SODIUM LINE REVERSAL PLASMA TEMPERATURE
MEASUREMENT SYSTEM

Topical Report

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by

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ABSTRACT

The Sodium Line Reversal System is one of the advanced optical diagnostic instruments developed at DIAL to measure temperatures in the coal combustion environments of large scale facilities. The principles of operation, a description of the system and its capabilities, and the operational details of this instrument are presented in this report.

INTRODUCTION

This topical report provides technical and operational details of a versatile, optical temperature measurement system (Sodium Line Reversal System) developed for the Heat Recovery/Seed Recovery (HRSR) program of Magnetohydrodynamics (MHD) under DOE Contract DE-AC02-80ET-15601 at the Diagnostic Instrumentation and Analysis Laboratory (DIAL), Mississippi State University (MSU).

DIAL was organized as a result of a project entitled "Testing and Evaluation of MHD Materials and Substructures," initiated by an interdisciplinary group of MSU engineering faculty members in 1976 and sponsored by the Department of Energy from 1976-1980. As part of this research project, MSU constructed a test stand for simulation of the gas-slag-seed stream and thermal conditions that would exist in various structures of a coal-fired baseline MHD power plant. The major mission of DIAL is to develop and apply advanced optical diagnostic techniques and instrumentation systems which provide nonintrusive, remote, real-time measurements in an industrial-like environment of large scale facilities. Such diagnostic instruments can provide the information required to more clearly characterize the various processes involved in the ash/seed-laden gas stream of the coal-fired MHD flow. Other objectives of DIAL include providing technical support to the national MHD program, technology transfer, and test stand operation to support diagnostic instrumentation development. The microprocessor-controlled instruments developed at DIAL are being used for measurements by MSU and other DOE/MHD contractors.

PURPOSE OF THE INSTRUMENT

The Sodium Line Reversal System (SLR) is a nonintrusive optical instrument used to measure average flame temperature. It was developed as a packaged system, automated for repeated measurements with little operator intervention. It has been designed to make measurements in a harsh industrial environment.

The line reversal method of temperature measurement is very old. However, all such measurements have been confined to laboratory environments. SLR is the only currently available packaged and portable instrument which could be taken to the field for flame temperature measurements.

To use this system for measurement, the flame should contain sodium and must be optically accessible. Also, SLR cannot measure temperature accurately below 2000-2200 degrees F, depending on the flame condition.

PERFORMANCE REQUIREMENTS

The functions performed by the SLR system include:

1. Measure and display average flame temperature within 5 seconds;
2. Save raw data for detailed analysis;
3. Display and save line shape data;
4. Collect spectral data over a specified region of wavelength;
5. Send data over a communication line;
6. Make measurements continuously with minimum operator control.

The instrument is controlled by a microprocessor system, allowing measurements from a remote location.

TECHNICAL APPROACH

The line reversal method of flame temperature has been used for over 80 years. The basis of this method is Kirchoff's laws of thermal radiation, formulated in 1856. This was applied to the measurement of flame temperature in 1903 using the sodium line reversal method.¹ Since that time it has seen wide application for a variety of situations.

For the simple flame case, i.e. no particles and constant temperature, the radiative transfer equation²⁻⁵ is given by

$$\frac{dI_v}{dx} = \alpha_v (B_v - I_v) \quad (1)$$

where I_v = specific intensity

x = position coordinate

α_v = absorption coefficient,

B is the Planck blackbody function and ν is the frequency.

The integrated equation is

$$I_v(L) = B_v(T_g) (1 - e^{-\alpha_v L}) + I_v(0) e^{-\alpha_v L} \quad (2)$$

where L = distance through the flame and $I_v(0)$ is the intensity of a light source which is viewed through the flame. Sodium line reversal can be described quite simply for this case. When a light source is viewed at the wavelength of one of the sodium D line transitions, the reversal condition is said to be met when the intensity $I_v(L)$, reaching the detector is the same whether the flame is present or not. When this condition is met, $I_v(0) = B_v(T_g)$ and the brightness temperature of the source is the same as the temperature of the gas.

In principle, a calibrated light source could be adjusted to the reversal point and the temperature determined directly. In practice, this is not necessary. The Stanford MHD group has given a sequence of four measurements which allow calculation of the gas temperature for the constant properties case. In these measurements, two wavelengths are used, one on the sodium D line, but not at the line center, and one nearby, but off the line. Since the two wavelengths are close to each other, the detector response is essentially unchanged. In addition, the intensity of the source $I_\nu(0)$ is essentially the same at the two wavelengths. However, off the D line, only the last term in Equation 2 is non-zero and $\alpha_\nu = 0$.

