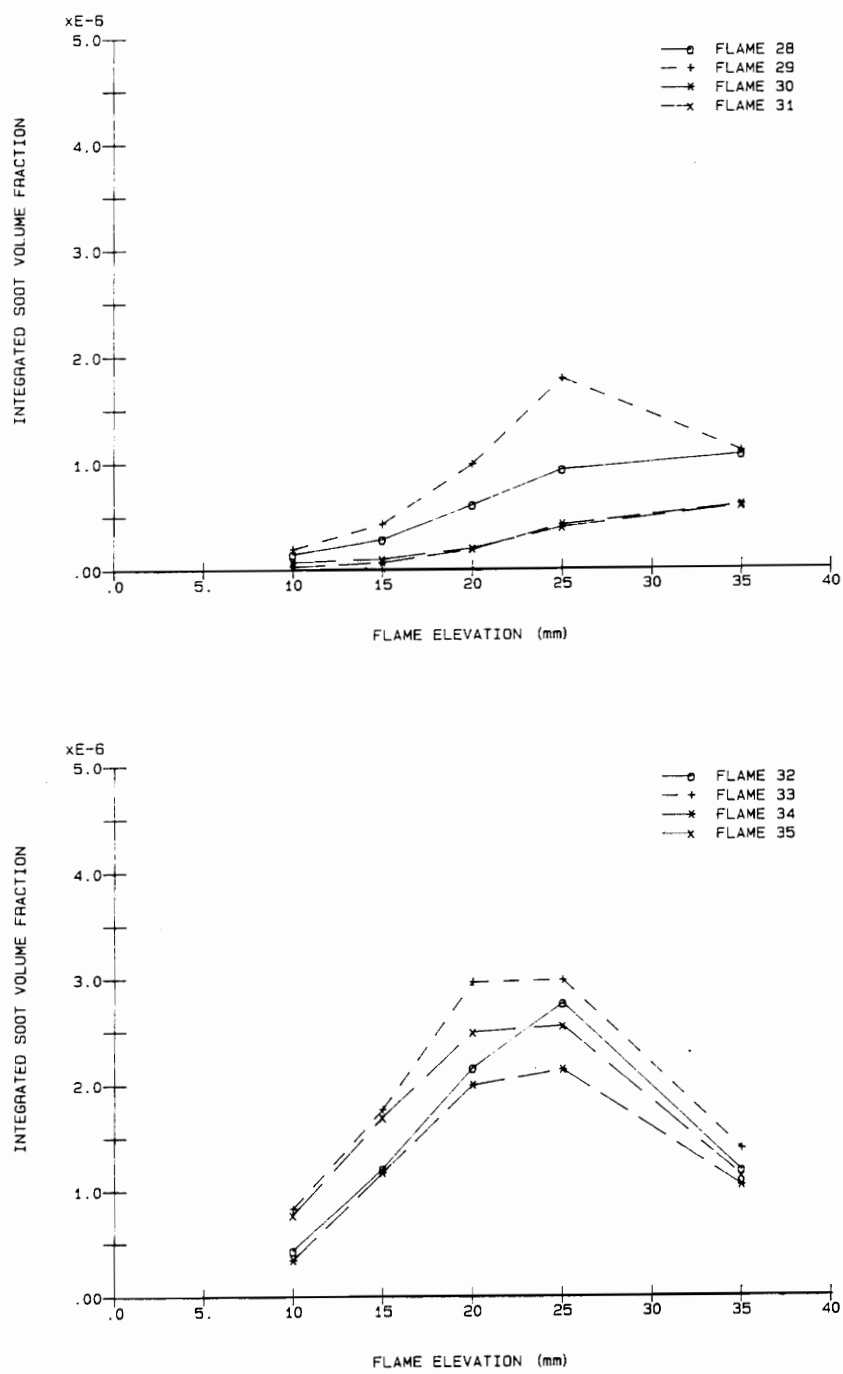


Figure 42. Integrated Soot Volume Fractions
Top: Single Mode Propane Flames
Bottom: Dual Mode Propane Flames

The bottom of Figure 40 shows the integrated soot volume fraction distributions for the dual mode nitrogen-diluted ethene flames. Again, the elevated-injection flames (4 and 8) produce more soot than the flush-injected flames. The 23% oxygen index flames (2 and 4) still seem to produce more soot than the 18% oxygen index flames (6 and 8). This is not as clear as it was for the single mode flames, since flames 2 and 8 are approximately equivalent. The integrated soot volume fraction peaks at the 20 mm elevation except for flame 2, where the levels at 20 and 25 mm are about equal. The integrated soot volume fractions are higher at every elevation for dual mode flames with respect to their single mode counterparts (compare flames 1 and 2, 3 and 4, etc.). The much higher slopes indicate both faster rates of growth and decay than in the single mode flames.

The top of Figure 41 shows the integrated soot volume fraction distributions for the dual mode argon-diluted ethene flames. The general trends show that the higher integrated soot volume fractions correlate well with elevated injection and the higher oxygen index, although this is not true at every elevation. The integrated soot volume fraction of three of the flames peak at 25 mm, and the other peaks at 20 mm. These flames tend to have lower integrated soot volume fractions than the nitrogen-diluted dual mode flames, and are low enough that flames 1 and 3 (single mode, 23% oxygen index) have comparable levels of soot.

The bottom of Figure 41 shows the integrated soot volume fraction distributions for the dual mode carbon dioxide-diluted ethene flames. These flames still show that higher soot volume fractions occur for the elevated-injection flames. However, the influence of the oxygen index is not clear. Flame 27 (18% OI) produces more soot than flame 21 and about the same as flame 23 (both at 23% OI). The two flames at 23% oxygen index peak at 25 mm, and the two flames at 18% oxygen index peak at 20 mm.

The top of Figure 42 shows the integrated soot volume fraction distributions for the single mode propane flames. The flames at 23% oxygen index (28 and 29) produce more soot than the flames at 18% oxygen index (30 and 31). At the 23% oxygen index, elevated injection produces more soot than flush injection. At the 18% oxygen index, the influence of injection height is not clear. The integrated soot volume fraction peaks at 25 mm for flame 29, and at 35 mm for the other flames. All of these flames were able to subsequently oxidize this soot, since there were no visible emissions from the tips of the flames.

The bottom of Figure 42 shows the integrated soot volume fraction distributions for the dual mode propane flames. In this case, the increase in soot levels with elevated injection is clear for both oxygen indexes. However, the effect of the oxygen index is not as clear. Flame 35 (18% OI) has higher soot levels than flame 32 (23% OI) up to and including the 20 mm elevation. The peak integrated soot volume fraction occurs at 25 mm for all of the flames except flame 33, where the levels are about equal at 20 and 25 mm. All of these dual mode flames have higher soot levels than the single mode propane flames.

A comparison of Figures 40 and 42 shows several similarities between the single mode flames. Both show that the integrated soot volume fraction increases for the higher oxygen index. Both indicate that the integrated soot volume fraction increases for elevated injection. Moreover, both figures show that the relative increase due to injection height is greater for the flames at 23% oxygen index. Both figures show peak integrated soot volume fractions at 25 mm or higher. The differences between the flames is that the soot levels are greater and the peak soot level occurs earlier for the ethene flames.

The dual mode flames (Fig.'s 40-42) show similarities as well. The peak integrated soot volume fraction occurs at 25 mm or less, and there is generally an increase in soot levels for elevated injection heights. In contrast to the single mode flames, the increase in soot levels for the higher oxygen index is not as clear. The dual mode flames tend to have higher integrated soot fractions and the peak tends to occur earlier.

4.5 TOTAL SOOT FACTORS

One final measure of flame sootiness, the total soot factor, is defined by a normalized area under the integrated soot volume fraction distributions. The ASYST program for calculating total soot factors is in Appendix E. The total soot factor therefore represents the average amount of soot found in a flame between the 10 mm and 35 mm elevations. The total soot factor was used to rank the relative sooting tendencies of the flames. Table 5 shows the result of these rankings.

The table offers additional support of some of the observations in the last section. The single mode flames at 23% oxygen index are ranked higher than their 18% oxygen index counterparts (1 > 5, 3 > 7, 28 > 30, and 29 > 31). The single mode flames at 1.0 cm injection height are ranked higher than their flush-injection counterparts (3 > 1, 7 > 5, 29 > 28, and 31 > 30). Finally, the single mode ethene flames are ranked higher than the similar single mode propane flames (1&3 > 28&29, and 5&7 > 30&31).

The effects of oxygen index and injection height among the dual mode flames is inconsistent. Consider only the dual mode ethene flames first. For the nitrogen and the carbon dioxide-diluted flames, the injection height is a more important factor than the oxygen index (4&8 > 2&6, and 23&27 > 21&25). For the argon-diluted flames, the oxygen index is a more important factor than the injection height (13&15 > 17&19). For

TABLE 5
TOTAL SOOT FACTOR RANKINGS

TOTAL SOOT FACTOR $\times 10^6$	FLAME NUMBER	FLAME CHARACTERISTICS (SEE KEY BELOW)							
0.38	30	N ₂	/	0.18	/	0.0	/	SM	/ C ₃ H ₈
0.39	31	N ₂	/	0.18	/	1.0	/	SM	/ C ₃ H ₈
0.74	5	N ₂	/	0.18	/	0.0	/	SM	/ C ₂ H ₄
0.85	7	N ₂	/	0.18	/	1.0	/	SM	/ C ₂ H ₄
0.98	28	N ₂	/	0.23	/	0.0	/	SM	/ C ₃ H ₈
1.20	29	N ₂	/	0.23	/	1.0	/	SM	/ C ₃ H ₈
1.47	25	CO ₂	/	0.18	/	0.0	/	DM	/ C ₂ H ₄ / 1887
1.64	34	N ₂	/	0.18	/	0.0	/	DM	/ C ₃ H ₈ / 1877
1.72	1	N ₂	/	0.23	/	0.0	/	SM	/ C ₂ H ₄
1.91	21	CO ₂	/	0.23	/	0.0	/	DM	/ C ₂ H ₄ / 1846
1.95	32	N ₂	/	0.23	/	0.0	/	DM	/ C ₃ H ₈ / 1951
1.99	17	Ar	/	0.18	/	0.0	/	DM	/ C ₂ H ₈ / 2211
2.05	35	N ₂	/	0.18	/	1.0	/	DM	/ C ₃ H ₈ / 1877
2.33	6	N ₂	/	0.18	/	0.0	/	DM	/ C ₂ H ₄ / 1877
2.38	33	N ₂	/	0.23	/	1.0	/	DM	/ C ₃ H ₈ / 1951
2.56	27	CO ₂	/	0.18	/	1.0	/	DM	/ C ₂ H ₄ / 1887
2.56	23	CO ₂	/	0.23	/	1.0	/	DM	/ C ₂ H ₄ / 1846
2.57	19	Ar	/	0.18	/	1.0	/	DM	/ C ₂ H ₄ / 2211
2.74	3	N ₂	/	0.23	/	1.0	/	SM	/ C ₂ H ₄
2.87	13	Ar	/	0.23	/	0.0	/	DM	/ C ₂ H ₄ / 2251
3.13	15	Ar	/	0.23	/	1.0	/	DM	/ C ₂ H ₄ / 2251
3.21	2	N ₂	/	0.23	/	0.0	/	DM	/ C ₂ H ₄ / 1951
3.26	8	N ₂	/	0.18	/	1.0	/	DM	/ C ₂ H ₄ / 1877
4.11	4	N ₂	/	0.23	/	1.0	/	DM	/ C ₂ H ₄ / 1951

KEY: DILUENT / OXYGEN INDEX / INJECTION HEIGHT (cm) /
COMBUSTION MODE / DIFFUSION FUEL / ADIABATIC
FLAME TEMPERATURE (K)

WHERE: N₂, Ar, CO₂ = DILUENT GASES
SM = SINGLE MODE, DM = DUAL MODE
C₂H₄ = ETHENE AS DIFFUSION FUEL, C₃H₈ = PROPANE

the case of dual mode propane flames, the injection height is the more important factor (33&35 > 32&34).

The table shows that dual mode ethene flames are ranked higher than dual mode propane flames, in agreement with the results of the single mode flames ($2 > 32$, $4 > 33$, $6 > 34$, and $8 > 35$). The table also shows that the dual mode flames are ranked higher than their single mode counterparts ($2 > 1$, $4 > 3$, $6 > 5$, $8 > 7$, $32 > 28$, $33 > 29$, $34 > 30$, and $35 > 31$).

Among similar dual mode ethene flames, the effect of the diluent gas is consistent. The nitrogen-diluted flames are ranked higher than the argon-diluted flames which are rated higher than the carbon dioxide-diluted flames ($2 > 13 > 21$, $4 > 15 > 23$, $6 > 17 > 25$, and $8 > 19 > 27$). However, this is only true for *similar* flame pairs. It does not mean that all nitrogen-diluted flames are ranked higher than all of the argon-diluted flames, since flames 13, 15, and 19 are all ranked higher than flame 6.

Among similar dual mode flames, the effect of the predicted adiabatic flame temperature is not consistent. At the 23% oxygen index, the coolest flames (CO₂-diluted, 21&23) are ranked the lowest, but the hottest flames (Ar-diluted, 13&15) are ranked in the middle. At the 18% oxygen index, the hottest flames (17 and 19) are still ranked in the middle. However, the coolest flames (N₂-diluted, 6&8) are now ranked the highest.

This discussion has been in terms of absolute rankings, i.e. A is greater than or less than B. In the next chapter, the discussion will focus on how much A is greater than B and whether or not the difference is significant.

4.6 TEMPERATURE MEASUREMENTS

The results of the thermocouple measurements are shown in Figure 43. These are the premixed flame temperature profiles above the burner. The temperature at 0.0 mm was extrapolated from the data at 0.5 mm and 1.0 mm. For the argon-diluted flames, this leads to the assumption that the maximum temperature occurs at the burner surface (0 mm). For the other premixed flames, the maximum temperature was measured 1 mm above the burner. At the 23% oxygen index, the highest peak temperature occurs in the argon-diluted flame, and the lowest peak temperature occurs in the carbon dioxide-diluted flames. At the 18% oxygen index, the highest peak temperature occurs in the argon-diluted flame and the lowest peak temperature occurs in the nitrogen-diluted flame.

Figure 44 shows the result of the CHEMKIN-predicted OH radical concentrations based on the measured temperature profiles. These profiles are shown to a height of 1.1 mm above the burner. The highest peak OH mole fractions occur for the argon-diluted flames. These flames also have the highest temperatures at the 0.1 mm elevation. The lowest peak OH mole fraction occurs for the nitrogen-diluted 18% oxygen index flame, which also has the lowest measured temperature at the 0.4 mm elevation.

Consider the three intermediate flames: the carbon dioxide-diluted flames and the nitrogen-diluted 23% oxygen index flame. The CO₂-diluted flames have higher peak OH mole fractions than the N₂-diluted 23% oxygen index flame. However, the relative temperatures and mole fractions do not always correspond for these flames. At an elevation of 0.1 mm, the highest temperature corresponds to the CO₂/18% flame and the lowest temperature corresponds to the CO₂/23% flame. Both of these flames have higher OH mole fractions than the N₂/23% flame at this elevation. At the 0.2 mm elevation, the highest temperature still corresponds to the CO₂/18% flame, but the lowest temperature corresponds to the N₂/23% flame. However, the N₂/23% flame has the highest OH mole

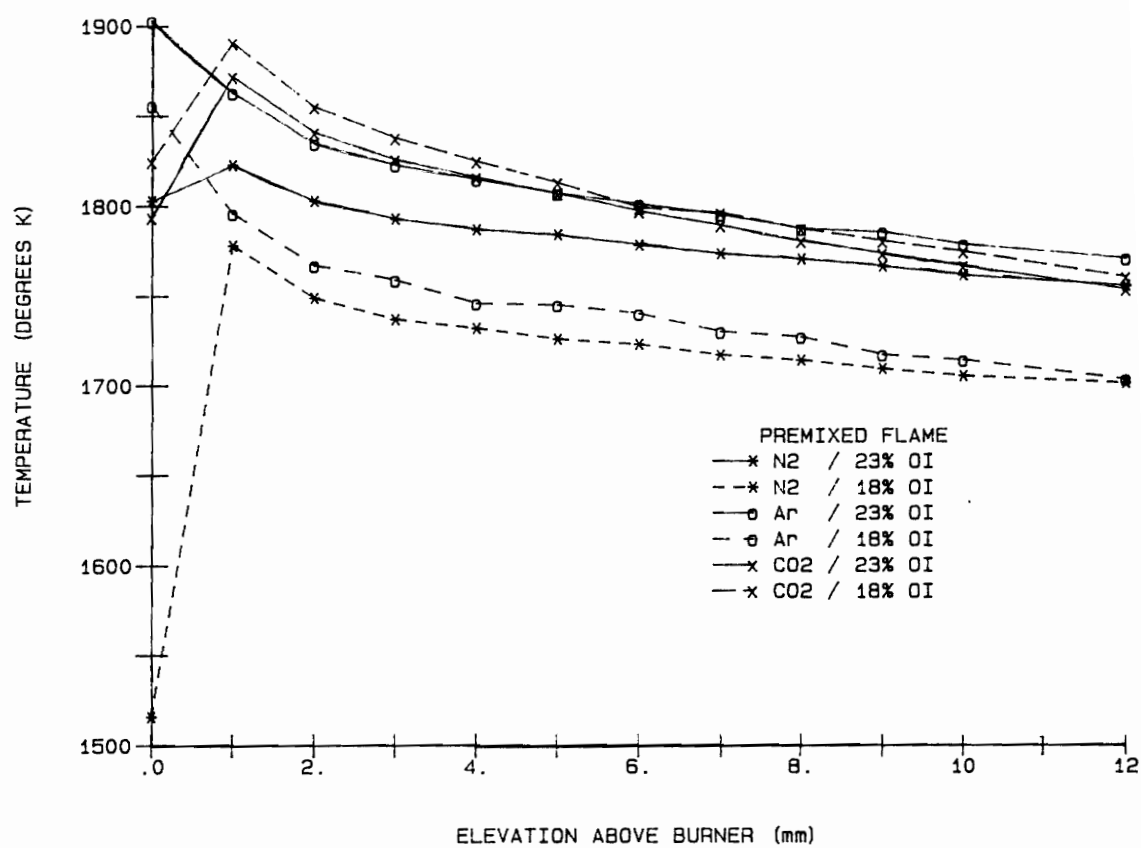


Figure 43. Measured Temperature Profiles Above Premixed Flames

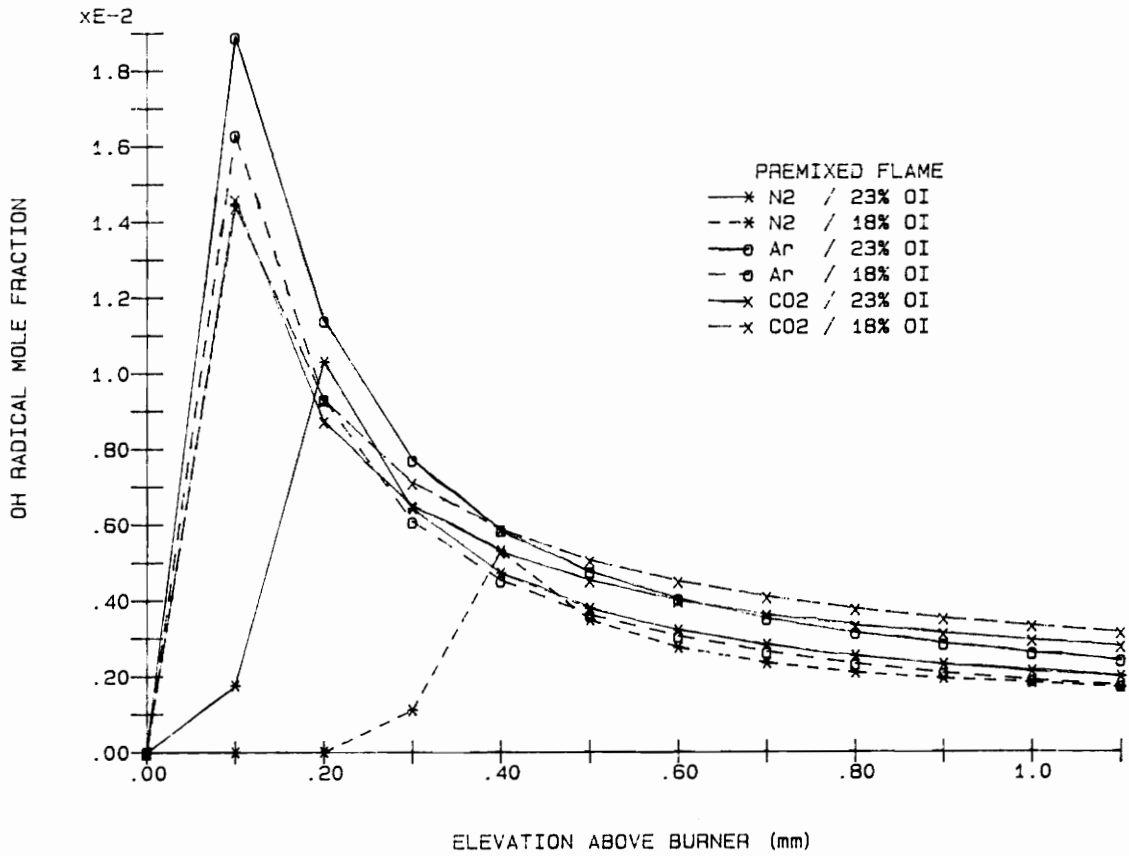


Figure 44. Calculated OH Radical Concentrations Above Premixed Flames

fraction of the three flames at this elevation. The stoichiometry of the CO₂-diluted flames is different from the nitrogen-diluted flame, and this may account for the inconsistencies between the temperatures and OH mole fractions.

The magnitude of the OH mole fractions are similar for all of the flames above the 0.4 mm elevation. The relationship between the mole fractions correlates well with the relative temperatures of the flames at the 1.0 mm elevation. The CO₂-diluted flames have both the highest temperatures and the highest mole fractions at this elevation. At the other extreme, the argon- and nitrogen-diluted 18% oxygen index flames have the lowest temperatures and the lowest OH mole fractions at this elevation.

CHAPTER 5: DISCUSSION OF RESULTS

In this chapter, the trends observed in the previous chapter are examined in more detail. The results are compared to similar measurements by other researchers. The trends are also compared to what one would expect based on previous studies.

In the first section, the measurements of flame 1 are compared to the results of Santoro et al. [23] to show that these results are consistent with other researchers. The second section examines the various measures of the soot volume fraction. The local and integrated soot volume fraction distributions are analyzed first, and then the total soot factors are compared. The competition between combustion mode, oxygen index, injection height, diluent gas, and diffusion fuel will be compared, and the relative effect of these parameters on the total soot factor will be assessed. In the final section, the measured temperature profiles are compared to the predicted adiabatic flame temperatures. In this section, the results from the gas sampling system are also briefly discussed.

5.1 COMPARISON TO PUBLISHED RESULTS

One of the earliest goals of this research was to be able to reproduce the results of Santoro et al. [23] to confirm the experimental procedure. Flame 1 is the most similar to one of the flames Santoro measured: single mode, flush injection, and ethene as the diffusion fuel. The only difference is in the oxygen index, 23% instead of 21%. The qualitative nature of the extinction profiles agrees well. At lower flame elevations, a double-peaked profile occurs. As the flame elevation increases, the middle of the profile fills in, until it is almost flat. At the highest elevations, the profile is much

smaller and has only a single broad peak. Quantitatively, Santoro's profiles showed greater extinction, but his flame was about three times broader than flame 1.

The calculated soot volume fractions also tend to agree with Santoro's results. The shape of the distributions is correct, as is the order of magnitude of the soot volume fractions. Most of Santoro's volume fractions were in the 10^{-7} to 10^{-6} range, although his peak volume fractions were almost 10^{-5} . The maximum soot volume fraction in flame 1 was about 2×10^{-6} . The experimental results have shown that a lower oxygen index leads to more soot in single mode flames, so the higher soot volume fractions in Santoro's flame is consistent with these results. The agreement between our measurements and these published results therefore seems to be satisfactory. The following sections review the results of the temperature measurements, local soot volume fraction distributions, integrated soot volume fraction distributions, and the total soot factor rankings.

