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DEVELOPMENT AND LABORATORY TESTING OF A THERMAL EMISSION VELOCIMETER (U)
AUG 81 J D TROLINGER, M J HOUSER F33615-76-C-3145

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DEVELOPMENT AND LABORATORY TESTING OF A
THERMAL EMISSION VELOCIMETER FOR APPLICATION
TO AN EROSION NOSE TIP TEST FACILITY

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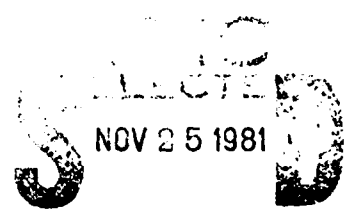
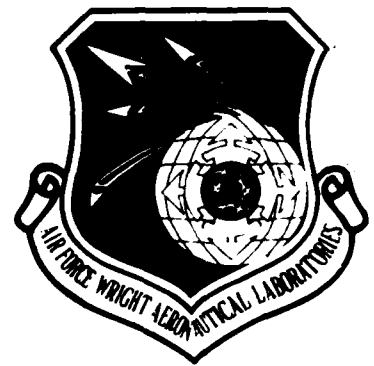
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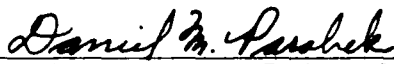
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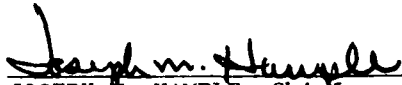
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) A thermal emission velocimeter concept was explored and a system was developed for use in measuring particle velocities up to 5,000 meters per second in a reentry erosion facility. The particles, ranging from 10 to 100 micrometers in diameter, are generated at the Flight Dynamics Laboratory to study reentry nose tip erosion and ablation. The approach passively utilizes optical components of a laser transit anemometer coupled to a microprocessor data management system. The system was laboratory tested and has inherent characteristics which should produce quality data in the severe and noisy environment of a reentry test.		

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facility. The system sensitivity has been calculated to measure velocity of micrometer sized particles whose temperatures are minimally 1700°K.

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FOREWORD

This report was prepared as part of a scientific investigation principally carried out by Dr. James Trolinger of Spectron Laboratories, Inc. of Costa Mesa, California as visiting scientist under the University of Dayton Air Force Contracts F33615-76-C-3145 and F33615-79-C-3030. The performance period was July 1979 through November 1980. This work was an element of in-house Work Unit 24041307, "Development of Testing Techniques and Aero-Optical Diagnostics to Advance Aerodynamic Ground Simulation" of Task 240413, "Aerodynamic Ground Test Technology".

Mr. Daniel M. Parobek of the Experimental Engineering Branch of the Aeromechanics Division was contract monitor and principal investigator of the in-house work unit.

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LIST OF SYMBOLS

A_p	= particle projected area
d	= fiber final image diameter
d_o	= fiber diameter
d_1	= fiber first image diameter
$E_{b(\lambda_1-\lambda_2)}$	= energy in bandwidth $\lambda_2-\lambda_1$
F_o	= focal length of lens zero
F_1	= focal length of lens one
F_2	= focal length of lens two
l	= effective final image length
r	= distance from optical axis to fiber final image centerline
r	= distance from optical axis to fiber centerline
r_o	= distance from optical axis to first image centerline
r_1	= distance from optical axis to first image centerline
s	= final image centerline separation
s_o	= fiber optic centerline separation
$\bar{V}$	= velocity
σ	= radiation constant

LIST OF FIGURES

1. Thermal Emission Velocimeter System
2. Analyzing Sample Space
3. Thermal Emission Velocimeter - Laboratory Test

LIST OF TABLES

- I TEV System Parameters
- II TEV System Specifications

I. INTRODUCTION

In reentry test facilities which simulate the erosion of nosetips by impact of small particles, a key diagnostic capability is the measurement of the velocity of the particles since, at the present time, it is not possible to predict this velocity with sufficient accuracy. A number of attempts to achieve such measurements have met varying degrees of success. The approaches have included:

