



National Aeronautics and
Space Administration

NASA CR-185595

Lyndon B. Johnson Space Center
Houston, Texas 77058

DEMONSTRATION OF THE FEASIBILITY OF LASER INDUCED FLUORESCENCE FOR ARC JET FLOW DIAGNOSTICS

Job Order 83-102

(NASA-CR-185595) DEMONSTRATION OF THE
FEASIBILITY OF LASER INDUCED FLUORESCENCE
FOR ARC JET FLOW DIAGNOSTICS (Lockheed
Engineering and Sciences Co.) 29 p CSCL 07D

N90-16013

Unclas
G3/25 0256751

Prepared By

Lockheed Engineering & Sciences Company
Houston, Texas

Contract NAS 9-17900

For

STRUCTURES AND MECHANICS DIVISION

And

ADVANCED PROGRAMS OFFICE

October 1989

LESC-27642

1974

1975

•

•

•

•

DEMONSTRATION OF THE FEASIBILITY OF LASER INDUCED FLUORESCENCE
FOR ARC JET FLOW DIAGNOSTICS


Job Order 83-102

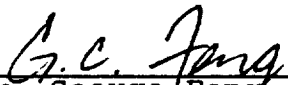
PREPARED BY

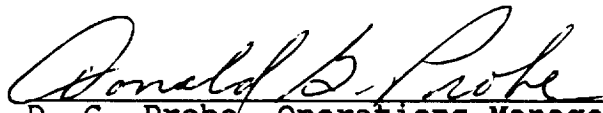

Sivaram Arepalli

APPROVED BY

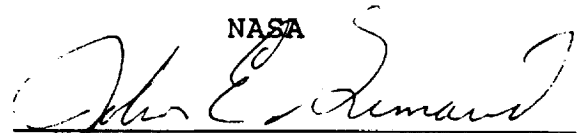
LESC

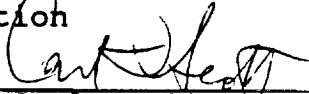

T. M. Heaton, Engineering Supervisor
Experimental Heat Transfer Section

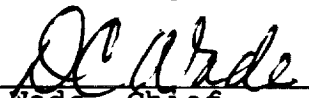

Dr. George Feng, Engineering Manager
Systems Engineering Department


D. G. Probe, Operations Manager
Structures and Mechanics
Department

NASA


John Grimaud, Head
Experimental Heat Transfer
Section


Dr. Carl Scott,
Aerothermodynamics Group
Leader
Advanced Programs Office


Don Wade, Chief
Structures and Mechanics
Division

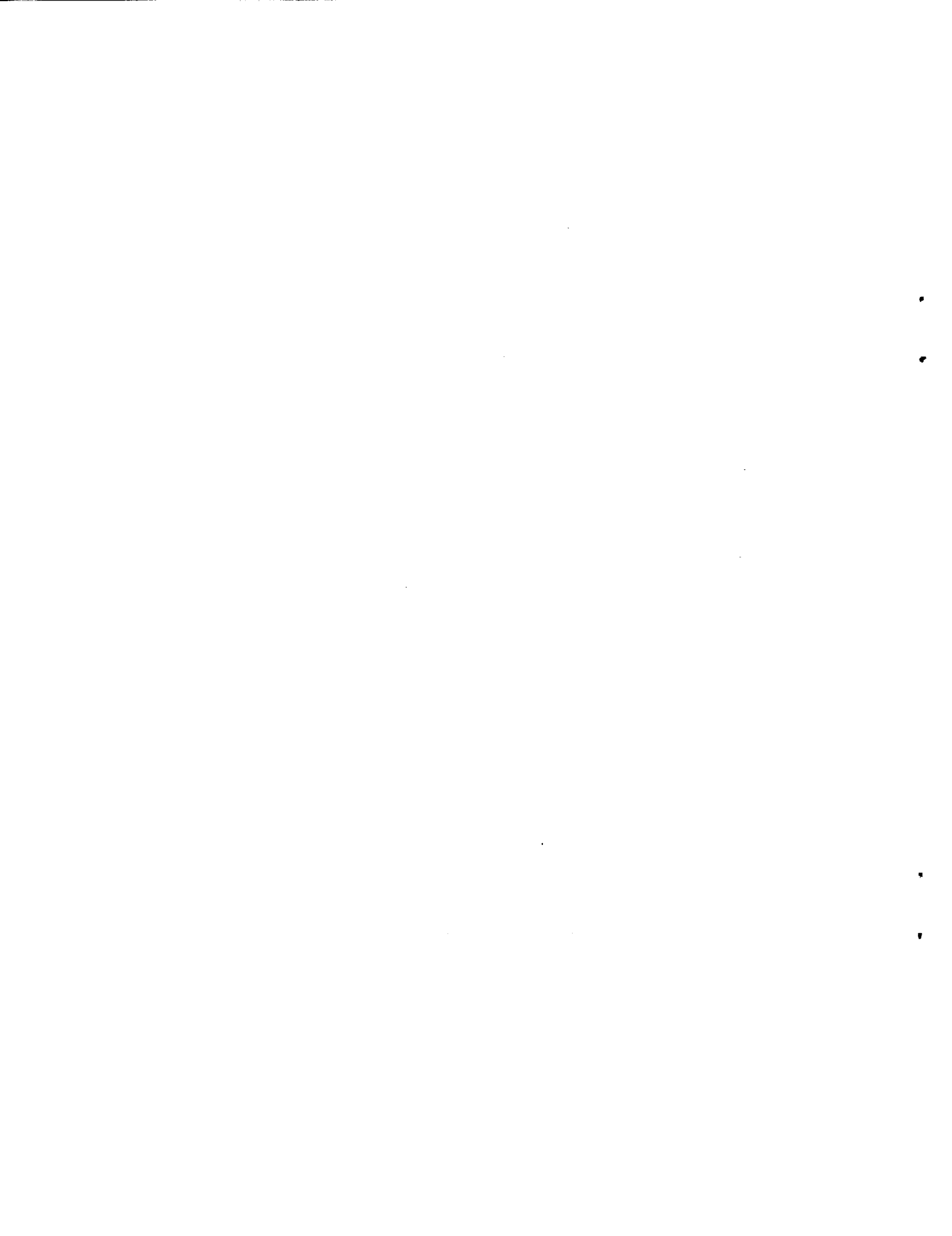
Prepared By
Lockheed Engineering and Sciences Company

For
Structures and Mechanics Division
And
Advanced Programs Office

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LYNDON B. JOHNSON SPACE CENTER
HOUSTON, TEXAS

October 1989

LESC-27642





National Aeronautics and Space Administration
Lyndon B. Johnson Space Center

REPORT DOCUMENTATION PAGE

1. Report No. NASA CR-185595		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle DEMONSTRATION OF THE FEASIBILITY OF LASER INDUCED FLUORESCENCE FOR ARC JET FLOW DIAGNOSTICS				5. Report Date October 1989	
				6. Performing Organization Code	
7. Author(s) Sivaram Arepalli Lockheed Engineering and Sciences Company				8. Performing Organization Report No. LESC-27642	
				10. Work Unit No.	
9. Performing Organization Name and Address Lockheed Engineering and Sciences Company 2400 NASA Road One Houston, TX 77058				11. Contract or Grant No. NAS 9-17900	
				13. Type of Report and Period Covered Contractor Report	
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Lyndon B. Johnson Space Center Houston, TX 77058				14. Sponsoring Agency Code	
				15. Supplementary Notes	
16. Abstract Laser Induced Fluorescence (LIF) studies are carried out on nitric oxide and oxygen molecules in the arc jet flows at the NASA Johnson Space Center Reentry Testing Facility. Measurements are taken in the free stream and from a blunt body shock layer. Tests are performed under different flow conditions to determine the feasibility and sensitivity of the LIF technique for various species. This is developed as a part of high enthalpy flow diagnostics and will be useful to elucidate the rotational and vibrational temperatures. Adequate sensitivity for the detection of O ₂ and NO is demonstrated. Proposed improvements of the existing system are presented.					
17. Key Words (Suggested by Author(s)) Laser Induced Fluorescence Flow Diagnostics Reentry Testing Arc Jets			18. Distribution Statement Unclassified - unlimited		
19. Security Classification (of this report) Unclassified		20. Security Classification (of this page) Unclassified		21. No. of pages 30	22. Price

