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HIGH-REPETITION-RATE TEMPERATURE MEASUREMENT OF  
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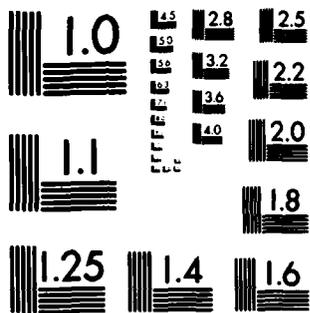
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HIGH-REPETITION-RATE TEMPERATURE MEASUREMENT  
OF LABORATORY COMBUSTION FLAME BEAM DEFLECTION

D. F. Grosjean  
L. P. Goss

AD-A171 471

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Dayton, OH 45440-3696

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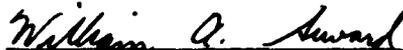
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<p>Details of a method of obtaining time-resolved measurements of gas temperatures in a combustion environment are given. The noncontact optical laser-beam deflection technique utilizes rapid heating at a gas-solid interface as an acoustic source and is capable of acquiring localized temperature values at a repetition rate of &gt; 1 kHz. Measurements taken on a pre-mixed propane-air laboratory flame show a 12.5-Hz thermal oscillation at the flame edge and no significant oscillation at the center. Two signal-processing approaches are described: 1) digitization and recording of the entire signal and subsequent digital processing, and 2) electronic detection of the signal peak, accompanied by real-time processing of the time difference.</p>				
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PREFACE

This is the final report for Task 19 of Contract No. F33615-81-C-2013 (prime contractor - San Jose State University). The report was prepared by the Research Applications Division of Systems Research Laboratories, Inc. The Government Contract Monitor was Dr. B. N. Ganguly. The work was performed by Mr. Dennis F. Grosjean and Mr. Benjamin Sarka, Jr., with Dr. Larry P. Goss as the SRL technical monitor.

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## TABLE OF CONTENTS

Section	Page
I INTRODUCTION	1
II BACKGROUND	2
III EXPERIMENTAL ARRANGEMENT	5
IV RESULTS	18
V RECOMMENDATIONS	23
References	29

## LIST OF ILLUSTRATIONS

<u>Figure</u>		<u>Page</u>
1	Schematic Diagram of Optical Arrangement for High-Repetition-Rate Temperature Measurements.	6
2	Optoacoustic Deflection Signal Resulting from Scan of 1-mm-Wide Mask Located 1 mm above Probe Beam. Target-to-beam distance = 0.75 cm. Mask oriented perpendicular to probe beam.	7
3	Block Diagram of Signal-Processing Electronics.	9
4	Electrical Circuit Schematic of Detector-Head Electronics.	11
5	Electrical Schematic of Burst-Generator Circuit.	12
6	Electrical Schematic of Clock Circuit.	13
7	Electrical Schematic of Rack-Power-Supply Circuit (sheet 1 of 2).	14
8	Electrical Schematic of Rack-Power-Supply Circuit (sheet 2 of 2).	15
9	Electrical Schematic of ECL-to-Scope Adapter Circuit.	16
10	Typical Optoacoustic Beam Deflection Signals in Flame and in Room-Temperature Air.	19
11	Plots of Temperature vs. Time in Pre-Mixed Propane-Air Flame at Various Radial Distances 3 cm above Burner Surface.	21
12	Probability Distribution Function of Measured Temperatures Corresponding to Center Position of Fig. 11.	22
13	Block Diagram of Data-Acquisition Technique for Fast Temperature Recording and Real-Time Display.	24
14	Electrical Schematic of Present Peak-Detector Circuit.	25
15	Electrical Schematic of Time-to-Digital Converter Circuit.	26
16	Electrical Schematic of Real-Time Oscilloscope Display Circuit.	27

Section I  
INTRODUCTION

The availability of tunable, high-peak-power laser sources has stimulated research in the area of combustion diagnostics, with the goal being to understand the basic fluid and chemical properties of combustion. Temperature and majority species are usually determined by means of Raman techniques,<sup>1</sup> while radical intermediates in a much lower concentration are often probed using laser-induced fluorescence (LIF). Newly developed techniques include optogalvanic,<sup>2</sup> optoacoustic,<sup>3</sup> and photothermal deflection spectroscopy (PTDS)<sup>4</sup> which not only complement the well-established Raman and LIF techniques but also widen the applicability of laser diagnostics in the area of combustion studies.

The extension of these techniques to high frequencies--essential to an understanding of turbulence phenomena--has suffered from the lack of high repetition rate, high-peak-power laser sources. High-frequency thermometry has, to date, been carried out using fine-wire thermocouples or Rayleigh scattering. Both methods are extremely difficult to apply to a practical flame system.

This report describes the first high frequency demonstration of a thermometric technique which can be applied to diverse, practical flame environments. The technique, based on that first described by Zapka, et al.,<sup>5</sup> involves measurement of the propagation velocity of an acoustic impulse between two measurement points defined by monochromatic beams. The method is nonintrusive at the point of measurement, does not require focus coincidence of multiple beams, and can be used with a number of commercially available high-repetition-rate lasers.

Background for the development of the high-frequency technique is contained in Section II, and Section III describes the experimental arrangement. The results are shown in Section IV, and recommendations for improving the demonstrated technique are contained in Section V.

## Section II

### BACKGROUND

The work of Zapka, Pokrowsky, and Tam<sup>5</sup> was the first demonstration of the optoacoustic laser-beam deflection (OLD) method. These authors utilized the focused beam of a 200-mJ Nd:YAG laser to effect a gas breakdown. Propagation of the resulting acoustic pulse was detected upstream in the gas flow of a burner by observation of the deflections of two He-Ne laser beams separated by 1 cm. The time between deflections represented the difference in arrival time of the acoustic pulse.

The optoacoustic technique is a relatively simple method of determining temperature by measuring the speed of sound. The velocity of an acoustic wave which is propagating through a flame is dependent upon the temperature of the flame. The relationship between the temperature and the acoustic-wave propagation velocity is given by

$$T = \frac{v_0^2 \bar{m}}{R \left[ 1 + \frac{R}{\bar{C}_V(T)} \right]} \quad (1)$$

where  $\bar{m}$  is the average molecular weight of the gases in the flame,  $R$  the universal gas constant,  $v_0$  the sound velocity, and  $\bar{C}_V(T)$  the temperature-dependent average molar specific heat at constant volume in the flame.

The solution of Eq. (1) for temperature  $T$  requires  $\bar{m}$  and  $\bar{C}_V(T)$  to be known. In a premixed propane-air flame, the main gaseous component is  $N_2$ , with the other major components being  $CO_2$  and  $H_2O$ . An adiabatic flame code<sup>6</sup> can be used to yield the gaseous composition of the flame as a function of temperature from which  $\bar{m}$  and  $\bar{C}_V(T)$  can be calculated and used to extract a temperature from a sound-velocity measurement.

A basic limitation of the original work resulted from the method of sound-pulse generation. The required gas breakdown dictates the use of a high-power laser, limiting the choice of excitation sources. In addition, a blast wave resulting

from the breakdown may perturb the measurement region and produce erroneous results.

Recent work by Kizirnis, *et al.*,<sup>7</sup> has shown that a suitable acoustic pulse can be generated without the occurrence of a gas breakdown. In this case local heating at a gas/solid interface (thin tungsten wire) caused by a mildly focused, low-power pulsed laser served as the acoustic source. Results obtained on a propane-air premixed flame were similar to those from measurements made using the CARS technique.

In another recent study<sup>8</sup> of fifteen potentially useful target materials, tungsten received a high rating at room temperature, but the amplitude of the acoustic impulse in the presence of a flame dropped rapidly as a function of the number of pulses. Titanium was found to be the most acceptable material for use with the laboratory flame of interest at this time. The acoustic-pulse amplitude was essentially independent of the number of pulses, making it ideal for high-rep-rate operation. In fact, a slight increase in signal amplitude was observed at the higher rep rates.

Since optical absorption at a gas-solid interface covers a broad spectral range, wavelength requirements of the pump laser are greatly relaxed. Also, the necessary optical power appears to be within the range of several commercially available high-rep-rate lasers, including the copper-vapor and rare-gas-halide systems. Consequently, a 1.5-kHz XeCl laser has been utilized in the present experiment to demonstrate the efficacy of the OLD technique to produce time-resolved measurements of temperature fluctuations within a propane-air premixed flame.

This technique can be extremely useful for the study of turbulence phenomena in a combustion environment only if acceptable time resolution and spatial resolution can be attained. This places some severe demands upon signal processing. Since gas breakdown is not desirable, the acoustic energy is limited, leading to a limited signal amplitude. Uncertainty in the time of arrival of the acoustic pulse at each probe beam increases as the signal level decreases toward the system noise level. This uncertainty becomes significant at high spatial resolution where the probe beam separation--and, hence, the time difference between

arrival of the pulse at each beam--decreases. Therefore, two signal-processing approaches were seen as viable for the present effort: (1) digitization and recording of the entire signal and subsequent digital processing and (2) electronic detection of the signal peak accompanied by real-time processing of the time difference.