1. Multiple exposure holograph and photography
2. Streak Photography
3. Laser Doppler Velocimetry
4. Active Transit Anemometry
5. Thermal Emission Velocimetry (Passive Transit Anemometry)
6. Trapping the particles in beeswax

None of these has advanced to a highly refined state, even though they have been pursued in at least ten laboratories in the USA for the past ten years. The difficulty of the problem can be summarized by the following set of conditions which are faced:

1. Velocities up to 5000 m/sec.
2. Particle sizes down to 10 micrometers diameter.
3. Extremely harsh environments relative to acoustic noise, contamination, electromagnetic fields, mechanical vibrations, and high temperatures.

4. Short run times (a few seconds)
5. High turbulence and ambient light
6. Limited sensor access at the periphery of the test flow.

Each of the above mentioned velocity measurement methods has been used with some success. However, the data is normally of questionable quality and accuracy and is normally not extensive; that is, too few data points are collected per run.

In a previous development, a 3-spot version of an active transit anemometer was used to calibrate a particle acceleration system to velocities of 4500 m/sec. This was in preparation for its mating with the Flight Dynamics Laboratory (FDL) Re-Entry Test Facility (RENT)⁽¹⁾. While the system produced usable data, refinements of the known shortcomings would produce greater amounts of more accurate data. Subsequently, a counter-fringe type velocimeter was also developed with the capability of processing 5000 m/sec particle velocity data. However, both of these approaches would require considerable development to assure successful acquisition of high quality and data rate velocity information due to the harsh RENT environment and the inaccessibility to the test area during testing.

However, an approach inherently less sensitive to the harsh environment and capable of being remotely located and controlled during the run would be advantageous. This infers a passive approach with elimination of the need for a high powered laser and related beam controlling optics. This can be accomplished by transmitting signals, via fiberoptics, to remotely located photo detectors. Recently, a system which has this potential and is known

as a Thermal Emission Velocimeter was developed and used successfully at AEDC⁽²⁾. The system looks optically at two points in space. When a hot particle passes through the two points, its thermal emission is detected and timed. Knowing the time and distance between two points leads to velocity.

This concept has been adapted with existing hardware into a device which has been successfully laboratory tested and ready for testing in a facility. This report describes the system and its current status.

II. SYSTEM DESIGN AND TESTS

General

Figure 1 illustrates the system concept and layout. To assemble the system, an old Spectron Development Laboratories, Inc. (SDL) transit anemometer was used⁽³⁾. Normally, the system projects two focused beams in space and collects return scattered light into two spot sensors. A rotating prism assembly provides for rotation of the spots. This was readily adaptable for TEV measurement.

Since the system is passive, transmitted light is unnecessary. The imaged points are rotated by the prism assembly to precise alignment with the flow. The points are imaged on two apertures which limit the image space volume (sample volume).

Electrical noise has presented a serious obstacle in previous tests. To reduce this, the optical signal is carried through fibers to a control room, suffering little loss of signal over the 75-foot length.

In addition to solving the electrical noise problem encountered with high-speed, sensitive electronics, it also brings the signal to a place where the operator can safely work and make instrument adjustments and decisions during a test.

At this point, the light enters two photodetectors, the outputs of which can be observed on an oscilloscope. The outputs are also fed to an interval timer which determines the length of time between the two pulses generated by a particle passing through the two sensed regions in space.