For sale by the National Technical Information Service, Springfield, VA 22161-2171

NASA-JSC

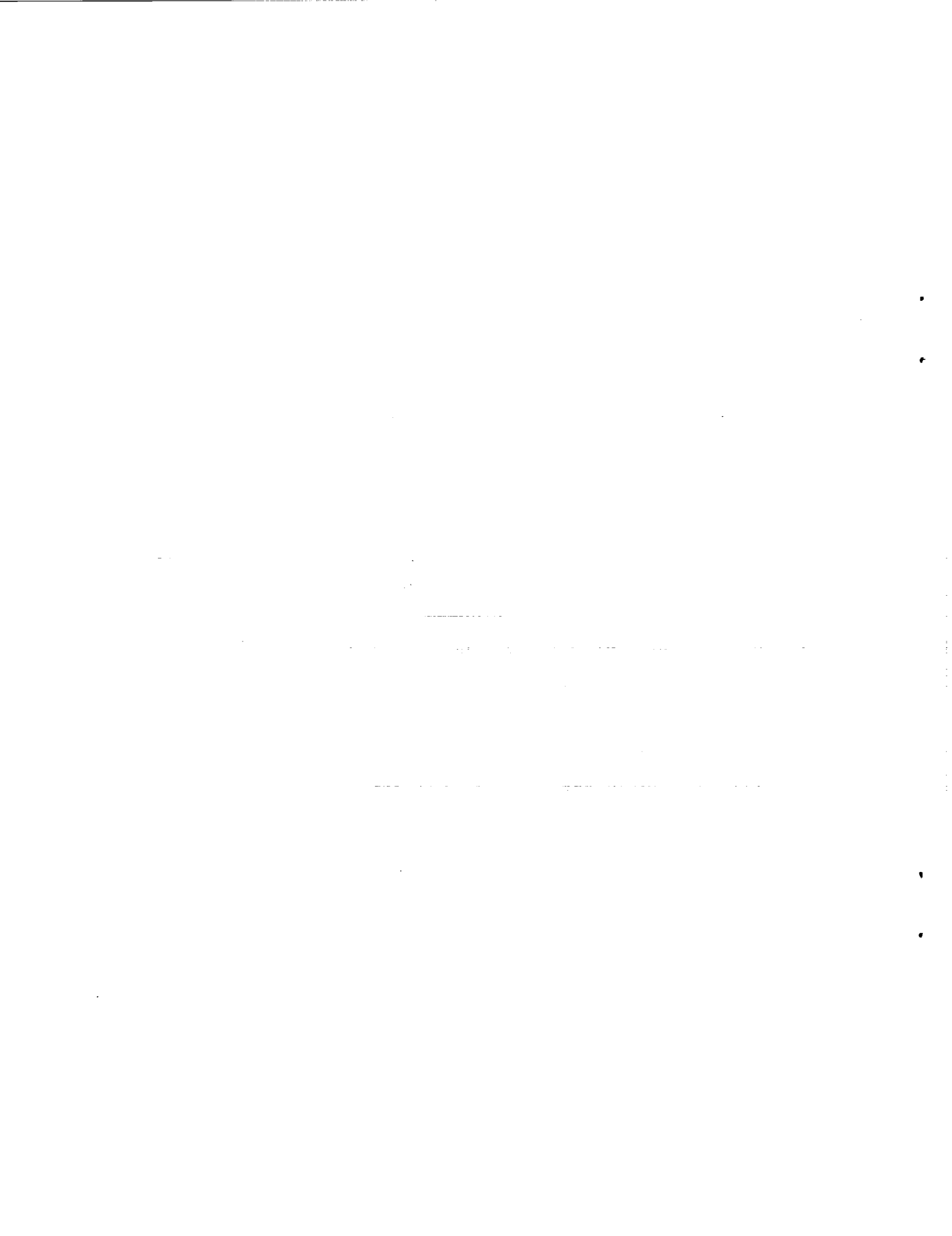
JSC Form 1424 (Rev Jan 88) (Ethernet Jan 88)

CONTENTS

<u>Section</u>	<u>Page</u>
ABSTRACT	1
1. INTRODUCTION	2
2. EXPERIMENTAL DETAILS	4
2.1 The Facility and the Flow Conditions	4
2.2 The Laser System	5
2.3 Detection and Control Electronics	7
3. RESULTS	11
4. FUTURE PLANS	13
5. CONCLUSIONS	13
6. REFERENCES	15

FIGURES

1. Energy Level Diagrams for NO, O and O ₂	18
2. LIF Experimental Setup	19
3. Electronics Block Diagram	20
4. Variable Delay Double-Pulse Generator	21
5. Timing Diagram for LIF Data Collection	22
6. LIF of (0,0) Band of NO (A-X) in the Free Stream; 1500 BTU/lb	23
7. LIF of (0,0) Band of NO (A-X) in the Free Stream under Different Enthalpy Conditions	24
8. LIF of O ₂ (B-X) in the Shock Layer of a Blunt Body at an Enthalpy of 1500 BTU/lb	25



DEMONSTRATION OF THE FEASIBILITY OF LASER INDUCED FLUORESCENCE
FOR ARC JET FLOW DIAGNOSTICS

ABSTRACT

Laser Induced Fluorescence (LIF) studies are carried out on nitric oxide and oxygen molecules in the arc jet flows at the NASA Johnson Space Center Reentry Testing Facility. Measurements are taken in the free stream and from a blunt body shock layer. Tests are performed under different flow conditions to determine the feasibility and sensitivity of the LIF technique for various species. The LIF technique is developed as a part of high enthalpy flow diagnostics and will be useful to elucidate the rotational and vibrational temperatures. Adequate sensitivity for the detection of O_2 and NO is demonstrated. Proposed improvements of the current system are presented.

1. INTRODUCTION

There is a strong need for non-intrusive diagnostic techniques to be developed for the arc jet flow studies in order to fully understand the non-equilibrium flow conditions the spacecrafts encounter during the reentry. The arc jet facilities simulate the spacecraft reentry conditions and are used for testing the thermal protection materials. A complete characterization of the arc jet non-equilibrium flows is necessary for determining the effects of atom recombination on thermal protection materials in order to understand the convective and radiative heat transfer to the spacecraft during reentry (Ref. 1-8). The non-equilibrium flow studies require the measurement of the concentration, velocity and temperatures of the different atomic, molecular and ionic species present in the arc jet flows. The major species of interest under the spacecraft reentry flow environment are: N_2 , O_2 , NO , N , O , N_2^+ , O_2^+ , NO^+ , N^+ , O^+ and electrons. Concentrations of these species change when the enthalpy of the flow changes. At low enthalpy, O_2 is dissociated almost completely and a substantial NO concentration is expected (up to a few percent mole fraction) in the flow. At high enthalpy, the concentration of NO decreases (fraction of a percent) and N_2 is also dissociated. The arc jet flow diagnostics at NASA/JSC reported previously included emission studies (Ref. 6-8). Light was collected from the flow field, and using various simulation techniques, the data was analyzed to obtain the temperatures. The drawbacks of this technique are :

- 1) For this line of sight method of collection, it is difficult to

define the spatial region of the emitting species, 2) The collection is typically averaged over different layers of the flows, 3) Only intense light emitting species can be monitored and 4) Long averaging times (few seconds) are needed to obtain adequate signal. With the use of photodiode arrays and some special optical collection arrangements, even with the emission studies, it is now possible to obtain information regarding temperatures across the shock layer of nitrogen discharge flows. The latest presentations (Ref. 6-8) describe the nature and complexity of these problems. Calculated spectra are compared with observed spectra to obtain information regarding rotational and vibrational temperatures. The uncertainty of excitation mechanisms in case of N_2^+ limit the usefulness of emission studies to determine temperature because of nonequilibrium. Similar problems exist for N_2 study as well (Ref. 9).