Two measurements are made at each frequency:

- 1) lamp and emission
- 2) emission only

by using a chopper. The four simultaneous equations which result are sufficient to allow the temperature to be calculated from⁶

$$T_g = \left[\frac{1}{T_L} + \frac{\lambda}{C} \ln \left(1 + \frac{M_1 - M_3}{M_4 - M_2} \right) \right]^{-1} \quad (3)$$

where $C = (hc/k)$

λ = average wavelength position

T_L = lamp temperature

M_1, M_2 the lamp unblocked and blocked measurements on the D line at λ_2

M_3, M_4 similar measurements off the line at λ_1 .

The position of λ_2 will affect the calculated temperatures if the flame has cooler boundary layers. Some years ago, Strong and Bundy did a study of the effect of boundary layers on the temperature determined from line reversal when the emitted radiation is viewed through a cooler boundary layer.⁷ For illustration,

consider the temperature distribution shown in Figure 1. For the case of emission only, the intensity observed by a viewer would be:

$$I_v = (1 - e^{-\alpha_1 L_1}) B_v(T_1) e^{-\alpha_2 L_2} e^{-\alpha_1 L_1} + (1 - e^{-\alpha_2 L_2}) B_v(T_2) e^{-\alpha_1 L_1} + (1 - e^{-\alpha_1 L_1}) B_v(T_1) \quad (4)$$

The radiation emitted from each region is attenuated by absorption in the following region(s). The observed sodium emission lines would look like those in Figure 2. The minima at the line centers are due to the absorption of the radiation emitted by the hotter sodium atoms in the core by the cooler sodium atoms in the boundary layer. The fact that the absorption does not simply yield a line with a reduced intensity is due to the fact that the linewidth is narrower for the cooler atoms so that the greatest effect occurs at the line center.

Dailey and Kruger have considered integration of the radiative transfer equation (Equation. 1):

$$I_v(L) = e^{-\int_0^L \alpha_v(x) dx} \int_0^L e^{\int_0^x \alpha_v(x') dx'} \alpha_v(x) B_v(x) dx + e^{-\int_0^L \alpha_v(x) dx} I_v(0) \quad (5)$$

for an example of a more realistic temperature profile.⁵ They also considered a number of sources of error in line reversal measurements.

This temperature calculation, which assumes that the flame has constant properties and no particles, has been programmed into the microprocessor system. It is referred to as the "clean" equation. The position of λ_2 is chosen to be on the "wing" of the sodium line to minimize boundary layer errors.

Figure 1. Temperature profile in a plane.

Figure 2. Calculated emission line shapes for the sodium D lines from a flame viewed through a cooler boundary layer.

For HRSR gas conditions, there will indeed be particles present. For the case of particulate matter present with the assumption that the particles are blackbodies at the same temperature as the gas, the radiative transfer equation becomes

$$\frac{dI}{dx} = B_v(\alpha_v + \eta) - I_v(\alpha_v + E_v) \quad (6)$$

where η = absorption coefficient for particles and E = extinction/absorption ratio for particles and the other quantities are the same as in Equation 1. For the case of constant properties, where the temperature is constant along the line-of-sight:

$$I_v(L) = B_v(1 - e^{-(\alpha_v + E_v)L}) + I_v(0) e^{-(\alpha_v + E_v)L} \quad (7)$$

where $\gamma = \frac{\alpha_v + h}{a_v + h}$.

A series of eight measurements at two frequencies on the wings of the line yield enough data to solve for the temperature without assumption about η or E . Four of the measurements are lamp unblocked and blocked with the flame present and the other four are lamp unblocked and blocked before the flame is present, at the two frequencies. The values of α_v at the two frequencies should be sufficiently different values to insure that the resulting equations are linearly independent. Since the frequency differences are small, it is possible to assume that collection efficiencies, B_v , E and η are the same in the resulting equations. The temperature of the lamp must still be known and the gas temperature is then calculated by B_v using the Planck law.

The microprocessor system has been programmed to solve these equations for the gas temperature.

Source of error, including the effects of particulate matter have been pointed out by Thomas³, Sasaki⁸, and Snelleman⁹.

SYSTEM DESCRIPTION

A diagram of the system is shown in Figure 3. The packaged instrument is contained in five units.

- 1) Source-side optical components
- 2) Lamp power supply
- 3) Detector-side optical components
- 4) Detector-side electronics
- 5) Microprocessor control unit

All five units may be removed from the flame.