The technique of full digitization and recording of both probe-beam signals requires high-speed digitizers ( $\geq 50$  MHz) and a large amount of memory. This, however, is the preferred data-acquisition method in developing the time-resolved OLD technique because of the flexibility inherent in digital signal processing. This is the method utilized for the present study and discussed in the next section. The method of real-time processing of the probe-beam signals suffers from a current inability to detect the position of the signal peaks in time with sufficient accuracy. Recommendations for implementation of this method resulting in a real-time oscilloscope display are discussed in Section V.

## Section III

### EXPERIMENTAL ARRANGEMENT

The optical arrangement is shown schematically in Fig. 1. As mentioned earlier, the basic technique involves measurement of the velocity of an acoustic pulse as it travels through a flame. A thin strip of titanium is used as the target. The pump laser provides a 6-mJ,  $\sim 30$ -nsec-wide pulse at 308 nm. Although this laser--built for the Air Force Aero Propulsion Laboratory<sup>9</sup>--is not a commercial product, suitable 200-Hz systems are readily available. It is anticipated that the visible output of available Cu-vapor lasers which are capable of operation at  $\sim 5$  kHz will also serve as an acceptable pump source. The main requirements of the pump source are (1) a short pulse of  $\leq 100$  nsec duration at an energy of  $\geq 5$  mJ, and (2) a wavelength range within the absorption band of the solid surface.

For maximum spatial resolution the rectangular-shaped output of the XeCl laser was focused onto the target in such a way that the long dimension was along the axes of the target (perpendicular to the direction of gas flow). This orientation resulted in minimal spreading of the cylindrically shaped acoustic wave. Figure 2 shows the result of scanning with a 1-mm-wide slot through the path of the acoustic pulse. The mask was oriented perpendicular to, and located  $\sim 1$  mm above, a HeNe probe beam; the figure shows the waveshape of the detector output. Also, the signal with the mask removed is shown. From these data the spatial resolution along the probe beams was estimated to be 2-3 mm for the probe beams located 0.75 cm from the target. At 1 cm from the target, a resolution of  $\sim 3$ -4 mm was obtained.

The sources of the probe beams were two independent 8-mW HeNe lasers. Many other cw sources may be used since the wavelength is not critical. The main requirements are (1) sufficient power such that a high-speed transient is detectable, (2) sufficiently low noise in the frequency range of the transient, and (3) sufficiently small beam waist in the detection region to define the location of the deflections and, consequently, the separation of the measurement points. Points 2 and 3 are the most difficult to achieve.

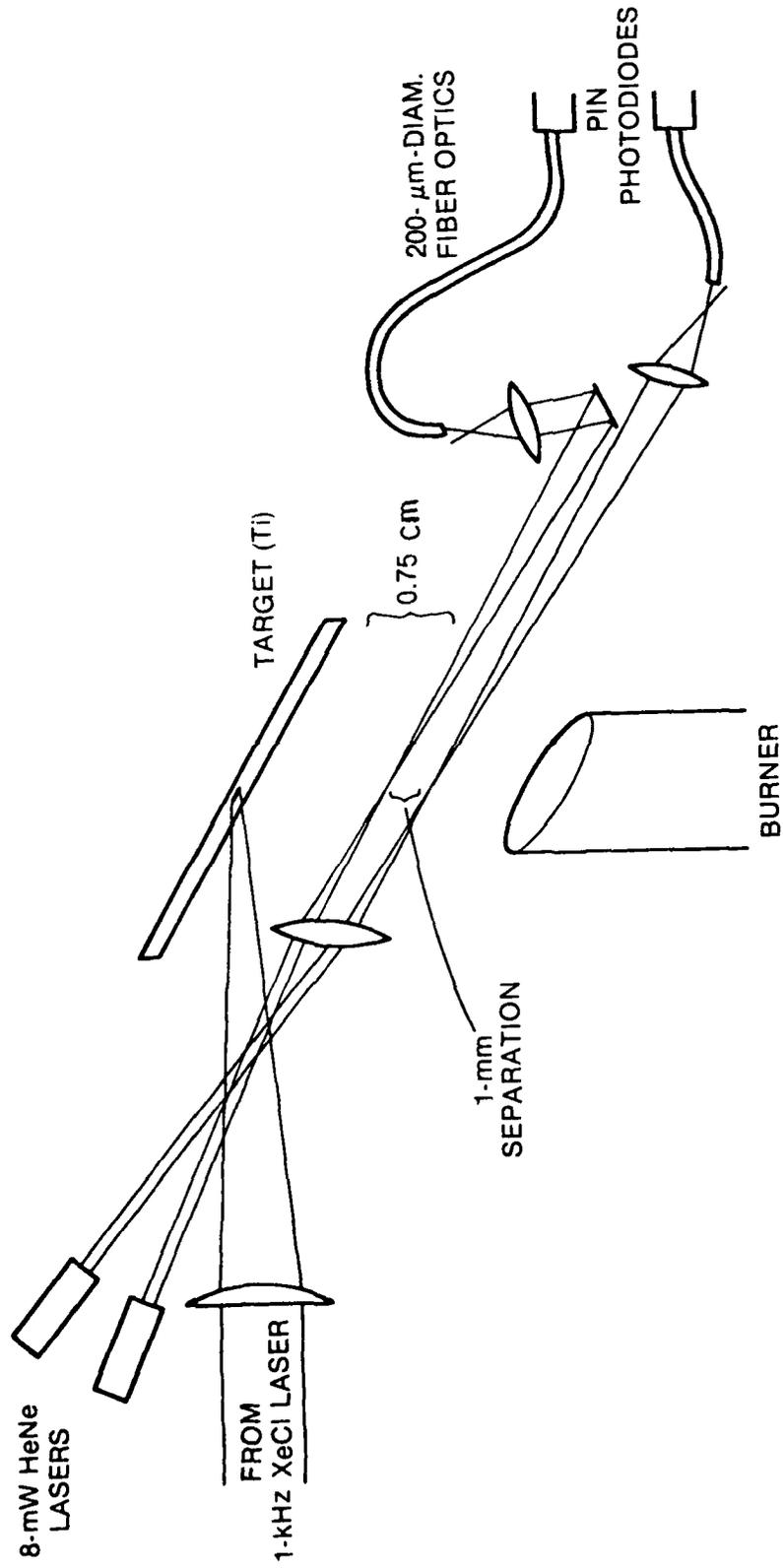


Figure 1. Schematic Diagram of Optical Arrangement for High-Repetition-Rate Temperature Measurements.

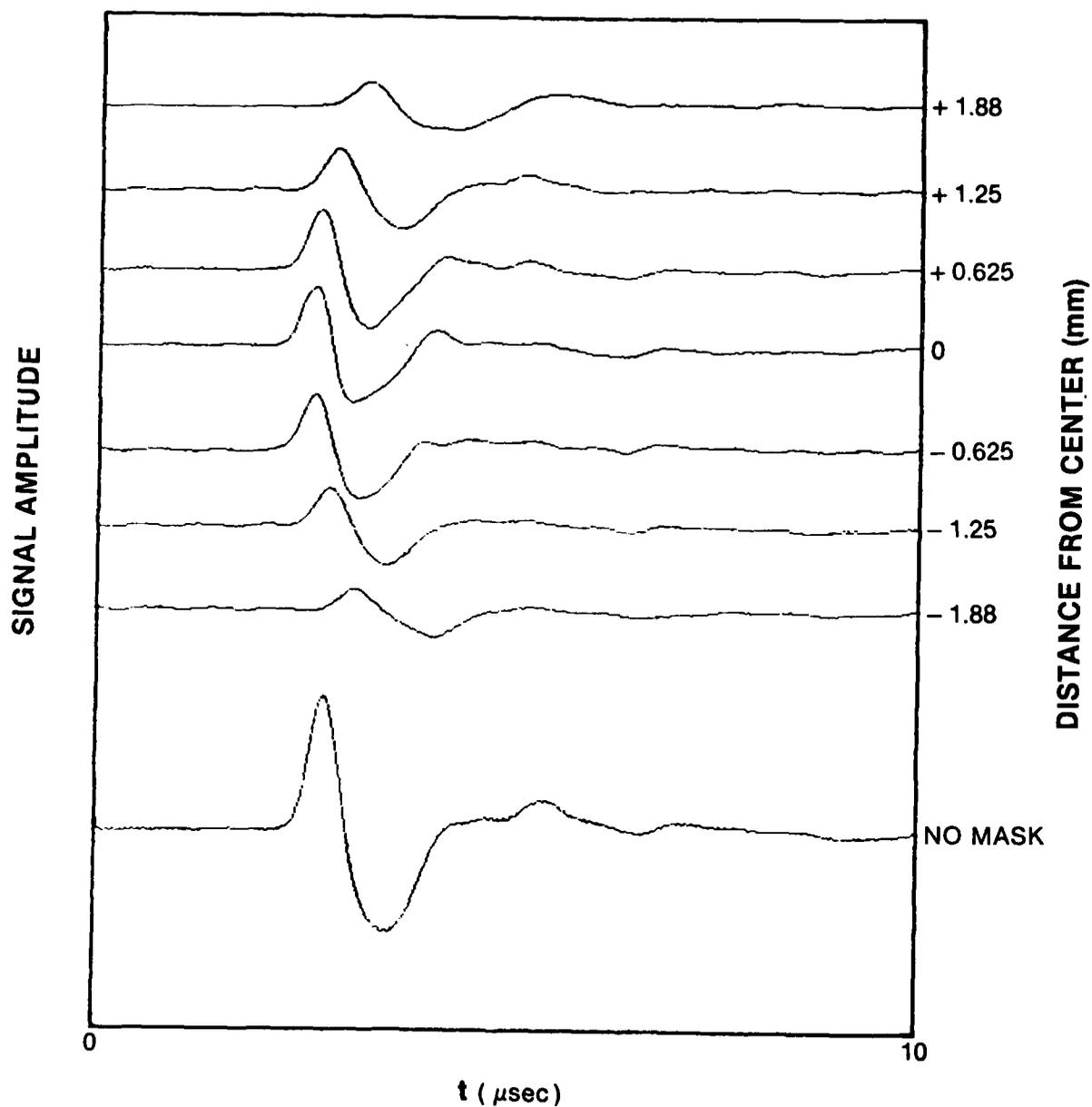


Figure 2. Optoacoustic Deflection Signal Resulting from Scan of 1-mm-Wide Mask Located 1 mm above Probe Beam. Target-to-beam distance = 0.75 cm. Mask oriented perpendicular to probe beam.