TEV SYSTEM

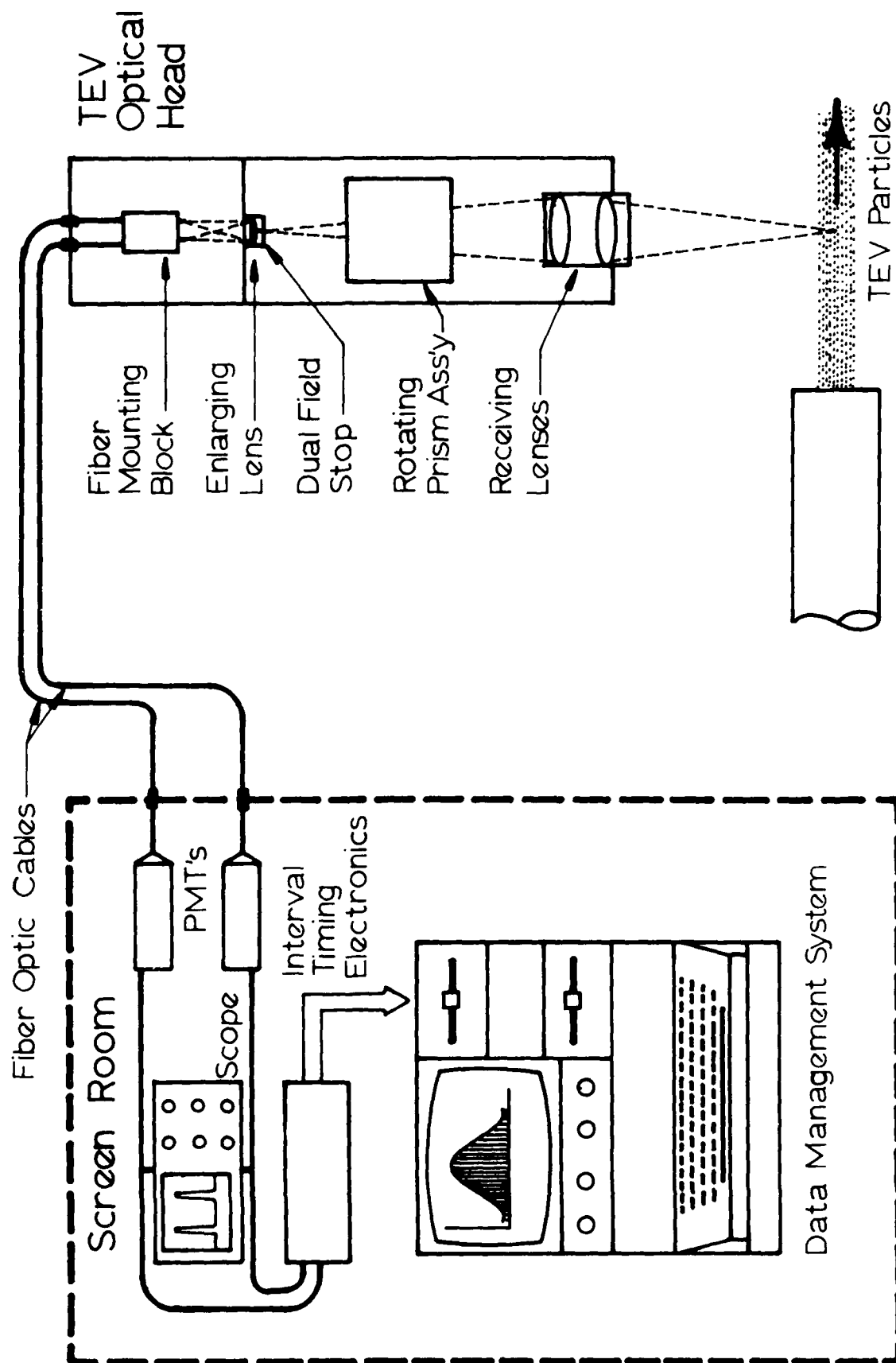


Figure 1. Thermal Emission Velocimeter System

The signal is then fed to a microcomputer which stores the signals on disks. The problem then becomes one of data interpretation and analysis.