5.2 LOCAL SOOT VOLUME FRACTION DISTRIBUTIONS

Figures 26 and 27 compared the local soot volume fractions for a single mode flame and its dual mode counterpart. Examination of the shapes of these distributions suggests that the dual mode flame is maturing sooner than the single mode flame. Soot growth along the centerline of the dual mode flame is accelerated, and the profile shapes show the greatest differences in the early parts of the flames. The magnitude of the profiles shows that the dual mode flame has higher levels of soot at all elevations except 35 mm, where the single and dual mode flames show equal soot levels. These trends suggest that the effect of dual mode combustion is seen primarily in the early parts of the flame, where particle inception and particle growth is occurring.

5.3 INTEGRATED SOOT VOLUME FRACTION DISTRIBUTIONS

None of the flames emitted soot from the tip, so all of the soot formed was later consumed. Although more soot is formed in the dual mode flames, it is significant that all of this soot is subsequently oxidized. This indicates that dual mode combustion also has some influence on the oxidation of soot particles.

The integrated soot volume fraction distributions show that the slope in the soot formation zone is generally greater for the dual mode flames than for the single mode flames. This could occur because more precursors are formed, or there is a greater rate of surface growth, or some combination of these effects. The mechanism would be more clear if scattering measurements were available (which leads to particle number density and average particle size information). The ability of the dual mode flames to oxidize all of the soot formed suggests that the increase in soot volume fraction is primarily due to an increase in the number of particles formed.

Oxidative attack of soot would be enhanced by a high amount of surface area per unit of soot volume fraction. This would mean that the particles would not be significantly larger than those formed in the single mode flames. A greater number of these particles would be needed to account for the higher soot volume fractions in the dual mode flames. One prediction of this hypothesis is that scattering measurements would show a significant increase in particle number density, but a smaller increase (if any) in the surface growth rate and average particle size.

The current experimental results can not prove this hypothesis, since other explanations of the oxidative efficiency are possible. For example, oxidation could be enhanced by the presence of radicals, although Figure 49 shows the strong attenuation of the radical concentration with height above the burner. Even for the flush-injected

flames, the oxidation zone is at least 20 mm above the burner. The radical concentrations would be much lower than the values shown in Figure 49 at this elevation. Oxidation could also be enhanced by higher temperatures in the oxidation zone. The experimental results do show that the dual mode feed air temperature is at least 1700 K for all of the dual mode flames 10 mm above the burner, and the average decay rate is about -10 K / mm. The feed air temperatures should be on the order of 1500 K throughout the oxidation zone. The luminosity of the dual mode flames was much more intense and more white in color than the single mode flames (yellow-orange in color). The shift in wavelength from red towards blue offers qualitative evidence that the dual mode diffusion flames are indeed hotter than the single mode diffusion flames.

5.4 COMPARISON OF TOTAL SOOT FACTORS

The relative influence of the flame parameters can be assessed by comparing the total soot factors of the flames. In Tables 6, 7, and 8, similar flames are compared by calculating the total soot factor ratio of two flames that differ by one of the parameters. In Table 6, the effect of injection height is examined. In Table 7, the effect of changing the combustion mode is examined. In Table 8, the effect of the oxygen index is examined. These tables will be referred to in the following paragraphs, where the relationships between the parameters are discussed. The purpose of this discussion is to determine which parameters are significant during dual mode combustion.

One of the conditions for "significance" is based on the estimated error limits of the extinction measurements. The estimated error limits for these experiments are +/- 12% [procedure in reference 36]. This figure is based on the repeatability of the measured extinction profiles and estimates of the convolution errors. Any parameter that causes a mean increase in the total soot factor greater than 12% is considered significant.

TABLE 6
EFFECT OF INJECTION HEIGHT ON TOTAL SOOT FACTOR AMONG
SIMILAR FLAMES

DILUENT GAS/MODE	OXYGEN INDEX	(FLAME NUMBERS) INJECTION HEIGHT		TOTAL SOOT FACTOR RATIO
		1.0 cm	0.0 cm	
ETHENE FUELED:				
N2/DUAL	23%	4	2	1.28
N2/DUAL	18%	8	6	1.40
Ar/DUAL	23%	15	13	1.09
Ar/DUAL	18%	19	17	1.29
CO2/DUAL	23%	23	21	1.34
CO2/DUAL	18%	27	25	1.74
N2/SINGLE	23%	3	1	1.59
N2/SINGLE	18%	7	5	1.15
PROPANE FUELED:				
N2/DUAL	23%	33	32	1.22
N2/DUAL	18%	35	34	1.25
N2/SINGLE	23%	29	28	1.22
N2/SINGLE	18%	31	30	1.03

TABLE 7
EFFECT OF COMBUSTION MODE ON TOTAL SOOT FACTOR AMONG
SIMILAR FLAMES

OXYGEN INDEX	INJECTION HEIGHT (cm)	(FLAME NUMBERS)		TOTAL SOOT FACTOR RATIO
		DUAL MODE	SINGLE MODE	
ETHENE FUELED:				
23%	0.0	2	1	1.87
23%	1.0	4	3	1.50
18%	0.0	6	5	3.15
18%	1.0	8	7	3.84
PROPANE FUELED:				
23%	0.0	32	28	1.99
23%	1.0	33	29	1.98
18%	0.0	34	30	4.32
18%	1.0	35	31	5.26

TABLE 8
EFFECT OF OXYGEN INDEX ON TOTAL SOOT FACTOR AMONG SIMILAR
FLAMES

COMBUSTION MODE	INJECTION HEIGHT (cm)	(FLAME NUMBERS) OXYGEN INDEX		TOTAL SOOT FACTOR RATIO
		23%	18%	
SINGLE	0.0	1	5	2.32
SINGLE	1.0	3	7	3.22
SINGLE	0.0	28	30	2.58
SINGLE	1.0	29	31	3.08
DUAL	0.0	2	6	1.38
DUAL	1.0	4	8	1.26
DUAL	0.0	13	17	1.44
DUAL	1.0	15	19	1.22
DUAL	0.0	21	25	1.30
DUAL	1.0	23	27	1.00
DUAL	0.0	32	34	1.19
DUAL	1.0	33	35	1.16

5.4.1 Injection Height Effects

The elevated flames showed higher soot volume fractions than the flush-injected diffusion flames. For the dual mode flames, this could have been due to lower temperatures and radical concentrations at higher elevations. Or, it could have been due to pyrolysis of the fuel on the walls of the injection tube. However, this result was observed for the single mode flames as well. In these flames, there should be no temperature or radical gradients in the feed air. Hura and Glassman [12] reported that ethene diffusion flames show a significant increase in soot levels with up to 10% oxygen addition to the fuel stream. Thus, there is a possibility that the leakage of air into the diffusion fuel jet occurs at the flame stabilization region on the tube, leading to increased soot volume fractions. This hypothesis is supported by the fact that the flush and elevated single mode flames show a greater difference at the higher oxygen index, under conditions that would favor greater oxygen infiltration (compare flames 1 & 3 to flames 5 & 7 on Figure 42). According to this reasoning, it would be assumed that there is more oxygen infiltration when the tube is elevated.

Hura and Glassman also reported that the alkanes did not show a significant increase in soot levels with up to 10% oxygen addition. Flames 28 through 31 were measured to investigate these observations. These single mode flames were measured using propane as the diffusion flame fuel instead of ethene. Although the ethene diffusion flame produces more soot than the propane diffusion flame, both flames show the same relative increase in total soot at the higher injection point. Table 6 shows that the mean increase in the total soot factor for ethene flames was about 36%. This includes the argon-diluted 23% OI dual mode flames, whose mean increase is not necessarily significant (only 9%, whereas error limits are $\pm 12\%$). The mean increase in the total soot factor for propane flames was about 18%, including the single mode 18% OI flames

(3% increase). Ignoring these doubtful cases changes the mean total soot factor increases to 40% for ethene flames and 23% for propane flames. According to Hura and Glassman, the two fuels should have shown a significantly different response if infiltration of oxygen into the fuel jet were responsible for the increase in total soot with injection height.

Raising the injection height of a dual mode flame to 1.0 cm raises the average total soot factor by about 33% (Range: 9 to 74%). Raising the injection height of a single mode flame to 1.0 cm raises the average total soot factor by about 25% (Range: 3 to 59%) The effect of injection height is significant for both combustion modes.

The increase in soot levels with injection height for dual mode flames goes against what is known about the response of pure diffusion flames to higher combustion temperatures. If it is true that higher temperatures lead to more soot in pure diffusion flames, the dual mode flames should show a decrease in total soot at elevated injection heights, since the feed air becomes cooler downstream from the premixed flame zone. One possible explanation of the increase for dual mode flames could be attributed to fuel pyrolysis caused by the heated center tube prior to injection. For flush injection, the diffusion fuel can be assumed to be close to room temperature at the point of injection. At elevated injection, it is possible that the diffusion fuel has been heated significantly and/or significant amounts of soot precursors have been formed prior to injection. However, none of these factors would help explain why the single mode flames also show an increase in soot levels with injection height. If oxygen infiltration is indeed responsible for the increase in soot with elevated injection, then the results of these experiments are not fully consistent with the results of Hura and Glassman.

5.4.2 Combustion Mode Effects

The following discussion refers to the results shown in Table 7. For flames with a 23% oxygen index, the total soot increases by about 84% (range: 50 to 99%) for dual mode combustion with respect to single mode combustion. For flames with an oxygen index of 0.18, the total soot increases by about 314% (range: 215 to 426%) for dual mode combustion with respect to single mode combustion. It appears that the effect of dual mode combustion is significant for either oxygen index. Moreover, the effect of dual mode combustion is not merely significant, but it is significantly different for the two oxygen indexes. Based on the mean increases, the effect of dual mode combustion is about 3.7 times greater at 18% oxygen index than at 23% oxygen index.

5.4.3 Oxygen Index Effects

Table 8 shows that the total soot factor increases by about 180% (range: 132 to 222%) in the single mode flames for a 23% oxygen index with respect to an 18% oxygen index. For the dual mode flames, the mean increase was about 24% (range: 0 to 44%). This includes one case of doubtful significance (flames 23 and 27). Ignoring this anomolous case changes the mean increase to 28%. Although the effect of oxygen index is significant for both combustion modes, the magnitude of the effect is significantly different. The mean increase is 6.4 to 7.5 times greater for single mode flames.

5.5 MEASURED VS. PREDICTED TEMPERATURES

The maximum measured temperatures did not agree with the predicted adiabatic flame temperatures in a relative sense. Table 9 summarizes the measured and predicted temperature relationships. For the 23% oxygen index flames, the expected trend was $\text{Ar} > \text{N}_2 > \text{CO}_2$ (hottest to coolest) based on the adiabatic flame temperature. The measured trend was $\text{Ar} > \text{CO}_2 > \text{N}_2$. For the 18% oxygen index flames, the expected trend was Ar

TABLE 9
COMPARISON OF CALCULATED ADIABATIC FLAME TEMPERATURES AND
MAXIMUM MEASURED TEMPERATURES FOR PREMIXED FLAMES

FLAME I.D.	CALCULATED T_{ad} (K)	MAXIMUM MEASURED TEMPERATURE (K)	TEMPERATURE DIFFERENCE (K)
N ₂ /23%	1951	1823	128
N ₂ /18%	1877	1778	99
Ar/23%	2251	1903*	348
Ar/18%	2211	1856*	355
CO ₂ /23%	1846	1872	-26
CO ₂ /18%	1887	1891	-4

* = extrapolated data

$> \text{CO}_2 > \text{N}_2$. The measured trend was $\text{CO}_2 > \text{Ar} > \text{N}_2$. This indicates that the CO_2 -diluted flames were hotter than expected with respect to the argon-diluted flames.

The measured temperatures did not agree with the predicted adiabatic flame temperatures in an absolute sense, either. The argon-diluted premixed flames were about 350 K lower than the adiabatic temperatures, whereas the carbon dioxide-diluted premixed flames slightly higher than expected. The combined effect was that the expected temperature differences were not achieved. A temperature difference of about 400 K had been expected for the 23% oxygen index flames, but only an 80 K difference was achieved. For the 18% oxygen index flames, a temperature difference of 113 K was measured (expected: about 330 K).

One possible explanation for these results is that the deviation from adiabatic behavior may be different for the flames. The diluent can significantly affect the flame speed; argon would increase the flame speed and carbon dioxide would decrease the flame speed with respect to nitrogen. A higher speed flame should stabilize closer to the burner and therefore should be less adiabatic. Table 9 supports this hypothesis, since the deviation from adiabatic flame temperature does seem to correlate with the specific heat of the diluents.

It is also possible that the measured vs. calculated temperature differences are within the error limits of the temperature measurements. The thermocouple temperature correction program predicted a measurement error on the order of 100 K for each flame. This program bases the temperature correction on the radiative and convective heat loss from the thermocouple bead. The gas thermal conductivity is based on a fuel rich (1.50 equivalence ratio) $\text{H}_2/\text{O}_2/\text{Ar}$ flame. However, all of the measured flames were fuel lean

methane flames. The assumed thermal conductivity should lead to greater errors for the nitrogen- and carbon dioxide-diluted flames than the argon-diluted flames.

Another reason for the observed temperature differences could be due to errors in the accuracy of the rotameters. Gas flow rate errors would change the stoichiometry of the flames, and therefore change the flame temperatures. The following paragraphs review the results of the gas sampling tests and an analysis of the effect of flow rate errors on the adiabatic flame temperatures.

During the experiments, the accuracy of the artificial air mixtures were checked several times. For these cold samples, the diluent and oxygen flows were collected in the sample bag and tested according to the procedure outlined in section 3.2.4. The results of these tests were:

DILUENT GAS	OXYGEN INDEX		ROOM AIR
	EXPECTED	MEASURED	
CO ₂	0.23	0.233	0.210
	0.18	0.179	0.211
N ₂	0.18	0.179	0.209
Ar	0.23	0.234	0.213

The results show that the rotameters used for air, diluent, and oxygen flows are capable of producing artificial air mixtures with an oxygen index accuracy within 5% of the desired oxygen index.

For the hot gas samples, the methane flow rate was an unknown variable. However, the methane flow rate was assumed to be known in order estimate the amount of moisture removed from the gas sample. Analysis of the hot gas samples using this assumption resulted in measured oxygen indexes within 5% of what was expected. The

results from both the cold and the hot gas samples therefore indicate that the premixed flames stoichiometries are accurate within 5 percent.

Nevertheless, the known methane flow rate assumption was analyzed to check its effect on the adiabatic flame temperature and post-combustion oxygen index. Table 10 shows the predicted effect of a 10% error in the methane flow rate on the carbon dioxide-diluted flames. The oxygen and diluent flow rates were kept constant as the fuel flow rate varied. The table shows that about a 6% change in the adiabatic flame temperature results from a 10% methane flow rate error. These results also show that the oxygen index error is 9 to 11 percent for a 10% methane flow error.

The gas samples analyses indicated an oxygen index error on the order of five percent or less. Based on the methane flow rate error analysis, this would indicate an error of about $\pm 5\%$ in the fuel flow rate. And further, this would indicate a change in the adiabatic flame temperature of about $\pm 3\%$. For the CO₂-diluted flames, this is about ± 60 K. This error is on the same order as the maximum temperature differences noted earlier (80 and 113 K). This analysis indicates that the differences between the measured and adiabatic flame temperatures can be accounted for by the error limits of the thermocouple temperature correction program and the rotameter flow rates.

TABLE 10
CHANGE IN CALCULATED ADIABATIC FLAME TEMPERATURE FOR CO₂-
DILUTED PREMIXED FLAMES ASSUMING +/- 10% ERROR IN METHANE
FLOW RATE

OXYGEN INDEX	METHANE FLOW (%)	ADIABATIC FLAME TEMPERATURE (K)	ACTUAL OXYGEN INDEX
0.23	90	1726	0.25
	100	1843	0.23
	110	1952	0.21
0.18	90	1764	0.20
	100	1883	0.18
	110	1992	0.16
OXYGEN INDEX	% CHANGE IN METHANE FLOW	% CHANGE IN T _{ad}	% CHANGE IN ACTUAL OI
0.23	-10%	-6.3%	+8.7%
	+10%	+5.9%	-8.7%
0.18	-10%	-6.3%	+11%
	+10%	+5.9%	-11%

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

The effects of vitiated air on diffusion flames has been investigated in a unique two stage burner. Soot volume fractions have been measured in these dual mode flames. The parameters of combustion mode (single vs. dual), oxygen availability (18% vs. 23% oxygen index), premixed mode flame temperature (Ar, N₂, CO₂ diluents), radical concentrations (0.0 vs. 1.0 cm injection), and diffusion fuel (ethene vs. propane) were varied to study their effect on the soot yield in these flames. The results of these measurements show that:

- 1) Dual mode combustion has been shown to significantly increase the amount of soot formed. Increases of greater than 50% were observed in all cases relative to single mode flames. The effect is much larger for the 18% oxygen index flames than the 23% oxygen index flames, and slightly larger for propane flames than ethene flames. Dual mode combustion also leads to greater soot luminosity, and presumably greater rates of radiant heat transfer.

- 2) The total soot factor increased for all flames with an elevated injection height. If the increase is due to oxygen infiltration, then the results of this study are not entirely consistent with the results of previous studies.

- 3) The effect of the oxygen index alone seems to be more significant for the single mode flames. Put another way, the difference between 18% oxygen index and 23% oxygen index single mode flames is significantly greater than the difference between 18% oxygen index and 23% oxygen index dual mode flames.

Soot production is increased significantly during dual mode combustion regardless of the injection height, diffusion fuel, or oxygen index. According to (2) above, the effect of dual mode combustion is particularly strong for flames with an oxygen index of 18%. However, (3) above indicates that among dual mode flames the influence of oxygen index is perhaps negligible. This could mean that among the characteristics of vitiated air, high temperatures and/or radical concentrations are more important than oxygen depletion.

While it has been shown that the effect of dual mode combustion is significant in these experiments, it is not entirely clear whether the effect is due to temperature, or radicals, or both. Temperature effects are likely, since it is already known that higher temperatures promote sooting in diffusion flames. If temperature effects dominate the effect of radicals, it has not been possible to resolve these effects among the nitrogen, argon, and carbon dioxide diluted dual mode flames. The magnitude of the total soot factor does not correlate well with either the calculated adiabatic flame temperatures or the maximum measured temperatures. Since the radical concentrations are based on the temperature profiles, the total soot factors fail to correlate well with the predicted radical concentrations as well. It is entirely possible that the accuracy of the measurements and the apparent similarity of the temperatures are responsible for the poor correlation.

Finally, experimental evidence supports but cannot confirm the hypothesis that dual mode combustion promotes the formation of soot precursors. According to this hypothesis, it is more an increase in the particle number density than an increase in the average particle diameter which accounts for the higher soot volume fractions. This mechanism would explain the dual mode flames' ability to subsequently oxidize the soot completely.

6.2 RECOMMENDATIONS FOR FURTHER WORK

Many things can be done in an attempt to improve the accuracy and resolution of the extinction measurement system. Although the flickering instability may prove to be impossible to control, lateral motion of the flame could be improved. Lateral flame stability has a great effect on the smoothness of the measured extinction profiles, particularly at the edges of the visible flame zone where the soot volume fraction gradients are the greatest. The flame must be effectively isolated from room air currents. Other researchers have achieved this by putting a chimney around the burner [23]. This usually consists of a sheet metal tube with optical access slits. Such a chimney was built for these experiments. Unfortunately, it worsened the flame stability. The chimney amplified the entrainment of room air through the slots. Santoro et al were able to minimize this effect by putting screens and flow restriction plates in the chimney to control the rate of air infiltration. Future investigators should attempt to find a combination of screens and plates to improve the chimney design.

The smoothness and accuracy of the extinction profiles can be improved further by using the chopper/lock-in amplifier, thereby improving the signal to noise ratio. A new photodiode has been purchased which has two improvements over the photodiode used for these experiments. First, this photodiode works in the photoconductive mode, which lowers its rise time to the order of nanoseconds. This should allow high chop rates and eliminate the loss of signal that occurred with the slower photodiode. Secondly, the new photodiode has a much larger surface area. Other investigators (R. J. Santoro, W. L. Flower) seemed to have fewer problems when using larger detectors. Dr. Flower suggests using a laser beam spot size that is two-thirds the detector diameter. The new photodiode is an EG&G model DT-110 with an active area of 100.0 mm².

The rotameter calibrations can be improved, particularly for the smaller tube sizes (601 and 602). The metering device was designed for flow rates on the order of hundreds of cc's per second, and the throughput of the smaller rotameter tubes is on the order of tens of cc's per second to less than 10 cc/s. These rotameters should be calibrated using soap bubble meters.

Although the flickering problem is not in itself pertinent to the goals and scope of this research program, it seems to offer many possibilities for a separate research effort. The current knowledge of this problem is insufficient to explain why the single mode argon- and carbon dioxide-diluted flames could not be stabilized, but the nitrogen-diluted single mode flames could. Nor is there an explanation why the rate of coflowing feed air affects the instability. Past attempts to model this problem have always assumed a quiescent atmosphere, and it appears that the feed air flow has some effect on the stability. This problem has displayed several paradoxes. The (single mode) argon- and carbon dioxide-diluted artificial feed airs have a higher density than the nitrogen-diluted air, whereas all of the dual mode airs are much less dense due to their much higher temperatures. Is the density of nitrogen "just right," or is some other factor responsible for its ability to suppress flicker? Its stability enhancement does seem to increase with the coflowing air velocity or momentum flux, yet there are other flames that cannot be stabilized despite much higher velocities and momentum fluxes.

There is much more information to be gained from the flames already studied. It is important to measure other soot properties such as the average particle size and the particle number density. These parameters cannot be found unless the scattering properties of the soot particles are measured. In addition, the scattering properties determine the validity of assuming Rayleigh behavior. The use of Mie theory would probably change the value of the soot volume fractions based on extinction data/Rayleigh

theory alone. This information is critical for analyzing where the dual mode combustion has the most effect on the soot history in the flames. If the soot volume fraction increases in a flame, is it due to more particles, or larger particles, or some combination of these? Is the particle size distribution more or less uniform than before? Is there any evidence that suggests the particles deviate more or less from spherical shapes? The answers to these questions help to identify where the biggest changes are taking place: soot precursor generation, particle growth rates, tendency to agglomerate, and/or oxidation rates.

More information can be gained by measuring the radical species concentrations in the flames. This involves more extinction measurements and possibly fluorescence measurements using the frequency-doubled ring dye laser. These measurements would check the accuracy of the CHEMKIN analysis of radical species concentrations above the burner. More importantly, they might reveal whether the radical concentrations within the diffusion flame have changed significantly.

It has been difficult to separate the temperature and radical effects in these experiments, since higher radical concentrations are naturally associated with higher temperatures. If the single mode feed air could be supplied at high temperatures, similar to the temperature of the premixed flame gasses but without the radicals, this would be a big improvement in separating the temperature and radical species effects.

The temperature differences achieved by using the different diluent gasses were less than expected. Part of this was to be expected since it was necessary to change the carbon dioxide-diluted flames' stoichiometry. Instead of a 300K temperature difference, this lowered the predicted temperature difference to only about 100K (based on calculations of adiabatic flame temperatures). If the nitrogen- and argon-diluted flames

were changed to this same stoichiometry, their adiabatic flame temperatures would increase as well. This effect may be attenuated somewhat due to the burner cooling water; the higher the adiabatic flame temperature, the greater the heat transfer to the burner cooling coils.

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APPENDIX A

EXTINCTION PROFILES

Figures 45 through 68 show the measured extinction profiles for the flames studied. The solid lines show the ASYST curvefits through the raw data. At the end of the figures, Table 11 lists the shift applied to center each profile.

