DIAGNOSTIC INSTRUMENTATION AND ANALYSIS LABORATORY

DIAGNOSTIC DEVELOPMENT AND SUPPORT OF MHD TEST FACILITIES

**Final Progress Report
for the contract period
March 1980 - March 1994**

**W. S. Shepard, Director
R. L. Cook, Deputy Director**

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**Prepared for the United States
Department of Energy
Under Contract No. DE-AC02-80ET-15601**

FE-15601-52
Dist.Cat.UC-90g

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Diagnostic Instrumentation and Analysis Laboratory
Mississippi State University
Mississippi State, Mississippi 39762

MASTER

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LIST OF TOPICAL REPORTS

- No. 1 *Testing and Evaluation of Heat Recovery/Seed Recovery: Thermal, Chemical and Optical Data from MHD Simulation Tests*
R.A. Kumar, W.G. Steele, A.G. Wehr, J.B. Nail, R.L. Cook and J.A. Etheridge
- No. 2 *Diagnostic Instrumentation for the United States Magnetohydrodynamic Heat Recovery/Seed Recovery Development Program: Lecture Presented to MHD/HRSR Scientists and Engineers of the People's Republic of China, July 10 - 31, 1981*
D.L. Murphree
- No. 3 *The Magnetohydrodynamic Research Program of the MHD Energy Center at Mississippi State University and Structural Features of MHD Radiant Boilers: Lectures Presented to MHD/HRSR Scientists and Engineers of the People's Republic of China, July 10 - 31, 1981*
W.S. Shepard
- No. 4 *Testing and Evaluation of Heat Recovery/Seed Recovery: Design and Pretest Analysis of an MHD Radiant Boiler Test Loop*
W.M. Owen and W.G. Steele
- No. 5 *Two-Color Laser Transmissometer*
J.S. Lindner, P.R. Jang and J.C. Luthe
- No. 6 *Gas Analysis System*
R.A. Green
- No. 7 *Devices for Maintaining Optical Access in High Temperature Coal Combustion Environments*
R.L. Cook and L.R. Hester
- No. 8 *Sodium Line Reversal Plasma Temperature Measurement System*
T. Philip, L.E. Bauman and R.D. Benton

- No. 9 *Laser Doppler Velocimeter Particle Velocity Measurement System*
W. W. Wilson, D.V. Srikantaiah, T. Philip and A. George
- No. 10 *Multi-Color Pyrometer Temperature Measurement System*
R.A. Green and T. Philip
- No. 11 *Coherent Anti-Stokes Raman Spectroscopy System for Point Temperature and Major Species Concentration Measurements*
J.P. Singh and F.Y. Yueh
- No. 12 *Potassium Emission/Absorption System*
L.E. Bauman
- No. 13 *Particle Size Distribution System*
W. Okhuysen
- No. 14 *Intrusive Multi-Probe System*
R.A. Green and C.W. Bouchillon
- No. 15 *Visible/Infrared Emission Spectroscopy System*
D.L. Monts
- No. 16 *Faraday Rotation System*
L.E. Bauman and W. Wang

SUMMARY

The Diagnostic Instrumentation and Analysis Laboratory (DIAL) at Mississippi State University (MSU), under U.S. Department of Energy (DOE) Contract No. DE-AC02-80ET-15601, *Diagnostic Development and Support of MHD Test Facilities*, developed diagnostic instruments for magnetohydrodynamic (MHD) power train data acquisition and for support of MHD component development test facilities. Microprocessor--controlled optical instruments, initially developed for Heat Recovery/Seed Recovery (HRSR) support, were refined, and new systems to measure temperatures and gas-seed-slag stream characteristics were developed. To further data acquisition and analysis capabilities, the diagnostic systems were interfaced with DIAL's computers. Technical support was provided for the diagnostic needs of the national MHD research effort. DIAL personnel also cooperated with government agencies and private industries to improve the transformation of research and development results into processes, products and services applicable to their needs.