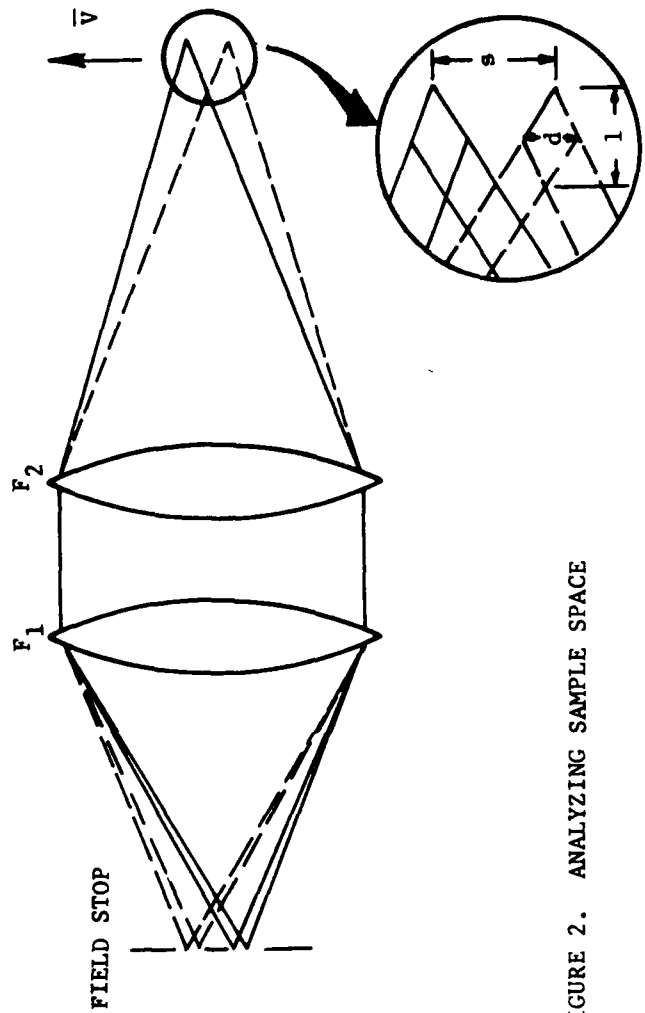
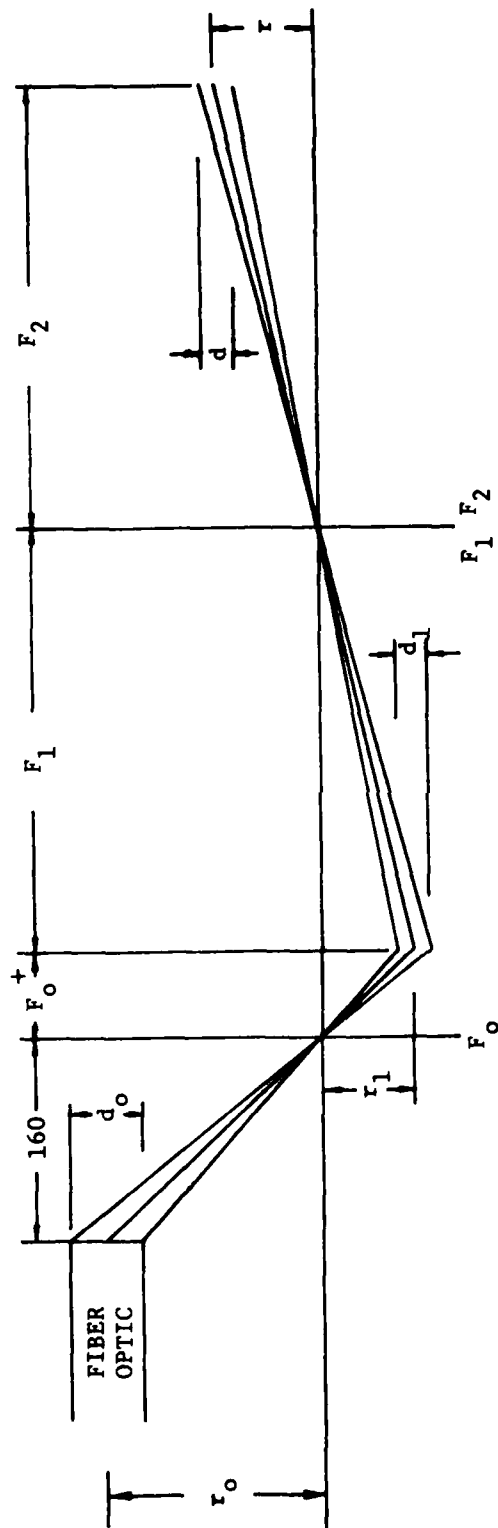
Optics

Figure 2 shows the optical system layout with a corresponding equation to determine the sample space. The geometrical sample volume is shown in the lower right-hand inset with spots separated by S and with length ℓ . The design problem is to make the spots far enough apart to provide accurate time measurement with the counter, to keep the sample volume small enough to contain less than two particles (on the average), to reject light outside the sample volume, and to collect efficiently as much light as possible from the sample volume. Table I lists a set of parameters and resulting transit times and sample volumes.