The initial LIF measurements reported here probe the different species with a known excitation mechanism using selective excitation with a narrow band laser. An attempt is made to test one-photon as well as two-photon schemes and the species under study are oxygen atoms, oxygen molecules and nitric oxide molecules (Fig. 1). Nitric oxide should be one of the easiest to measure because it is known that detection levels are lowest amongst the species of interest (Ref. 10). An attempt will be made to extend these studies to nitrogen at a later date because of more complexity is involved in probing the nitrogen atoms and molecules.

The arc jet facilities are normally large and the test cells are typically of the order of at least 2 or 3 meters in diameter. This test cell size requires the collection optics to be at least 2 or 3 meters away from the source, hence, adversely affecting the light collection efficiency and the application of multi-photon techniques which are common practice in smaller facilities. One can attempt to insert some optical elements (lenses or mirrors) inside the test cell, but they will be exposed to very hostile environments such as the splash of hot gases and of water vapor from the steam ejector vacuum pump. The techniques that are being developed at NASA/JSC are applicable to other systems with similar hostile environments.

This report presents a preliminary study of the applicability of LIF techniques for arc jet diagnostics.

2. EXPERIMENTAL DETAILS

2.1 The Facility and the Flow Conditions

The diagnostic techniques described in this report are carried out in one of two test chambers (Test Position No.2) of the Atmospheric Reentry Materials and Structures Evaluation Facility (ARMSEF) which can be operated at powers upto about 10 MW. This facility is used primarily for testing thermal protection

materials and components used on spacecraft such as Space Shuttle Orbiter, the Apollo, etc.. Also, the facility is used for determining the catalytic atom recombination rates on materials (Ref. 1-3). The capabilities and uses of the dc-arc heated reentry testing facility was documented in an earlier report (Ref. 11). Typically, a mixture of N_2 and O_2 will be passed through a dc constricted arc (4-6 feet long) and the heated mixture is expanded through a conical nozzle into a vacuum chamber. The expanded flow thus acquires supersonic speeds and is called the free stream. If a test article is placed in the free stream, a shock wake and a shock layer are produced around the article. The arc current is adjustable from 200 to 1000 amps dc and the total gas mass flow rate can be from 0.01 to 0.5 lb/sec. A typical run-condition used in this LIF feasibility study, is given in Table 1. The experimental setup is shown in Fig. 2. The development of the plasma diagnostics for this facility has also been discussed in a variety of publications (Ref. 6-8).

TABLE 1

Arc current, amps	280
Gas flow rate, kg/sec	0.073
Total Enthalpy. MJ/kg	4.41
Free Stream Stagnation Pressure, Pa	0.0224

2.2 The Laser System

Laser Induced Fluorescence is obtained using a YAG pumped dye

laser system that generates tunable ultraviolet laser radiation. Remote capability and ease of operation prompted the selection of a pump wavelength of 355 nm and second harmonic generation of the dye laser output. The experimental setup is shown in Fig. 2. The YAG laser is a Quantel International* laser model no. 682-10 with a capability of retrofitting with a diode laser for single mode operation. Its specifications at 5 nsec pulse width are:

<u>Wavelength</u>	<u>Pulse Energy</u>
1064 nm	1200 mJ (bandwidth of 0.04 cm^{-1} or 0.005 nm)
532 nm	700 mJ
355 nm	250 mJ
266 nm	100 mJ

Typical pulse energy used is about 100-120 mJ for a 355 nm pump beam. The lower energy operation is dictated by the dye laser configuration as explained below.

A Lambda Physik** dye laser, model no. 3002E is used with different doubling crystals and an intracavity etalon. The dye laser is equipped with 355 nm and 532 nm pumping optics. A type I BBO crystal doubles the 450 nm dye laser radiation. The scanning of the dye laser is accomplished with a microprocessor based scan

* Quantel International, 3150 Central Expressway, Santa Clara, CA 95051.

** Lambda Physik, 289 Great Road, Acton, MA 01720.

control system mounted on the dye laser housing. The microprocessor can be triggered remotely and can be used under computer control. For the current studies, the microprocessor is programmed to scan the dye laser and used the external TTL (Transistor-Transistor-Logic) trigger to control the scans. One advantage of the Lambda dye laser is that the tilting of the doubling crystal is achieved passively using a curve-fit program and eliminates the "tracking" problems associated with the active feed back control. A Coumarin-450 (Coumarin 2) laser dye is used which has a wavelength scanning range of 430 to 470 nm. A typical experimental run has the following conditions:

pump laser wavelength = 355 nm	pulse energy = 120 mJ
dye laser wavelength = 450 nm	pulse energy = 12 mJ
doubled wavelength = 225 nm	pulse energy = 1.2 mJ
bandwidth of the doubled dye laser radiation = 0.01 nm	

No attempt is made to use much higher pump energies because of the danger of burning the grating inside the dye laser. Another grating to be obtained in the near future, will allow the use of full power of the YAG laser.

2.3 Detection and Control Electronics

The LIF setup requires a way of scanning the laser and recording either the excitation spectrum or a fluorescence spectrum. The simpler route of scanning the excitation spectrum is chosen. This

is achieved by collecting a particular wavelength band of the laser induced fluorescence while scanning the wavelength of the laser radiation. In the collection optics, two filters are used, an ultra-violet filter, Hoya U330 and a long pass filter, Schott R695#. For oxygen atoms, the fluorescence is at 777 nm and 845 nm (Ref. 12); for nitric oxide, it is from 225 to 400 nm (Ref. 13) and for oxygen molecule, it is from 225 to 540 nm (Ref. 14).

A Hamamatsu R955P photomultiplier tube (PMT) with S-20 spectral response was chosen for photon counting operation. It can withstand the strong background light from the plasma and shock layer present during the laser diagnostic runs. The maximum anode current rating of the R955P is 100 μ amps.. When operated in the photon counting mode, the maximum count rate is 166 MHz at 1000 V. The typical background rate from the free stream emission is approximately 100 counts/sec and from the shock layer is approximately 200,000 counts/sec (discriminator set at -20 mV) when a U330 filter is used and the PMT voltage set at -750 V. The count rate will go up by a factor of at least 10 when lenses are used to improve the light collection. The output of the PMT is fed directly to a Gated Photon Counter (Stanford Research Systems* model no. SR400). This instrument can be used to discriminate

Oriel Corporation, 250 Long Beach Blvd., Stratford, CT 06497.

@ Hamamatsu Corporation, 360 Foot Hill Road, Bridgewater, NJ 08007-0910.

* Stanford Research Systems, 1290 D Reamwood Avenue, Sunnyvale, CA 94089.

against the dark counts as well as to count only during a fixed time interval. Two independently selectable gates A and B can be used for background suppression. The A-gate is opened 500 nsec before the laser light pulse and is open for 10 μ sec. The B-gate is also opened for 10 μ sec but at a time delay of 1 msec. The output from the A-gate is directed to the X-Y recorder. The ramp voltage for the X-axis is provided by the dye laser. The B-gate is used to note the background counts and is operated both in the CW (open all the time) and gated mode. The CW mode facilitates to look at the background emission intensities and to keep track of the safety limits on the PMT anode current ratings.

The discriminator voltage for the photon pulses can be selected and it was basically determined by the signal to noise ratio. A typical set is :

<u>Discriminator Voltage</u>	<u>Dark counts</u> (Noise, N)	<u>Light counts</u> (Signal, S)	<u>S/N</u>
-10 mV	50	800	16
-20 mV	15	225	15
-30 mV	5	75	15
-40 mV	1	15	15

These tests were run with a tungsten lamp and a U330 filter on the PMT (operated at -650 V). Final operating conditions were however determined by the noise (RF) pickup from the laser as well as the dc arc heater. A discriminator voltage of -20 mV is selected and

the PMT operated at -750 V.