Although low-frequency fluctuations due to flame turbulence and extraneous acoustic noise can be easily eliminated by electronic high-pass filters, general-purpose HeNe lasers were found to exhibit amplitude oscillations at  $\sim 1$  MHz. In addition, this noise was polarization dependent in that the use of polarizing elements, such as beam splitters, caused an increase in the observed noise level. Unpolarized low-noise lasers were used in the present study, although the signal-to-noise ratio was marginally acceptable at times.

In the ideal case the beam waist in the detection region would be smaller than the acoustic wavelength. Assuming that this wavelength is determined by the pump-laser pulse width ( $\sim 30$  nsec for the XeCl source used here), the probe beams should be limited to a diameter of  $\sim 40$   $\mu\text{m}$  at gas temperatures of  $\sim 2000$  K and  $\sim 15$   $\mu\text{m}$  at room temperature. From the pulse width of Fig. 2, the present setup appears to have a beam diameter of  $\sim 200$   $\mu\text{m}$ . This has proven to be acceptable for measurement precision of better than  $\pm 100$  K. Attempts to utilize beam diameters of  $\geq 1$  mm demonstrated a significant influence of beam wander upon the target, manifested by a phase shift resulting from the nonuniform intensity distribution of the probe beam.

The entrances of the fiber optics shown in Fig. 1 serve as the motion-detection points of the deflected probe beams; the output ends are incident upon commercial fast photodiodes. The fiber optics may be eliminated, and the probe beams may be set incident on the edge of the active detector region. The 200- $\mu\text{m}$ -diam. fibers, however, provided a high degree of alignment flexibility in this experiment.

A block diagram of the processing electronics is shown in Fig. 3. The signal currents of the fast optical diodes were routed through current-to-voltage converters, filtered for removal of low-frequency components (3-dB point = 75 kHz), buffered into high-speed amplifiers, and terminated at high-speed analog-to-digital converters (LeCroy 6102 amplifier and MM8818 transient recorders). The 8-bit digitized outputs were stored in real time in cache memories (LeCroy MM8103 modules configured for 98 Kbytes maximum per channel). After completion of a scan, the data were read into a microcomputer (HP 9836) and processed. The timing of the transient recorders was controlled in the

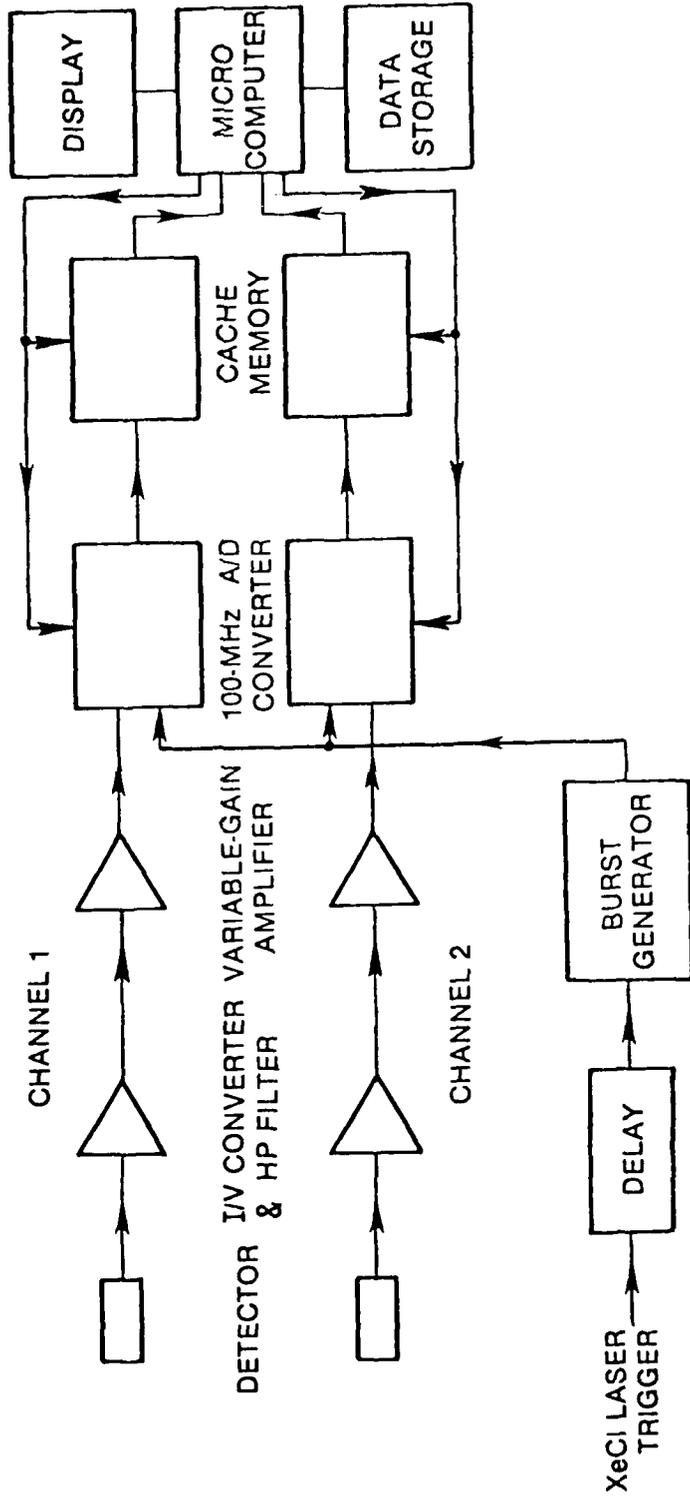


Figure 3. Block Diagram of Signal-Processing Electronics.

following manner. A delayed trigger pulse from the pump laser effected a pulse train of 256 or 512 bytes (selectable) simultaneously to the digitizers at a 50-MHz clock rate. This ensured time synchronization between the signals of the two probe-laser beams. Data acquisition was terminated when a selected portion of the cache memories was filled.

Schematics of the electronics constructed for this effort are contained in Figs. 4-9. The signal-conditioning circuit of Fig. 4 is located within the detector housing and buffered for a 50- $\Omega$  output for compatibility with the high-speed LeCroy amplifiers. The LeCroy transient digitizers are operated in the "external-clock" mode. By sending a burst of pulses only during the time of interest (in the time vicinity of the acoustic pulse arrival at the He-Ne probe beams), only the data of interest are stored in the digital memory. That is, the dead-time between pump-laser shots is not recorded. The schematic of this burst circuit is contained in Fig. 5, and the crystal-controlled clock circuit is shown in Fig. 6. The burst module has the capability of emitting a string of 256, 512, 1024, or 2048 pulses; and the clock module outputs a 25-, 50-, or 100-MHz square wave.

All high-speed timing and counting circuits are ECL compatible and constructed in rack-mounted modules, with the exception of the detector electronics discussed previously. Figures 7 and 8 are schematics of the power-supply circuits for the modules, and Fig. 9 is a schematic of an adaptor-module useful for observation of an ECL signal on an oscilloscope utilizing a high-impedance plug-in. Due to the time constraints for circuit construction, the ECL chips used were the Motorola 10000 Series rather than the faster MECL III Series. Consequently, reliable operation at 100 MHz was not obtained; the highest practical clock rate is limited to 50 MHz.