The optical system was assembled and laboratory tested by illuminating the input with an LED driven by a signal generator. These confirmed the system design to a limited extent.

There are some potential problems which are impossible to test in the laboratory. These include:

- (a) High turbulence in a test flow could create image distortion, increasing sample volume size and changing spot separation.
- (b) Large particles outside the geometrical sample volume could possibly be detected even though most of their light is blocked by the stops. A threshold setting must be adjusted during shakedown facility testing to limit these.



$$\frac{d}{d_o} = \frac{r}{r_o} = \frac{F_2}{F_1} = \frac{F_o}{160}$$

$$s = 2r$$

FIGURE 2. ANALYZING SAMPLE SPACE

- (c) A particle could pass through one detected spot and not through the other. The spot alignment capability of this instrument should minimize this problem. These occurrences should provide numbers which are random size and removable by correlation of the stored data.
- (d) Thermal emission quantity is still debatable. Since particle temperatures are not well known, the amount of illumination available for detection is debatable. Also, there is some question whether the detected illumination in AEDC tests was from thermal or chemical sources.

Electronics

There were several approaches to the electronics problem. The detected signal could be correlated directly providing on-line data filtering. Since a fast correlator may not be available, this concept was set aside.

The signal and velocity can be observed on an oscilloscope. In Brayton's original work, the oscilloscope screen was photographed by a high-speed camera to provide fast data retrieval and storage. Although this technique will not be set aside entirely, an alternate data storage method was chosen.

The data can be stored in the memory of a microcomputer and later dumped onto a disc, after which any amount of processing can be performed. To try this method, a Hewlett Packard 5345A Electronic Counter was acquired and interfaced to the system. The signals first pass through a high-speed discriminator which improves signal to noise and locates the center of the pulse. It then is fed to the HP 5345A. The output of the HP 5345A was interfaced to an Apple II microcomputer and tested. The overall system worked well (after some refinement) in all laboratory testing done.

This method will process a rate of velocity data points to about 500 per second. This is significantly less than could be handled by a fast correlator. However, if data quality is good, it should provide ample statistics. The rate is limited by how fast the counter can output data to the micro-computer.

The testing of the system also included the fiber optic link since an LED was used to simulate the particle transit. The fiber optics performed without any problem. Figure 3 shows the complete system as laboratory tested.

Table II lists the system specifications. The system should be easy to install. It will require a mounting point and be aimed at the nozzle center. It is currently designed to set 622 mm from the nozzle centerline, but this is somewhat flexible in that an alternate F_2 could be chosen.