The source-side optics consist of a calibrated light source, collimating lens, filter wheel, optical chopper, fiberoptic input assembly, QSF 1000A fiber, and a remote output assembly with a focussing lens. The light source is a ribbon filament, tungsten lamp (GE 18A/T10/1P), which is maintained at a constant temperature. The effective source brightness is varied by inserting optical density filters in the light path. Three filters are mounted on a wheel with stepper motor control of the wheel position. Typical filters used to cover a wide temperature range are optical densities of 0.0 (no filter), 0.5 and 1.0. Using these filters as an example, a measured lamp temperature of 2478 K gives effective lamp temperatures of 2486 K, 2216 K, and 2002 K.

An optical chopper is used to provide an alternate lamp on/lamp off signal. The chopper frequency (67 Hz) is set for a certain delay time of the data collection routine. The chopper frequency may be decreased provided the timing parameters are appropriately modified.

The detector-side optical components consist of a collimating lens, unit magnification telescope with iris aperture, fiberoptic input assembly and QSF 600A

fiber to the remote fiberoptic output assembly, focusing lens, monochromator and photon counting system.

The monochromator is a Jobin-Yvon 0.6m monochromator with a 1200 grooves/nm grating. The stepper motor scan system is externally controlled by the microprocessor. Twenty-five steps is one Angstrom. The slits of the monochromator have been fitted with stepper motor control as well.

The photon counting system is a Princeton Applied Research Model 1140 Quantum Photometer with a Hamamatsu R446 photomultiplier tube. The tube has a very flat response over the wavelength region of the sodium lines. Most of the PAR 1140 is not used by the microprocessor system but is available for manual operation. A linear output is available at the control unit as well as the scan control unit. The pulses from the PM tube are counted by the microprocessor after the amplifier/discriminator and one-pulse shaping operation. A general purpose counting card, which has a preset counting interval of 4.5 msec, is used for pulse counting. The emission only and lamp plus emission signals which are referred to as blocked and unblocked signals are collected alternately.

The operator interacts with the system using the front panel shown in Figure 4. Input to the system is through keypad. The temperatures and numerical entries are shown on a liquid crystal display (LCD). Permanent copy of the system operations and temperatures are printed on a twenty-column line printer. The keypad is dual level with sixteen keys so that after allowing for ten numerals, there are twenty-one keys for system commands and variables. The first level function on each key is shown as the lower entry. The second level function (upper entry is obtained by pushing the 2nd key and then the function key. The key labeled CLR clears the LCD and returns the keypad to first level. If the 2nd key is pushed inadvertently, simply push CLR and the second level function DST will print the date and the keypad will be returned to first level.

A restart switch is located next to the power switch for interrupting the system operation. After RESTART the microprocessor is ready for a system command again.

Figure 3. Block diagram of the sodium D line reversal temperature measurement system.

Figure 4. SLR front panel: user interface components.

EVALUATION METHOD AND RESULTS

The SLR system was initially tested using bench-top measurements. Later it was put on the test stand for more realistic measurements. The measured temperatures were within 4% of the actual (predicted) temperature. Considering various sources of errors the observed variation is quite acceptable.

The continuous mode of measurements worked very well. The system could display an average of ten individual measurements in every five seconds. Based on the flame conditions the system adjusts the instrument setup by itself to provide correct temperatures. Typical output from the system is given in Appendix A.

The measurements conducted at the University of Tennessee Space Institute (UTSI), Argonne National Laboratory (ANL), Component Development and Integration Facility (CDIF), and Coal-Fired Flow Facility (CFFF) have further validated the reliability of the instrument in industrial-like environments.

CURRENT STATUS

The SLR system is fully operational. It has proven its ability to measure reliable average flame temperature in harsh environments through the measurements at UTSI, ANL, & CDIF. SLR is one of the instruments taken in the mobile instruments laboratory of DIAL to other MHD sites for flame temperature measurements.

Existing systems are ready and available to make measurements at any location with appropriate optical windows. A new instrument could be put together within six months, upon request.

At present, there are no plans for further development, other than needed modifications to the system. However, it would be desirable to replace some of the existing components, especially microprocessor control parts, with newer state-of-the-art components.

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APPENDIX A: INSTRUMENT OPERATION

A.1 SYSTEM VARIABLES

A system initialization routine SINIT is normally run after power-up. This routine gives an initial value for certain variables. These values are listed in parentheses in the following list of variables.