As previously mentioned a Hewlett-Packard Model 9836 desktop computer is used as the system controller. Two main software routines were developed--one for control of the acquisition process (SYSTEM) and one for data reduction (AUTOCOR3). Communication between the LeCroy CAMAC standard crate--containing amplifiers, digitizers, and cache memories--is accomplished through an IEEE-488 standard interface. Digitizer functions are initiated through software interrupts via the "soft" function keys. After data are loaded into the cache

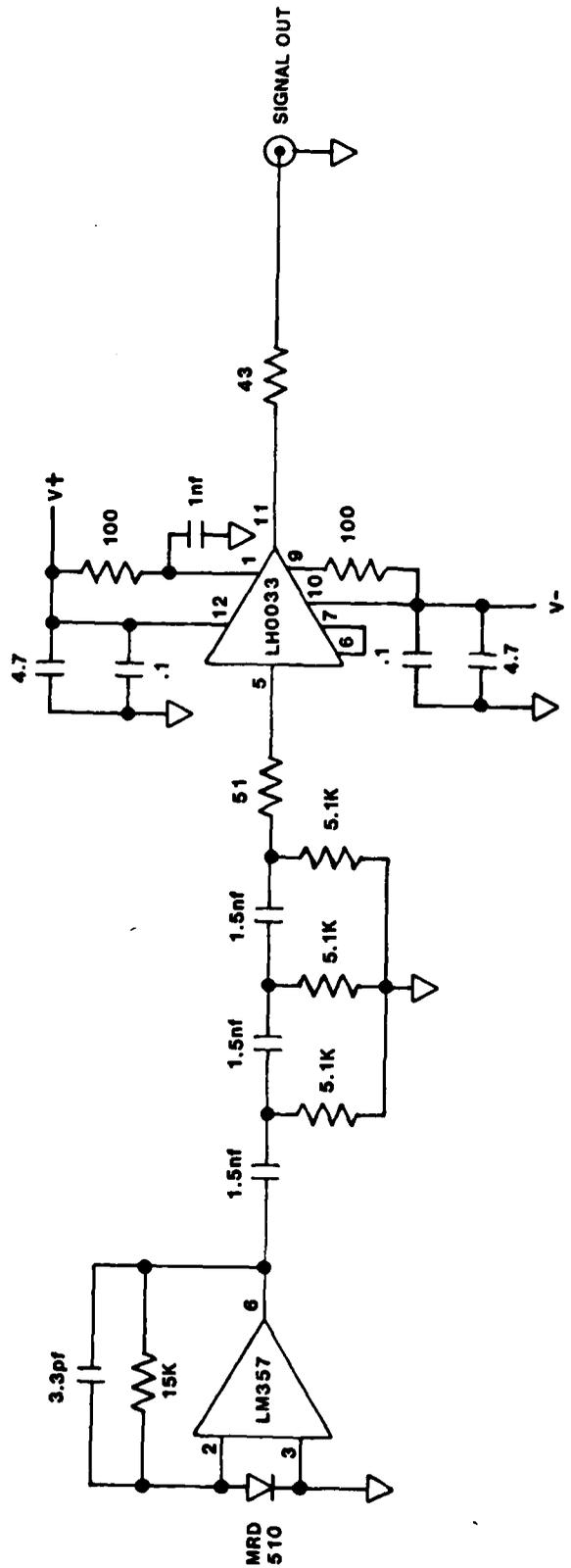
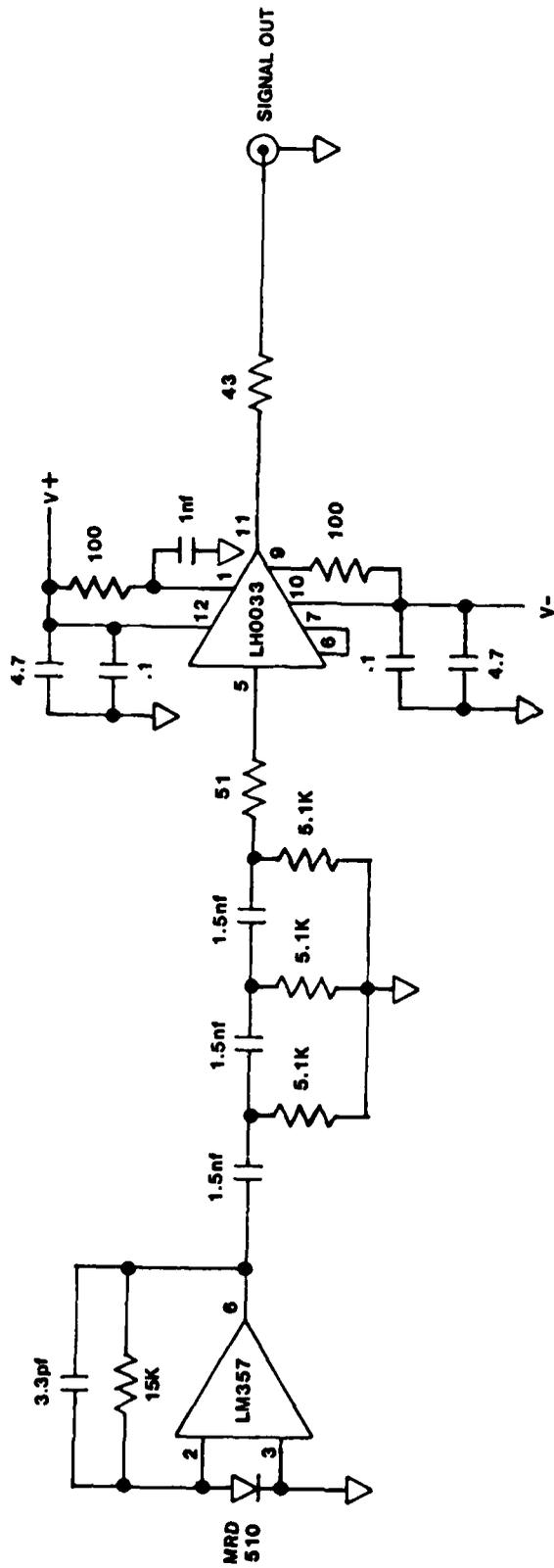


Figure 4. Electrical Circuit Schematic of Detector-Head Electronics.

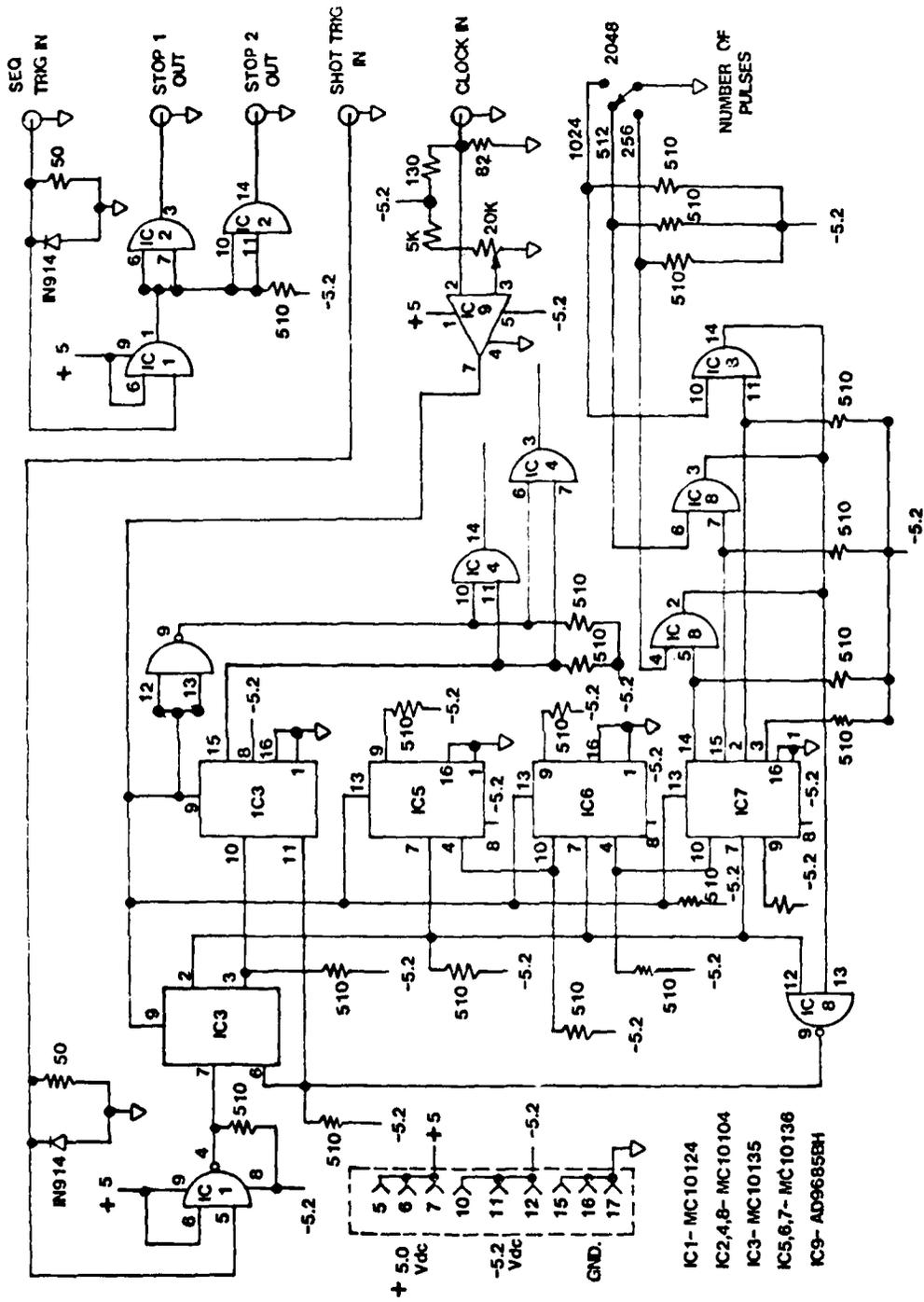


Figure 5. Electrical Schematic of Burst-Generator Circuit.