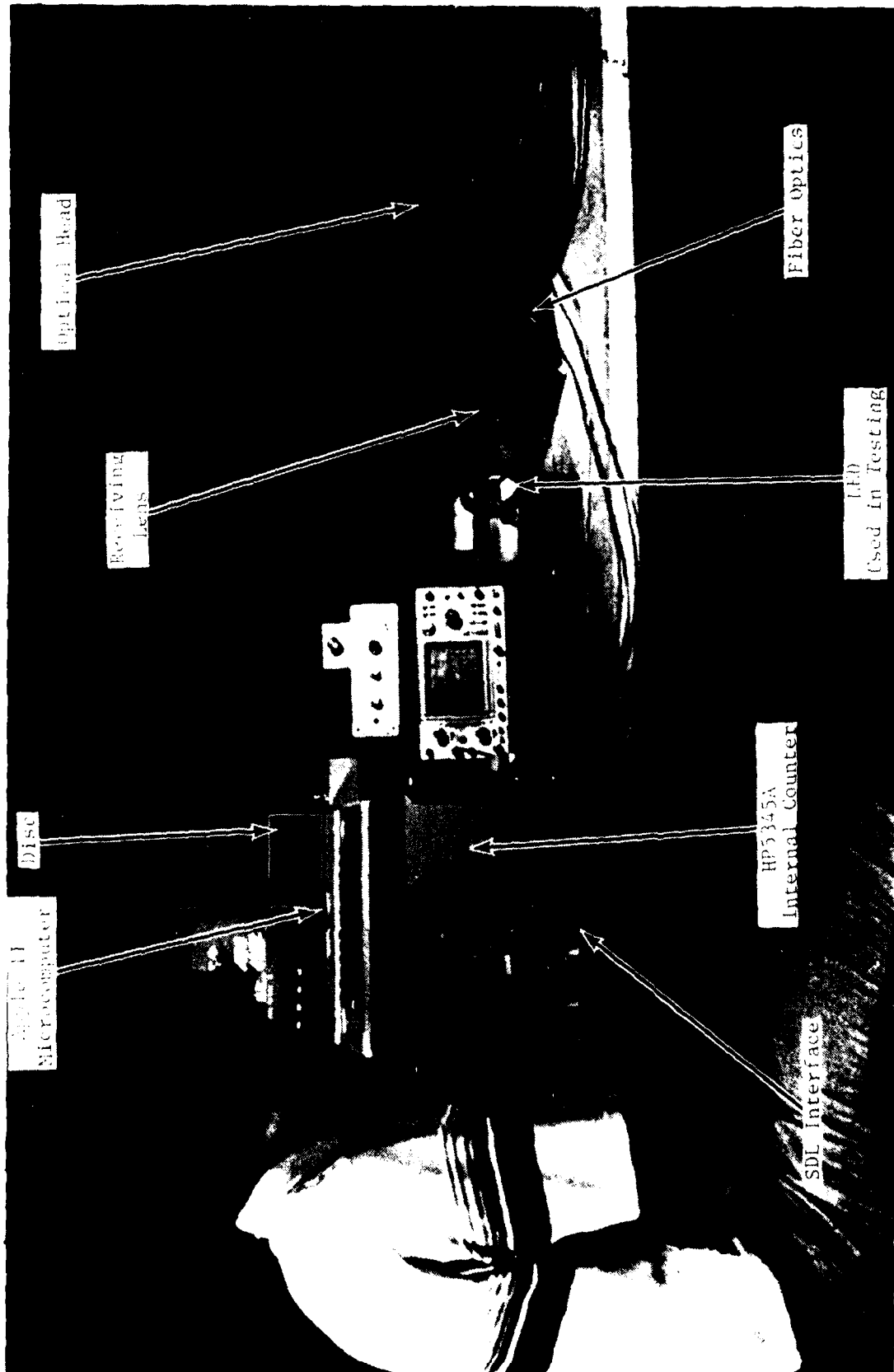


Figure 3. Thermal Emission Velocimeter - Laboratory Test

TABLE I
TEV SYSTEM PARAMETERS

s_0 (mm)	F_0^+ ($\frac{1}{160}$)	s (mm)	d (mm)	Approx. Probe Vol. (mm ³)	$\frac{s}{d}$	Transit Times (usec)		
						$V=8000$ f/s	$V=12000$ f/s	$V=15000$ f/s
6	2.5	3.91	.150	12.3	26	1.60	1.07	0.86
7	2.5	4.56	.150	14.3	30	1.87	1.25	1.00
8	2.5	5.22	.150	16.4	35	2.14	1.43	1.14
6	7	1.40	.054	1.1	26	0.57	0.38	0.31
7	7	1.63	.054	1.3	30	0.67	0.45	0.36
8	7	1.86	.054	1.5	35	0.76	0.51	0.41

TABLE II
TEV SYSTEM SPECIFICATIONS

OPTICAL HEAD

$L \times W \times H = 36" \times 7" \times 9"$

$F_1 = 622 \text{ mm (24.5")}$

$F_2 = 381 \text{ mm}$

Fibers: Valtec PC10 fused silica, medium loss, 230 μm core diameter

DATA ACQUISITION/MANAGEMENT

PMT: (2) EM1 type 9781R (extended spectral response 185 - 750 nm)