A variable list is accessed using the VAR key. Q VAR prints the variable number, mnemonic and value of each variable in the list (Figure A.1.a). A single variable is accessed by entering its list number and then VAR, e.g. 10 VAR lists the mnemonic and current value for the tenth variable in the list. After selecting a variable, pressing the VAR key leaves the value unchanged. To change the variable, enter the new value and then VAR. CLR must be entered after displaying the final variable (TIME) before entering a new value. The variables in the order of the list are as follows:

1. MHD-ID (0): Variable to indicate the measurement facility
0 = bench-top
1 = MSU
2 = UTSI
3 = ANL
4 = CDIF
2. Readings/PT (10): The number of counting periods (4.5 msec) for each blocked or unblocked measurement.
3. Steps/PT (01): Steps of scan per measurement point. A point in the measurement interval in terms of scan steps for PRLT, INIT-2 and INIT-4.
4. A1L (71): Criteria used for choosing LAMBDA2, $A1L = e^{-\text{optical depth}}$ = $e^{-\alpha_1 L}$. Entered and printed times 100.

5. A2L (82): Criteria used for choosing LAMBDA3, $A2L = e^{-\alpha 2L}$. Entered and printed times 100.
6. SMT Scan (585000): The start wavelength for the smooth routine in Angstroms times 100.
7. H% (20): The inverse of that fractional part of the peak intensity minus the background which sets the upper limit for selection of LAMBDA 1 in INIT-3 or INIT-3 SMOOTHING. H% = 20 implies an upper intensity limit of 5% of the peak.
8. L% (25): Same as 6 but setting the lower limit. L% = 25 implies a lower intensity limit of 4% of the peak.
9. Peak: Wavelength in Angstroms times 100 of the peak intensity on the sodium line as found by INIT-2. Peak should be approximately 5890A.
10. LAMBDA1: Wavelength off the Na line used for the temperature calculations. Printed and entered as Angstroms times 100.
11. LAMBDA2: Wavelength on the Na line used for the temperature calculations. Entered same as LAMBDA1, e.g. 589000.
12. LAMBDA3: Wavelength on the Na line used for the temperature calculation including particle effects. Entered same as LAMBDA1 and 2.
13. LAMP TEMP: Lamp temperature in Kelvin measured at a wavelength of 6500A.
14. Scan (585000): Current wavelength position. Printed and entered same as LAMBDA1.
15. Filter (00): Current filter positioned on the optical axis. 0, 1, and 2 are filters starting with the lowest optical density. 3 is an opaque position.
16. OP. Filter: Filter used by the INIT-3 Smooth routine. Must be used with an appropriate slit selected from the results of INIT-2.

17. SLIT at (0): Slit position in steps. The slit widths will be the value divided by 2 in microns and the slit heights will be the value times 0.02 in millimeters. For example, SLIT at 100 means the slit widths are 50 μm and the heights are 2mm.
18. M7 (0): The unblocked pre-flame intensity value for the slit/filter combination selected by INIT-2 as determined by INIT-1.
19. M8 (0): Same as above but the blocked pre-flame intensity value. M7 and M8 are used with SMT Filter to enter valid pre-flame data for the selected SMT filter/slit combination.
20. OPTAU: Transmission of source-side optics, excluding the filters, at 5890A. Entered and printed as times 1000.
21. F1TAU: Transmission of the first filter, 0 position, at 5890A. Entered and printed as times 1000.
22. F2TAU: Transmission of the second filter, same as F1TAU.
23. F3TAU: Same as F1TAU for third filter, i.e., FILTER at 2.
24. K (0): Variable used to select the wavelength region.
0 = sodium (585 nm - 700 nm)
1 = potassium (700 nm - 815 nm)

When a region is selected, the monochromator will be set at the lower limit for that region.

25. DDLY (00): Delay from recognition of the chopper sync pulse to the start of the photon counting interval.
26. TO: Temperature for the selected filter corrected for OPTAU, emissivity and the filter transmission, F#TAU.

The next three variables apply during CONT routine operation.

27. PRNT.INTRVL: One valid measurement set is printed per PRNT INTRVL number of minutes.
28. LAM1.INTRVL: The number of LAMBDA2 and LAMBDA3 adjustments prior to a repeat of INIT-3.
29. CTS: The number of individual temperature measurements in each CONT cycle.
30. AUTO (1): A variable switch to use computer selected or operator input parameters during measurements.

0 = The computer will use the current slit width, filter, and the M_7 , M_8 values without any scaling during the temperature measurement. It is the operator's responsibility to make sure that the M_7 and M_8 values are consistent with the slit width, filter and "Readings/pt."

1 = The computer will use the slit width and filter selected by INIT-12 and the M_7 and M_8 values obtained by INIT-1 during temperature measurements. Also the M_7 and M_8 values will be scaled for any change in the "Readings/pt."
31. GPIB (0): variable switch to enable to disable data transfer over GPIB bus.
0 = disable; 1 = enable.
32. DATE: Year Month Day
33. TIME: hours:minutes:seconds

The variables which are changed most often are printed with the DATA key. Figure 5 illustrates the variable list and the DATA key output.