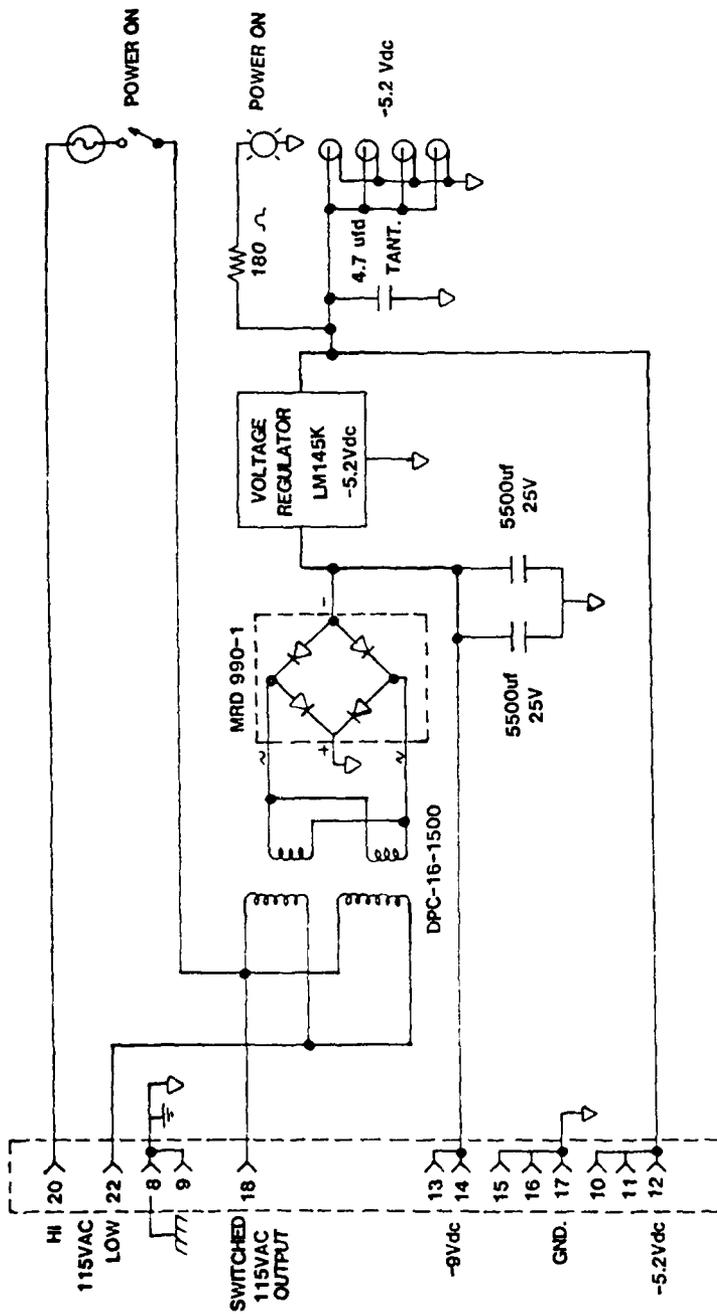


Figure 7. Electrical Schematic of Rack-Power-Supply Circuit (sheet 1 of 2).

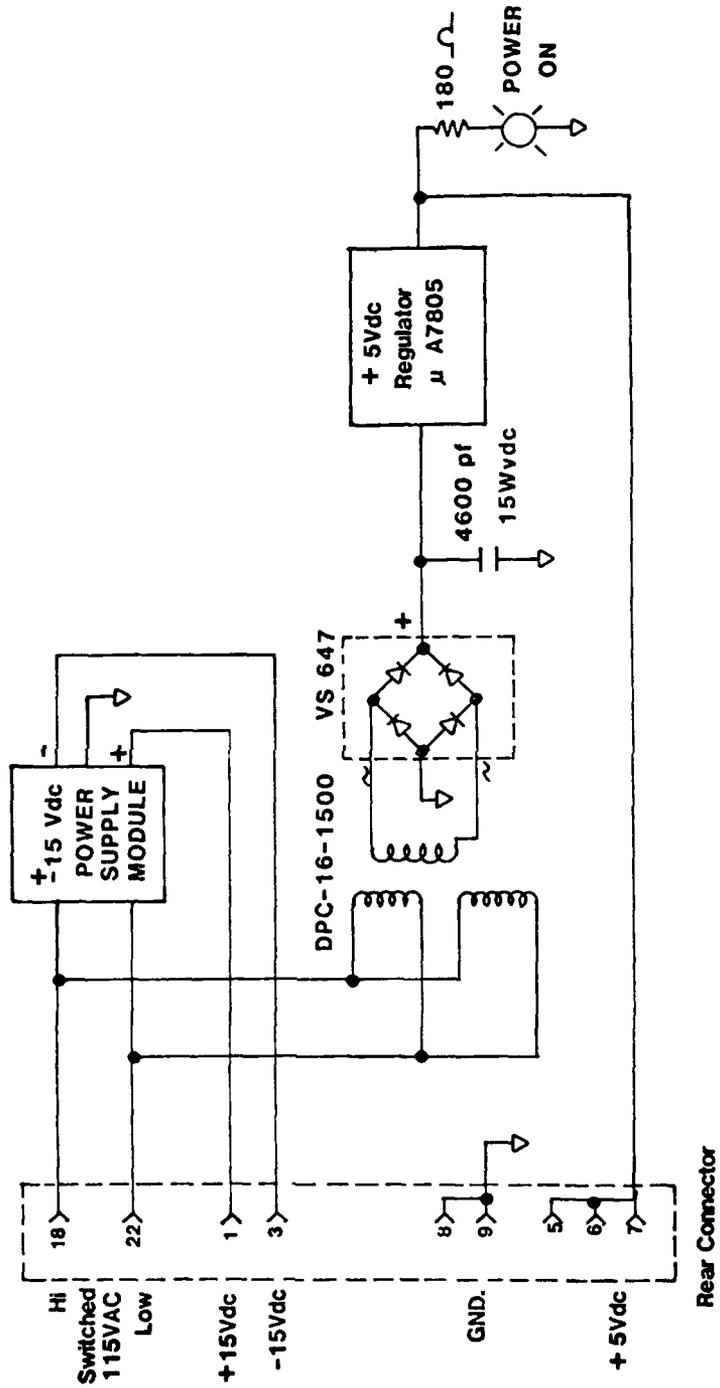


Figure 8. Electrical Schematic of Rack-Power-Supply Circuit (sheet 2 of 2).

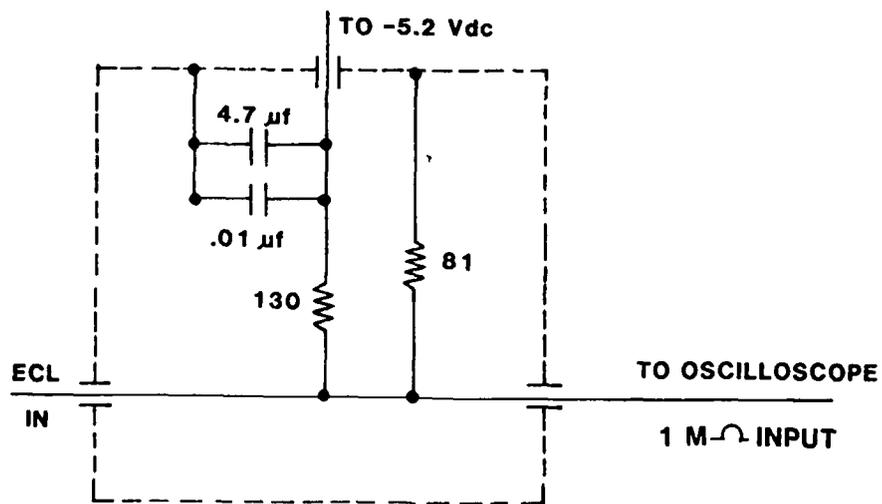


Figure 9. Electrical Schematic of ECL-to-Scope Adapter Circuit.

memories, they may be displayed on the CRT and/or stored on floppy disks. Since it was necessary to handle large amounts of data, HP enhanced BASIC 2.1 was used for fast data transfer and calculation.

## Section IV

### RESULTS

Figure 10 shows typical signals acquired in room-temperature air and in a pre-mixed propane-air flame. The 2.59- $\mu$ sec separation of the probe signals at room temperature indicates an effective beam separation of 1.00 mm. The drop in signal amplitude at high temperatures is primarily due to the decreased gas number density. This amplitude decrease causes difficulty in determining the positions of the peaks since the signal-to-noise ratio is quite small. This situation is aggravated by the fact that the effective frequency of the signal is very close to the noise frequency. It was found necessary to use a fourth-order, bandpass digital filter (auto-regressive, moving average) in processing the data for separation of the acoustic pulse signal from the high-frequency noise of the HeNe probe laser.