The initial contract, *Testing and Evaluation of Heat Recovery/Seed Recovery*, established a data base on heat transfer, slagging effects on heat transfer surfaces, metal durability, secondary combustor performance, secondary combustor design requirements, and other information pertinent to the design of HR/SR components at the Coal-Fired Flow Facility (CFFF) located at the University of Tennessee Space Institute (UTSI), Tullahoma. To accomplish these objectives, a combustion test stand was constructed that simulated MHD environments, and mathematical models were developed and evaluated for the heat transfer in hot-wall test sections.

Two transitions occurred during the span of this contract. In May 1983, the objectives and title of the contract changed from *Testing and Evaluation of Heat Recovery/Seed Recovery* to *Diagnostic Development and Support of MHD Test Facilities*. In July 1988, the research laboratory's name changed from the MHD Energy Center to the Diagnostic Instrumentation and Analysis Laboratory.

Editor's Note

Sixteen Topical Reports (see List of Topical Reports, page ix) were written detailing the development history and current status of twelve instruments and also reporting data from early simulation tests and design work. Summaries for each of the twelve instrument reports are included in this report along with complete reports for four instruments whose development did not reach the field testing stage before the conclusion of this contract.

DIAGNOSTIC INSTRUMENTS

Sodium Line Reversal System

The Sodium Line Reversal System (SLR) was one of the first advanced optical diagnostic instruments developed to measure temperatures in the coal combustion environments of large scale facilities. It is a versatile, optical temperature measurement system developed for the Heat Recovery/Seed Recovery (HRSR) project of the U. S. Department of Energy's (DOE) Magnetohydrodynamics (MHD) Program by the Diagnostic Instrumentation and Analysis Laboratory (DIAL) at Mississippi State University (MSU).

The SLR system 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, to make measurements in a harsh industrial environment.

The line reversal method of temperature measurement is very old. However, measurements have been confined to laboratory environments. The SLR system developed by DIAL is the only currently available packaged and portable instrument which can be taken to the field for flame temperature measurements. To use this system for measurements, the flame should contain sodium and must be optically accessible. It cannot measure temperature accurately below 2000 - 2200°F, depending on the flame condition.

The SLR system is fully operational. Its ability to measure reliable average flame temperatures in harsh environments has been proven through the measurements in the Coal-Fired Flow Facility (CFFF) at the University of Tennessee Space Institute (UTSI), Tullahoma, the Argonne National Laboratory (ANL), Argonne, Illinois, and the Component Development Integration Facility (CDIF), Butte, Montana. It is one of the instruments taken in DIAL's mobile instrument laboratory to other MHD sites for flame temperature measurements. Existing systems are ready and available to make measurements at any location with appropriate optical windows.

The principles of operation, a description of the system and its capabilities, and the operational details of this instrument are presented in Topical Report 8.

Multi-Color Pyrometer

The Multi-Color Pyrometer (MCP), another of the early advanced optical diagnostic instruments developed at DIAL, measures temperatures in the coal combustion environments of large scale facilities. The MCP was used to make remote, automatic, surface temperature measurements of slag-coated downstream MHD plant components developed for the HRSR project.

Thermocouples have been used for many years to measure wall temperatures in combustion facilities. Although thermocouples do not measure the true surface temperature, if enough is known about the material in which the thermocouple is embedded, a surface temperature can be computed. The required information includes the material's thermal conductivity and the distance between the thermocouple and the surface. When dealing with slag-coated surfaces, both pieces of information are difficult to determine.

Pyrometric methods of temperature measurement overcome all of these problems. Unlike thermocouples, which measure temperature at some point below the surface, a pyrometer measures the temperature of the surface by quantifying the thermal radiation emitted by the surface and relating it to a temperature. Pyrometric techniques for temperature measurement are also affected by the emissivity of the surface measured. To obtain the actual temperature, the emissivity must be either known or measured, or a two-color temperature measurement technique must be employed, eliminating the need to know the emissivity explicitly. It is this two-color technique which was chosen by DIAL for implementation in the MCP system.