A.2: COMMANDS

Commands not requiring a numerical entry are as follows:

1. 2nd SINIT: This command initializes the system variables. DO NOT PUSH THIS KEY ACCIDENTALLY, as all system conditions and variables will be reinitialized.
2. 2ND P.INT: This command prints intermediate values in the "dirty" temperature equation as shown in Figure A.2.b. The nn 2nd T6 command must have been run and the values listed will be for the last temperature calculated. The values in order and as in Equation 7 of Appendix A are listed below. The subscript denotes the value at LAMBDA2 as 1 and LAMBDA3 as 2. The numbers are multiplied by the scale value printed.

a_1^L , a_2^L , h_{EL} , g_1/g_2 , g_1 , g_2 , E , h_L , $B(T_g)/I(0)$ and $M1 - M8$

3. CLR: This command clears the LCD.
4. 2ND GPIB: This command simply prints the date. This innocuous command is under the CLR key so that the CLR key can be used to return the keypad to first level if the 2ND key has been inadvertently pushed. (Also see 488 2ND GPIB).
5. 2ND X-MIT: sends an 11-byte header followed by any data from the raw data buffer over the GPIB bus. The header is used during data analysis.
6. DATA: This command prints selected system variables and conditions. (Figure A.1.b).
7. CONT: Starts the continuous routine.
8. 2ND PRO: Places the microcomputer in the keystroke store mode.

9. R/S: Returns the keyboard from the keystroke store mode to immediate mode. If not in the program mode when pressed it executes the last program stored.

The following commands all use the numerical value entered and shown on the LCD in executing the command. The command should be started by pressing CLR, entering the desired number (nn) then the command key.

1. nn VAR: nn equal to zero lists all of the variables. nn not equal to zero lists the variable selected and remains in the enter mode until VAR is struck again. For nn greater than the number of variables an error message is output. Exception is nn = 99. 99VAR will allow the operator to access INT-1 variables (Figure A.1.c) and change them.
2. nn 2ND CAL: Sends nn times the following test values over the RS-232 or 8-bit parallel interface: T4=2000, T6=2100, A1L=400 A2L=200 ETAEL=-49, and ETAL=09.
3. nn 2ND SCAN: This command causes the wavelength drive to move to the value entered. The value should be in Angstroms times 100. For example, to send the scan position to the first sodium D line, enter 589000 2ND SCAN.
4. nn 2ND SLIT: This command causes the entrance and exit slits of the monochromator to open or close to the numerical value displayed in steps. The slit widths will be the value divided by 2 in microns and the slit heights will be the value times 0.02 in millimeters. For example 40 2ND SLIT will cause the monochromator slits to be 20 microns in width and 0.8 millimeters high.
5. nn 2ND FLTR: This command causes the 0, 1, 2, or 3 (opaque) filter to be rotated into the optical path. This routine also calculates the corrected lamp temperatures so that if a new LAMP TEMOP of F_TAU is entered through

the variable list after running INIT 1, this command should be executed to recalculate the corrected lamp temperature.

6. nn 2ND S-N: This command finds the average value, root mean square deviation and the ratio of the two for the blocked and unblocked light intensities. The entered number is the number of data collections intervals used in the routine, analogous to Readings/PT. This routine is typically used on the Na line to determine a reasonable value for Readings/PT. An example of 10 2ND S-N is shown in Figure A.2.c.
7. nn 2ND INIT: nn may have the value 1, 2, 3, or 4

nn = 1. This command, INIT-1, is used before the flame is on to find the maximum slit position for each filter, to calculate the corrected lamp temperatures for each filter, and to store background (M8) and lamp only (M7) data for each filter for two slit positions. All of these values are found for two different criteria:

- 1) Lamp intensity of 400,000 counts/second. This keeps the light intensity well within the linear range for photon counting. The slit positions are entitled SP. SP MAX will be reset to largest SP.
- 2) Lamp intensity of 80,000 counts/second. Slit positions are entitled WSP. The slit positions are used when the Na peak is less than 400,000 counts/second.

The routine first returns the slits,—filter and scan to their initial values—the slits are set to 0, the filter positioned at 0, and the scan set to 5850 A. Ensuing measurements are made at 5850A. The slits are opened one step at a time and the intensity of the unblocked beam measured after each step. This intensity is compared to the 80 K criterion, if less than 80 K the slits are opened another step and the intensity measured again, if greater than 80 K the slit value is stored at WSP for the 0 filter. The blocked (M8)

and unblocked (M7) measurements are then taken for this WSP and stored. The slits are then single stepped from the WSP value and intensity measurements made until the 400K criterion is met or exceeded, this slit value is stored as SP. The blocked (M8) and unblocked (M7) measurements are taken and stored for this SP and filter position. The slits are returned to zero and then the filter position is changed and WSP, SP, and their respective M7s and M8s found for Filter 1 and then Filter 2. The filter wheel is rotated to the blocked position (Filter 3) in preparation for INIT-2.