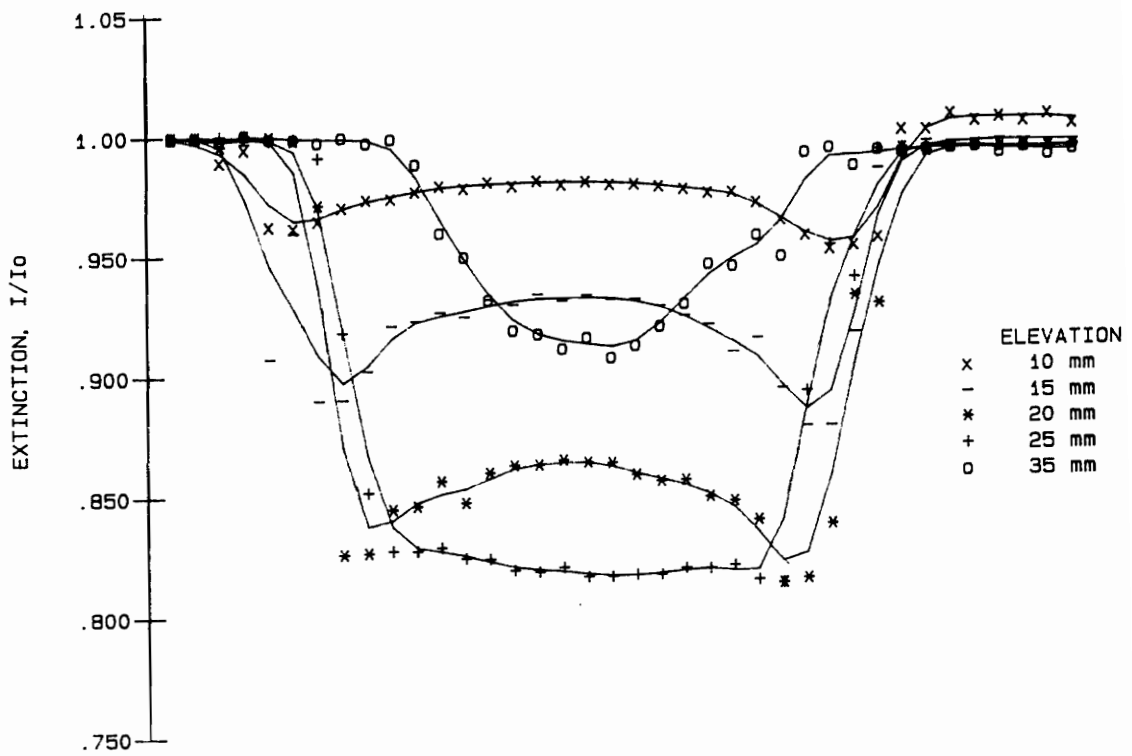


Figure 45. Raw and Smoothed Extinction Profiles, Flame 1

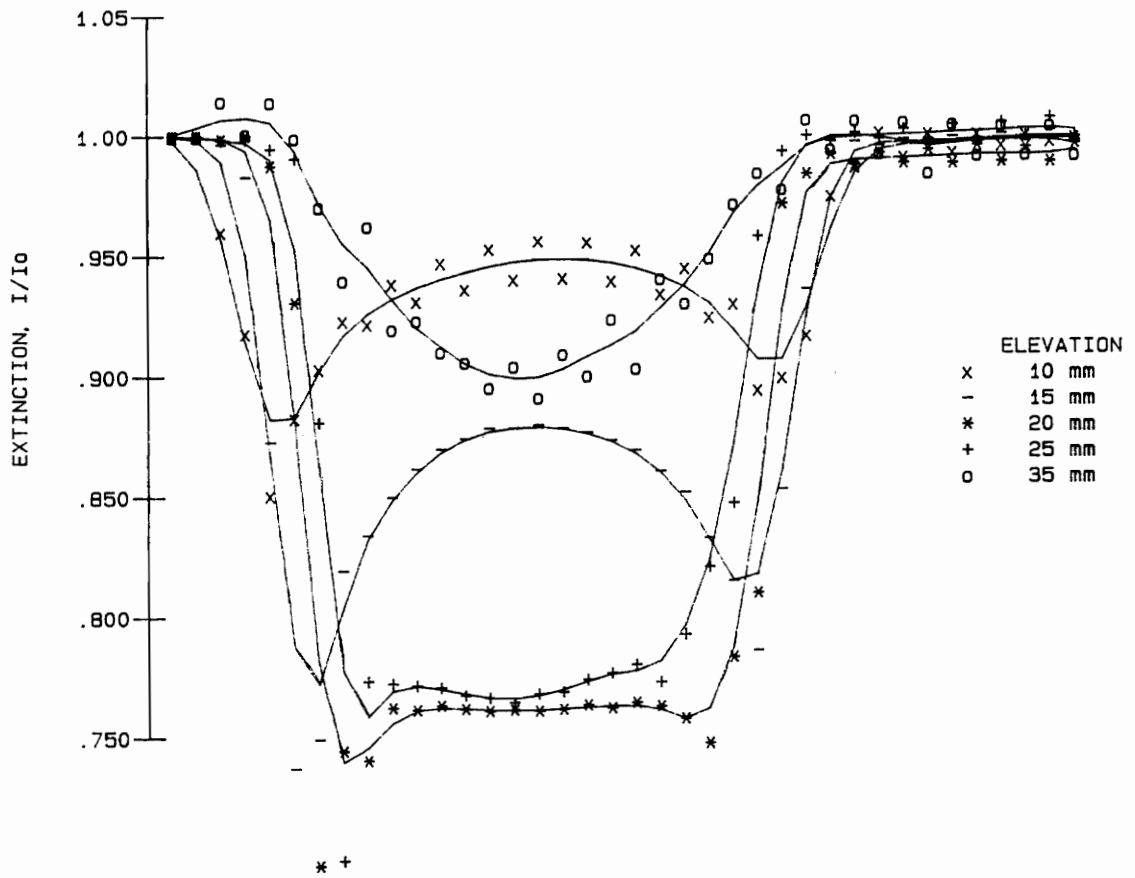


Figure 46. Raw and Smoothed Extinction Profiles, Flame 2

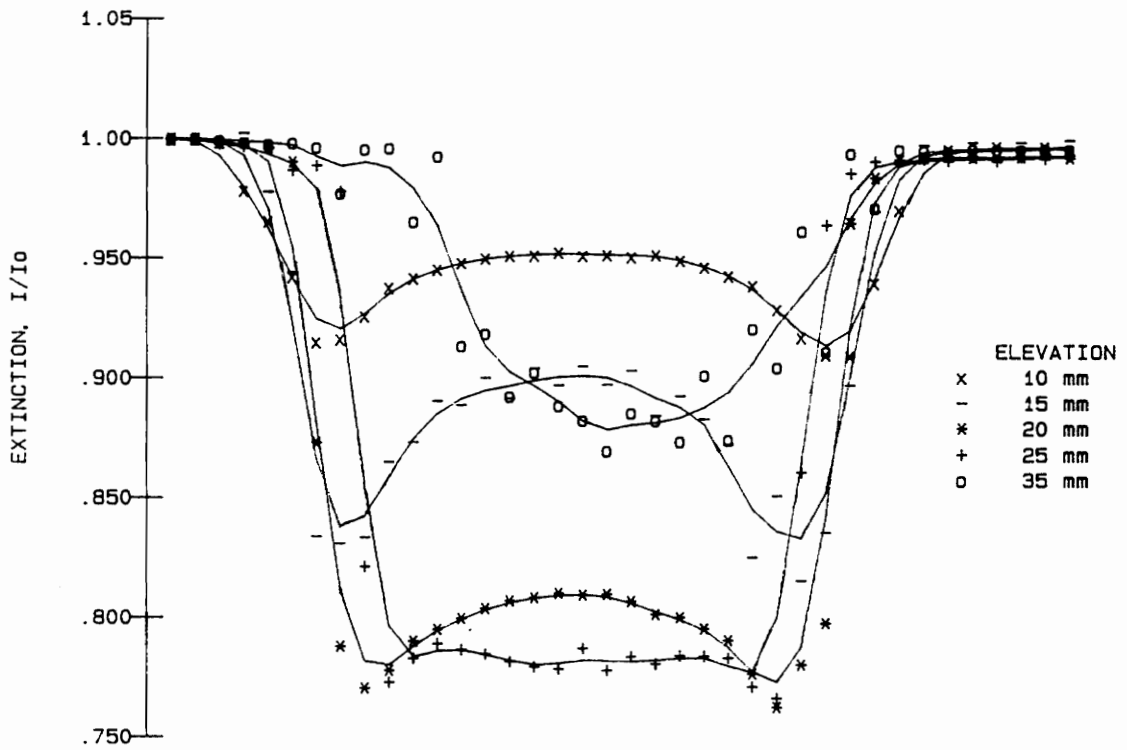


Figure 47. Raw and Smoothed Extinction Profiles, Flame 3

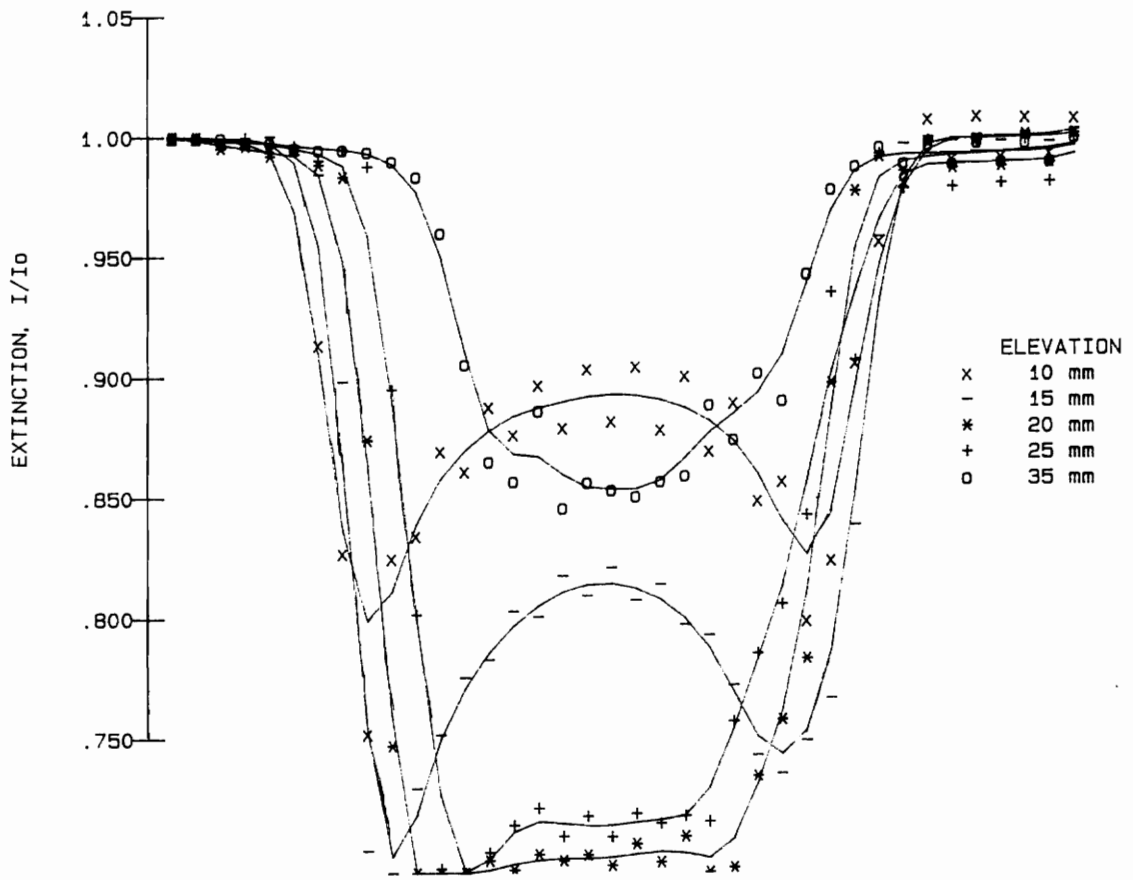


Figure 48. Raw and Smoothed Extinction Profiles, Flame 4

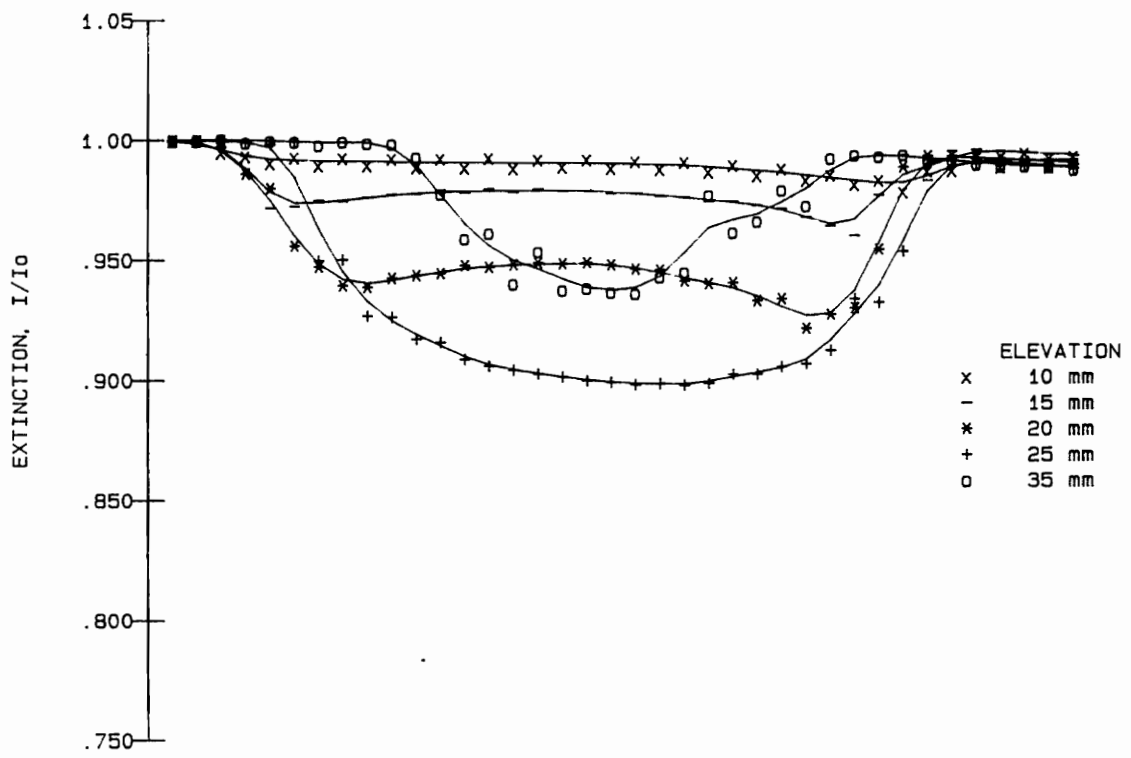


Figure 49. Raw and Smoothed Extinction Profiles, Flame 5

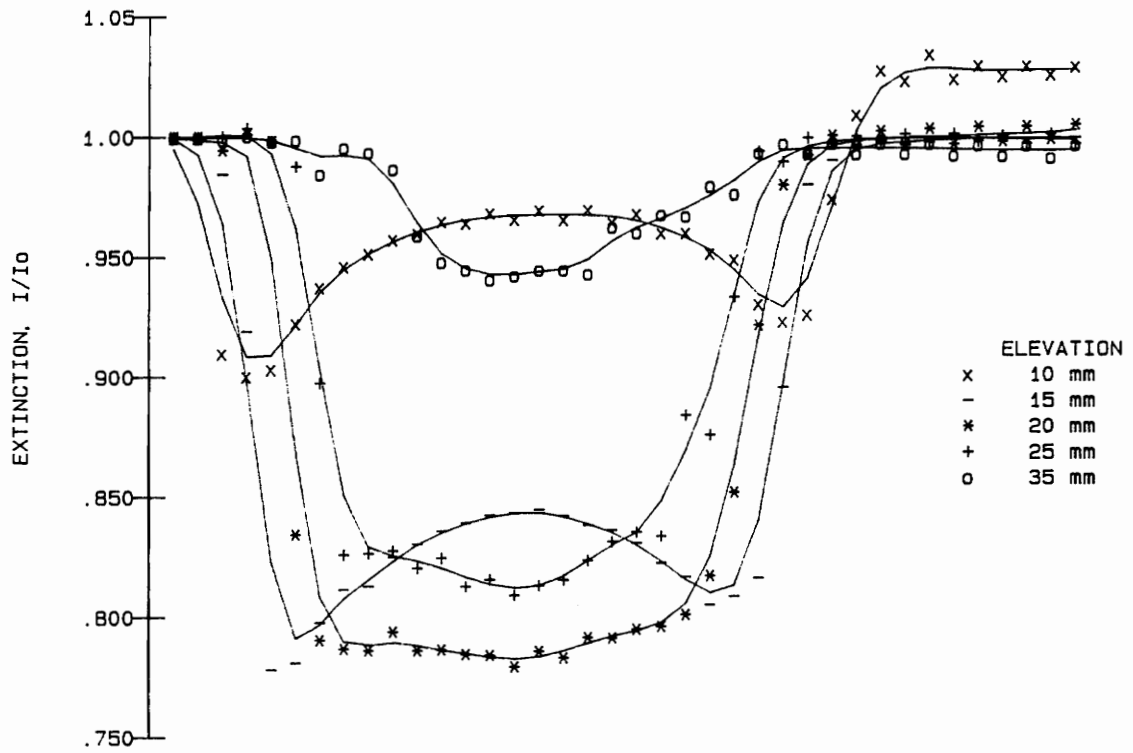


Figure 50. Raw and Smoothed Extinction Profiles, Flame 6

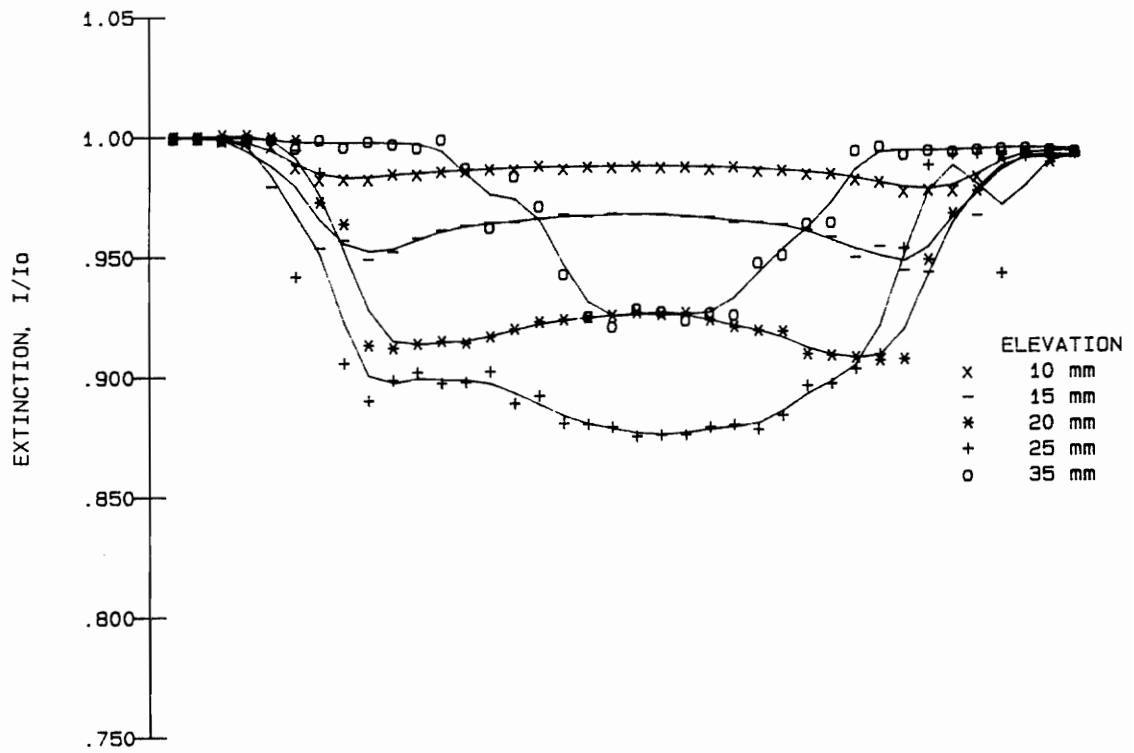


Figure 51. Raw and Smoothed Extinction Profiles, Flame 7

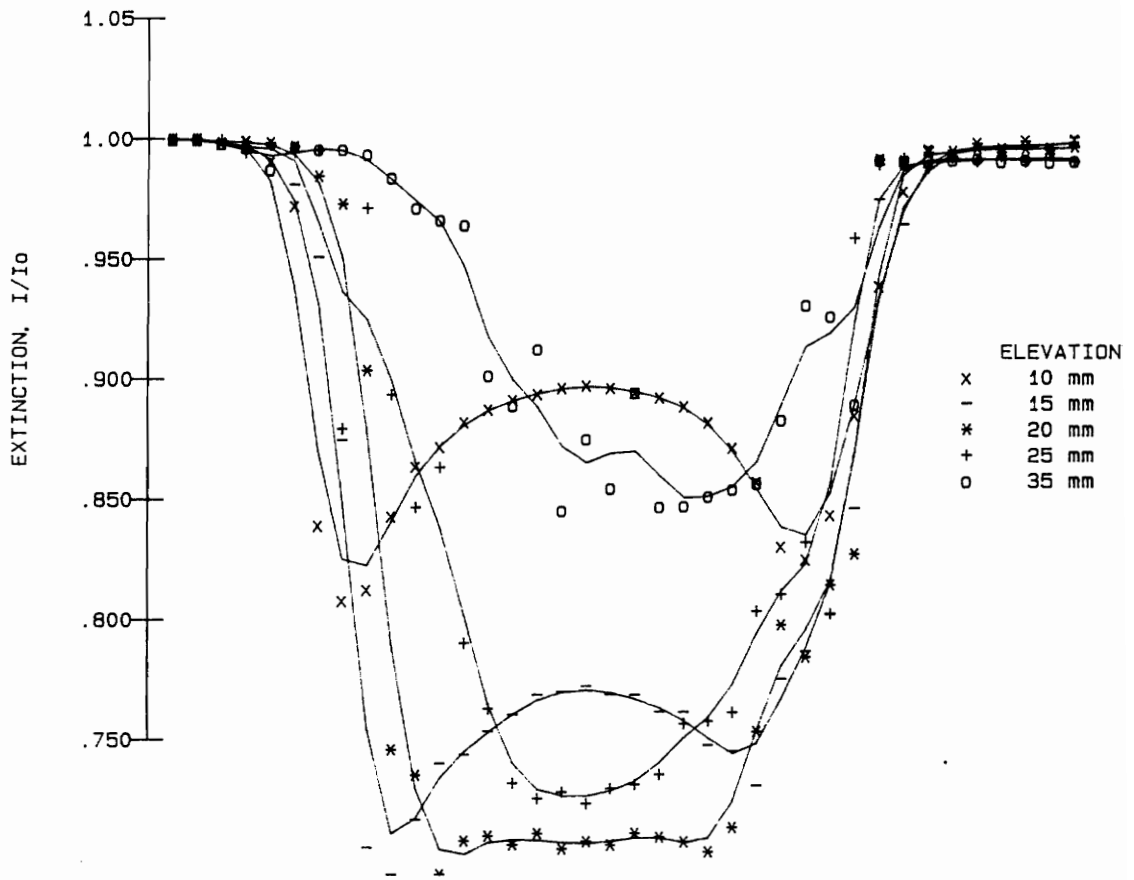


Figure 52. Raw and Smoothed Extinction Profiles, Flame 8

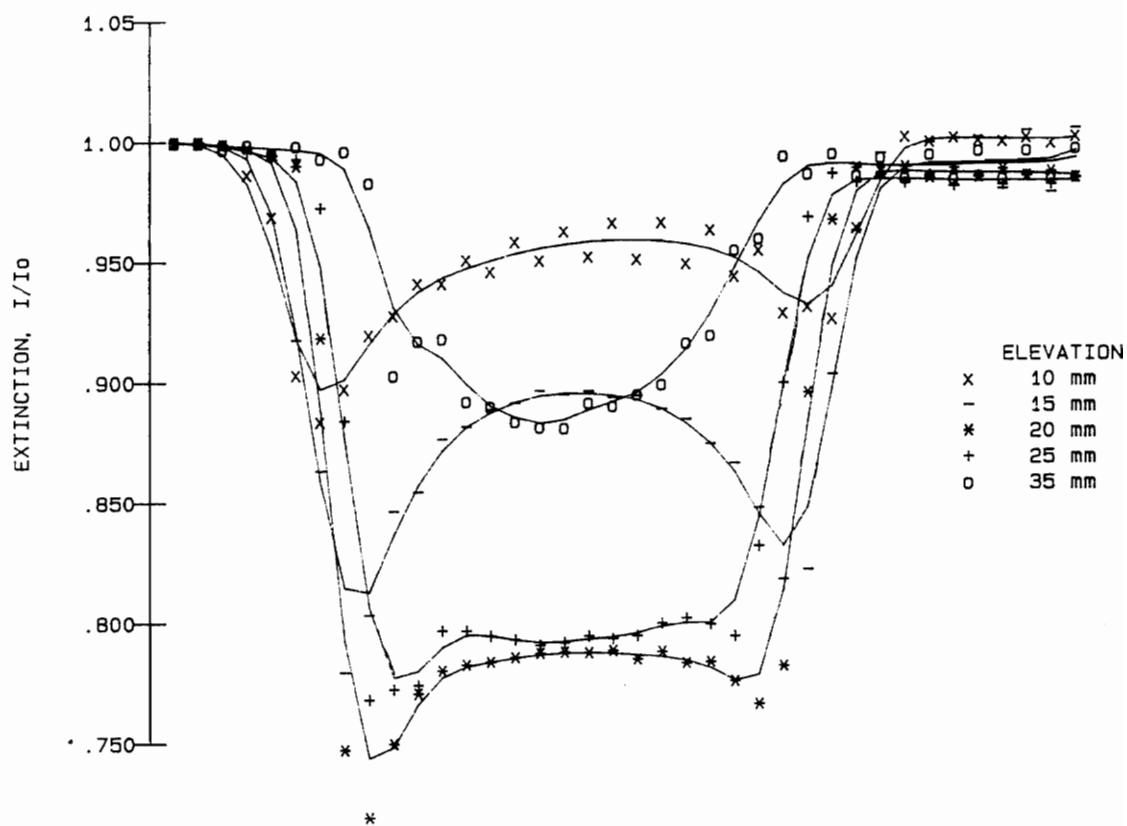


Figure 53. Raw and Smoothed Extinction Profiles, Flame 13

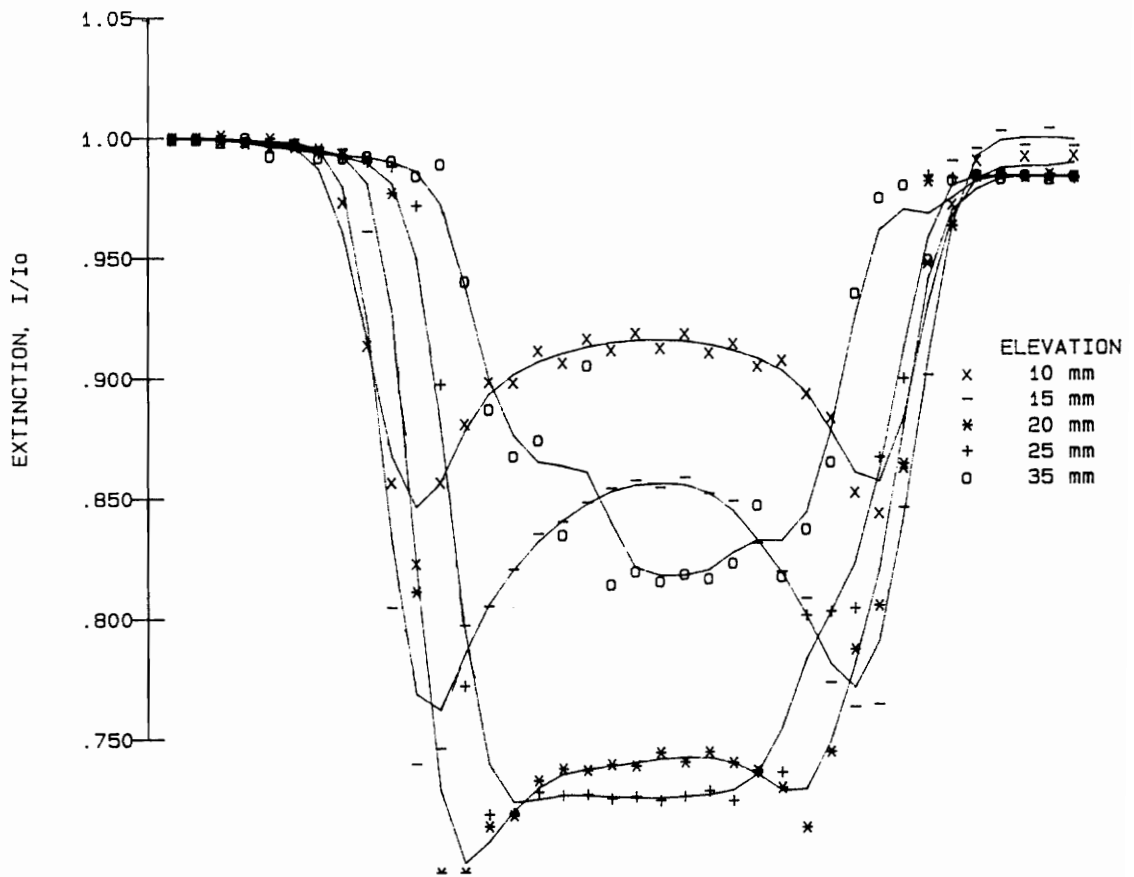


Figure 54. Raw and Smoothed Extinction Profiles, Flame 15

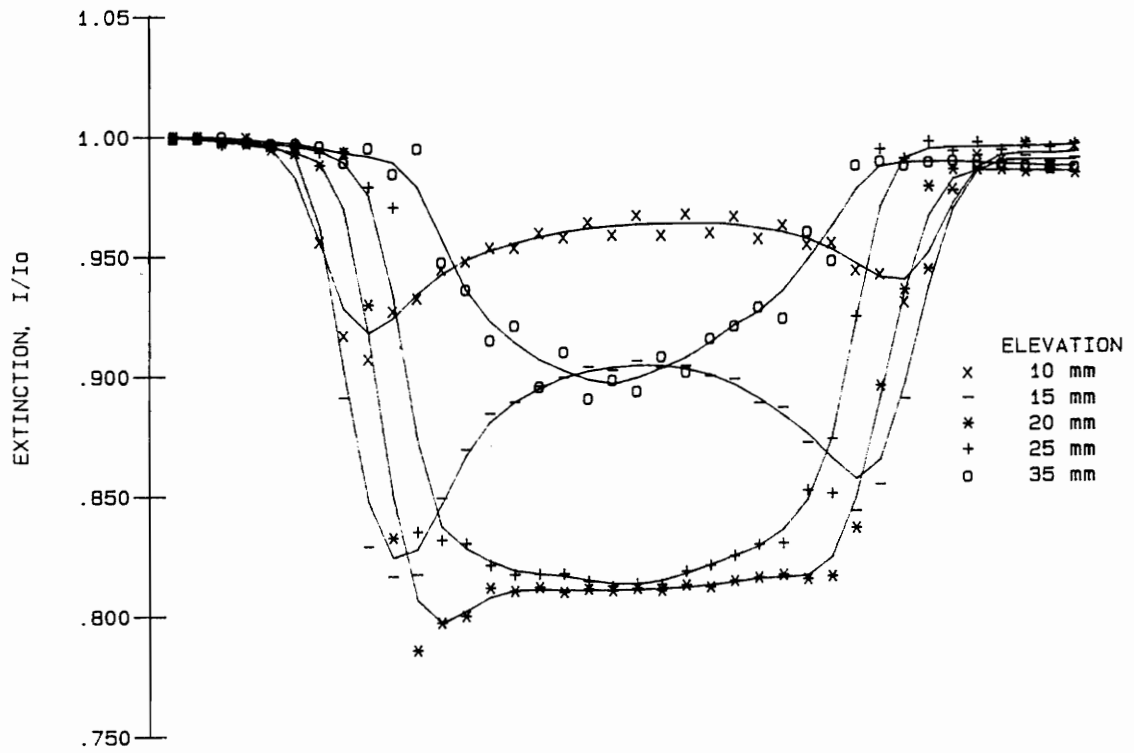


Figure 55. Raw and Smoothed Extinction Profiles, Flame 17

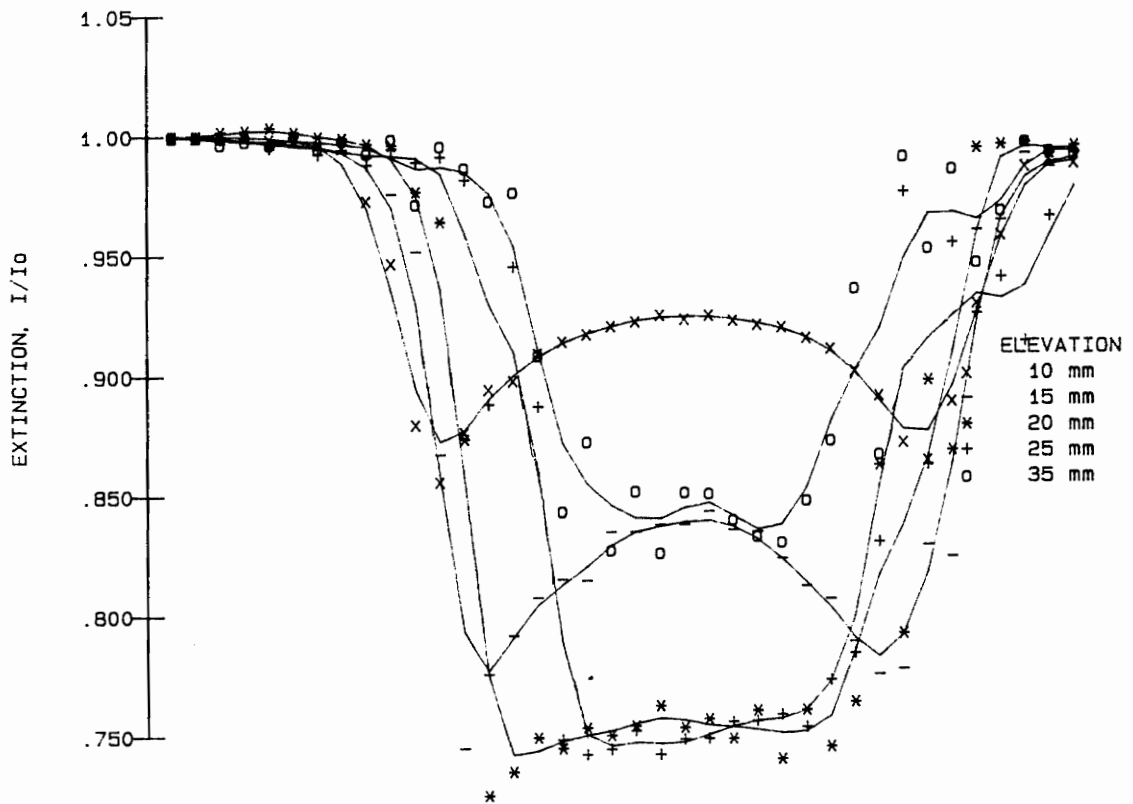


Figure 56. Raw and Smoothed Extinction Profiles, Flame 19

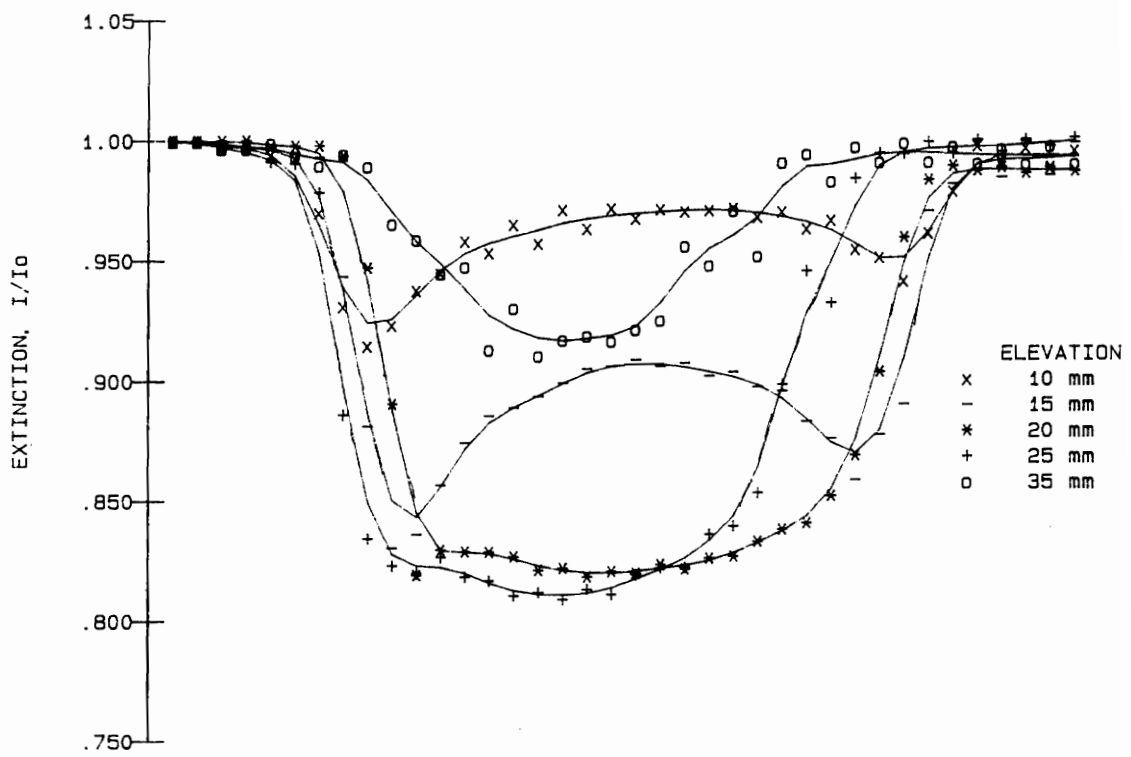


Figure 57. Raw and Smoothed Extinction Profiles, Flame 21

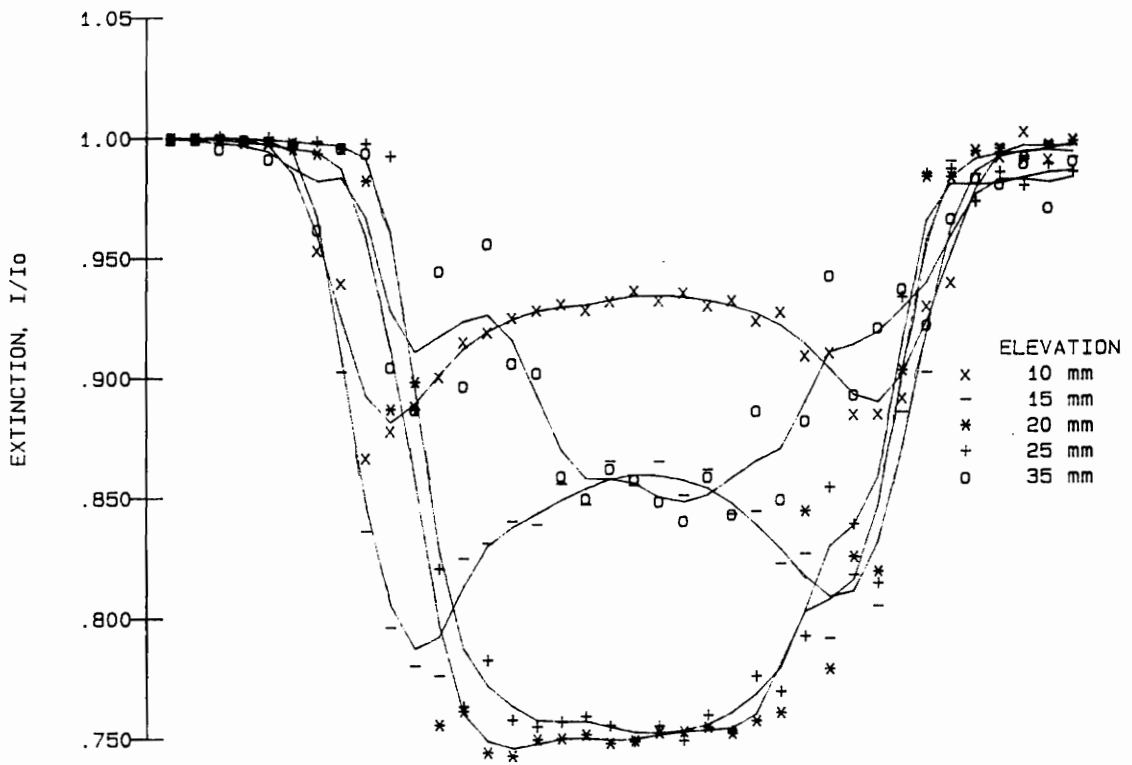


Figure 58. Raw and Smoothed Extinction Profiles, Flame 23

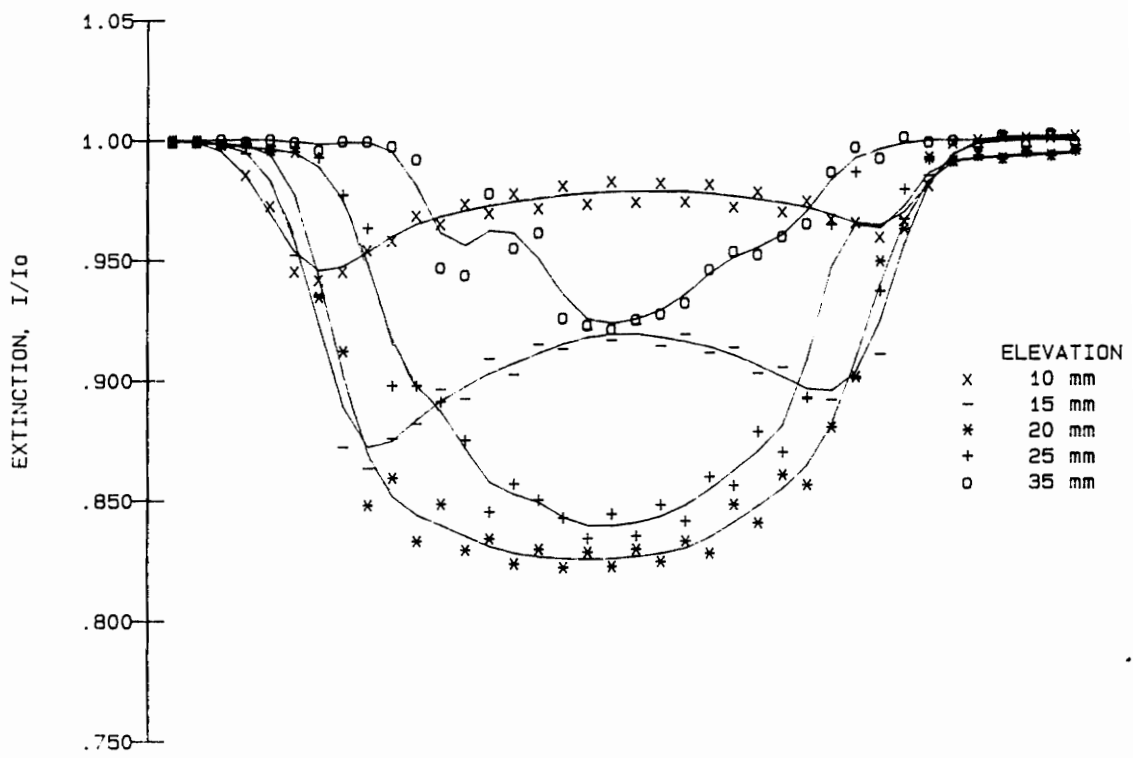


Figure 59. Raw and Smoothed Extinction Profiles, Flame 25

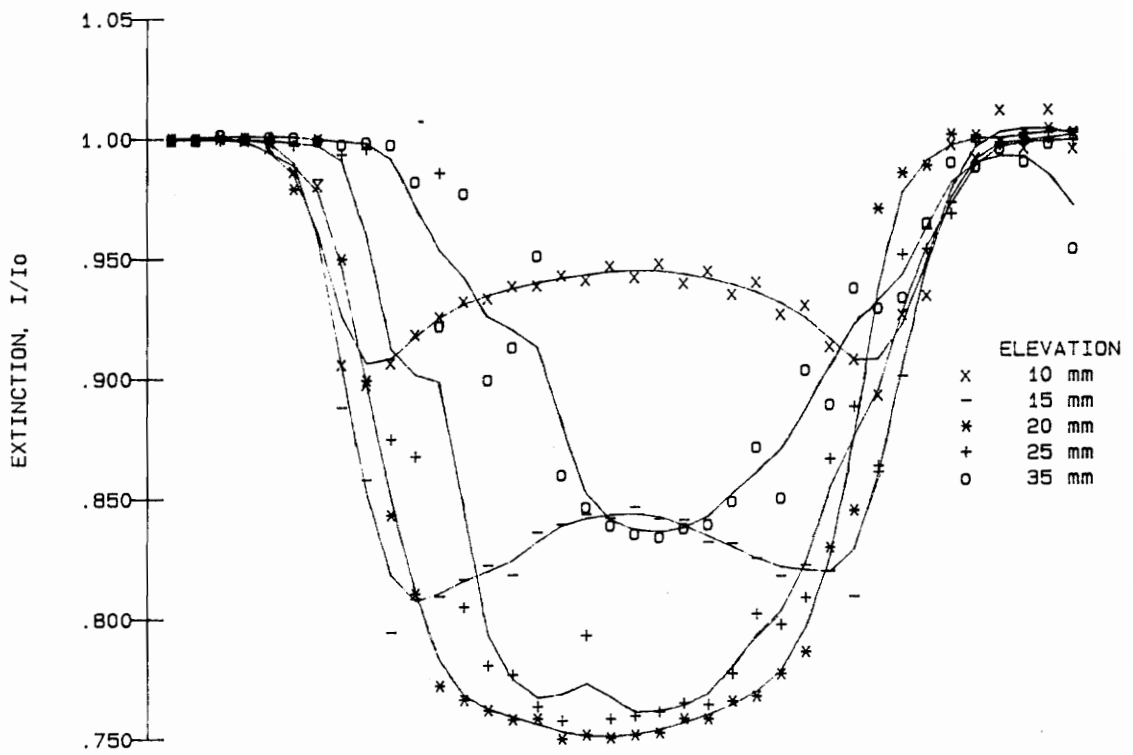


Figure 60. Raw and Smoothed Extinction Profiles, Flame 27

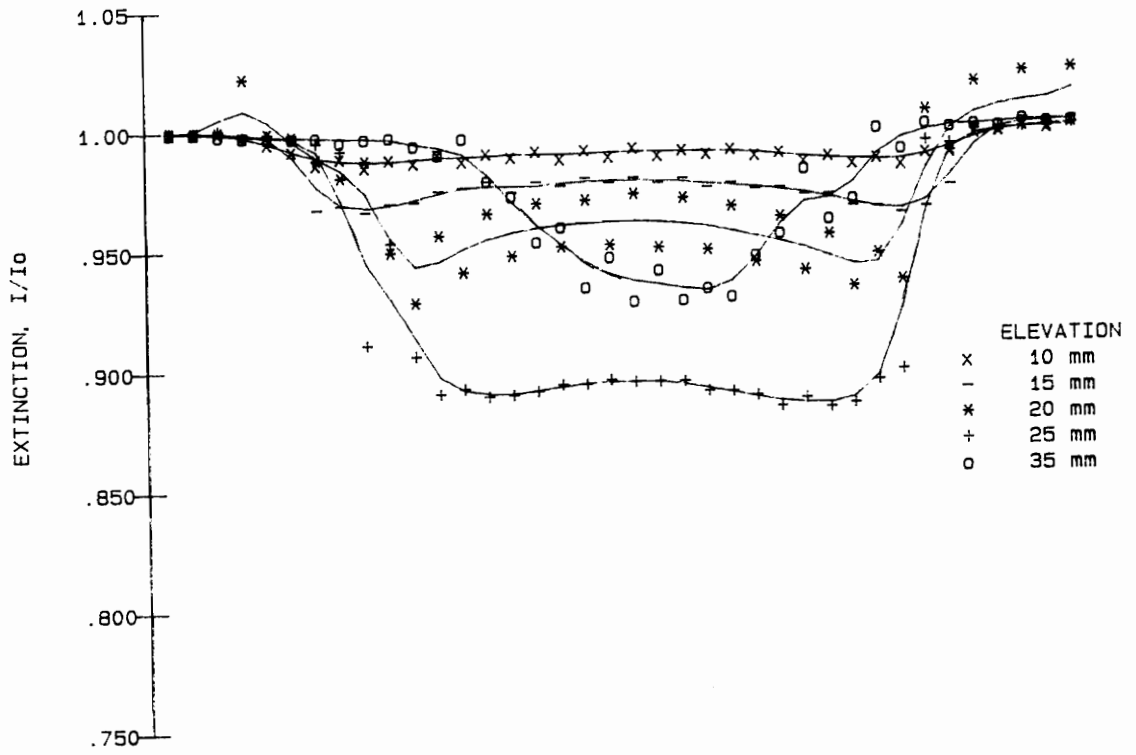


Figure 61. Raw and Smoothed Extinction Profiles, Flame 28

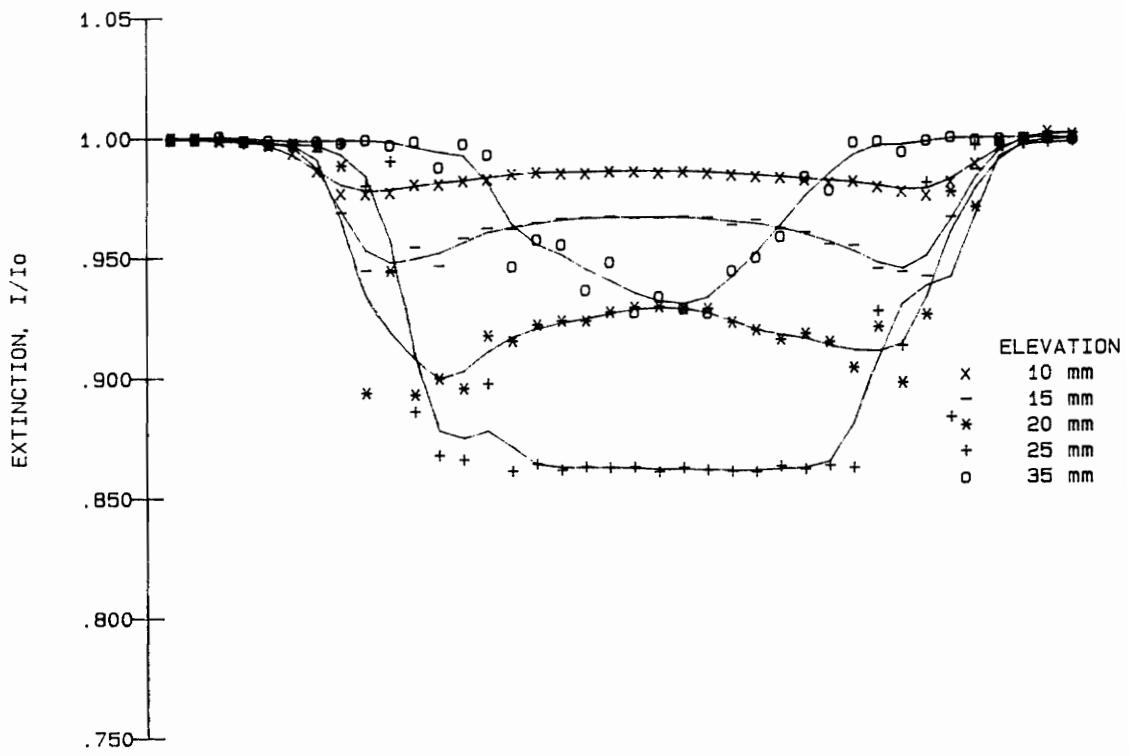


Figure 62. Raw and Smoothed Extinction Profiles, Flame 29

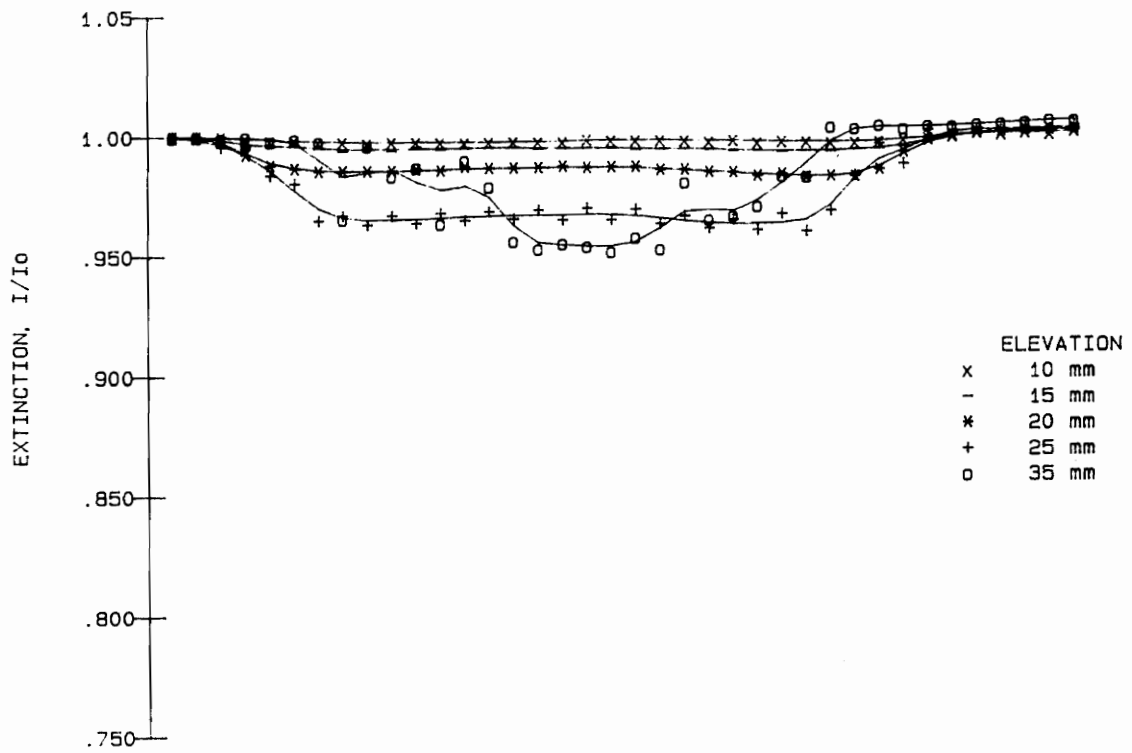


Figure 63. Raw and Smoothed Extinction Profiles, Flame 30

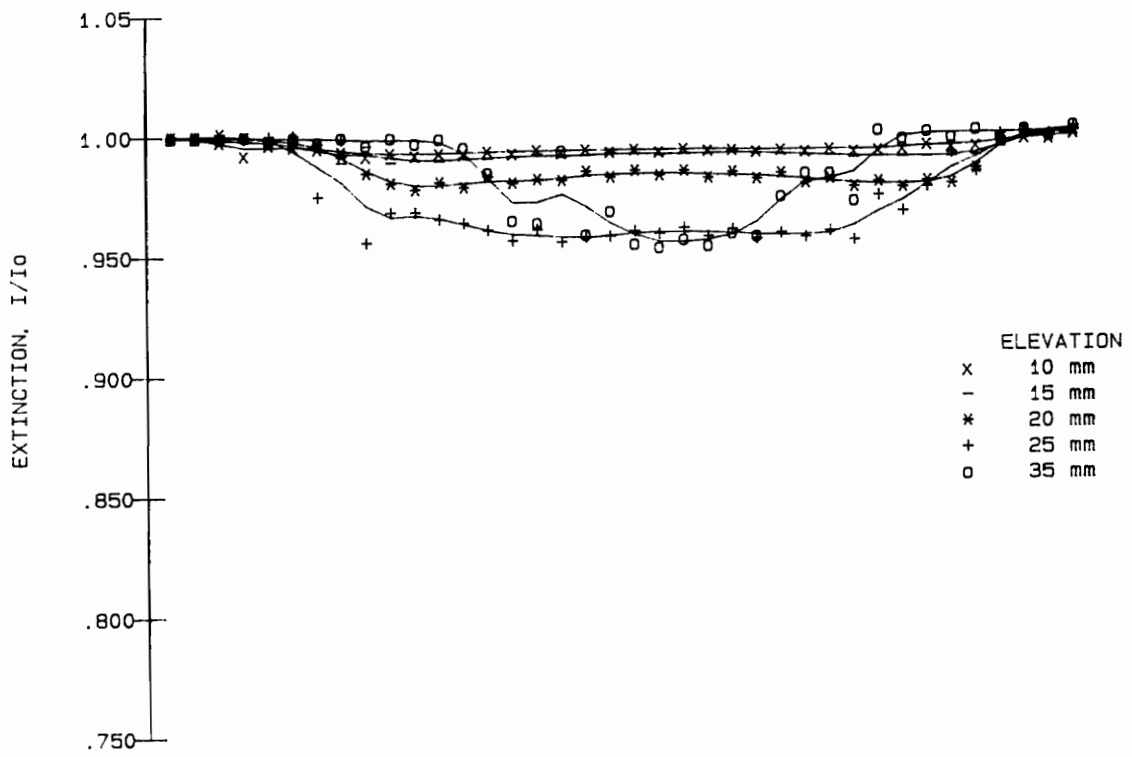


Figure 64. Raw and Smoothed Extinction Profiles, Flame 31

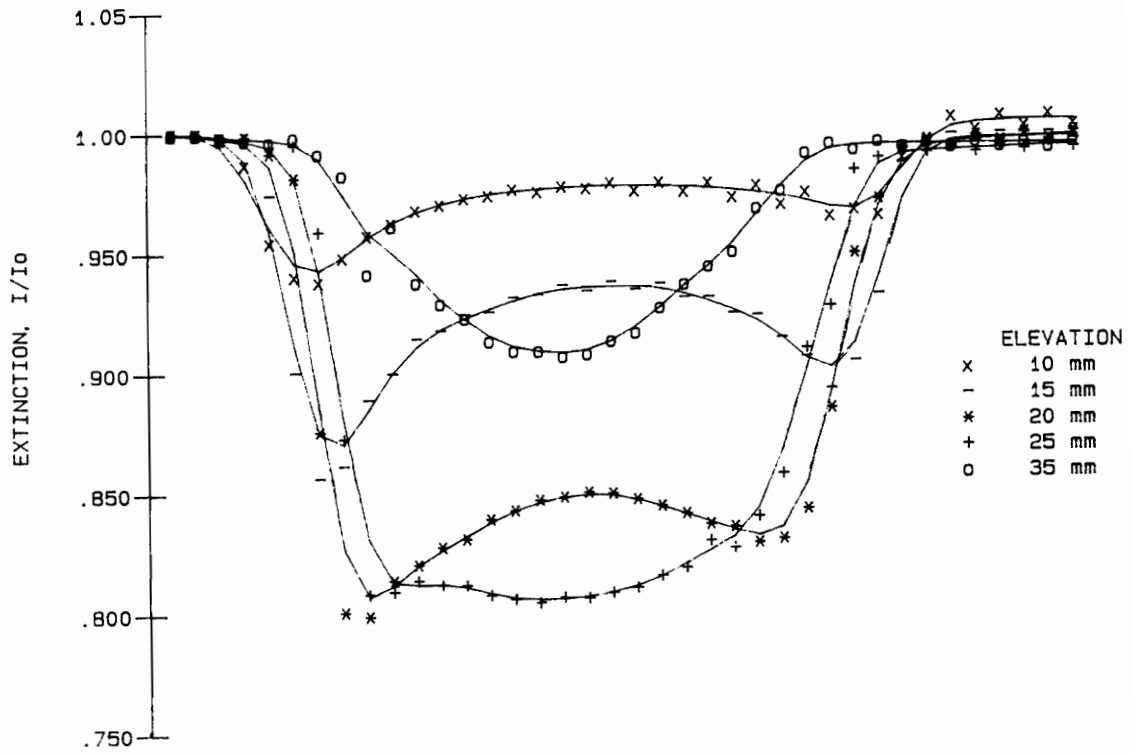


Figure 65. Raw and Smoothed Extinction Profiles, Flame 32

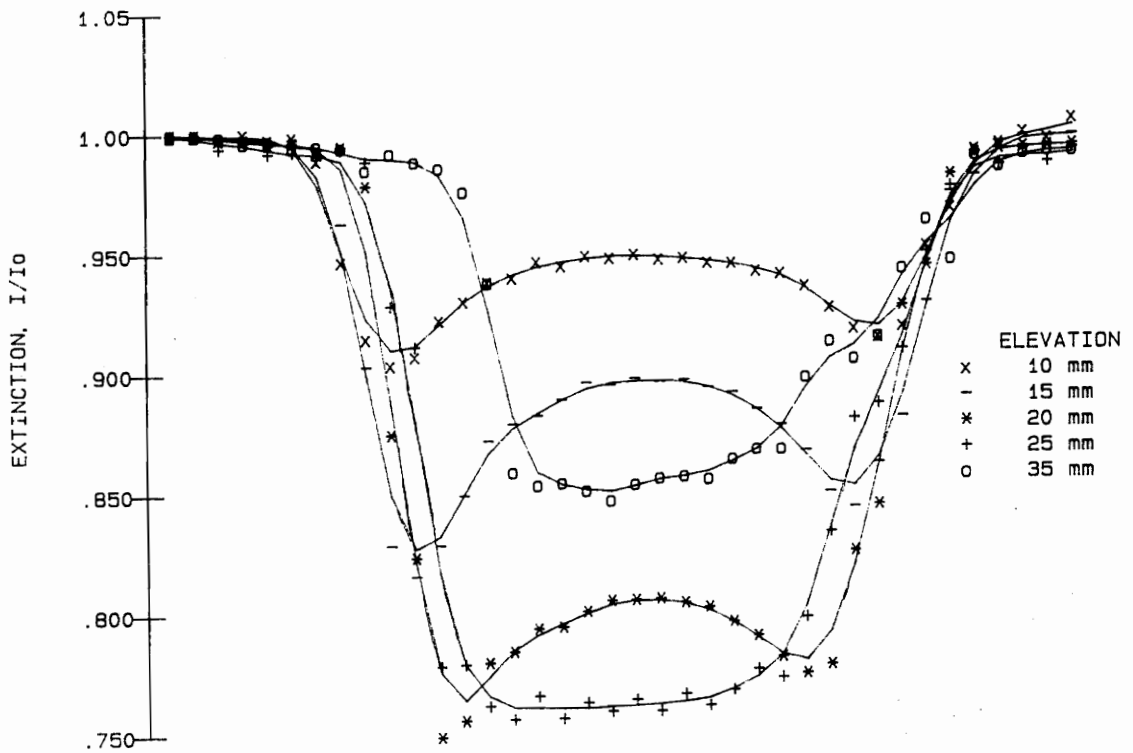


Figure 66. Raw and Smoothed Extinction Profiles, Flame 33

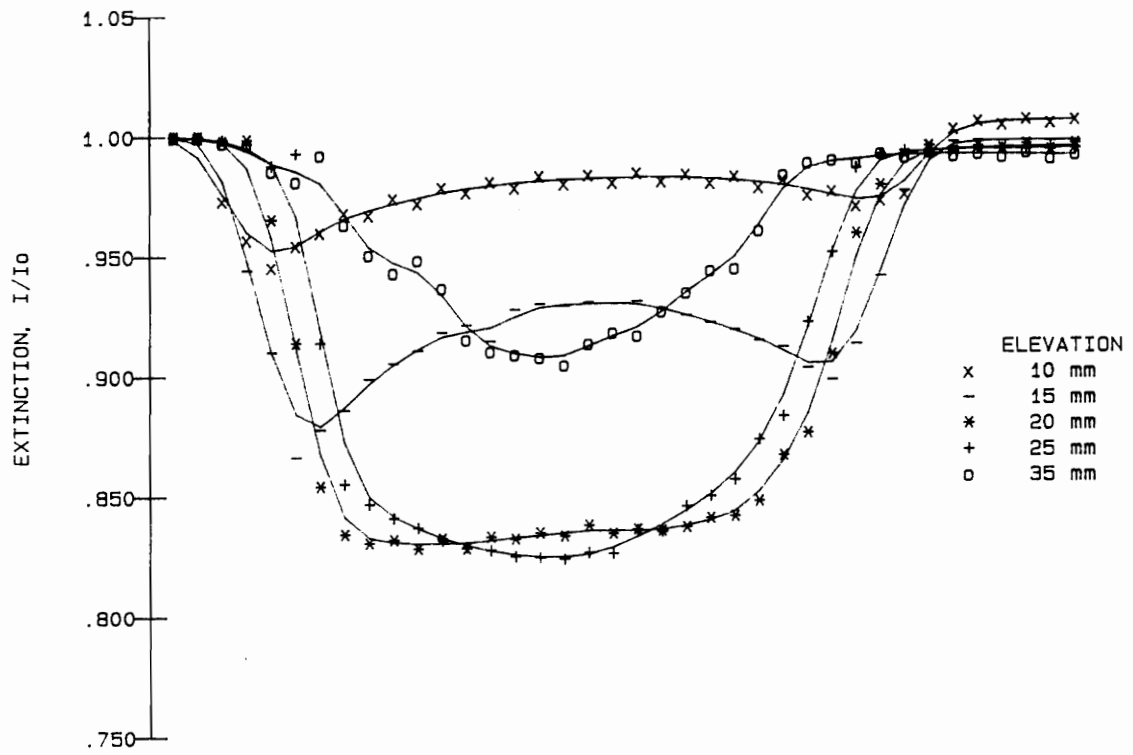


Figure 67. Raw and Smoothed Extinction Profiles, Flame 34

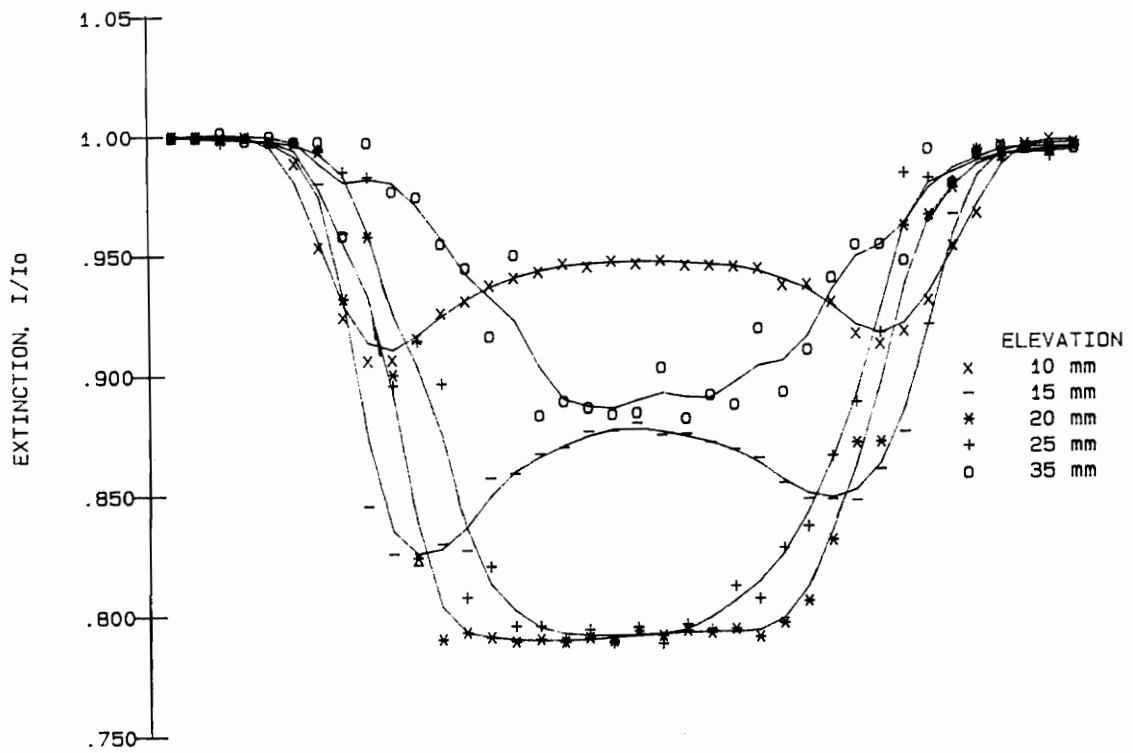


Figure 68. Raw and Smoothed Extinction Profiles, Flame 35

TABLE 11
EXTINCTION PROFILE SHIFTS

FLAME NUMBER	FLAME ELEVATION (mm)				
	10	15	20	25	35
1	3	2	2	2	1
2	3	3	3	3	4