The basic electronic block diagram is shown in Fig. 3. A master pulse generator (Digital Delay Generator, Stanford Research Systems, model no. DG535) gives out a TTL pulse every 4 seconds and the dye laser moves to the next wavelength position with a step size of 0.02 nm, generates 35 trigger pulses at 10 Hz which are used to fire the YAG laser. The external triggering of the YAG laser is accomplished as follows. The trigger-out pulse from the dye laser initiates a charge-command pulse (5 V, 100 μ sec wide) to charge the capacitors in the flashlamp power supply of the YAG. Flashlamps are then fired using a second pulse generated with about 90 msec time delay. The variable delay double-pulse generator used is shown in Fig. 4. The YAG is then Q-switched after about 200 μ sec with a 15 V, 10 μ sec wide pulse generated from the internal circuitry of the YAG power supply. Photon counter is triggered with a pulse from the "variable Q-switch out" from YAG power supply. This pulse has an adjustable delay and is currently adjusted so that its rising edge is about 500 nsec before the light pulse. The laser light pulse is monitored using a fast photodiode (Electro-Optics Technology ϕ , model no. ET2000 with 200 psec risetime). There is an insertion delay of about 25 nsec in the gate generation of the photon counter. The A and B gates on the photon counter could be adjusted with different time

ϕ Electro-Optics Technology, Inc., 4057 Clipper Ct., Fremont, CA 94538.

delays and different time durations as indicated above. The timing diagram is shown in Fig. 5.

3. RESULTS

The LIF signal from NO (Fig. 6) in the free stream was obtained for a low enthalpy air flow (280 amp; 0.16 lb/sec; 2000 BTU/lb). Under these arc heater conditions, the mole fraction of NO is estimated to be about 4% (10^{15} /cc at the optic axis) using a single-temperature non-equilibrium nozzle flow code (NATA code, Ref. 15). The LIF was collected using a Hoya U-330 filter before a R955P photomultiplier tube biased at about -800 V. Coumarin-2 dye was used in the dye laser and a BBO crystal was used to generate the second harmonic of the dye laser output. The laser was scanned from 224.5 to 227.5 nm and the measured output pulse energy at the exit port of the dye laser was about 0.5 mJ. The excitation spectrum obtained for the NO fluorescence consists of lines belonging to the (0,0) transition of the A-X gamma band system (Fig. 1). This ${}^2\Sigma^+ - {}^2\pi$ (A-X) transition contains 12 branches ($P_{11}, P_{12}, P_{21}, P_{22}; R_{11}, \dots, R_{22}; Q_{11}, \dots, Q_{22}$) and forms four band heads. The two sub-bands arise because of the splitting of ${}^2\pi$ into ${}^2\pi_{1/2}$ and ${}^2\pi_{3/2}$ (Ref. 16). Figure 7 shows the LIF spectrum of NO under different flow conditions. Notice a decrease in the total number of counts with increasing enthalpy which agrees with the expected lower NO concentrations. Some changes in the rotational band contours point out the changes in the rotational temperature as well. These rotational bands will be pursued systematically in

the near future.

Strong LIF from O_2 is observed (Fig. 8) in the shock layer of a cooled copper blunt body, also under low enthalpy conditions. The O_2 measurement was taken at about 1 cm from the body. Dye laser was scanned from 225.25 nm to 227.25 nm and fluorescence was collected using a Hoya U-330 filter before a R955 photomultiplier tube. The applied voltage is about -750 V for the photomultiplier tube and discriminators are set at -20mV. The maximum LIF signal is about 350 counts, whereas the background signal from emission is only 1 or 2 counts (The curve in Fig. 8 however has been scaled up to be comparable with the NO spectra which were taken with a PMT voltage of -800 V).

The O_2 fluorescence is from Schumann-Runge band system (Ref. 16 and 17) and the rotational as well as vibrational temperatures could be obtained from its analysis. The excitation spectrum (Fig. 8) consists of lines belonging to (0,3), (2,4) and (5,5) transitions of the B-X Schumann-Runge system (Fig. 1). This $^3\Sigma_u^- - ^3\Sigma_g^-$ (B-X) transition contains two main branches P and R and two satellite branches PQ and RQ. Under high resolution, all these show triplets giving 12 branches in all (Ref. 16). The observed lines are identified as shown in Fig. 8 excepting one strong line which is marked "??". More definitive conclusions about the assignments will be obtained in the future when the dispersed fluorescence is recorded with a monochromator (Ref. 14).

Attempts to monitor LIF of oxygen atoms using a R695 filter before the PMT has not yet succeeded. As shown in Fig. 1, this scheme involves a two-photon excitation process and will require higher dye laser pulse energies as compared with the one-photon processes in case of nitric oxide and oxygen molecules.

4. FUTURE PLANS

A systematic study will be carried out to obtain rotational and vibrational temperatures from the LIF data on NO and O₂. Attempts will be made to carryout LIF on oxygen atoms. A new grating for the dye laser will allow greater pump energies to be used and will result in double the pulse energy for the 225 nm radiation. At that time, tighter focusing of the dye laser will be tried to obtain the two-photon excitation spectrum of oxygen atoms. Various possible schemes for nitrogen molecules including the two-photon techniques will also be attempted.

In the very near future, Resonance Doppler Velocimetry (RDV, Ref. 18) of copper atoms which are present in our arc jet flows will be attempted. A separate feasibility study has been done to measure the doppler width and doppler shift of copper in an oven (Ref. 23) and will be applied to the arc jet flows to obtain flow velocity and static traslational temperature. A ring dye laser pumped by an argon ion laser will be used for these studies. The tunable radiation at 327 nm will be obtained using an intracavity doubler.

5. CONCLUSIONS

For the first time, LIF spectra have been measured in an arc jet flow. In spite of problems associated with the "dirty" arc jet flows, LIF from nitric oxide and oxygen molecules is obtained. The measurements have a promise of direct temperature determinations in the arc jet free stream as well as the shock layer.

ACKNOWLEDGMENT

Thanks are due to Dr. Carl Scott for his constant encouragement and help, to Eric Yuen for his assistance in the experimental setup and to Dr. Bill Marinelli for helpful suggestions.

6. REFERENCES

1. Scott, C. D., "Catalytic Recombination of Nitrogen and Oxygen on High Temperature Reusable Surface Insulation," in Progress in Astronautics and Aeronautics: Aerothermodynamics and Planetary Entry, Vol. 77, edited by A. L. Crosbie, AIAA, New York, 1981, pp. 192-212.
2. Scott, C. D. "Catalytic Recombination of Nitrogen and Oxygen on Iron-Cobalt-Chromia Spinel," AIAA Paper 83-0585, Jan. 1983.
3. Kolodziej, P. and Stewart, D. A. "Nitrogen Recombination on High-Temperature Reusable Surface Insulation and the Analysis of its effects on Surface Catalysis", AIAA Paper 87-1637, June 1987.
4. Park, C., "Comparison of Electron and Electronic Temperatures in Recombining Nozzle Flow of Ionized Nitrogen-Hydrogen Mixture Parts 1 and 2," Journal of Plasma Physics, Vol. 9, 1973, pp. 187-234.
5. Sharma, S. P. and Park, C., "A Survey of Simulation and Diagnostic Techniques for Hypersonic Non-Equilibrium Flows," AIAA Paper 87-0406, Jan. 1987.
6. Blackwell, H. E., Yuen, E., Arepalli, S. and Scott, C. D., "Nonequilibrium Shock Layer temperature Profiles from Arc Jet

- Radiation Measurements," AIAA Paper 89-1679, June 1989.
7. Blackwell, H. E., Wierum, F. A., Arepalli, S. and Scott, C. D., "Vibrational Temperature from Measurements of N_2 and N_2^+ Shock Layer Radiation," AIAA Paper 89-0248, Jan. 1989.
 8. Blackwell, H. E., Wierum, F. A. and Scott, C. D., "Spectral determination of Nitrogen Vibrational Temperatures," AIAA Paper 87-1532, June 1987.
 9. Blackwell, H. E. (private communication).
 10. Westblom, U. and Alden, M., "Simultaneous Multiple Species Detection in a Flame Using Laser-Induced-Fluorescence," Applied Optics, Vol. 28, July 1989, pp. 2592-2599.
 11. Rochelle, W. C., Batley, H. H., Grimaud, J. E., Tillian, D. J., Murray, L. P., Lueke, W. J. and Heaton, T. M., "Orbiter TPS Development and Certification Testing at the NASA/JSC 10 MW Atmospheric Reentry Materials and Structures Evaluation Facility," AIAA Paper 83-0147, Jan. 1983.
 12. Alden, M., Hertz, H. M., Svanberg, S. and Wallin, S., "Imaging Laser-Induced Fluorescence of Oxygen Atoms in a Flame," Applied Optics, Vol. 23, Oct. 1984, pp. 3255-3256.