The MCP was designed to use commercial pyrometers in a two-color system to measure the temperature of slag-coated surfaces in MHD simulation facilities. Using the two-color method, the slag emissivity could also be determined. It is available and capable of sustained field operations with a minimum of advance notice. The MCP has proven to be a consistent performer over the years and is reliable as well as simple to operate. Operation can be performed on a continuous basis without operator involvement other than ensuring that the sight path to the target is clear of obstruction.

The principles of operation, a description of the system and its capabilities, and the operational details of this instrument are presented in Topical Report 10.

Laser Doppler Velocimeter

The Laser Doppler Velocimeter (LDV) was used extensively in field operations during the lifetime of the DOE MHD contract. The primary technical information obtained from the LDV experiments was mean particle velocities. This information allowed estimates of the particle velocity profiles (mean particle velocity as a function of spatial location) and turbulence, as well as the location of flow reversals and stagnation points in the flow stream.

The most comprehensive measurements were conducted at the Coal-Fired Flow Facility in Tullahoma, Tennessee. Complete velocity profiles were obtained in the aerodynamic duct, diffuser and at fourteen different port locations in the radiant furnace. The LDV results were extremely useful for evaluating and confirming the flow modeling predictions for the facility.

Numerous field trips were made to the Component Development Integration Facility in Butte, Montana. The majority of the LDV measurements were made in the diffuser section of the flow train, although one attempt was made in the combustor region. The LDV results at the diffuser showed a bimodal particle velocity distribution which was consistent with the formation of a shock wave at the measurement location.

Extensive measurements were made on a model of the MHD combustor at the TRW facility in California. Velocity profiles were made at numerous spatial locations as a function of operation pressure (flow rates). The results were used to verify the flow characteristics for the model.

A description of the LDV system, its principals of operation, its capabilities, as well as details of its operation, are covered in Topical Report 9.

Coherent Anti-Stokes Raman Spectroscopy System

The Coherent Anti-Stokes Raman Spectroscopy System (CARS) was developed as a laser-based, advanced, combustion diagnostic technique to measure temperature and major species concentrations. It provides nonintrusive, temporal and spatial measurements of temperature and major species concentrations in hostile, turbulent and harsh combustion environments.

The CARS system developed by DIAL is a versatile, mobile system with unique features that suit it for use in a coal-fired, large-scale MHD combustion facility. Among these features is the capability to make measurements in the presence of coal particles in the gas stream. The instrument has been used to measure temperatures from 300 to 2700 K; theoretically, though, the mobile CARS can measure higher temperatures. The concentration measurement range is 1 - 30%, depending on the species and combustion environment. Accuracy of the temperature measurement is ~ 1% in a clean flame and ~ 5% in a coal particle-loaded flame.

Some problems may occur while making measurements using the mobile CARS instrument. However, the problems lead to modifications to the system for better performance. It is important to select the site for parking the mobile laboratory and the phase-matching geometry to be used for a particular industrial facility very carefully. Potential problems in the field must also be evaluated before making measurements.

The principles of operation, a description of the system and its capabilities, and the operational details of this instrument are presented in Topical Report 11.

Gas Analysis System

A Gas Analysis System (GAS) has been configured by DIAL to analyze the gaseous combustion products from nearly any combustion source. GAS is a mobile system of commercially available gas analyzers capable of analyzing a sample for O₂, SO₂, CO, CO₂, NO_x, and combustibles (as percent CH₄). A gas chromatograph is also available as a separate instrument for gas analysis. The analyzers determine the specie concentrations and send a signal to a computer used for data logging.

GAS also has several sampling systems designed for use in various environments. A sampling system, capable of collecting and storing samples for later analysis, has also been designed. GAS has been used to determine gas compositions at MSU, at the CDIF, and at industrial facilities.

The development of modern instrumental methods of gas analysis has allowed for routine, near real time, unattended gas analysis to be conducted. The data obtained from these analyzers can be input to a control computer allowing for continuous monitoring and changing of combustion conditions. The result is efficient operation of combustion facilities.