N.B. The M7s and M8s are functions of VAR1, Readings/PT. For example, if VAR1=10, and the count criterion can be met for valid slit values, the M7s for SP should be approximately 20 K and the M7s for WSP should be approximately 3.6 K. Doubling VAR1 will double the M7s, tripling will triple them, etc. See Figure 6.a. for an example of INIT 1.

nn=2 This command, INIT-2, is run after the flame is on at the start of a run or whenever the flame conditions have changed drastically during a run. The routine selects a filter/slit combination from those determined by INIT-1 whose slit value is closest to that required to meet the same criterion at the peak Na emission only.

The current filter position (Filter @ 3) and the message, ** INIT-2 ** are printed. At 5850 A, the slits are opened until 400 K counts/sec are measured or until the largest slit value from INIT-1, SP for Filter 2, is reached. The routine scans toward longer wavelength in units of STEPS/PT and measures the blocked intensity at each point. If the measured intensity exceeds 40K counts/sec the slits are closed by 2% and the intensity remeasured and compared to the criterion until a count less than 400 K is measured. The wavelength is then stepped to the next point and the process repeated for the entire scan range (5850

To select LAMBDA2 (λ_2) the blocked (M2) and unblocked (M1) intensities at λ_1 are measured. The difference, $M1 - M2$, is determined. The routine scans to the peak and measures blocked (M4) and unblocked (M3) values and calculates $100 \{(M4 - M3)/(M2 - M1)\}$. For a calculated ratio less than A1L, the scan is stepped one step further from peak and the measurement and calculation repeated. For a calculated ratio greater than A1L, the scan position is taken as λ_1 .

LAMBDA3 (λ_3) is evaluated similarly, however, the initial search limits are λ_1 and λ_2 and A2L is the search criterion. Finally, λ_1 , λ_2 , λ_3 and the A1L and A2L values are output to the printer. If λ_2 could not be found, the message ?? TRY AGAIN ?? is output. The output from the three initializations are given in Figure A.3.

nn = 4 This routine is useful when the intensities are significantly above the baseline values, but are particularly noisy. The routine scans from the SMT scan variable wavelength taking blocked and unblocked measurements at every point defined by STEPS/PT and going two points beyond the peak determined in INIT-2. The extra points are required, since for a five-point smoothing of data, two points are required to either side of the smoothed point. All measurements are made with the SMT filter positioned in the source optical path. λ_1 , λ_2 and λ_3 are selected in the same manner as for INIT-3 but using smoothed data. The SMT scan range is 530 points, if this range is exceeded, the message INCREASE STEP SIZE is printed.

8. nn 2ND T4: This command calculates the entered number of temperatures using the "clean" equation. As the routine proceeds each temperature is displayed on the LCD and an average temperature is printed for every 10 calculations. After all the temperatures have been calculated, a simple

statistical method is used to determine if a value should be left out of the final average. The bad value is printed; then a new average is displayed. The individual temperatures may be printed immediately afterwards by keying CLR 2ND PRLT. An example is shown in Figure 7.a.

9. nn 2ND T6: This command calculates the entered number of temperatures including the effect of particulates. The temperatures are displayed and averaged as for the "clean" equation (T4). As before, CLR 2ND PRLT will print the individual temperatures.
10. nn 2ND PRLT: This command is used to collect and plot the Na D lineshape. Intensity values (lamp blocked and unblocked) are collected and stored every STEPS/PT from wherever the scan position is. The entered number is the number of points on the line which will be plotted. CLR 2ND PRLT will print the numbers on which the histogram is based. The scan is returned to the starting wavelength. Figures 6, 7, and 8 show examples of the PRLT routine for the lamp hotter than the flame, about equal to the flame, and much cooler than the flame, respectively.
11. 488 2ND GPIB. Disables the keypad and puts the SLR system under the GPIB control. In this mode, the SLR system receives commands from the GPIB controller computer; (refer to the Interactive Data Acquisition/Control Manual for details). Hit "RESTART" button to exit from this mode and re-enable the keypad.