After filtering of the acquired signals, a correlation operation was performed in order to determine the time difference of the positive peaks of the recorded signals. The ratio of the time difference ( $\Delta t_r$ ) measured at a reference temperature ( $T_r$ ) to the time difference ( $\Delta t_f$ ) measured in the flame yields a first-step temperature  $T'$  by

$$T' = \left( \frac{\Delta t_r}{\Delta t_f} \right)^2 T_r \quad (2)$$

Since the relationship between velocity and temperatures is dependent upon the molecular weight of the gas, a correction to  $T'$  is required.<sup>5,7</sup> The procedure utilized here was to apply the calculated first-step temperature to an adiabatic model for a propane-air flame and then apply a correction factor based upon the resultant mass.<sup>6</sup> If the chemical composition of the flame is known, the uncertainty in the corrected temperature is determined by the uncertainty in the measurement of the acoustic travel times; statistical sampling will improve this. For unknown stoichiometry the range of error introduced by  $\bar{m}$  and  $C_V(T)$  can be bounded by the composition limits. For the unconfined flame of interest here, lean and rich fuel-air ratios determined the temperature boundaries. The mean values of the limits calculated as a function of  $\Delta t_r/\Delta t_f$

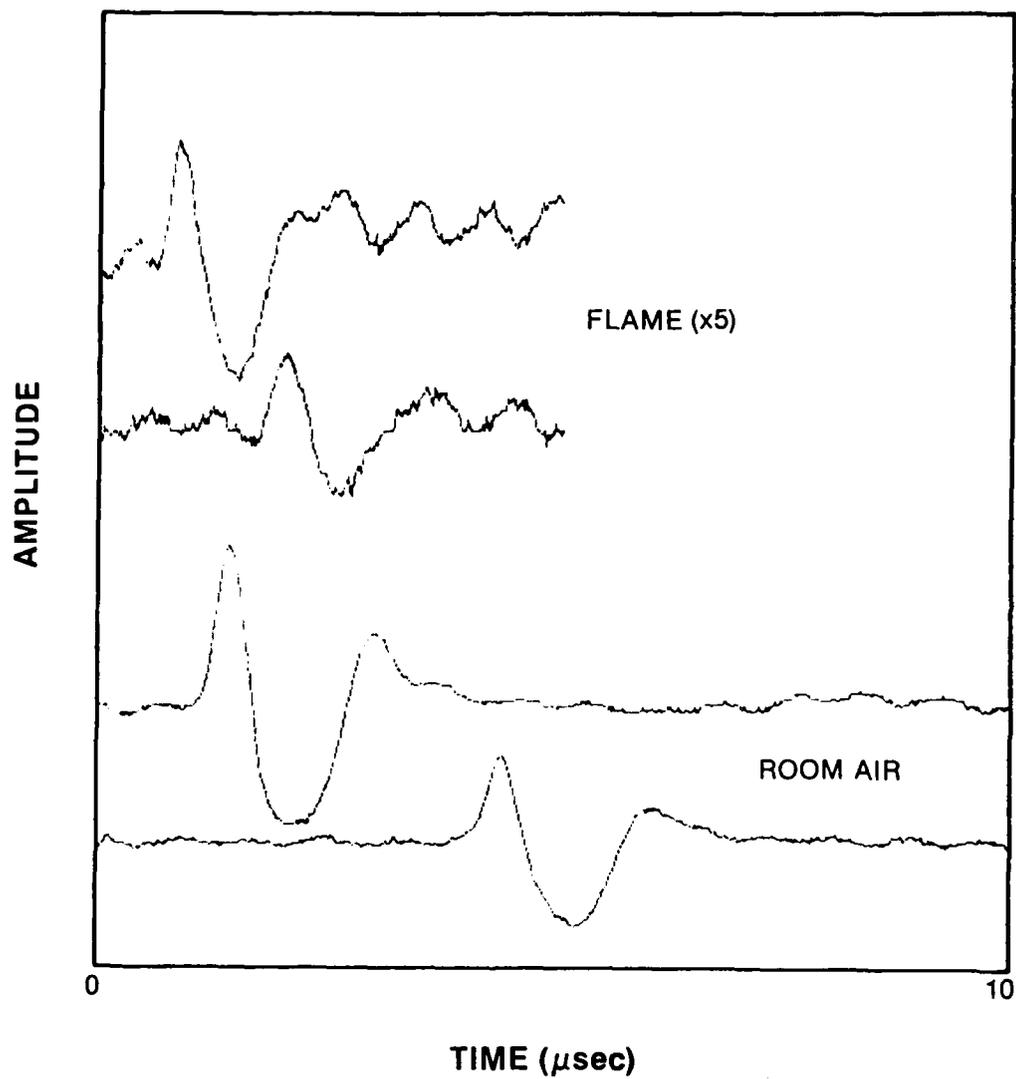


Figure 10. Typical Optoacoustic Beam Deflection Signals in Flame and in Room-Temperature Air.

represent the values reported here. The error range is small at high temperatures ( $\pm 2.3\%$  at  $\sim 2200$  K) and increases to  $\pm 10\%$  at  $\sim 1750$  K.

Typical results obtained on a pre-mixed, propane-air flame are shown in Fig. 11. The flame source was a 3.5-cm-diam. Meker-type laboratory burner. Measurements were made 3 cm above the surface. A low-frequency oscillation of 12.5 Hz is clearly developed at the edge of the flame (16-mm radial point). At 14 mm the oscillation is distorted; by 12 mm, it completely disappears. The low-frequency oscillations observed in this type of flame were also observed by Hanson, *et al.*,<sup>10</sup> while recording OH profiles by means of a digital camera system. The value of the maximum average temperature of Fig. 11 peaks at the 12-mm point and then decreases as the radial distance decreases. The data shown were acquired at a rep rate of 200 Hz. Scans at 1 kHz failed to reveal any significant higher-frequency thermal oscillations.

The temperature probability distribution function (PDF) of the data acquired at the flame center is shown in Fig. 12. The temperature was calculated to be  $2010 \pm 73$  K. A CARS measurement made on the same burner under similar conditions yielded a temperature value of  $2030 \pm 110$  K. The excellent agreement with the CARS technique indicates the precision of the high-rep-rate optoacoustic laser-beam deflection method of temperature measurement. The lower RMS values of the new technique are encouraging, especially since the accuracy of this technique increases at lower temperatures. As the gas temperature decreases, the acoustic velocity decreases and the gas density increases. These characteristics result in higher time resolution and higher signal-to-noise ratios. Accuracy in determining the transit time of the acoustic pulse is, therefore, increased and a lower RMS error at low temperatures is obtained. This makes the OLD technique very useful when large temperature fluctuations are encountered.

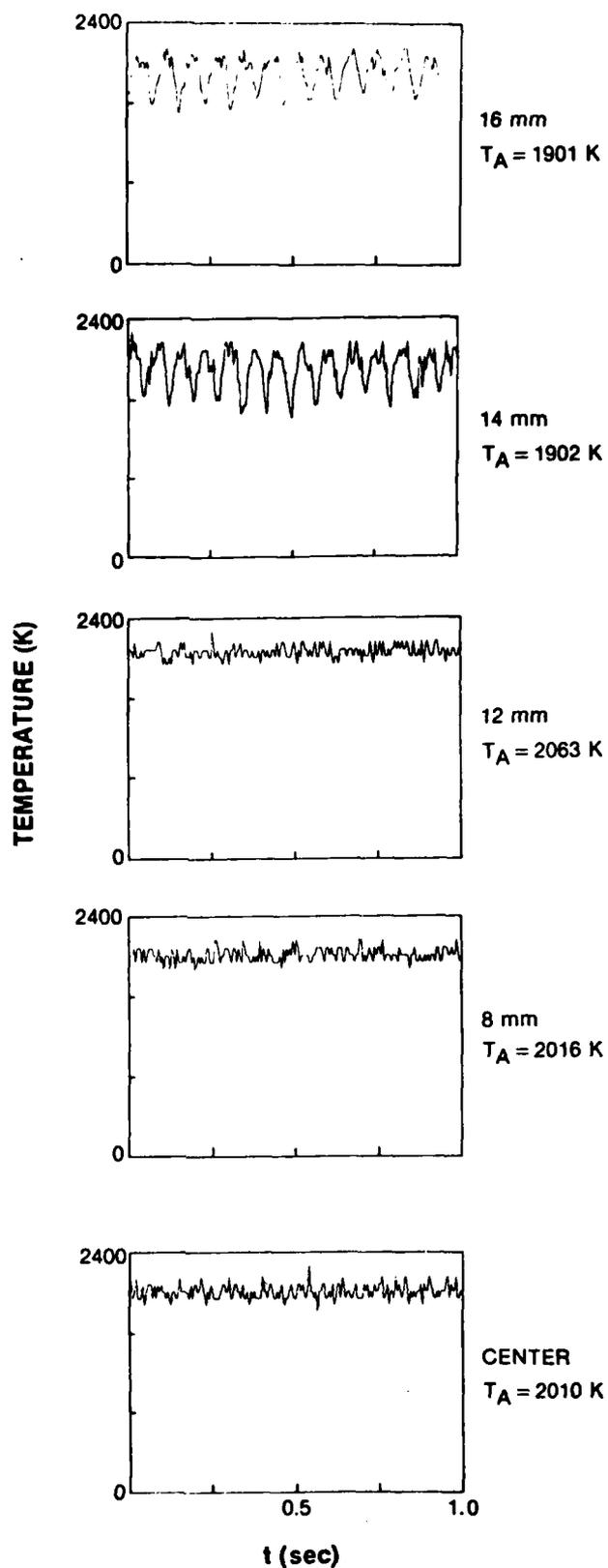


Figure 11. Plots of Temperature vs. Time in Pre-Mixed Propane-Air Flame at Various Radial Distances 3 cm above Burner Surface.