13. Zacharias, H., Anders, A., Halpern, J. B. and Welge, K. H., "Frequency Doubling and Tuning with $\text{KB}_5\text{O}_8 \cdot 4\text{H}_2\text{O}$ and Application to NO ($\text{A}^2\Sigma^+$) Excitation," Optics Communications, Vol. 20, Mar. 1977, p. 449; *ibid*, Optics Communications, Vol. 19, Oct. 1976, pp. 116-119.
14. Wysong, I. J., Jeffries, J. B. and Crosley, D. R., "Laser-Induced Fluorescence of $\text{O}(3\text{p}^3\text{P})$, O_2 and NO near 226 nm: Photolytic Interferences and Simultaneous Excitation in Flames," Optics Letters, Vol. 14, Aug. 1989, pp. 767-769.
15. Bade, W. L. and Yos, J. M., "The NATA code-- Theory and Analysis," NASA CR-2547 (1975).
16. Herzberg, G., Spectra of Diatomic Molecules, Van Nostrand, New York, 1950.
17. Krupenie, P. H., "The Spectrum of Molecular Oxygen," Journal of Physical and Chemical Reference Data, Vol. 1, No.2, 1972, pp. 423-534.
18. Cheng, S., Zimmerman, M. and Miles, R. B., "Supersonic-Nitrogen Flow-Field Measurements With the Resonant Doppler Velocimeter," Applied Physics Letters, Vol. 43, July 1983, pp. 143-145.
19. Bill Marinelli (private communication).