DIAL has demonstrated that the Gas Analysis System is a viable system. With minimal effort, industrial and commercial facilities can make a similar system using analyzers suited to their particular needs. The software developed by DIAL is available for use subject only to the constraints imposed by the U.S. government.

The Gas Analysis System is a field-ready instrument. The analyzers are rack mounted and ready for transport to any industrial site. The design, operation and data collection abilities of GAS are presented in Topical Report 6.

Particle Size Distribution System

The Particle Size Distribution System (PSD) was designed to determine the size distribution of slag and seed particles generated at an experimental coal-fired MHD power facility and to determine the efficacy of components developed for DOE's HRSR program.

PSD is an *in situ* instrument which sizes individual particles and counts the number of occurrences for several size classes and measures the concentration of particles in gas. Two methods which are commonly used are a total mass sample extraction and a size distribution measurement with an inertial separation probe assembly. Several commonly used methods of determining particle size and distribution do not give concentration measurements directly, and the conditions under which the sample is extracted will determine if the inevitable size bias can be overcome. The intrusive nature of the sample extraction process presents additional problems in high temperature or highly corrosive environments.

The PSD instrument has been developed to a state in which it is operational, but further development of the prototype is necessary. The instrument has been successfully utilized in situations where the number density and flow are quasi-steady. A more detailed account of this instrument's development can be obtained from Topical Report 13.

Two-Color Transmissometer

The Two-Color Laser Transmissometer (TCLT) is an instrument designed to measure, nonintrusively, average particle diameters and concentrations (loadings) in MHD environments. The knowledge of particle (fly ash, seed) characteristics in advanced coal-fired power plants is extremely important for predicting heat transfer rates, deposition, and environmental and economic aspects of plant operation. Specific examples of particulate behavior pertinent to the upstream and downstream portions of the MHD facility have been reported elsewhere.

The TCLT instrument has been used to determine particle diameters and number or mass densities in a number of different locations of an MHD pilot-scale power plant. Measurements have been performed in a diffuser, at various locations of the primary furnace, in real and simulated steam superheater modules, and in the gas stream before and after particulate retention equipment such as electrostatic precipitators (ESP) and baghouses. The nucleation of seed (K_2SO_4) particles has been studied in a controlled environment and compared to a theoretical model. Results from both theory and experiment are in reasonable qualitative agreement.

Between 1984 and 1990, the instrument consisted of three main components and their associated parts:

- Optical unit--which contains the lasers, optics, detectors, amplifiers, etc.;

- Microprocessor control unit--which permits the collection, storage, and minor manipulation of raw data through user input keypad commands;

- Microcomputer--which allows for the storage of raw and analyzed data (hard disk or floppy diskette), permits the calculation of the average particle diameters and loadings, and allows for statistical analysis and appropriate presentation of the results.

In addition to the main components described above, a second optical unit has recently been constructed. Use of two optical units permits

the determination of particle diameters and loadings at two different locations of a facility. Experiments such as the determination of fly ash carry-over from the upstream to the downstream portion of the facility and the determination of particulate collection efficiencies of components such as precipitators and baghouses can now be performed in essentially real time.

The current configuration of the instrument consists of the optical unit and the microcomputer equipped with a programmable analog-to-digital (A/D) conversion board.