3	1	1	1	1	0
4	1	1	0	0	0
5	0	2	1	0	0
6	4	4	4	4	4
7	0	0	0	0	0
8	1	2	0	1	0
13	2	2	2	2	3
15	-1	-1	-1	-1	-2
17	-1	-1	0	0	0
19	-3	-3	-3	-4	-4
21	0	-1	0	2	2
23	-1	0	0	-1	-2
25	1	1	1	1	0
27	0	0	1	-1	-2
28	0	0	-1	-1	-3
29	-1	-1	-2	-2	-2
30	0	1	1	2	1
31	0	-2	-2	-1	-2
32	1	1	2	2	2
33	-1	-1	-1	-1	-2
34	2	2	3	3	3
35	-1	0	0	0	-1

APPENDIX B:

FLICKERING OF LAMINAR DIFFUSION FLAMES

The phenomenon of flickering diffusion flames has been studied by other researchers. The results from many experiments clearly indicate that the frequency of flickering is independent of the fuel flow rate, burner diameter, and many other factors. Chamberlin and Rose reported the results of measurements made by other researchers. For a wide variety of fuels, and presumably a variety of burners, the flickering frequency was about 10 Hz [28]:

FUEL	NO. OF EXPERIMENTS	AVERAGE FREQUENCY (Hz) + SCATTER
NATURAL GAS	33	10.9 +/- 2.8
ETHYLENE	7	9.9 +/- 0.2
ETHANE	3	10.2 +/- 0.5
BUTANE	9	9.3 +/- 0.3

These results agree well with the measured flicker frequencies of both the single- and dual-mode flames studied here; the average rate was about 10 Hz.

The similarity to the findings of other researchers goes beyond the agreement in flicker frequency. Kimura [27] described exactly the behavior which was observed here. He states,

... in the case of combustion of laminar jets of propane in large chambers filled with atmospheric air ... A regular flame oscillation appears, when the fuel-flow rate is increased above a critical value and it is axially symmetrical. The oscillation has no connection with the size of the combustion chamber and the length of the fuel pipe, but it is suppressed by flowing the air in the chamber in the direction of the jet or by introducing primary air into the fuel gas. The frequency of the oscillation is almost fixed (in propane flames, 10-15 cps) for the relatively wide change in the fuel-flow rate and in the port diameter.

At the conception of this research program, the flickering of the diffusion flames was not anticipated. Should there be concern that flickering detracts from the burner's ability to simulate turbulent diffusion flames? According to Grant and Jones and Williams [28], the flickering behavior is still consistent with turbulent diffusion flames:

Based on a theoretical model of the effects of flame stretch on combustion, Williams has concluded that turbulent diffusion flames should be composed of a collection of laminar diffusion flames. The low-frequency wave structure that we have observed experimentally appears to verify this conclusion.