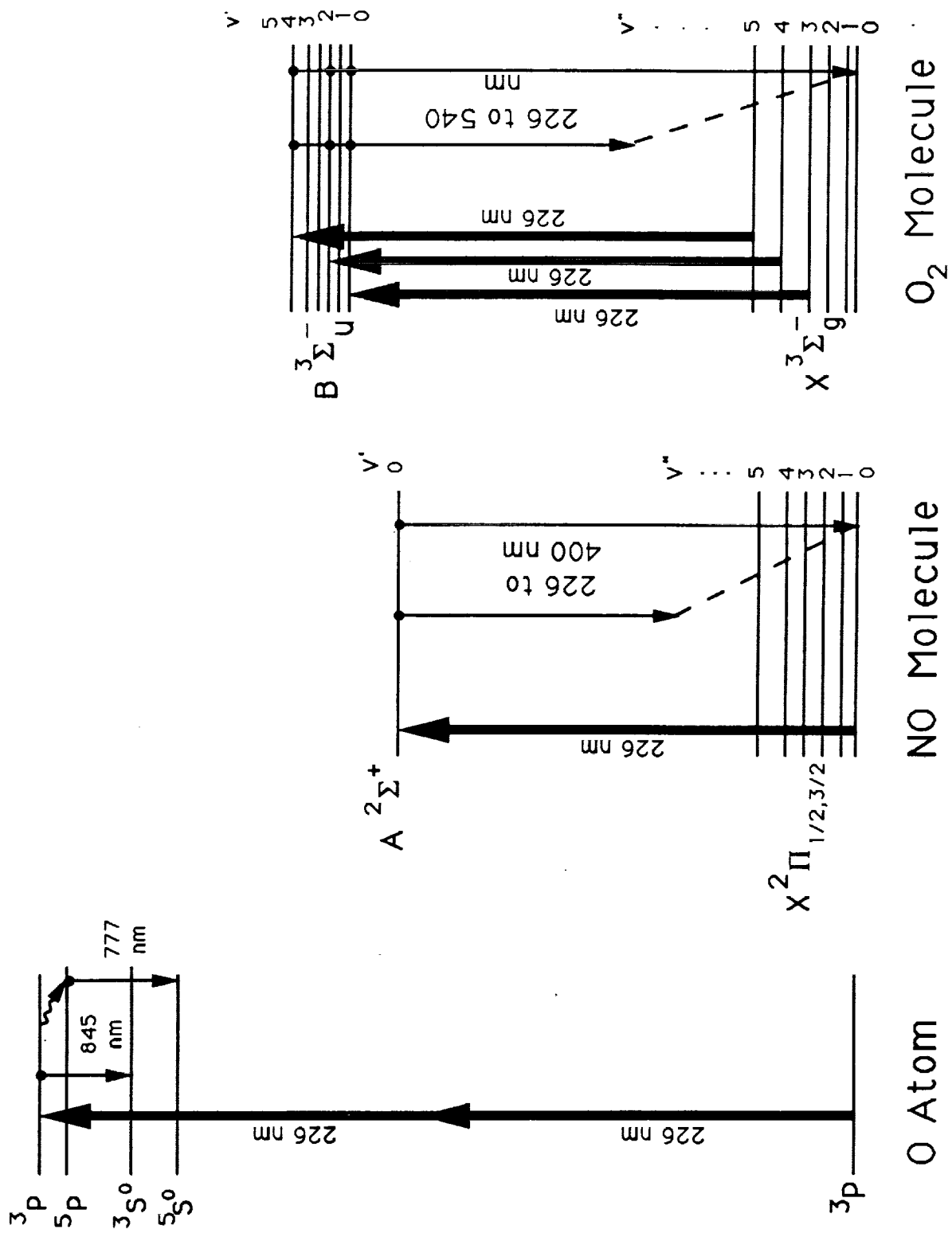


Figure 1. Energy level diagram for NO, O and O₂

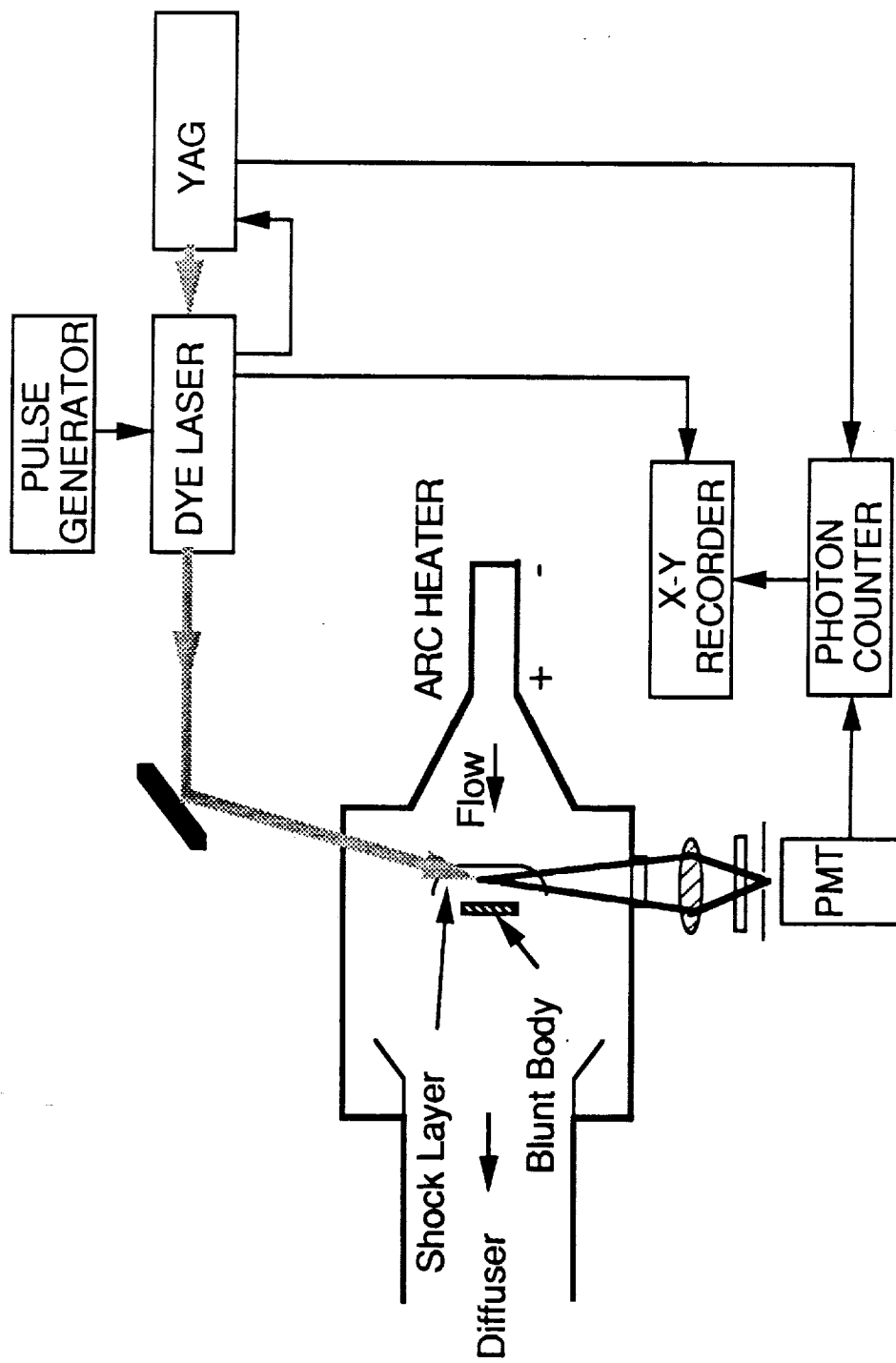


Figure 2. LIF experimental set up

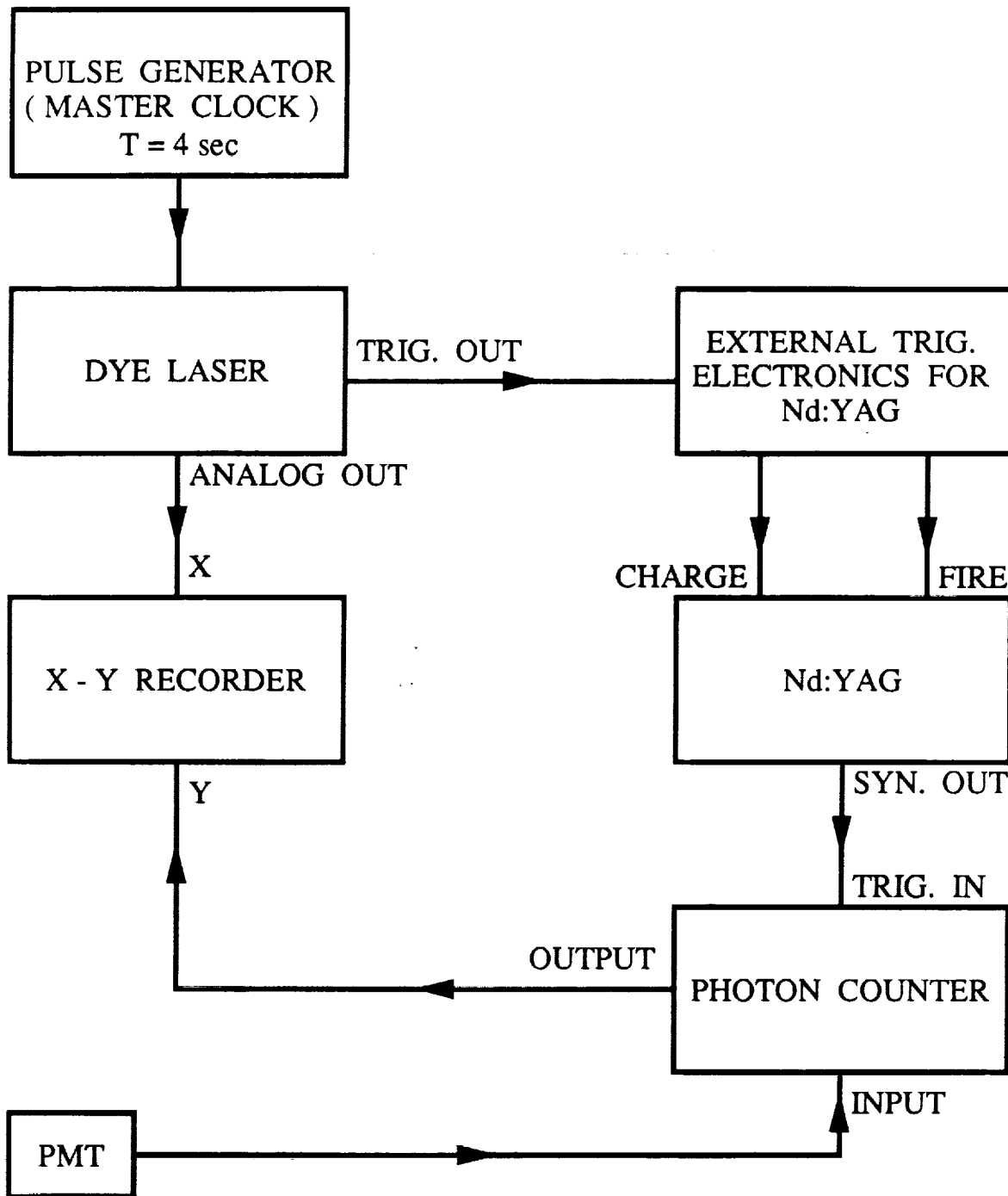


Figure 3. Electronics block diagram

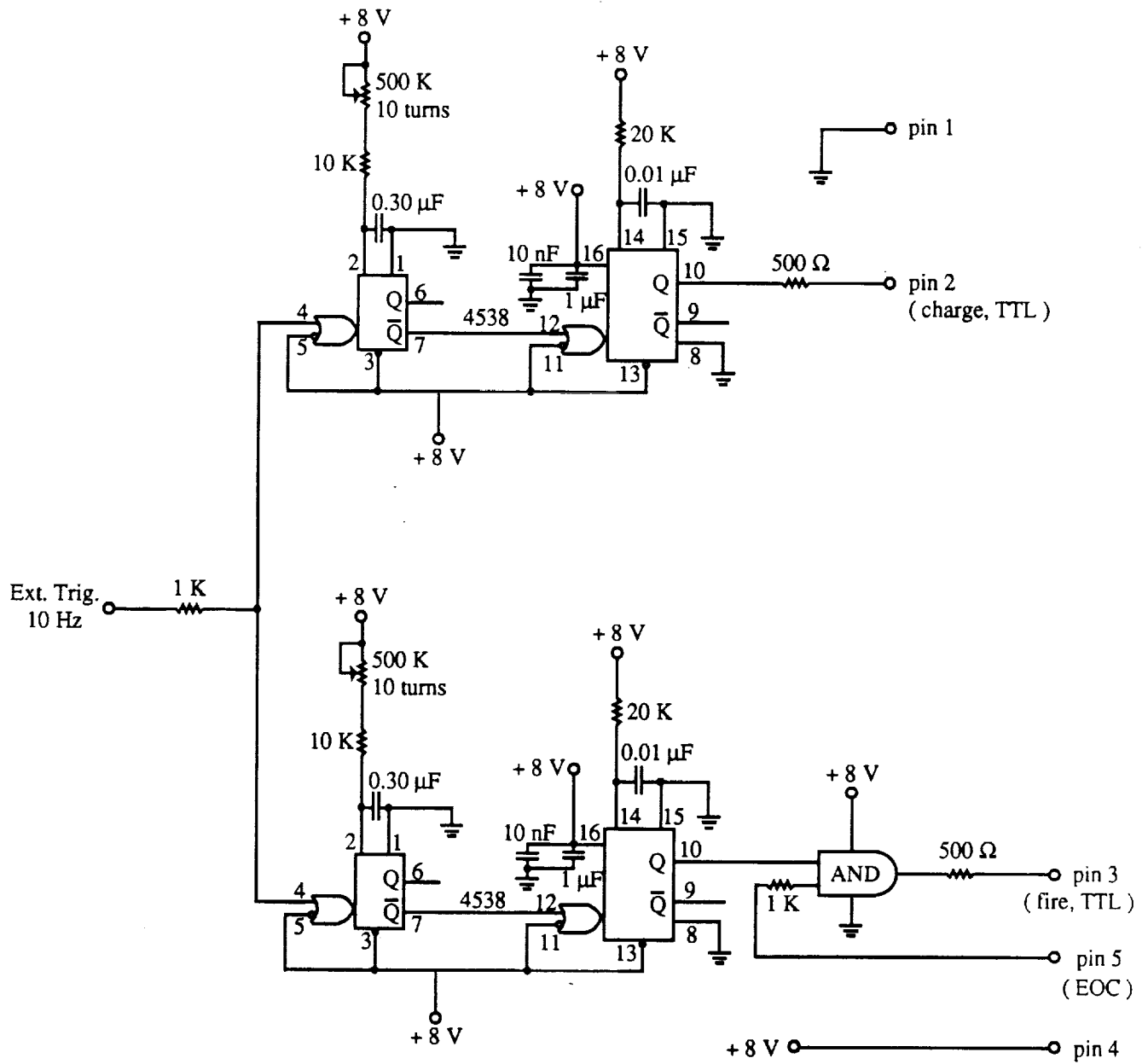