Intrusive Multi-Probe System

The Intrusive Multi-Probe System (IMPS) was developed at DIAL to facilitate making intrusive measurements in harsh, combustion environments. The IMPS has frequently been used to make temperature measurements in the particle-laden, high temperature, corrosive gas stream found in the superheater of a coal-fired MHD facility. In answer to the call to fill a niche where nonintrusive techniques were needed but access prohibited their implementation, IMPS provides the vehicle by which nonintrusive methods may be employed in an intrusive manner. Several techniques such as sodium line reversal and pyrometry are useful in the determination of important parameters in the operation of a combustion facility. Unfortunately, many times adequate optical access simply does not exist to allow the use of the nonintrusive methods. While the IMPS is capable of delivering several different sensors into various environments for measurements, most of DIAL's experience has been in using the Accufiber 310 Light Pipe Sensor to make surface temperature measurements. The Light Pipe Sensor is a sapphire rod protected by a quartz sheath which receives thermal radiation emitted from surfaces. The radiation is then transmitted via an optical fiber to a detector where the surface temperature is determined. The sensor, delivered by a water-cooled probe, can measure temperatures within the range of 950 to 3600°F (500 to 2000°C). The IMPS provides the means whereby this sensor can be inserted to within a fraction of an inch from the surface to be measured while protecting the sensor from stray radiation, excessive heat and particles. An important part of the IMPS is the ability to implement the computer-controlled insertion mechanism which will automatically insert and retract the probe with its sensors. When fully implemented this will allow for the automated operation of the IMPS from a remote location. A prototype of the computer-controlled insertion mechanism has been built and successfully tested. Only minor work remains to fully implement the technique. Significant experience has been gained in the operation of the IMPS at combustion facilities, and the system has been found to be highly reliable and accurate. The IMPS is not, however, limited to use at only conventional combustion facilities. Work is currently in progress to use the probe in a plasma torch to measure various surface temperatures. Application of the IMPS to components downstream of a plasma torch would be relatively simple.

A complete description of the instrument, its operation and capabilities can be obtained in Topical Report No. 14.

Potassium Emission/Absorption System

The Potassium Emission/Absorption System (PE/AS) is a multi-wavelength emission absorption instrument developed for measurement of gas temperature and seed atom density measurements on large-scale, combustion-fired MHD flows. With the assumptions of (1) ionizational equilibrium and (2) a lack of other important sinks or sources of electrons, the instrumental results can also be used to calculate the electron density and, combined with an electron mobility model, infer the electron conductivity, a crucial parameter for analysis of MHD power generation. The instrument, although it could be used on any well characterized absorption line present in the flow, was named for potassium, widely used for seeding high temperature flows with electrons because of its low cost and relatively low ionization energy.

By its nature, the instrument is based upon line-of-sight intensity measurements and so provides bulk results; however, measurements are made on the wings of the atomic absorption line to avoid cool boundary layer effects and yield measurements approximating that of the hot core of a flow. Measurements of a transmitted reference white light and the flame emission are made at two wavelengths to eliminate bias caused by particle emission/absorption or out-scattering, making the instrument applicable to particle-laden combustion systems, especially coal-fired systems. The two-wavelength method also significantly reduces problems with particle in-scattering, optical window fouling, and misalignments, problems that can be especially harsh on large-scale, coal-fired combustion systems. With relatively simple calculations and with a tungsten lamp as the reference white light source, the instrument is robust enough for use as a monitor/process control instrument.

The PE/AS instrument measures millisecond time-resolved intensities, the data collection is at the rate of one frame-per-second and results are reported as averages and standard deviations, i.e., as a probability distribution function, for a set of 50 frames covering about one minute. Although the instrument does not follow the flow properties in real time, the probability distribution functions provide an indication of the fluctuation in the flow properties.

The accuracy of the temperature measurement is determined by the accuracy in determining the reference lamp temperature and is approxi-

mately 20 K. On a stable bench-top flame, the instrument has a precision of better than 10 K. The accuracy of the seed atom number density determination is limited by the knowledge of the atomic absorption strength ($\pm 10\%$) and the lineshape model. The instrument precision for atomic density measurements on a bench-top flame is about 10%. Complications from particle effects, boundary layer profiles and inherent flow fluctuations will increase the uncertainties and reduce the precision. On typical MHD flows, the measurement standard deviations are typically ± 0 K and $\pm 25\%$ for the temperature and atomic density, respectively.

The PE/AS has been a field ready instrument for almost a decade and has been demonstrated to provide valuable experimental measurements for prototype MHD testing. Topical Report No. 12 draws together in a cohesive report the description, capabilities and scientific background for the Potassium Emission/Absorption System (PE/AS) and reports representative field test results.