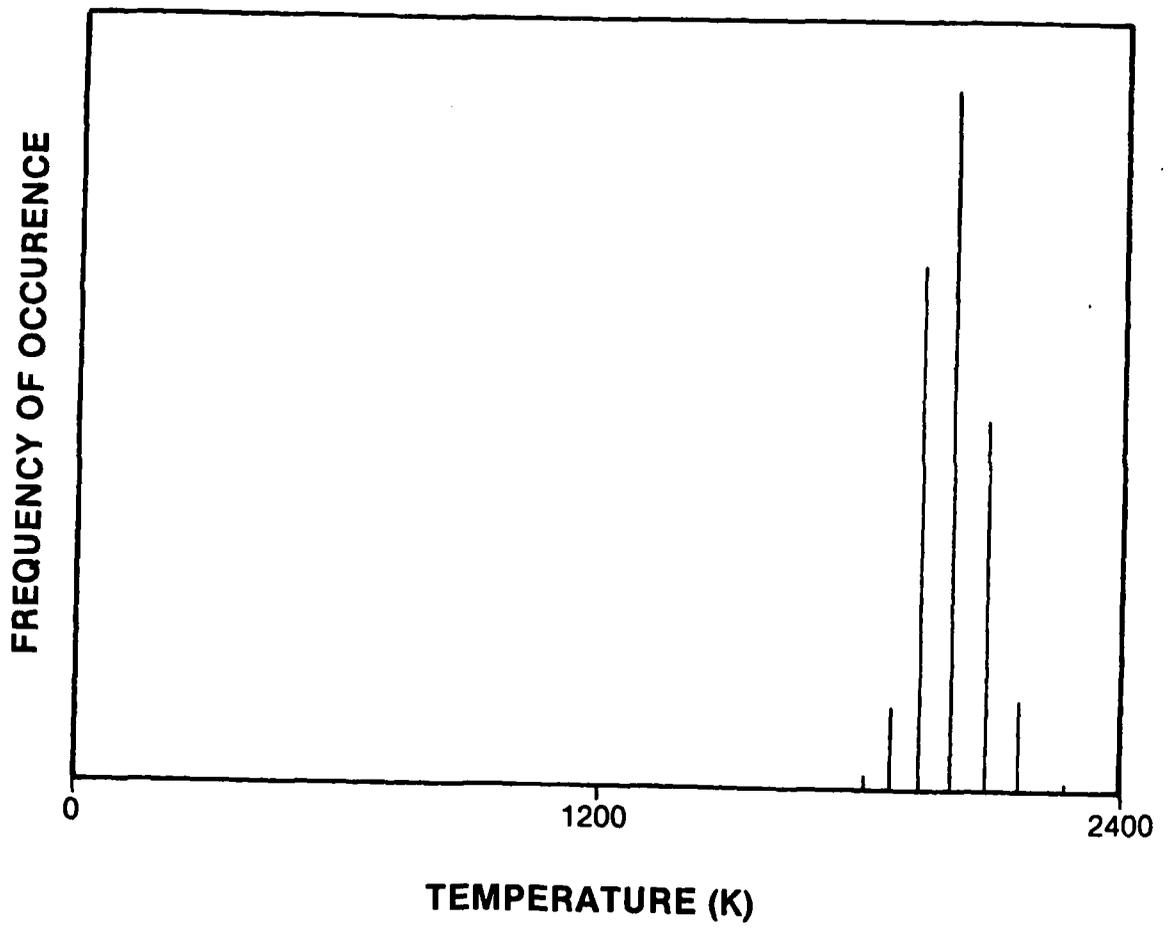


Figure 12. Probability Distribution Function of Measured Temperatures Corresponding to Center Position of Fig. 11.

## Section V

### RECOMMENDATIONS

The present application of the OLD technique represents the first attempt in this laboratory to acquire high-rep-rate temperature data. Many areas of improvement are evident. Numerous alternative combinations of high-rep-rate lasers and target materials are possible. The present method requires significant post-processing, resulting in a delay between acquisition of the data and a display of the results. With an increase in conversion efficiency of optical-to-acoustic energy--or a decrease in the probe-beam noise level--peak-detecting electronics can be utilized to obtain an immediate reading of time (velocity) changes. In other words, a real-time display of gas temperature is feasible.

Figure 13 is a block diagram of a method of creating such a display. The output of the time-to-digital (T/D) converter can be fed directly into a digital storage unit (e.g., desktop computer) or processed in real time to arrive at an oscilloscope display of approximate temperature (no mass correction). Figure 14 is a schematic of the peak detector built for this effort. At the present time this circuit is too slow for reliable detection of the fast signal peak. Once a suitable method of peak detection has been found, the system of Fig. 13 can be implemented.

Figure 15 is a schematic of the T/D converter constructed for this effort. It consists of a high-speed ECL synchronous counter; the output is converted for TTL compatibility. Figure 16 is a proposed design of the scaler and function modules which perform the mathematics of Eq. (2). With the temperature probe at room temperature, the scaler amplifier is adjusted for a circuit output of 1 V. As the temperature in the probe region increases, the output varies in proportion to the temperature. That is, a 5-V output would represent 1500 K.

In addition to improvement in data-acquisition speed, it should be possible to make accurate measurements utilizing a single probe beam in the form of a thin uniform sheet. The fact that the laser probe beam is collimated would result in an image of the acoustic disturbance, as the disturbance travels from one

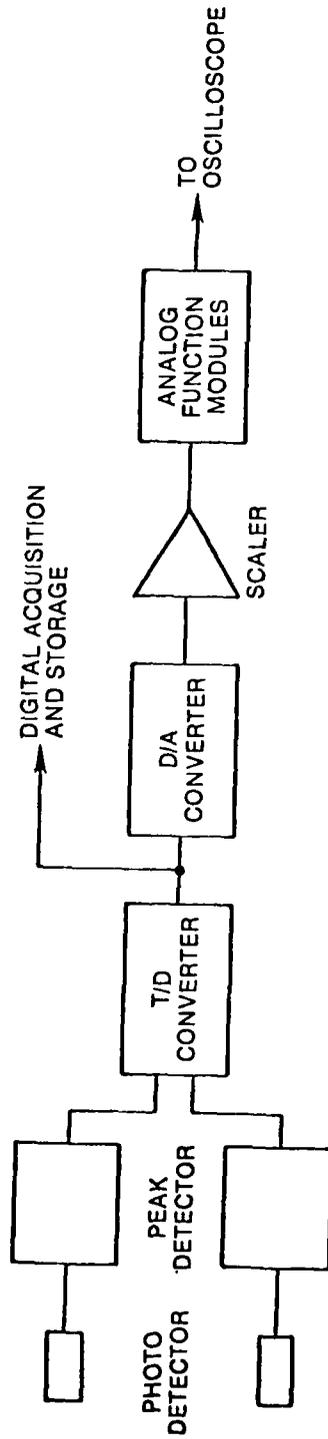


Figure 13. Block Diagram of Data-Acquisition Technique for Fast Temperature Recording and Real-Time Display.