Signal Processing:

- (a) high speed photography of oscilloscope signals
- (b) pulse discrimination combined with interval timing

Apple II Microcomputer:

- (a) control of image rotation
- (b) control of interval timer
- (c) storage of individual transit times
- (d) processing and display of velocity distributions

SAMPLE OPTICAL CONFIGURATIONS

$d_o = \text{fiber core diameter} = .230 \text{ mm}$

$s_o = 2 r_o = \text{fiber separation}$

assume $\lambda \sim \begin{cases} 1 \text{ mm for } 7x \\ 2 \text{ mm for } 2.5x \end{cases}$

Basic Requirement

The radiant emission available per particle and the system sensitivity to that emission are critical factors affecting the successful operation of the device. The nominal particle diameter is taken as 100 nm at a temperature of 3000° K and blackbody radiation is assumed. The radiant emission from such particles within the spectral response limits (185 - 750 nm) of the photodetector is found to be

$$E_{b(\lambda_1 - \lambda_2)} = \sigma T^4 \left[\frac{E_{b(o-\lambda_2)}}{E_{b(o-\infty)}} - \frac{E_{b(o-\lambda_1)}}{E_{b(o-\infty)}} \right]$$

with

$$\sigma = 5.7 \times 10^{-8} \text{ W/m}^2 \text{ } ^\circ\text{K}^4$$

$$\lambda_1 = 185 \text{ nm}$$

$$\lambda_2 = 750 \text{ nm}$$

gives

$$E_{b(\lambda_1 - \lambda_2)} = 14780 \text{ W/m}^2$$

Taking into account the projected area of a 100 μm diameter particle,

$$A_p = \frac{\pi}{4} (100 \mu\text{m})^2 = 7.85 \times 10^{-9} \text{ m}^2$$

the transit time of a particle through a single sensing region of the TEV,

$$t = \frac{100 \times 10^{-6} \text{ m}}{4572 \text{ m/s}} = 21.9 \text{ nsec}$$

and the fraction of emission incident on the collection lens,

$$= \frac{\pi (38.1 \text{ mm})^2}{4\pi (622 \text{ mm})^2}$$

$$\text{F.L.} = 622 \text{ mm}$$

$$= 0.001$$

$$\text{DIA.} = 76.2 \text{ mm}$$

gives the energy input to the system as

$$\begin{aligned} E &= (14780 \text{ W/m}^2) (7.85 \times 10^{-9} \text{ m}^2) (21.9 \times 10^{-9} \text{ sec}) (.001) \\ &= 2.5 \times 10^{-15} \text{ joules/particle transit.} \end{aligned}$$

Assuming 50% optical efficiency and 10% quantum efficiency of the PMT with a cathode sensitivity of 57 mA/W, a gain of $.8 \times 10^6$, 50 Ω across the output and a 10X preamplifier gives 120 mV/pulse. This is more than ample light for detection and sufficient pulse amplitude to satisfy the discriminator threshold requirement. However, since particle emission varies as T^4 and the square of the diameter, the actual test facility particle conditions will play a crucial role in successful system functioning.

Laboratory experiments to determine a temperature threshold suggested that this device, without further modification, could detect about 2.5×10^{-16} joules/transit. Using the energy versus temperature relationship on the previous page gives a temperature equal to approximately 1700° K.

III. CONCLUSIONS

Based on the studies and computations presented herein, it is believed that a thermal emission velocimeter can provide required velocity data from the ERNT facility. The system removes some of the most serious problems encountered in the past.

Since it is a passive system, it does not depend on projecting anything into the flow. Therefore, it is much simpler. No laser safety problems exist. Since the light is conducted by fibers to a control room, the electronics problem is relaxed. An operator can monitor everything during the test.

Several options in data collection remain open. System installation should be the simplest.

The primary concern is the unknown particle temperature, a critical parameter for system operation.

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