Figure 4. Variable delay double-pulse generator

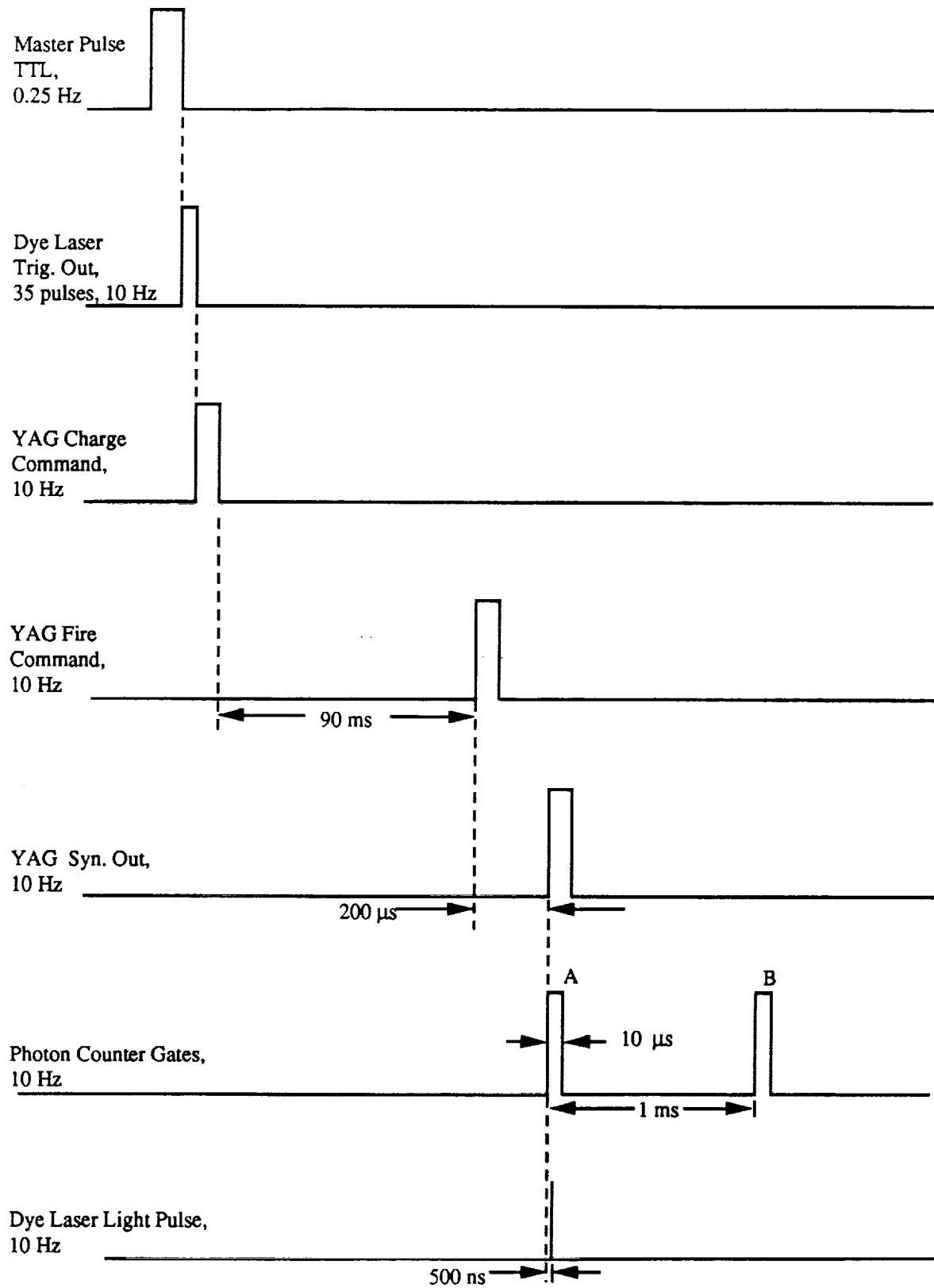


Figure 5. Timing diagram for LIF data collection

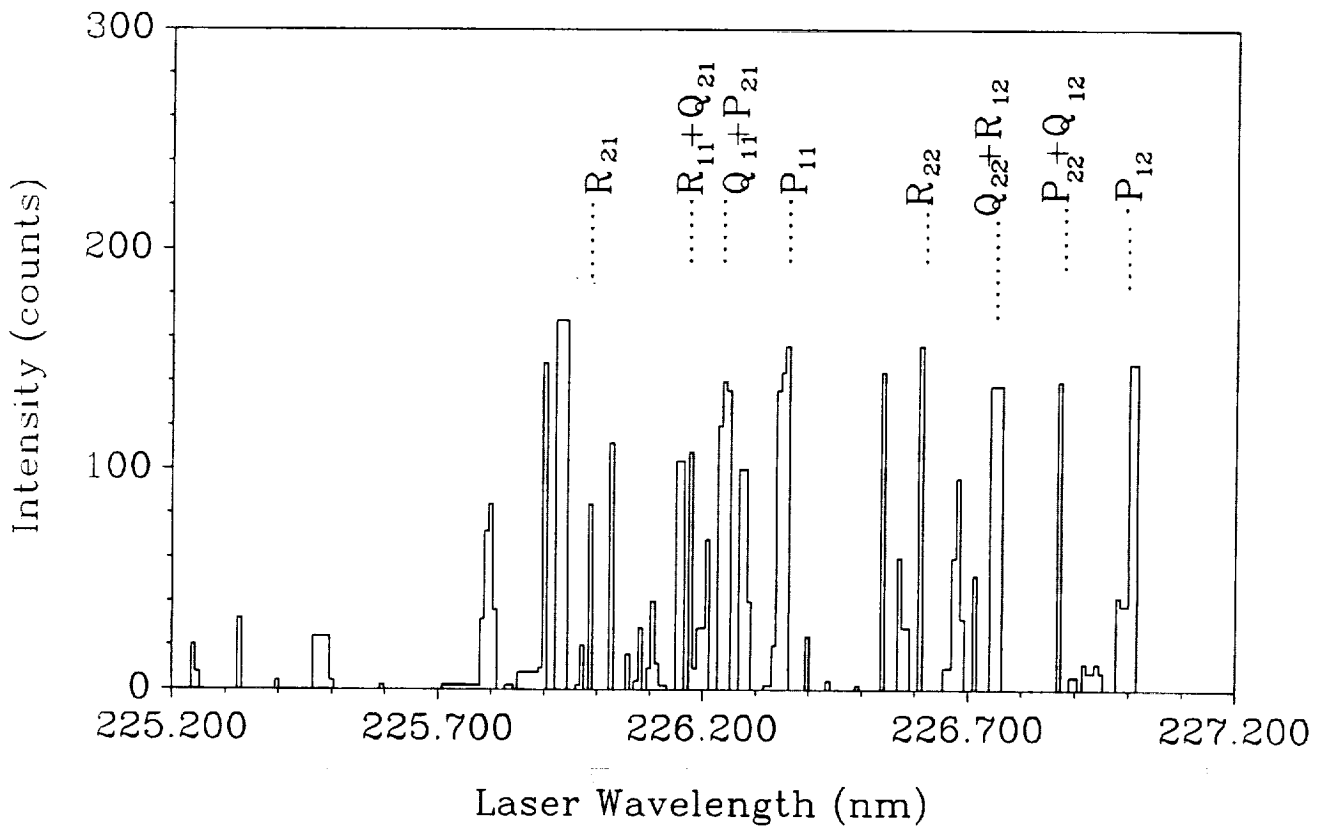


Figure 6. LIF of (0,0) band of NO (A-X); free stream; 1500 BTU/lb