All of the dual mode diffusion flames flickered; although the flow was still laminar, the height of the flame fluctuated. The flickering has two effects on this study. First, flickering makes it much more difficult to estimate the height of the diffusion flame. Whereas the stable (single mode) flame heights could be measured to ± 1 mm, this accuracy cannot be assumed for the flickering flames.

The second problem with measuring flickering flames is that the extinction measurements are time-averaged values. The photodiode output of a beam which passes through a flickering flame shows a sinusoidal oscilloscope trace at the same frequency as the flicker. The higher the elevation of the beam in the flame, the larger the magnitude of this sinusoidal waveform. It seems likely that the sinusoidal output is due to varying amounts of soot in the flame at the fixed height. A rough estimate of the flame height could be obtained by passing the beam through the centerline of the flame near the tip. If the photodiode output showed a clipped waveform, it shows that the flame is only intercepting the beam periodically. An estimate of the flame height could be obtained by lowering the beam until the output shows no sign of clipping. It could be assumed that the effective flickering flame height corresponds to this beam height. Unfortunately, this point was difficult to judge; this effective flame height did not stay constant and the

judgement of where clipping ceased remains a subjective problem. This method was not used to estimate the flame height of the flickering flames for this study. Flame heights were determined by trying to judge the lowest point of the flicker at the tip of the flame, for a diffusion flame injected flush with the burner. The diffusion fuel flow rate was kept constant for subsequent measurements at the 1 cm injection height, and it was assumed that the effective flame height remained constant. This was a good assumption for the stable diffusion flames; the flame height remained the same regardless of the injection height. However, the dual mode flickering diffusion flames showed "more" flicker when injected at 1 cm than with flush injection. Although the frequency of the flicker remained the same, the magnitude of the maximum flame length increased. These elevated flames were also more subject to transverse motion due to drafts. All of these factors indicate that the precision of the elevated flame extinction measurements is less than that of the flush-injected flames.