5/27/92 OK 33Time = 0:5:5 Day = 1 Month = 1 32Year = 87 32GPIB=0 30AUTO.=1 29CTS=5 28LAM1.INTRVL=3 27PRNT.INTRVL=60 26TO=2369 25DDLY=0 24K=0 23F3TA0=1140 22F2TA=3445 21F2TA0=10000 20OPTA0=920 19M8=0 18M7=0 17Slit @ 0 16P.F# =1 15Filter @ 0 14 Scan @ 585000 13Lamp TEMP.=2343 12Lambda3=588348 11Lambda2=588380 10Lambda1=586316 9Peak=589180 8L%=25 7H%=20 65MT Scan=585000 5A2L=82 4A1L=71 3Steps/PT=2 2Readings/PT=10 1 MHD ID=0 (a)	OK Readings/PT = 10 Scan @ 585000 Slit @ 0 Filter @ 0 T0=2369 Lamp TEMP.=2343 Peak =589180 Lambda3=588348 Lambda2=588380 Lambda1=586316 (b) OK WM8 = 8 SM8 = 57 WM7 = 3540 SM7 = 20032 WSP = 111 SP = 294 Filter # 2 WM8 = 4 SM8 = 20 WM7 = 3774 SM7 = 20161 WSP = 67 SP = 146 Filter # 1 WM8 = 2 SM8 = 5 WM7 = 3703 SM7 = 20546 WSP = 43 SP = 81 Filter # 0 * INIT - 1 Variables (c)
---	--

Figure A.1. Variable lists accessed through (a) VAR and (b) DATA.
(c) INIT-1 parameters using 99 VAR.

<p>OK 2113 338 2116 295 2110 333 2118 296 2113 279 2112 317 2109 333 2107 301 2111 321 2110 279 2/18/87 10:34:05</p> <p>OK R-FACTOR=14 AVG. ALFAL = 309 AVERAGE OF 10=2111 R-FACTOR=02</p> <p>TEMP. IN F = 3342 TEMP. IN K = 2112 Average of 10 Clean Flame 2/18/87 10:33:00</p> <p>(a)</p>	<p>OK M8=150 M7-20207 M6-83 M5-19778 M4=3361 M3=19954 M2=4724 M1=19375 E-314 Et L=81 Et EL=25 BTG1/I-724 G1/G2=914 Gamal=1174 ALFA2L=171 ALFA1L=295 * VALUE x 1000</p> <p>OK 00 2069 00 2111 00 2096 00 2077 00 2105 00 2127 00 2088 00 2102 00 2087 00 2111 00 2/18/87 10:40:11</p> <p>OK AVERAGE OF 10=2097 R-FACTOR=11</p> <p>TEMP. IN F = 3315 TEMP. IN K = 2097 Average of 10 Particles 2/18/87 10:38:21</p> <p>(b)</p>	<p>OK S/N=37 PMS DEV.=2903E-2 AVERAGE=1128 UNBLOCKED LINE</p> <p>S/N=04 RMS DEV. =359E-2 AVERAGE=1600 BLOCKED LINE # SAMPLES=20</p>
--	--	---

Figure A.2. Temperatures found using "clean" equation (a) and particulate equations and intermediate values (b) and S/N calculation (c).

<p>OK # Turn Sodium ON # 29 32 37 M8 FOR WSP 47 49 39 M8 FOR SP 3786 3774 3685 M7 for WSP 20517 20054 20663 M7 FOR SP 81 63 51 WSP 137 99 74 SP</p> <p>TO =1952 TAU = 1148 Filter @ 2 TO =2140 TAU = 3445 Filter @ 1 TO = 2360 TAU - 10000 Filter @ 0 ** INIT-1 ** 2/18/87 7:31:23</p> <p>(a)</p>	<p>OK A2L=82 A1L=71</p> <p>Lambda 3=588924 \$ Lambda2=588944 \$ Lambda1=588732 ** INIT-3 ** 2/18/87 9:30:21</p> <p>(c)</p> <p>OK Peak=589004 Selected Slit @99 Selected F# @1 ** INIT-2 ** Filter @ 3 2/18/87 9:28:41</p> <p>(b)</p>
--	--

Figure A.3. Example printouts of INIT-1 (a), INIT-2 (b) and INIT-3 (c).

35	OK
34	FINISH
33	*****35
32	*****34
31	*****33
*30	*****32
*29	*****31
28	***30
27	**29
****26	*****28
****24	*****27
23	**26
22	***25
21	***24
*20	*****23
*19	*****22
18	*****21
17	*****20
16	*****19
15	*****18
14	*****17
14	*****16
12	*****15
11	*****14
10	*****13
9	*****12
8	*****11
7	*****10
6	*****9
5	*****8
4	*****7
3	*****6
2	*****5
1	*****4
COUNTS / * = 1210	*****3
STEPS/PT=5	*****2
BLOCKED LINE	*****1
Readings /PT=10	COUNTS / * = 1210
# PTS 35	STEPS /PT=5
2/18/87 10:54:57	UNBLOCKED LINE

Figure A.4. Example of *PRLT* routine when the lamp is much hotter than the flame.