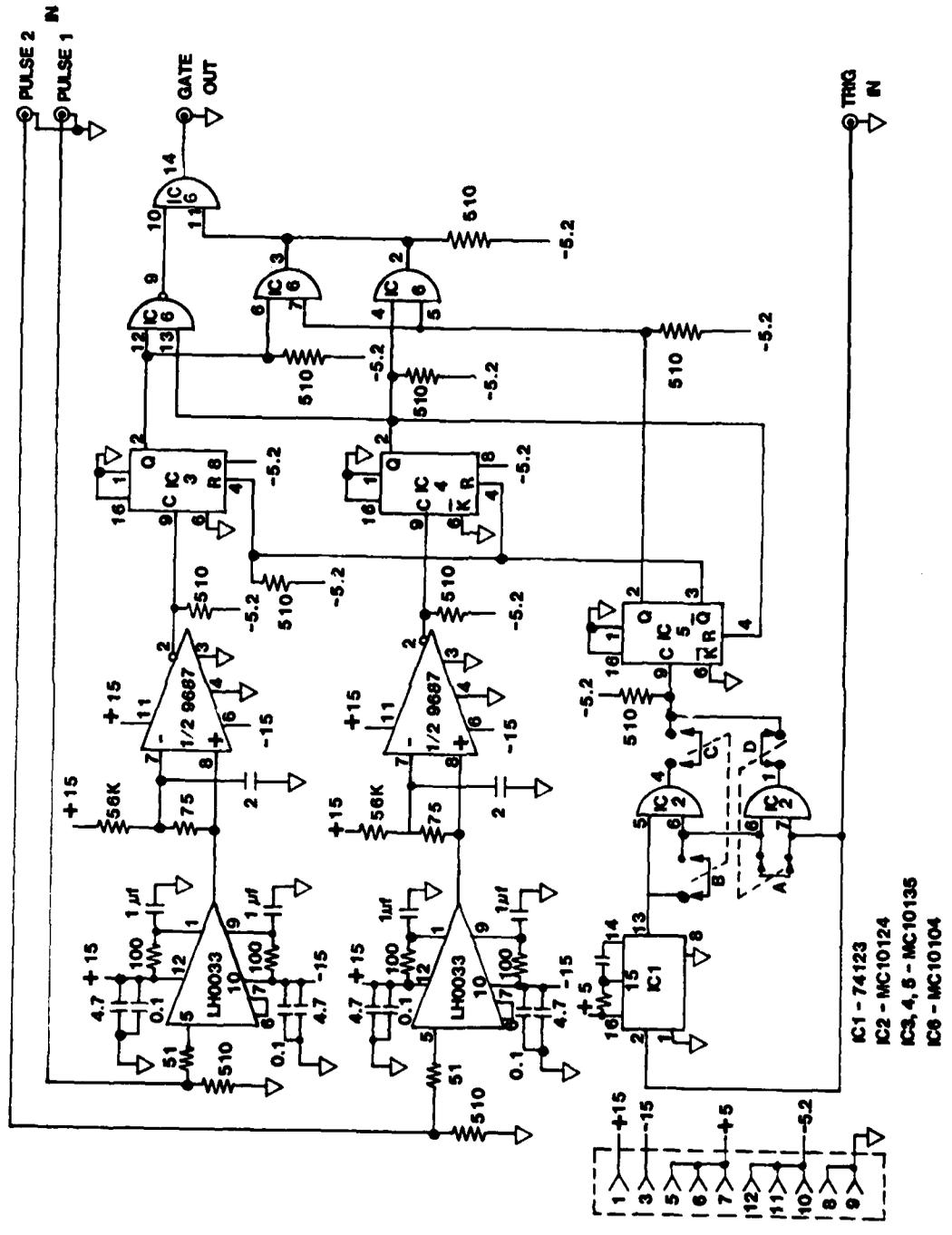
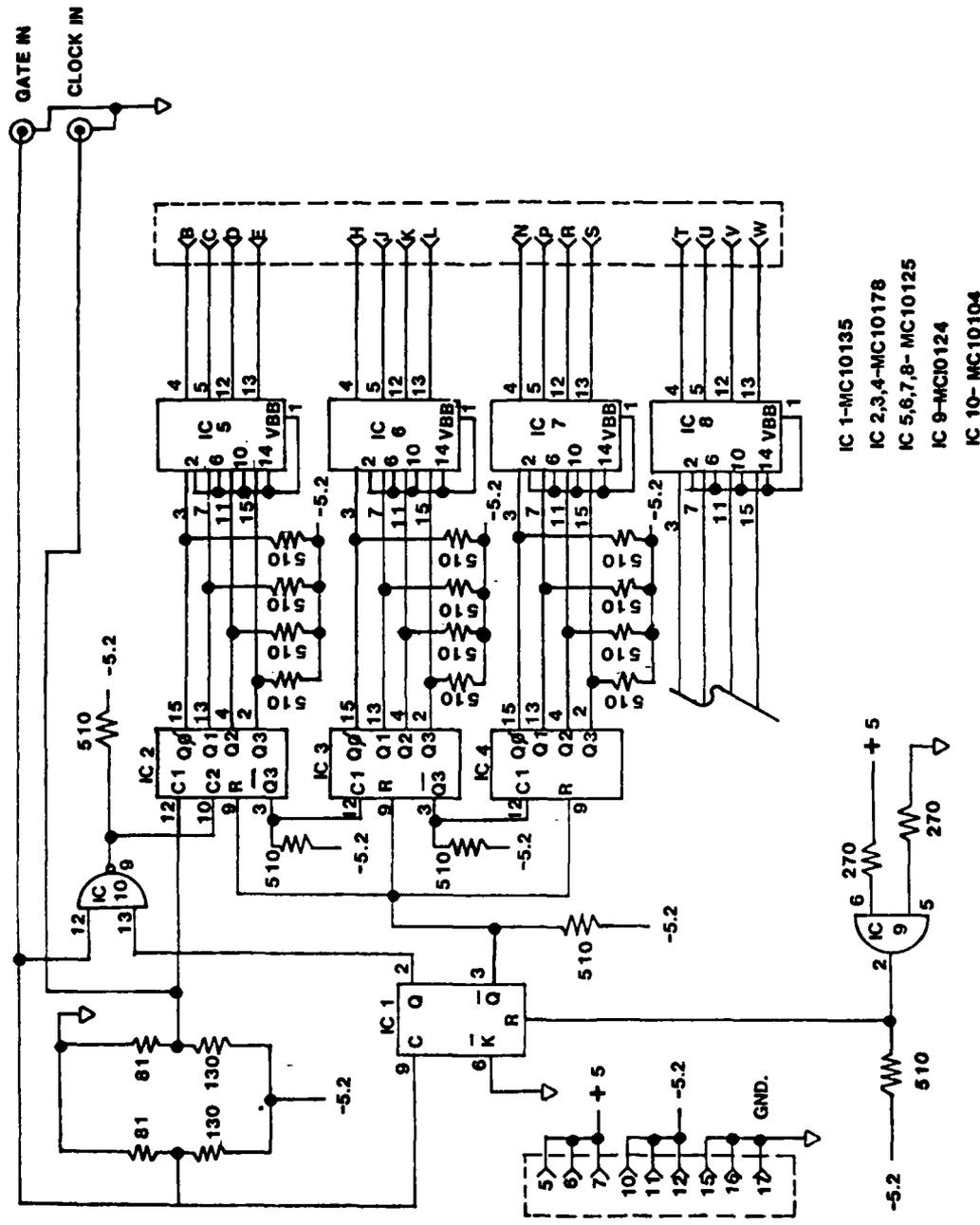


Figure 14. Electrical Schematic of Present Peak-Detector Circuit.



- IC 1-MC10135
- IC 2,3,4-MC10178
- IC 5,6,7,8-MC10125
- IC 9-MC10124
- IC 10-MC10104

Figure 15. Electrical Schematic of Time-to-Digital Converter Circuit.

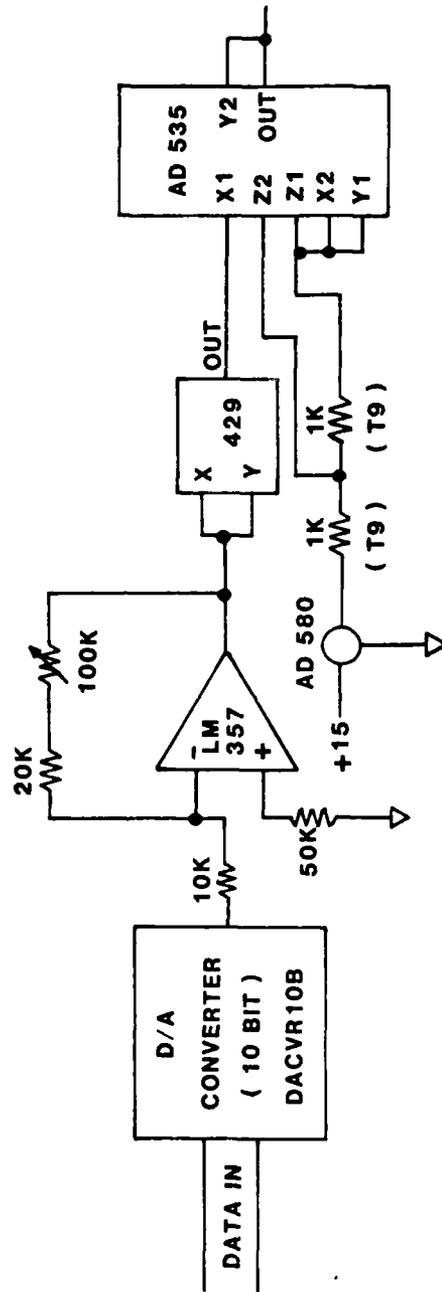


Figure 16. Electrical Schematic of Real-Time Oscilloscope Display Circuit.

edge of the beam to the other, appearing at the detectors. The measurement distance within the flame would then be proportional to the separation distance of the detectors. The major requirement of the single-beam method, however, is that the laser intensity be spatially uniform. Any nonuniformity will result in a dependence of the signal peak temporal position upon the probe-beam spatial position at the detectors. Beam wander, then, would introduce an uncertainty in the measurement point and, ultimately, in temperature determination.

The high-rep-rate application of the optoacoustic laser-beam deflection technique described here is the first demonstration of nonintrusive time-resolved temperature measurements in a flame. The relative ease of implementation and the ready availability of suitable pump sources results in this method having wide applicability in combustion diagnostics and modeling.

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