Single mode flames were not immune to flickering either. A diffusion fuel jet injected into quiescent air would flicker continuously at a high enough flow rate. At a lower flow rate, the flickering was intermittent. At a very low flow rate, the instabilities were rare enough that flickering was seldom observed. For the nitrogen-diluted single mode flames, the presence of co-flowing feed air improved the stability significantly. As the flow rate of the coflowing air was increased, it was possible in many cases to damp out the flicker.

It was not possible to damp out the flicker of the dual mode flames in this way. Surprisingly, the single mode argon and carbon dioxide-diluted flames also exhibited an undampable flicker. The flicker of the argon-diluted flames was so intense that the visible flame height could not be measured reliably; these flames were never measured primarily for this reason. The 23% oxygen index CO_2 -diluted flame also flickered

considerably, and the flicker could not be damped by increasing or decreasing the air flow rate. The 18% oxygen index CO_2 -diluted flame did not want to burn at all. The diffusion flame lifted off of the burner, presumably to the point where enough room air could infiltrate and support combustion. The single mode CO_2 -diluted flames were not measured either.

The flickering behavior of the argon- and carbon-dioxide diluted single mode flames was quite unexpected. Based on experience with the nitrogen-diluted single mode flames, it was assumed that the increased momentum flux of the feed air was responsible for the suppression of flickering. However, if this were the case, both argon and carbon dioxide should be more effective than nitrogen due to their higher molecular weights (40, 44, and 28, respectively). Clearly, the matching of the diffusion gas and the feed air velocities is not responsible, since all three types of artificial air were supplied at the same volumetric flow rate. Although a higher feed air velocity relative to the diffusion fuel velocity seemed to help stabilize the nitrogen-diluted single mode flame, the much greater relative velocities achieved in the dual mode flames were insufficient to suppress flickering there. Table 12 summarizes the relative flow rates between the diffusion fuel and the feed air / premixed flames.

The available models suggest that the cause of laminar diffusion flame instabilities/flicker is the density variation between the hot flame zone gases and the cool ambient air [27]. Apparently, the greater the density variation, the greater the instability driving force. The models have always assumed that the fuel jet is issued into quiescent air, so they offer no explanation why the nitrogen-diluted co-flowing air was able to suppress flickering. This appears to be a fortuitous occurrence. Argon- and carbon dioxide-diluted artificial air mixtures have higher densities than the nitrogen-diluted equivalent. However, all of the dual mode feed "airs" are much less dense than

TABLE 12
GAS FLOW VELOCITIES FOR THE FLAMES STUDIED

FLAME NUMBER	1st STAGE (PREMIXED) VELOCITY (cm/s)	2nd STAGE (DIFFUSIONAL) VELOCITY (cm/s)	VELOCITY RATIO
1	12	18	0.66
2	76	27	2.85
3	12	18	0.66
4	76	27	2.85
5	15	15	1.03
6	61	19	3.25
7	15	15	1.03
8	61	19	3.25
13	79	25	3.19
15	79	25	3.19
17	64	20	3.27
19	64	20	3.27
21	65	21	3.14
23	65	21	3.14
25	63	17	3.68
27	63	17	3.68
28	13	15	0.88
29	13	15	0.88
30	13	11	1.21
31	13	11	1.21
32	76	20	3.87
33	76	20	3.87
34	61	15	4.07
35	61	15	4.07

normal air due to their higher temperatures. It may be possible that the density of normal air is optimal for the suppression of instabilities.

APPENDIX C

DATA ACQUISITION AND REDUCTION PROGRAMS

Three computer programs are listed on the following pages. The first is a BASIC program that measures the photodiode voltage through the data acquisition board of the computer. It then stores the data in a file named by the user. The second BASIC program is used to account for the radiative and convective heat loss from the thermocouple bead. The last program is used for the convolution of profiles to get the local extinction coefficients. This is an ASYST program, so its format and commands are unique to that software package.

DATA ACQUISITION PROGRAM

```

10 DEFINT I-N
20 DEFSNG A-H,O-Z
30 DIM HPOS(20),VOLTS(21,100),NVOLTS(100),VOLTSMEAN(21)
40 NRUN = 1
50 NGAIN = 1
60 NTM = 0
70 CLKFREQ = 30!
80 N.ERR.CTL.WRD = 5
90 NCHAN1 = 0
100 NOV = 100
110 X$ = SPACE$(79)
200 ' LPCLAB BASIC definition file (short names)
202 ' This file may be MERGED with a user program to define
204 ' routine offsets and establish the LPCLAB segment.
206 '
208 LPINIT = 3 : LPTERM = 6 : LPSB = 9 : LPSCF = 12
210 LPRCF = 15 : LPST = 18 : LPDSC = 21 : LPESC = 24
212 LPAV = 27 : LPAOT = 30 : LPSETA = 33 : LPADS = 36
214 LPBAD = 39 : LPCAD = 42 : LPTAD = 45 : LPWAD = 48
216 LPSTOP = 51 : LPMV = 54 : LPMT = 57 : LPMC = 60
218 LPDV = 63 : LPGV = 66 : LPEFO = 69 : LPEFI = 72
220 LPODV = 75 : LPIDV = 78 : LPVTD = 81 : LPDTV = 84
222 LPATV = 87 : LPVTA = 90 : LPSECW = 93 : LPGEC = 96
224 '
226 DEF SEG=&H0 ' get the LPCLAB segment
228 LPCLSEG = PEEK ( &H4FE ) + 256*PEEK ( &H4FF )
230 DEF SEG=LPCLSEG ' REM address the LPCLAB segment
240 '
250 CALL LPSETA(NTM,NCHAN1,NCHAN1,NGAIN)
260 CALL LPSCF(CLKFREQ)
270 CALL LPSECW(N.ERR.CTL.WRD)
280 OPEN "COM1: 9600,N,8,2,CS,DS,CD" AS #2
290 PRINT #2,"B 1; L 1,1; L 2,1; T 2,0"
' BANDPASS,LINE,&LINE*2 FILTERS IN,
300 ' POST TIME CONSTANT = 0 SECONDS
310 PRINT #2,"T 1,7" 'SET PRE TIME CONSTANT TO 1 s
1000 'ROUTINE TO FORM AND UPDATE SCREEN IMAGE
1010 KEY OFF : CLS
1020 LOCATE 1,1 : PRINT "FILENAME (d:fn.ext) : ";
1030 LOCATE 3,1 : PRINT "VERTICAL POSITION (cm) : ";
1040 LOCATE 3,40 : PRINT "SHIELD GAS FLOWRATE : ";
1050 LOCATE 4,1 : PRINT "TUBE HEIGHT (mm) : ";
1060 LOCATE 4,40 : PRINT "AIR FLOWRATE : ";
1070 LOCATE 5,1 : PRINT "PREMIXED STAGE FUEL : ";
1080 LOCATE 5,40 : PRINT "PREMIXED FUEL FLOWRATE : ";
1090 LOCATE 6,1 : PRINT "DIFFUSION STAGE FUEL : ";
1100 LOCATE 6,40 : PRINT "DIFFUSION FUEL FLOWRATE : ";
1110 LOCATE 7,1 : PRINT "FLAME HEIGHT (mm) : ";

```

```

1115 LOCATE 7,40 : PRINT "OXYGEN FLOWRATE           : ";
1120 LOCATE 8,1 : PRINT "NOTE : ";
1130 LOCATE 10,9 : PRINT "HORIZONTAL"; : LOCATE 10,47 :
PRINT "HORIZONTAL";
1140 LOCATE 11,1 : PRINT "RUN#      POSITION      VOLTS";
1150 LOCATE 11,40 : PRINT "RUN#      POSITION      VOLTS";
1160 FOR I = 1 TO 10
1170 LOCATE 11+I,1 : PRINT I;
1180 LOCATE 11+I,40 : PRINT I+10;
1190 NEXT I
1195 LOCATE 12,30 : PRINT "<<(REF)";
1200 LOCATE 1,60 : PRINT "DATE : "; DATE$
1210 LOCATE 1,40 : PRINT "TIME : "; TIME$
1220 LOCATE 1,26 : INPUT "", FILE$
1230 LOCATE 3,26 : INPUT "", VPOS
1240 LOCATE 4,26 : INPUT "", TUBEHT
1250 LOCATE 5,26 : INPUT "", PREFUEL$
1260 LOCATE 6,26 : INPUT "", DIFFUEL$
1270 LOCATE 3,67 : INPUT "", SHIELDFLOW
1280 LOCATE 4,67 : INPUT "", AIRFLOW
1290 LOCATE 5,67 : INPUT "", PREFLOW
1300 LOCATE 6,67 : INPUT "", DIFFLOW
1305 LOCATE 7,67 : INPUT "", OXYFLOW
1310 LOCATE 8,8 : INPUT "", NOTE$
1315 IF NRUN=2 THEN LOCATE 24,1 : PRINT "IGNITE BURNER.
MEASURE FLAME HEIGHT.";
1320 IF NRUN=2 THEN LOCATE 7,26 : INPUT "", FLAMEHT
1330 IF NRUN=1 THEN LOCATE 24,1 : PRINT "REFERENCE RUN.
FLAME SHOULD BE OFF.";
1360 LOCATE 25,1 : PRINT X$; : LOCATE 25,1 : PRINT "ENTER
'Q' TO QUIT, 'R' TO RERUN, ANY OTHER KEY TO CONTINUE DATA
ACQUISITION.";
1370 A$=INKEY$ : IF (A$="Q") OR (A$="q") THEN GOTO 4000
1375 IF ((A$="R") OR (A$="r")) AND (NRUN>1) THEN NRUN=NRUN-1
1380 IF A$=NULL$ THEN GOTO 1370
1383 IF NRUN<11 THEN LOCATE 11+NRUN,10 : INPUT "",
HPOS(NRUN)
1387 IF NRUN>10 THEN LOCATE 1+NRUN,50 : INPUT "", HPOS(NRUN)
1390 LOCATE 25,1 : PRINT X$; : LOCATE 24,1 : PRINT X$; :
LOCATE 25,1 : PRINT "PLEASE WAIT.";
1400 GOSUB 2000 ' DATA AQUISITION ROUTINE
1405 GOSUB 3000
1410 LOCATE 25,1 : PRINT X$;
1420 IF NRUN<11 THEN LOCATE 11+NRUN,22 : PRINT USING
"##.###"; VOLTSMEAN(NRUN)
1430 IF NRUN>10 THEN LOCATE 1+NRUN,62 : PRINT USING
"##.###"; VOLTSMEAN(NRUN)
1435 BEEP
1440 NRUN = NRUN + 1
1450 IF NRUN<21 THEN GOTO 1315

```

```

1460 LOCATE 25,1 : PRINT X$; : LOCATE 25,1 : PRINT "THERE IS
A 20-RUN LIMIT.";
1470 A$=INKEY$ : IF A$=NULL$ THEN GOTO 1470
1480 GOTO 4000
2000 'INPUT SUBROUTINE
2005 'FOR I = 1 TO 25000
2008 'NEXT I
2010 CALL LPADS(NOV,NVOLTS(1))
2020 FOR I = 1 TO 100
2030 NVOLT = NVOLTS(I)
2040 CALL LPATV(NVOLT,NGAIN,VOLTS)
2050 VOLTS(NRUN,I) = VOLTS
2060 NEXT I
2070 'PRINT #2,"T 1,1"
2999 RETURN
3000 'CALCULATE MEAN VOLTAGE
3010 SUM = 0
3020 FOR I = 1 TO 100
3030 SUM = SUM + VOLTS(NRUN,I)
3040 NEXT I
3050 VOLTSMEAN(NRUN) = SUM / 100!
3999 RETURN
4000 LOCATE 25,1 : PRINT X$; : LOCATE 25,1 : PRINT "TYPE 'O'
FOR OTHER OPTIONS, 'S' TO SAVE THIS FILE, OR 'E' TO EXIT";
4005 IF TEMP=0 THEN TEMP = NRUN
4010 A$=INKEY$ : IF (A$="E") OR (A$="e") THEN GOTO 5999
4020 IF (A$="S") OR (A$="s") THEN NRUN = TEMP : GOTO 5000
4030 IF (A$<>"O") AND (A$<>"o") THEN GOTO 4010
4040 ' OTHER OPTIONS
4042 LOCATE 25,1 : PRINT X$; : LOCATE 25,1 : PRINT "TYPE 'C'
TO CHECK REF. VOLTAGE, 'R' TO RERUN A POINT, 'E' TO EDIT,
('Q'= QUIT)";
4044 A$=INKEY$ : IF (A$="Q") OR (A$="q") THEN GOTO 4000
4048 IF (A$="R") OR (A$="r") THEN GOTO 4100
4050 IF (A$="E") OR (A$="e") THEN GOTO 4200
4055 IF (A$<>"C") AND (A$<>"c") THEN GOTO 4044
4058 NRUN = 21 : LOCATE 24,1 : PRINT X$; : LOCATE 24,1 :
PRINT "PLEASE WAIT.";
4060 GOSUB 2000
4070 GOSUB 3000
4080 LOCATE 24,1 : PRINT X$; : LOCATE 24,1 : PRINT "CHECK
VOLTAGE = "; : LOCATE 24,17 : PRINT USING "##.###";
VOLTSMEAN(21);
4090 BEEP : GOTO 4000
4100 LOCATE 25,1 : PRINT X$; : LOCATE 25,1 : PRINT "ENTER
THE NUMBER OF THE RUN TO BE REDONE ";
4101 A$=INKEY$ : IF A$=NULL$ THEN GOTO 4101
4102 IF A$="1" THEN GOTO 4104
4103 RERUN = VAL(A$) : GOTO 4105
4104 B$=INKEY$ : IF B$=NULL$ THEN GOTO 4104 ELSE RERUN =
VAL(A$+B$)

```

```

4105 IF (RERUN<TEMP) AND (RERUN>0) THEN NRUN=RERUN ELSE GOTO
4100
4110 IF NRUN<11 THEN LOCATE 11+NRUN,10 : INPUT "",
HPOS(NRUN)
4120 IF NRUN>10 THEN LOCATE 1+NRUN,50 : INPUT "", HPOS(NRUN)
4130 LOCATE 25,1 : PRINT X$; : LOCATE 24,1 : PRINT X$; :
LOCATE 25,1 : PRINT "PLEASE WAIT.";
4140 GOSUB 2000 ' DATA AQUISITION ROUTINE
4150 GOSUB 3000
4155 LOCATE 25,1 : PRINT X$;
4160 IF NRUN<11 THEN LOCATE 11+NRUN,22 : PRINT USING
"##.###"; VOLTSMEAN(NRUN)
4165 IF NRUN>10 THEN LOCATE 1+NRUN,62 : PRINT USING
"##.###"; VOLTSMEAN(NRUN)
4170 BEEP
4199 GOTO 4000
4200 ' EDIT A COMMENT
4210 LOCATE 1,26 : INPUT "", FILE$
4220 LOCATE 3,26 : INPUT "", VPOS
4230 LOCATE 4,26 : INPUT "", TUBEHT
4240 LOCATE 5,26 : INPUT "", PREFUEL$
4250 LOCATE 6,26 : INPUT "", DIFFUEL$
4260 LOCATE 3,67 : INPUT "", SHIELDFLOW
4270 LOCATE 4,67 : INPUT "", AIRFLOW
4275 LOCATE 5,67 : INPUT "", PREFLOW
4280 LOCATE 6,67 : INPUT "", DIFFLOW
4283 LOCATE 7,67 : INPUT "", OXYFLOW
4285 LOCATE 8,8 : INPUT "", NOTE$
4299 GOTO 4000
5000 'EXIT ROUTINE
5010 OPEN FILE$ FOR OUTPUT AS #1
5020 WRITE #1,NRUN-1
5030 WRITE #1,VPOS
5035 WRITE #1,TUBEHT
5040 WRITE #1,AIRFLOW
5050 WRITE #1,SHIELDFLOW
5060 WRITE #1,PREFLOW
5070 WRITE #1,DIFFLOW
5075 WRITE #1,FLAMEHT
5080 WRITE #1,PREFUEL$
5085 WRITE #1,DIFFUEL$
5090 WRITE #1,NOTE$
5100 WRITE #1,TIME$
5110 WRITE #1,DATE$
5120 FOR I = 1 TO NRUN-1
5125 WRITE #1,HPOS(I)
5127 WRITE #1,VOLTSMEAN(I)
5130 FOR J = 1 TO 100
5140 WRITE #1,VOLTS(I,J)
5150 NEXT J
5160 NEXT I

```

```
5168 WRITE #1,OXYFLOW
5170 CLOSE #1
5180 CLOSE #2
5190 GOTO 4000
5999 STOP : END
```

THERMOCOUPLE CORRECTION PROGRAM

```

10 ' THERMOCOUPLE CORRECTION PROGRAM
20 '
30 ' CALCULATES A CORRECTED GAS TEMPERATURE Tg BASED ON THE
40 ' THERMOCOUPLE TEMPERATURE Tc BY ACCOUNTING FOR RADIATION
45 ' LOSSES. THE EQUATION IS
50 '
60 '  $T_g = T_c + (\text{SIGMA} * \text{EMISS} * D * (T_c^{**4} - T_w^{**4}) / \text{LAMBDA} / \text{NU})$ 
70 '
80 ' WHERE SIGMA = STEPHAN-BOLTZMANN CONSTANT,
90 '       EMISS = EMISSIVITY OF THERMOCOUPLE BEAD
100 '      D = BEAD DIAMETER
110 '      Tw = TEMPERATURE OF SURROUNDINGS
120 '      LAMBDA = THERMAL CONDUCTIVITY OF GASSES
130 '      NU = BEAD NUSSELT NUMBER
140 '
150 ' ASSUMPTIONS: 1) NU = 2.0
160 '               2) EMISS = 0.3
170 '               3) LAMBDA BASED ON A FUEL-RICH H2/O2/Ar
180 '                  FLAME, EQUIVALENCE RATIO = 1.5
190 '
200 SIGMA = 1.355E-12 ' CAL / (cm**2 * s * K)
210 EMISS = .3
220 NU = 2!
230 D = 8 ' ASSUME TC BEAD DIAMETER = 8 MILS
240 TW = 25 ' ASSUME ROOM TEMPERATURE = 25 DEGREES C
250 INPUT " WHAT IS THE THERMOCOUPLE TEMPERATURE (C)? " , TC
260 TC = TC + 273!
270 TW = TW + 273!
280 D = D * .00254
290 '
300 ' THERMAL CONDUCTIVITY USED IS THAT FOR A MIXTURE OF
310 ' EQUILIBRIUM PRODUCTS OF A RICH (PHI=1.50) H2/O2/AR
320 ' FLAME. LAMBDA SHOULD BE EVALUATED AT TGAS. AN
330 ' ITERATIVE PROCESS IS SUGGESTED. EXPERIENCE SHOWS THAT
340 ' ONLY 3 TO 6 ITERATIONS ARE NEEDED.
350 '
360 ' ITERATE TO GET LAMBDA AT THE GAS TEMPERATURE, Tg
370 ' USE 6 ITERATIONS
380 '
390 TG = TC
400 FOR I = 1 TO 10
410 LAMBDA = EXP(1.8588 + .8685 * LOG(TG/300!))
420 LAMBDA = LAMBDA * .00001
430 TCORR = SIGMA * EMISS * D * (TC^4 - TW^4) / LAMBDA / NU
440 TG = TC + TCORR
450 NEXT I
460 ER = .2 * TCORR

```

```
470 PRINT : PRINT " CORRECTED TEMPERATURE = ";TG;" +/-  
";ER;" K"  
480 ' HIT CTRL-BRK TO EXIT PROGRAM; IT CONTINUES OTHERWISE  
490 GOTO 250
```

ASYST CONVOLUTION PROGRAM

```

REAL SCALAR A           \ A IS THE SAMPLE SPACING
REAL SCALAR R           \ R IS THE RADIUS FROM CENTERLINE
REAL SCALAR PIN         \ PIN = PI / N
REAL SCALAR C2          \ C2 = -1 / (2*PI*A*N)
REAL SCALAR DELTA       \ DELTA = 2 * XPOS / NX
REAL SCALAR THETAJ      \ COS(THETAJ)
REAL SCALAR COSTHTAJ    \ SIN(THETAJ)
REAL SCALAR SINHTAJ     \ COSDELOA = COSTHTAJ * DELTA / A
REAL SCALAR COSDELOA
REAL SCALAR Y1
REAL SCALAR X1
REAL SCALAR W
REAL SCALAR R
REAL SCALAR XPOS .99 XPOS :=
REAL SCALAR YPOS .99 YPOS :=
INTEGER SCALAR NY       \ NUMBER OF Y POINTS IN
                        \ RECONSTRUCTED FIELD
INTEGER SCALAR NX       \ NUMBER OF X POINTS IN
                        \ RECONSTRUCTED FIELD
INTEGER SCALAR N        \ NUMBER OF ANGULAR SCANS
INTEGER SCALAR M        \ NUMBER OF EQUALLY-SPACED
                        \ PROJECTIONS

INTEGER SCALAR KABS
INTEGER SCALAR L
REAL DIM[ 100 ] ARRAY PHI
REAL DIM[ 100 ] ARRAY PROJ
REAL DIM[ 100 ] ARRAY CONV
REAL DIM[ 40 , 40 ] ARRAY F \ F IS THE RECONSTRUCTED
                        \ FUNCTION
REAL DIM[ 41 ] ARRAY P     \ P IS THE PROJECTION THRU
                        \ X SECTION

: CONVOLUTE              \ ON STACK: NX,NY,M,N,PROJ
NY :=
NX :=
M :=
N :=
0.0 F :=                 \ RESET F TO ZERO
M 1 - INV 2.0 * A :=     \ A = 2.0 / (M-1)
PI N / PIN :=           \ PIN = PI / N
2.0 PI * A * N * INV NEG C2 := \ C2 IS A FREQUENTLY-
                        \ OCCURING CONSTANT
2.0 XPOS * NX / DELTA := \ DELTA = 2*XPOS / NX
2.0 PI / A / N / PHI [ 1 ] := \ PHI(1) = 2 / (PI*A*N)
  M 1 DO
    I 1 * .25 - INV C2 * PHI [ I 1 + ] :=
  LOOP
N 1 + 1 DO

```

```

I 1 - PIN * THETAJ :=          \ THETAJ = (I-1)*PI / N
THETAJ COS COSTHTAJ :=
THETAJ SIN SINTHTAJ :=
COSTHTAJ DELTA * A / COSDELOA :=
  M 1 + 1 DO
    0.0 CONV [ I ] :=
    M 1 + 1 DO
      J I - ABS 1 + KABS :=
      PROJ [ I ] PHI [ KABS ] * CONV [ J ] + CONV [ J ] :=
    LOOP
  LOOP
  NY 1 + 1 DO
    2.0 YPOS * I * NY / YPOS NEG + Y1 :=
    XPOS NEG COSTHTAJ * SINTHTAJ Y1 * 1 + + A / COSDELOA - R
:=
  NX 1 + 1 DO
    R COSDELOA + R :=
    R R FIX >
    IF
      R FIX L :=
    ELSE
      R 0.5 - FIX L :=
    THEN
      L 0 <= L M >= OR NOT
      IF
        CONV [ L 1 + ] L NEG R + * CONV [ L ] L 1 + R NEG + * +
        F [ I , J ] + F [ I , J ] :=
      THEN
        LOOP
      LOOP
    LOOP
  LOOP
;

```

APPENDIX D

INDEX TO EXPERIMENTAL DATA STORAGE FILES

FLAME NUMBER	RUN NUMBERS DW_xxx.DAT TO DW_yyy.DAT
1	175-184, 220-229
2	185-194
3	144-153, 230-239
4	134-143
5	195-204
6	165-174
7	209-218
8	155-164
9	250-259
10	260-269
11	240-249
13	273-282
15	283-292
17	293-302
19	303-312
21	313-322, 333-342
23	323-332
25	345-354
27	355-364
28	365-374, 385-394
29	375-384, 395-404
30	405-414
31	415-424
32	425-434
33	435-444
34	445-454
35	455-464

APPENDIX E:

MISCELLANEOUS ASYST WORDS

This appendix contains many short programs that performed some special function or facilitated manipulation of data. The following index describes the purpose of each of these ASYST words.