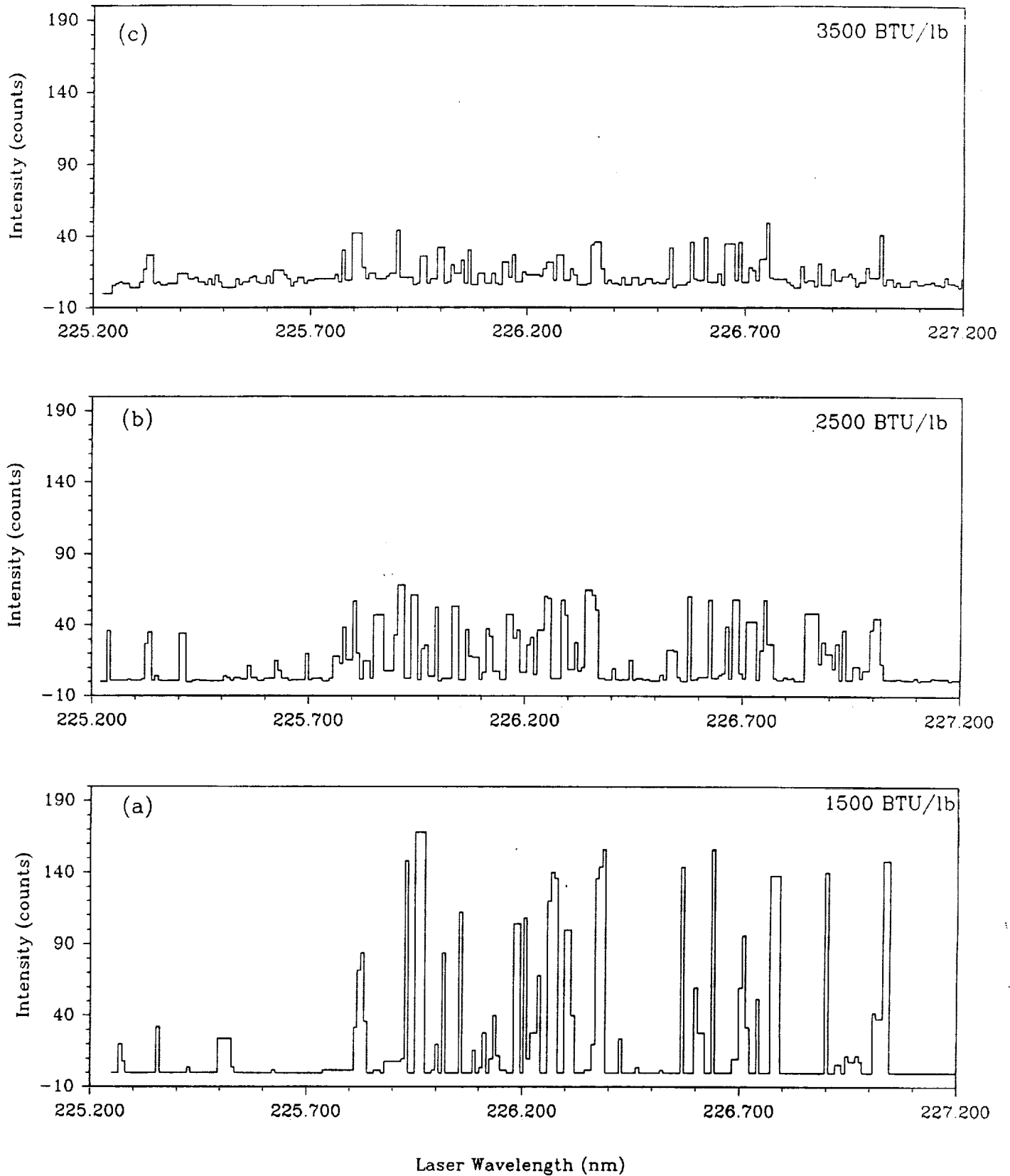


Figure 7. LIF of (0,0) band of NO (A-X) in free stream under different enthalpy conditions

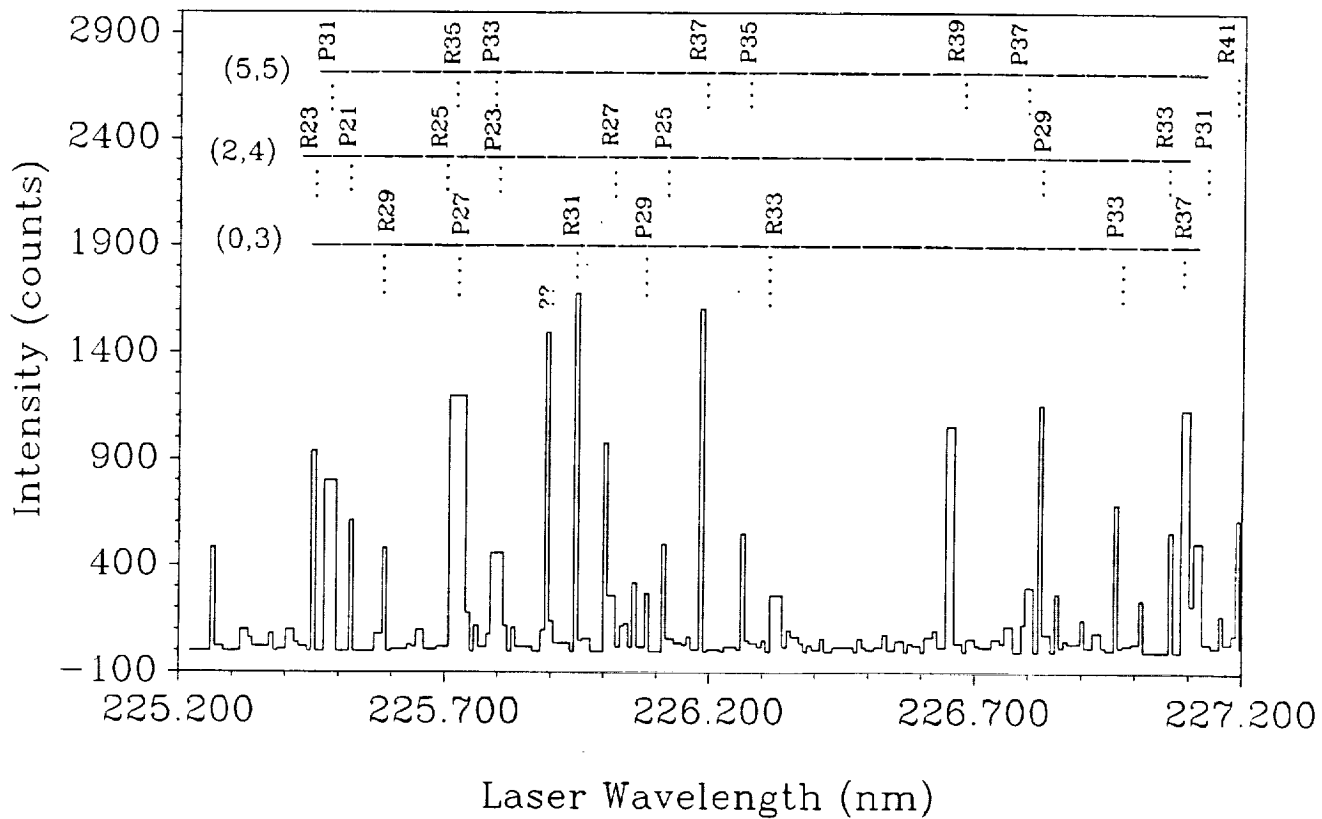


Figure 8. LIF of O_2 (B-X) in the shock layer of a blunt body at an enthalpy of 1500 BTU/lb.