*35		
*34	OK	
**33	FINISH	
32	***35	OK
31	***34	1674 20480
****30	*****33	2434 20685
*****29	*****32	2952 20529
*****28	*****31	3278 20464
*****27	*****30	3406 20621
*****26	*****29	5653 20889
*****25	*****28	7867 20491
*****24	*****27	8695 20347
*****23	*****26	11621 20614
*****22	*****25	16056 21963
*****21	*****24	17205 21890
*****20	*****23	16438 22015
19	**22	14223 22906
18	**21	11336 22888
*17	*****20	9508 22072
*16	*****19	7136 21688
*15	*****18	4927 20981
*14	*****17	4321 21241
13	*****16	2520 20847
12	*****15	1681 20591
11	*****14	1837 21253
10	*****13	1435 20722
9	*****12	1246 20948
8	*****11	984 20589
7	*****10	718 20649
6	*****9	673 20337
5	*****8	598 20435
4	*****7	555 20416
3	*****6	529 20445
2	*****5	474 20334
1	*****4	395 20696
COUNTS / * = 1347	*****3	404 20504
STEPS/PT = 5	*****2	398 20640
BLOCKED LINE	*****1	371 20386
Readings/PT = 10	COUNTS / * = 1347	385 20436
# PTS 35	STEPS/PT=5	2/18/87 10:52:48
2/18/87 10:50:18	UNBLOCKED LINE	

Figure A.5. Example of PRLT routine when the lamp and flame temperatures are about equal.
This is close to the reversal point.

```

*35
*34
*33
***32
*****31
*****30
*****29
*****28
*****27
*****26
*****25
*****24
*****23
*****22
*****21
*****20
*****19
****18
***17
**16
*15
*14
13
12
11
10
9
8
7
6
5
4
3
2
1
COUNTS / * = 2870
STEPS/PT=5
BLOCKED LINE
Readings/pT=10
# PTS 35
2/28/87 10:57:01

```

```

OK
FINISH
*****35
*****34
*****33
*****32
*****31
*****30
*****29
*****28
*****27
*****26
*****25
*****24
*****23
*****22
*****21
*****20
*****19
*****18
*****17
*****16
*****15
*****14
*****13
*****12
*****11
*****10
*****9
*****8
*****7
*****6
*****5
*****4
*****3
*****2
*****1
COUNTS / * = 2870
STEPS/PT=5
UNBLOCKED LINE

```

Figure A.6. Example of the PRLT routine when the flame is hotter than the lamp.

APPENDIX B: QUICK REFERENCE

This section describes the keystroke sequence for a specific function: Here nn is a non-zero number entered through the numeral keys.

Filter selection	<u>nn 2ND FLTR</u>
GPIB interface	
—SLR under GPIB control	<u>488 2ND GPIB</u>
—force transfer data to GPIB bus	<u>2ND X-MIT</u>
Initializations	
—for measurement, INIT-1	<u>1 2ND INIT</u>
—for measurement, INIT-2	<u>2 2ND INIT</u>
—for measurement, INIT-3	<u>3 2ND INIT</u>
—for measurement, INIT-4	<u>4 2ND INIT</u>
—for measurement, INIT-5	<u>5 2ND INIT</u>
—system	<u>2ND SINT</u>
INIT-1 values, operator input	<u>99 VAR</u>
Line shape, print	
—blocked intensity profile	<u>nn 2ND PRLT</u>
—blocked intensity values	<u>0 2ND PRLT</u>
—unblocked intensity profile	<u>nn 2ND PRLT</u>
—unblocked intensity values	<u>0 2ND PRLT</u>
LCD, clear	<u>CLR</u>
Particle parameters	<u>2ND PINT</u>
Signal-to-noise ratio	<u>nn 2ND S-N</u>
Slit width adjustment	<u>nn 2ND SLIT</u>
Temperature measurement	
—clean flame	<u>nn 2ND T4</u>
—particle laden flame	<u>nn 2ND T6</u>
—continuous mode	<u>2ND CONT</u>
Variables	
—display detailed list	<u>0 VAR</u>
—modify value of any variable	<u>nn VAR</u>
—examine value	<u>nn VAR</u>
—display a short list	<u>DATA</u>
Wavelength position setting	<u>nn 2ND SCAN</u>

END

**DATE
FILMED**

11 / 10 / 93