ASYST WORD	DESCRIPTION/PURPOSE
SAMPLE.PROJECTION	CREATES THE EXTINCTION PROFILE CORRESPONDING TO THE DISCONTINUOUS FUNCTION IN FIGURE 10
HAT.FUNCTION	CREATES THE ORIGINAL FUNCTION SHOWN IN FIGURE 10
GAUSSIAN.PROJECTION	CREATES BOTH THE EXTINCTION PROFILE AND THE ORIGINAL GAUSSIAN FUNCTION SHOWN IN FIGURE 4
GET.SUM, INTEGRATE, AND GET.INT.PHI	WORDS THAT CALCULATE THE INTEGRATED SOOT VOLUME FRACTION DISTRIBUTION
GET.ALL.INT.PHIS	LOOKS IN MANY DATA FILES AND RETRIEVES THE INTEGRATED SOOT VOLUME FRACTION DISTRIBUTIONS
ADDIT and GET.TOTAL.PHIS	CALCULATES AND RETRIEVES THE TOTAL SOOT FACTORS
BUMP.RIGHT and BUMP.LEFT	SHIFTS THE EXTINCTION PROFILES "BUMP" UNITS TO THE RIGHT OR LEFT

```

REAL SCALAR A          \ A IS THE SAMPLE SPACING
INTEGER SCALAR M        \ NUMBER OF POINTS IN PROFILE
REAL DIM[ 41 ] ARRAY P  \ P IS THE PROJECTION THRU
                        \ X-SECTION

: SAMPLE.PROJECTION      \ CREATES SAMPLE PROJECTION P(R)
0.05 A :=                \ (HAT FUNCTION)
21 -20 DO
I A * R := R             \ ASSIGN R = I*A
DUP ABS 0.5 <            \ IS ABS(R) < 0.5 ?
IF                        \ IF 0 < ABS(R) < 0.5 ...
DUP DUP * DUP
1.0 SWAP - Sqrt SWAP
0.25 SWAP - Sqrt +
P [ 21 I + ] :=
ELSE                      \ IF 0.5 <= ABS(R) <= 1.0 ...
DUP DUP *
1.0 SWAP - Sqrt
P [ 21 I + ] :=
THEN
DROP
LOOP
;

REAL DIM[ 41 , 41 ] ARRAY HAT

: HAT.FUNCTION
0.05 A :=
21 -20 DO
21 -20 DO
I A * DUP * J A * DUP * + Sqrt R :=
R 0.5 <
IF
1.0 HAT [ I 21 + , J 21 + ] :=
ELSE
0.5 HAT [ I 21 + , J 21 + ] :=
THEN
R 1.0 >
IF
0.0 HAT [ I 21 + , J 21 + ] :=
THEN
LOOP
LOOP ;

REAL DIM[ 100 , 100 ] ARRAY FUNC
INTEGER SCALAR NXINC
REAL SCALAR X
REAL SCALAR DX
REAL SCALAR Y
REAL SCALAR DY

```

```

: GAUSSIAN.PROJECTION      \ ON STACK: M,NXINC
M :=                      \ M = # OF PROJECTIONS IN A SCAN
NXINC :=                  \ NXINC = NUMBER OF INCREMENTS
2.0 M FLOAT / DY :=      \ USED IN NUMERICAL INTEGRATION
2.0 NXINC FLOAT / DX :=
M 1 + 1 DO                \ "Y" LOOP
  I 1 - DY * -1.0 + Y :=  \ Y = -1 + (I-1)DY
  0.0 PROJ [ I ] :=
  NXINC 1 + 1 DO          \ "X" LOOP
    I 1 - DX * -1.0 + X :=
    X X * Y Y * + -20.0 * EXP DUP FUNC [ J , I ] :=
    DX * PROJ [ J ] + PROJ [ J ] :=
  LOOP
LOOP
;

REAL DIM[ 5 ] ARRAY INT.PHI
REAL DIM[ 40 , 40 ] ARRAY F
REAL SCALAR SUM
REAL SCALAR LIMIT
REAL SCALAR COUNT
REAL SCALAR MINRAD
REAL SCALAR MAXRAD

: GET.SUM
0.0 SUM :=
0.0 COUNT :=
0.0 F :=
41 1 DO
41 1 DO
DUP [ I , J ] LIMIT >=
IF
DUP [ I , J ] SUM + SUM :=
DUP [ I , J ] F [ I , J ] :=
COUNT 1 + COUNT :=
THEN
LOOP
LOOP ;

: INTEGRATE
0.0 MINRAD :=
0.0 MAXRAD :=
0.0 SUM :=
XSECT[ ! , 20 ] DUP []MAX 0.05 * LIMIT := \ IGNORE DATA < 5%
                                           \ OF MAXIMUM
                                           \ INTEGRATION BASED ON CROSS-
                                           \ SECTION OF RECONSTRUCTION
41 1 DO
DUP [ I ] LIMIT >=
IF
MINRAD 0.0 =
IF

```

```

I MINRAD :=
THEN
I MAXRAD :=
DUP [ I ]
19.5 I FLOAT - ABS 0.025 *          \ R outer
DUP DUP * SWAP 0.025 - DUP * - * \ (R outer)^2 - (R inner)^2
SUM + SUM :=
THEN
LOOP
2.0 /          \ /2 TO AVERAGE BOTH HALVES OF XSECTION
MAXRAD MINRAD - 0.025 * 2.0 / DUP *          \ RADIUS OF FIELD
          \ WIDTH SQUARED
SUM SWAP /          \ NORMALIZE INTEGRATION BY XSECTION AREA
;

: GET.INT.PHI
6 1 DO
I SUBFILE FILE>UNNAMED.ARRAY
INTEGRATE INT.PHI [ I ] :=
DROP
LOOP ;

REAL SCALAR TOT.PHI.1
(etc.)
REAL SCALAR TOT.PHI.35

REAL DIM[ 5 ] ARRAY INT.PHI.1
(etc.)
REAL DIM[ 5 ] ARRAY INT.PHI.35

: GET.ALL.INT.PHIS
FILE.OPEN D:DWF1PHI.DAT
GET.INT.PHI INT.PHI INT.PHI.1 :=
FILE.CLOSE
(etc.)
FILE.OPEN D:DW35PHI.DAT
GET.INT.PHI INT.PHI INT.PHI.35 :=
FILE.CLOSE
;

: ADDIT
DUP [ 1 ] SWAP DUP [ 2 ] SWAP
DUP [ 3 ] SWAP DUP [ 4 ] 2.0 * SWAP
[ 5 ] 2.0 *
+ + + + 6.0 / ;

: GET.TOTAL.PHIS
INT.PHI.1 ADDIT TOT.PHI.1 :=
(etc.)
INT.PHI.35 ADDIT TOT.PHI.35 :=
;

```

```
REAL SCALAR BUMP
REAL DIM[ 38 ] ARRAY MV

: BUMP.RIGHT
39 BUMP - 1 DO
DUP [ I ] MV [ I BUMP + ] :=
LOOP
BUMP 1 DO
1.0 MV [ I ] :=
LOOP ;

: BUMP.LEFT
39 BUMP 1 + DO
DUP [ I ] MV [ I BUMP - ] :=
LOOP
39 39 BUMP - DO
DUP [ 39 BUMP - ] MV [ I ] :=
LOOP ;
```

APPENDIX F

ROTAMETER CALIBRATIONS

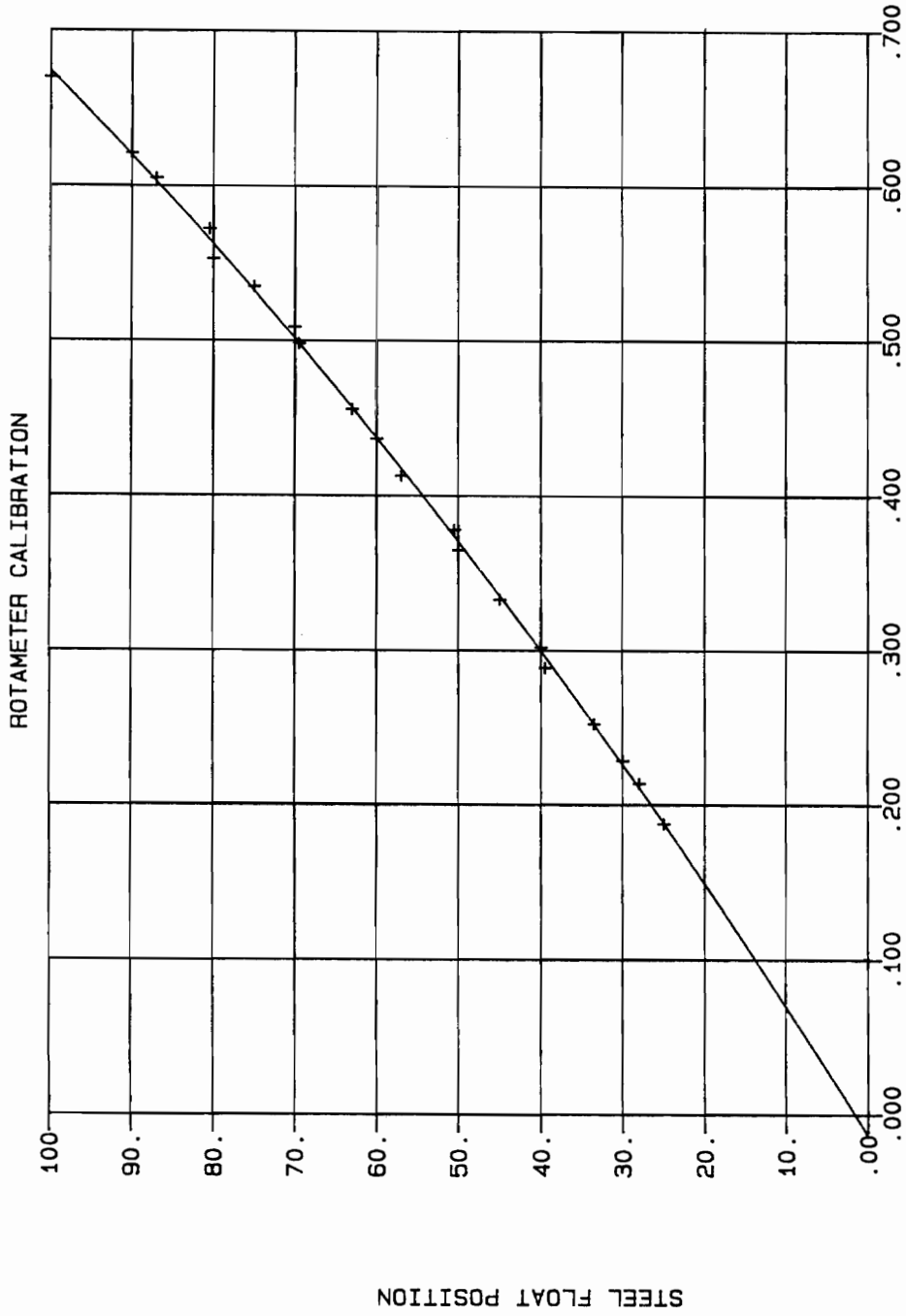
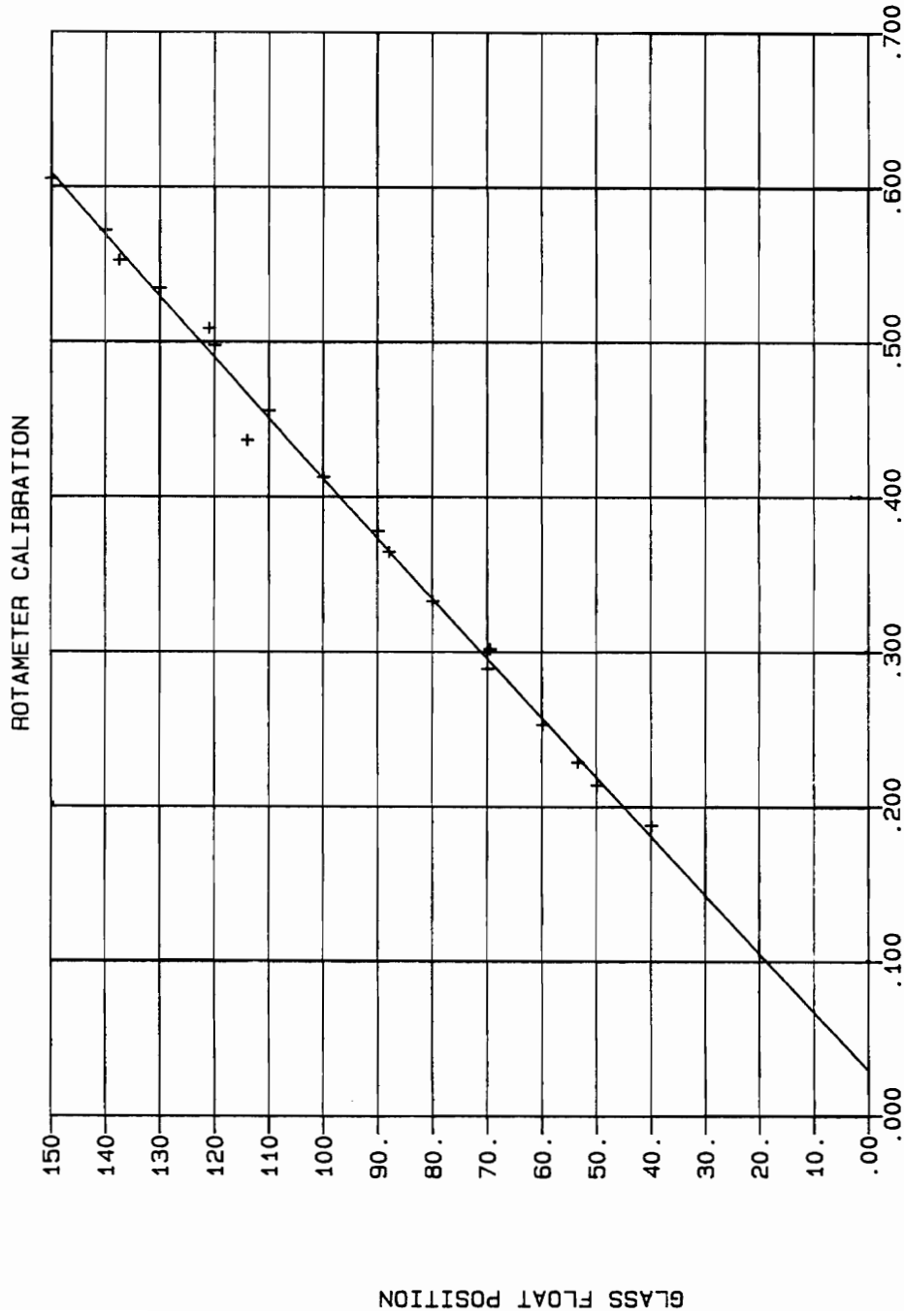


Figure 69. AIR FLOW RATE AT STP (L/s)
TUBE #1, TYPE 605, AT 40 psig
CURVE FIT: $X = -1.6E-5 Y^2 + 8.5E-3 Y - 1.4E-2$



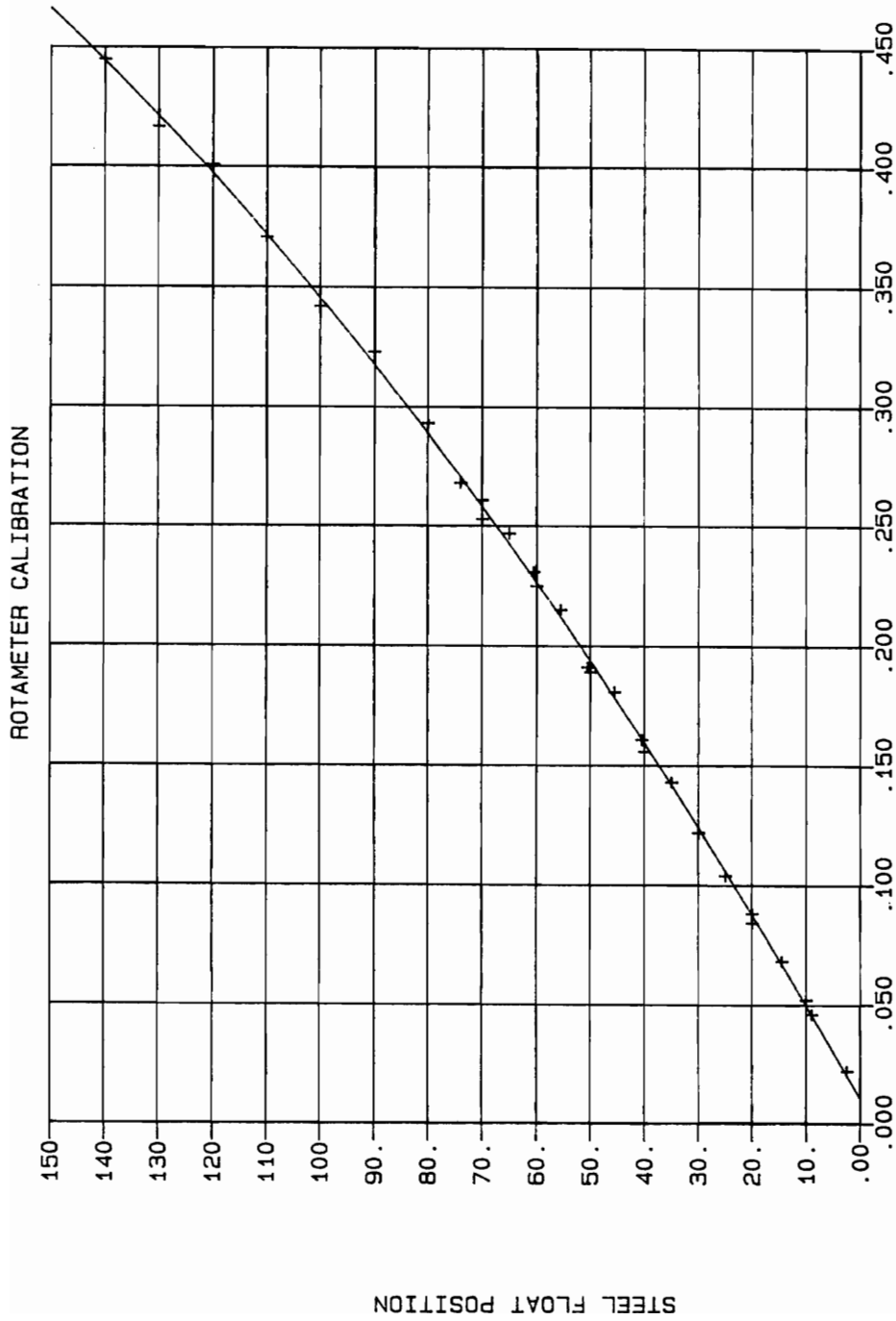


Figure 71. NITROGEN FLOW RATE AT STP (L/s)

TUBE #2, TYPE 604, AT 40 psig

CURVE FIT: $X = -6.3E-6 Y^2 + 4.0E-3 Y + 1.0E-2$

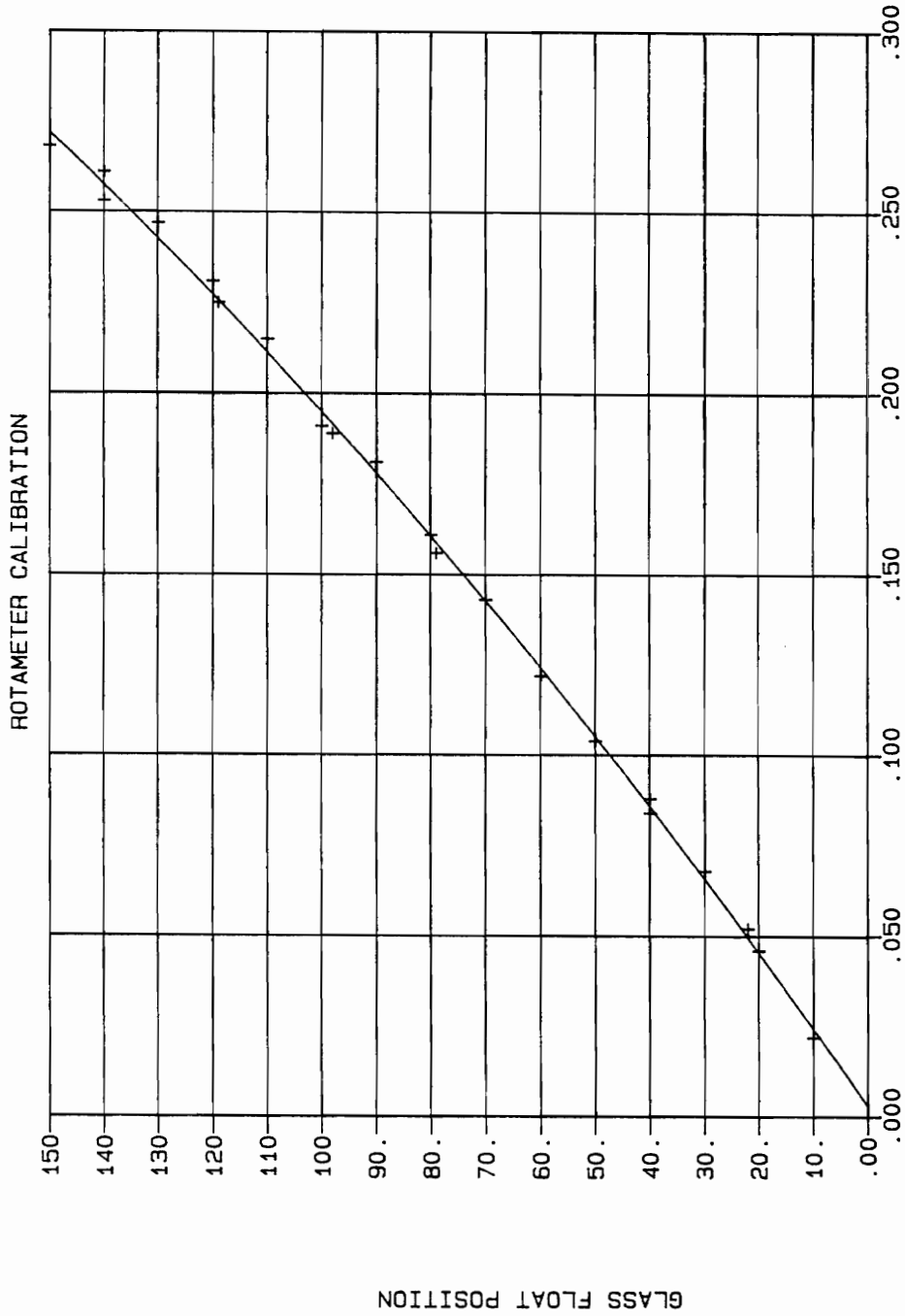


Figure 72. NITROGEN FLOW RATE AT STP (L/s)

TUBE #2, TYPE 604, AT 40 psig

CURVE FIT: $X = -2.5E-6 Y^2 + 2.2E-3 Y + 2.8E-3$

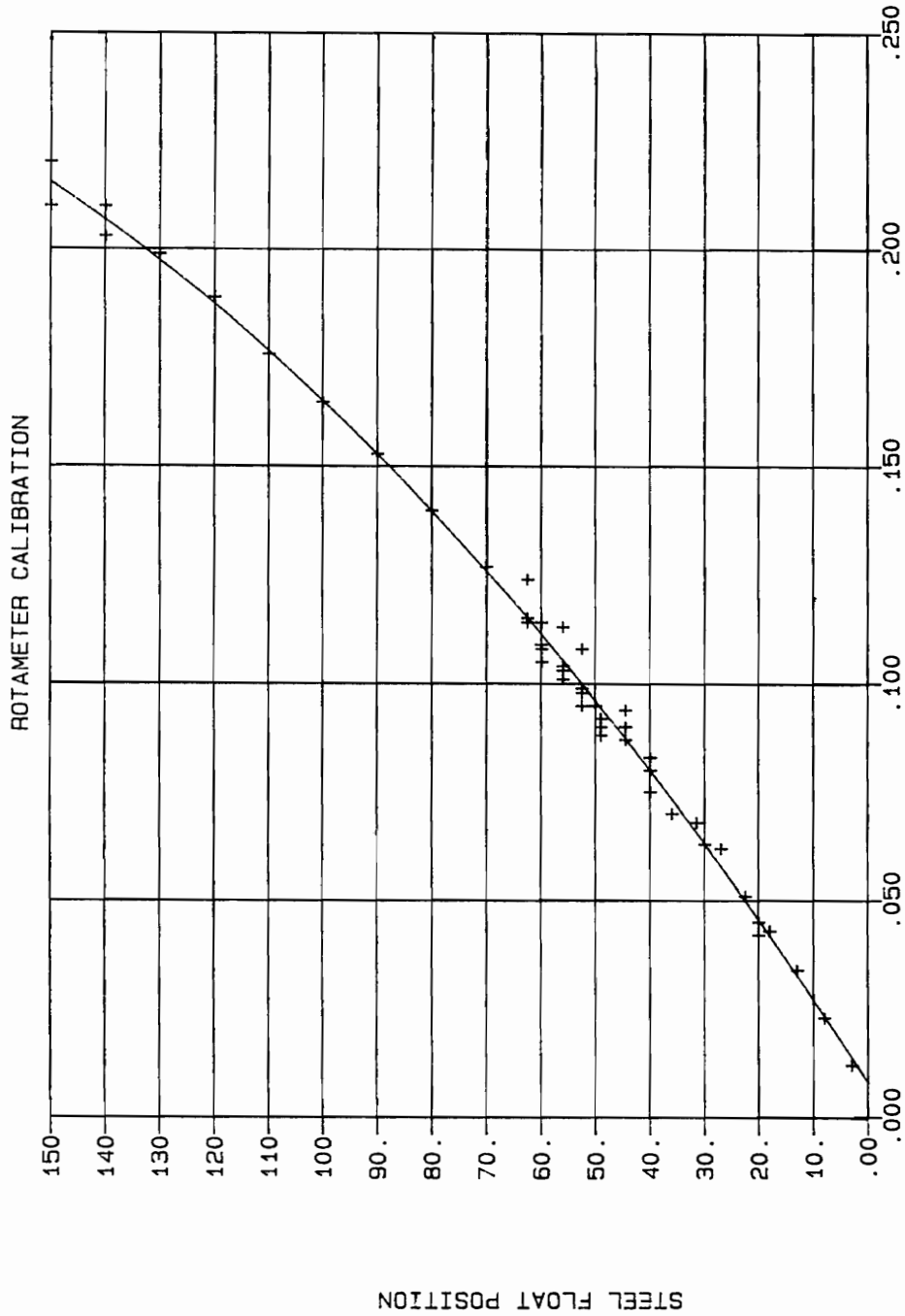


Figure 73. METHANE FLOW RATE AT STP (L/s)
TUBE #3, TYPE 603, AT 40 psig
CURVE FIT: $X = -3.8E-6 Y^2 + 1.9E-3 Y + 7.9E-3$

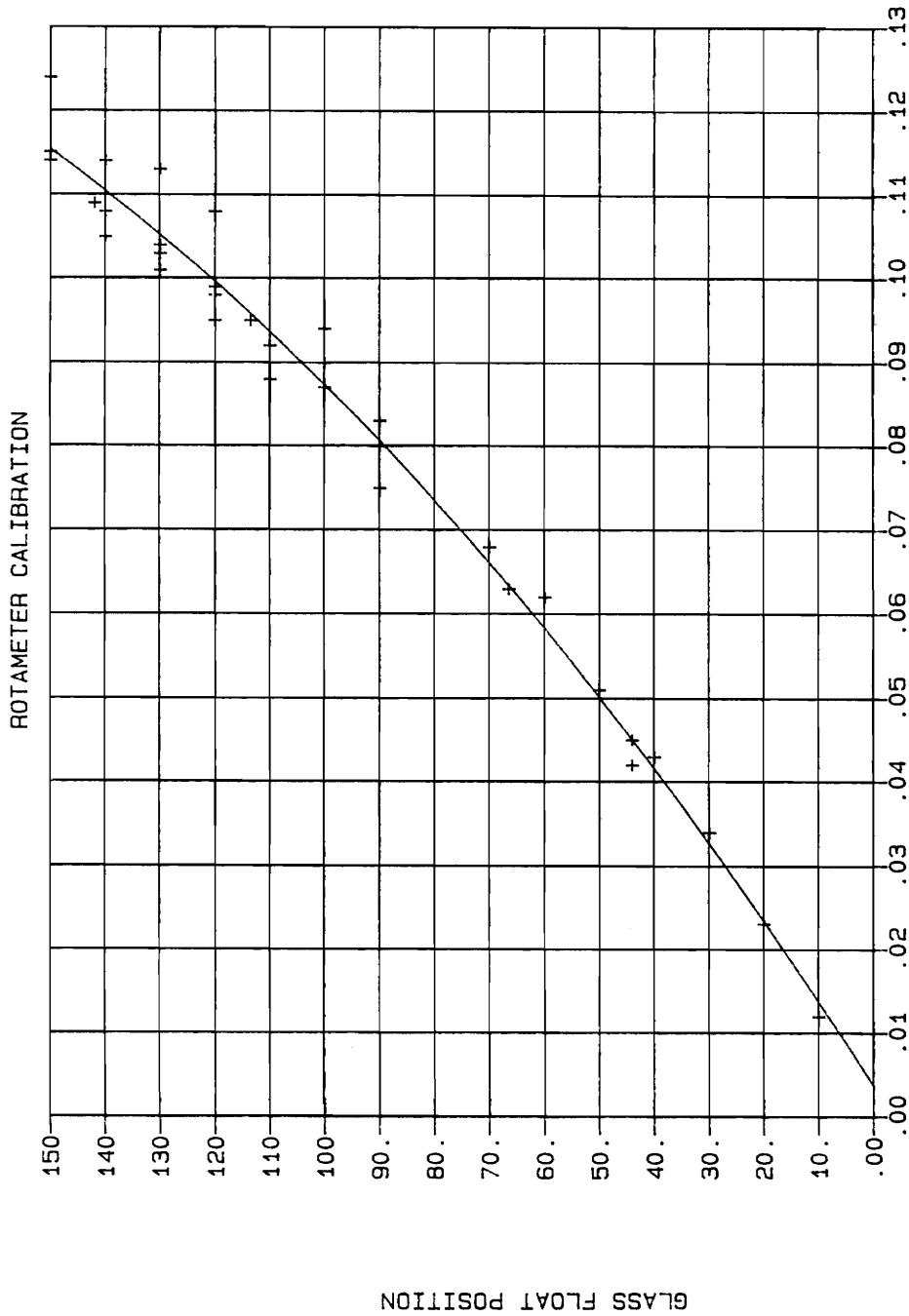


Figure 74. METHANE FLOW RATE AT STP (L/s)

TUBE #3, TYPE 603, AT 40 psig

CURVE FIT: $X = -1.8E-6 Y^2 + 1.0E-3 Y + 3.7E-3$

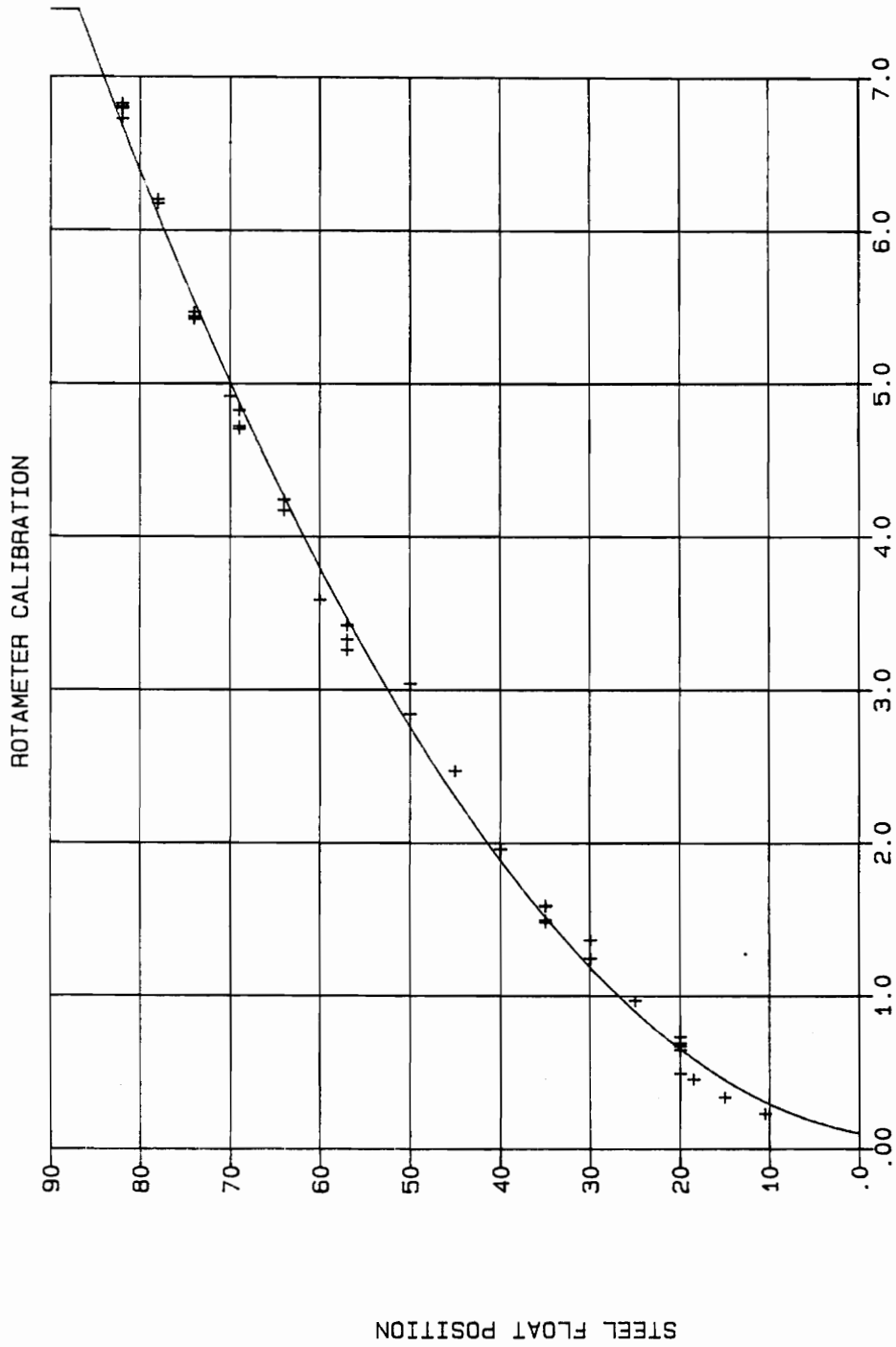


Figure 75. ETHENE FLOW RATE AT STP (cc/s)
 TUBE #4, TYPE 601, AT 40 psig
 CURVE FIT: $X = -8.5E-4 Y^2 + 0.011 Y + 0.10$

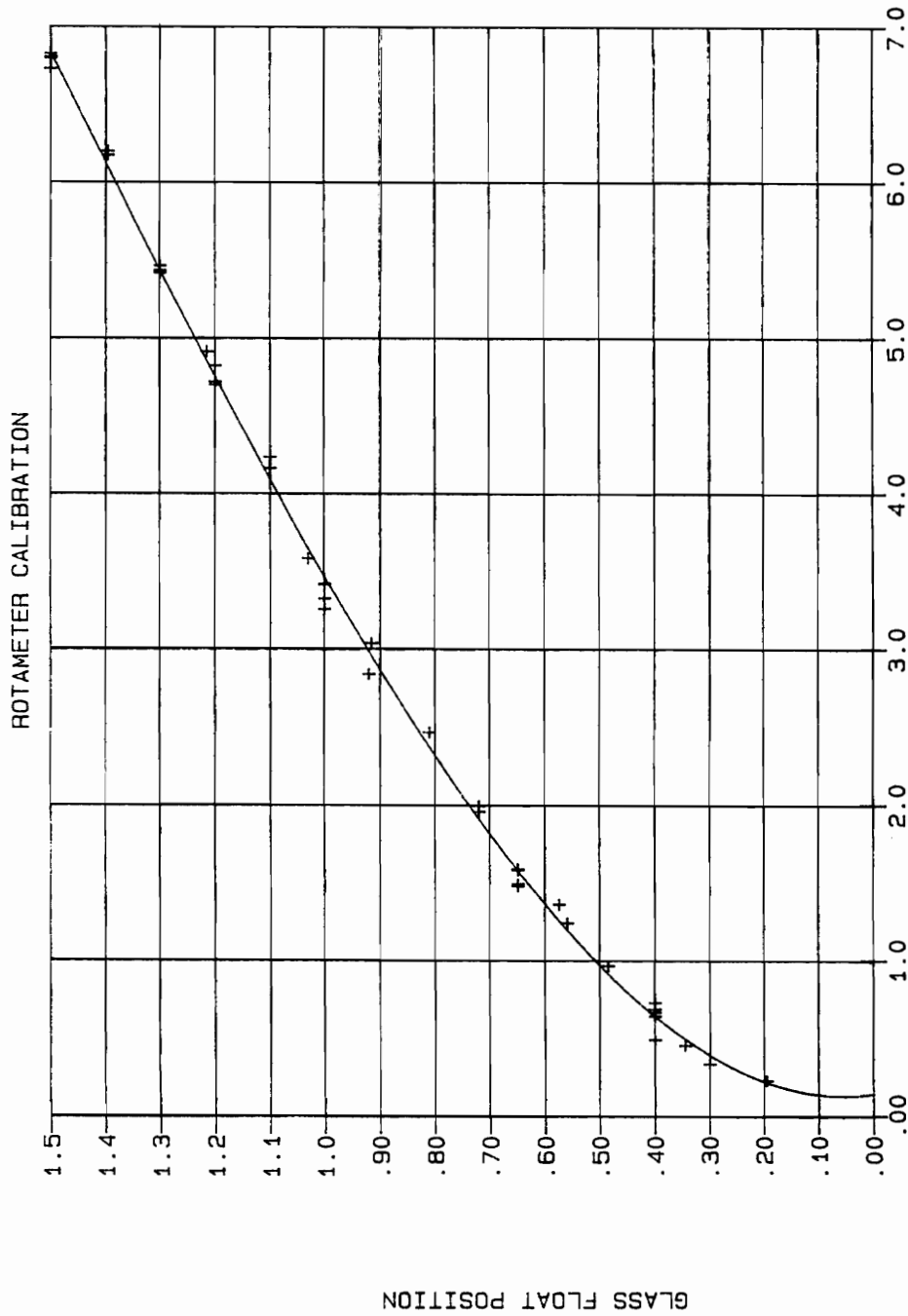


Figure 76. ETHENE FLOW RATE AT STP (cc/s)

TUBE #4, TYPE 601, AT 40 psig

CURVE FIT: $X = -1.1E-6 Y^3 + 4.9E-4 Y^2 - 5.4E-3 Y + 0.14$

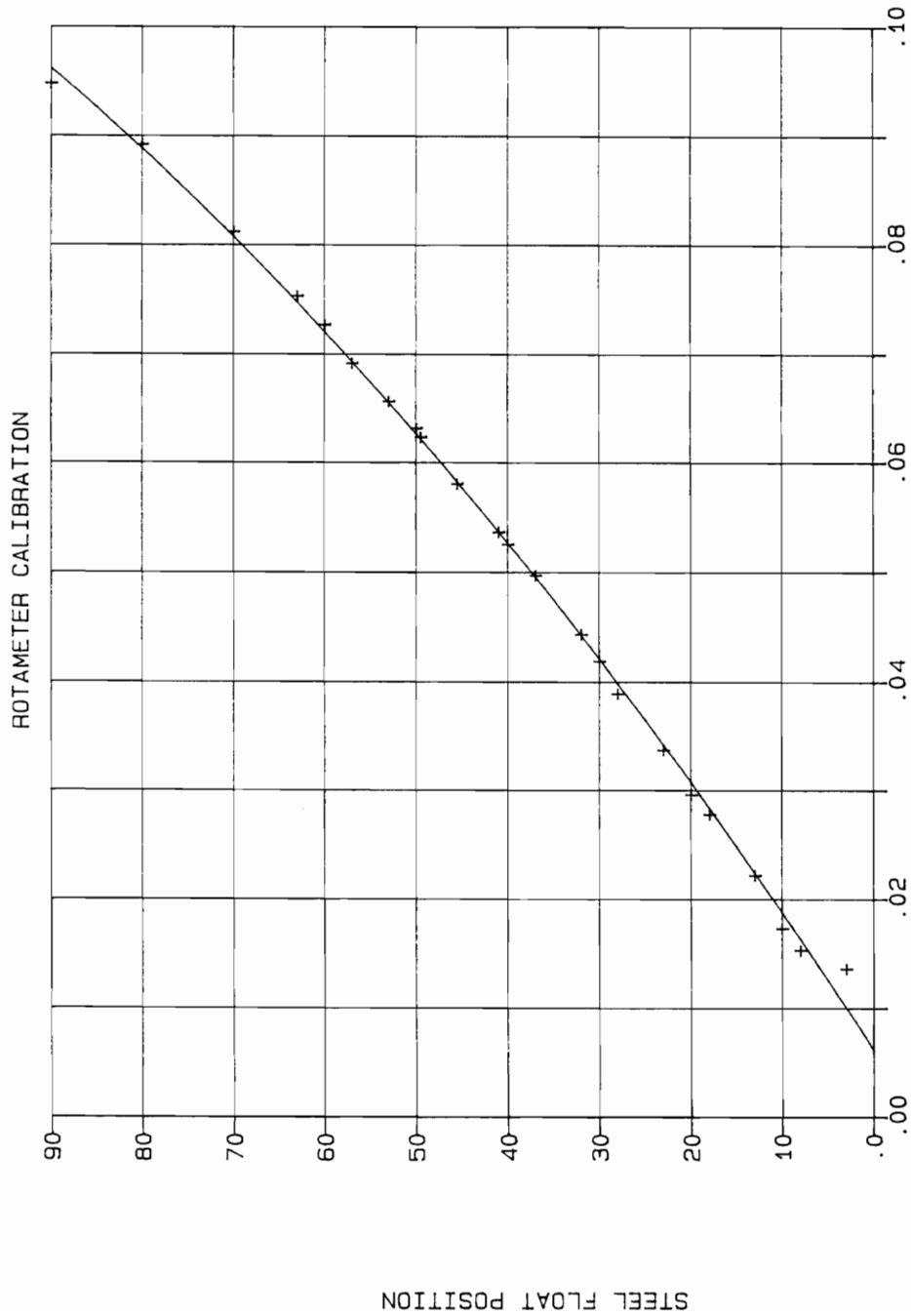


Figure 77. OXYGEN FLOW RATE AT STP (L/s)
 TUBE #5, TYPE 603, AT 40 psig
 CURVE FIT: $X = -3.3E-6 Y^2 + 1.3E-3 Y + 6.1E-3$

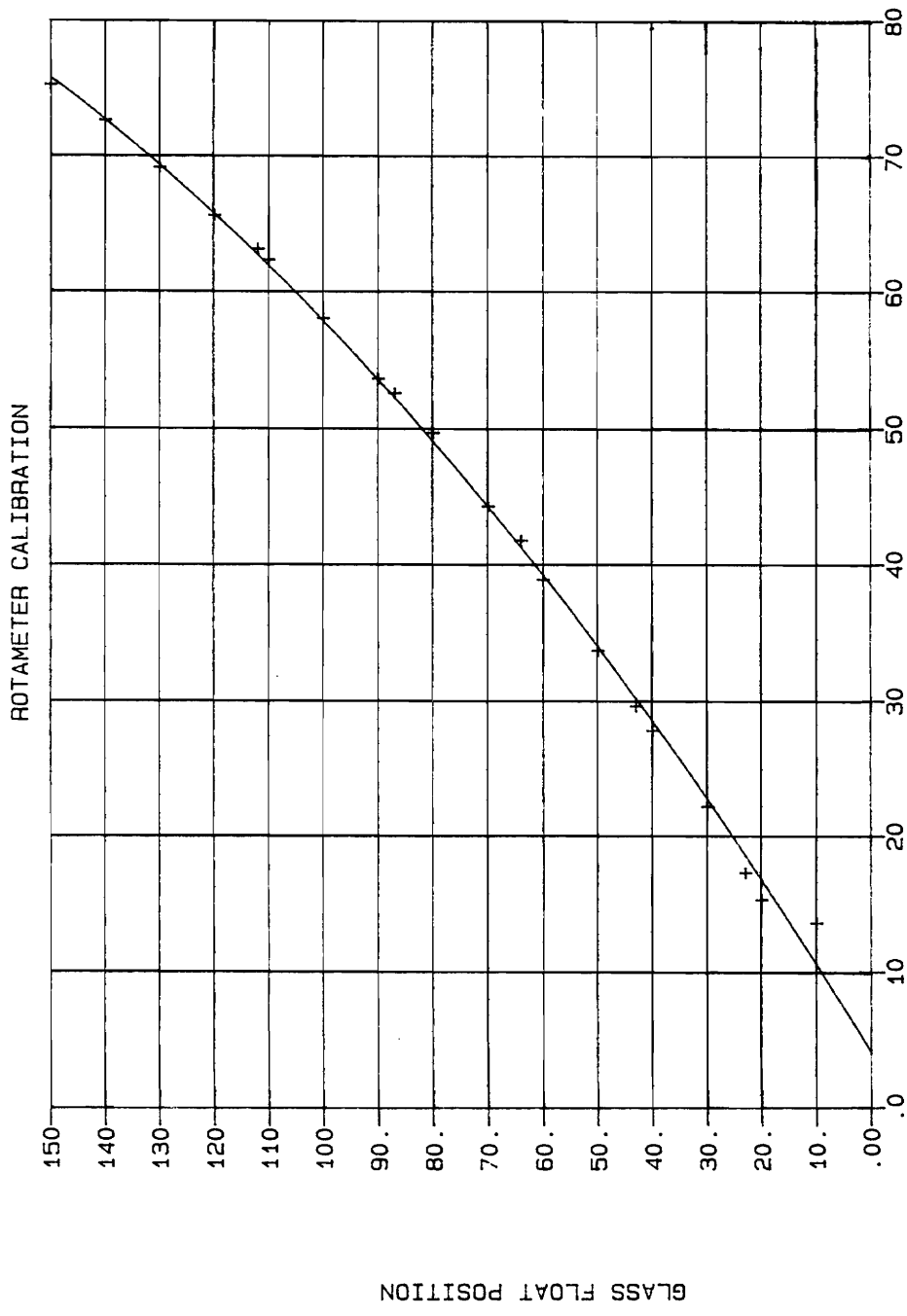


Figure 78. OXYGEN FLOW RATE AT STP (cc/s)
TUBE #5, TYPE 603, AT 40 psig
CURVE FIT: $X = -1.2E-3 Y^2 + 0.66 Y + 4.1$

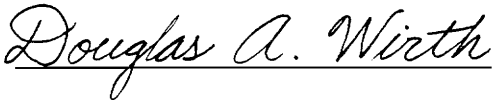
VITA

Douglas Allen Wirth was born on September 27, 1964 in Baltimore, Maryland. He graduated as co-Valedictorian from Mount Hebron High School in 1982, and attended Virginia Tech in the following fall.

While at Tech, he majored in mechanical engineering and graduated Magna Cum Laude. He participated in the cooperative education program for eight quarters with the Baltimore Gas and Electric Company. He is a member of Phi Delta Theta fraternity, and Tau Beta Pi and Pi Tau Sigma honor societies. He met Suzanne Scheid at Tech in 1984.

After graduation, he married Suzanne and returned for graduate school. He completed his Master of Science degree in mechanical engineering after two years.

His current plans are to attend Cornell University to obtain a Ph.D. in mechanical engineering. His research project will be very similar to some of the work done for this thesis. It involves optical tomography and absorption spectroscopy. He also hopes to continue his study of life in small college towns.


Douglas A. Wirth