Faraday Rotation System

The Faraday Rotation System (FRS) is a laser-based diagnostic system developed at DIAL to provide support for the demonstration of prototype-scale coal-fired combustion MHD electrical power generation. Intended for application in the MHD channel, the system directly measures electron density through a measurement of the induced rotation in the polarization of a far infrared laser beam after passing through the MHD flow along the magnetic field lines. A measurement of the induced polarization ellipticity provides a measure of the electron collision frequency which together with the electron density gives the electron conductivity, a crucial parameter for MHD channel performance.

The goal of this effort was to develop a robust and accurate monitor of the MHD flow conductivity. MHD power production depends critically upon the conductivity of the working fluid and knowledge of the conductivity will be crucial to the analysis of the performance of an MHD channel. Conductivity is a critical internal parameter and because of the many complex interactions, external measurements do not provide sufficient data for its measurement. The conductivity in a seeded plasma arises primarily from electrons in the flow since the considerably heavier ions have a very low mobility and therefore a measure of the electron conductivity is a good measure of the total conductivity. Intrusive probes, more typically used for measurements of conductivity, are not feasible in the high temperature, supersonic flow and particle-laden coal-fired MHD flows. Faraday rotation was deemed the most direct and simple method for nonintrusive measurement of electron conductivity in such extreme flows. No commercially available instruments exist for far infrared Faraday rotation measurements hence this development effort.

Laboratory demonstration experiments with the Faraday Rotation System show measurements of electron density that agree with an independent measurement by resonance line emission absorption and a Saha calculation. The measurements of electron collision frequency agree well with modeling calculations, giving electron conductivity results that are reasonable for the flame system used to provide the plasma. The uncertainty in the measurements were larger than desired for a demonstration of the system performance; however, a magnet with a larger pole gap would have been required for a longer path length in order to increase the angles and lower the percentage uncertainty.

The system in a rotating polarizer configuration is capable of measuring rotation angles to within $\pm 0.3^\circ$. For a nominal 3 T magnet, the system could be used to measure electron density times path length as low as $2.7 \cdot 10^{17} \text{ m}^{-2}$ using the 496 nm laser line. With the 118 nm methanol laser line, the maximum measurable density time path length would be $1.4 \cdot 10^{20} \text{ m}^{-2}$. In the beam splitting configuration the uncertainty in the angle is $\pm 0.6^\circ$ and these minimum and maximum values are $5.4 \cdot 10^{17}$ and $7.1 \cdot 10^{19} \text{ m}^{-2}$, respectively. A beam splitting measurement can provide a time resolution of 0.1 s which would provide adequate time resolution for diagnostics on an MHD flows. Recommendations for configuring the system performance on larger scale facilities have been made. The system is generally applicable to MHD flows over a wide range of size and plasma conditions because of the many laser wavelengths that can be used. Recommendations were made for laser wavelengths to use when applying the system to large-scale MHD flows. The theory of the measurements, a description of the system, its capabilities, laboratory demonstration measurements on seeded flames with comparison to emission absorption measurements, and the current status of the system are presented in Topical Report 16.

Multi-Purpose Imaging System

Two-dimensional, laser-induced fluorescence imaging has been shown to be a valuable technique for combustion diagnostics.¹ The time-resolved snapshots of the concentration gradients of the selected fluorescing species provided by this technique can yield much useful information about the combustion environment. For MHD systems, it would be particularly useful to take LIF snapshots of potassium atom concentrations at various times and places in the plasma stream. The ability to map concentration gradients in an MHD plasma will provide information on seeding uniformity and arc formation. Unfortunately, it is not possible to use the most common optical lines of the K atoms, the 4S to 4P transitions at 766.5 and 769.9 nm, for LIF imaging due to the large thermally excited emissions and self reversals found in these heavily K doped plasmas.²

The first problem in any fluorescence detection scheme is choosing appropriate excitation and observation wavelengths for the system of interest. It is generally desirable to choose an excitation wavelength that will raise the species of interest from its ground state to an excited state, that will in turn radiate to a third state.³ The advantages of using a three level scheme are that the observation and detection wavelengths are different, so that scattered (i.e. Mie and Rayleigh) light may be discriminated against. In addition, the fluorescence is not reabsorbed by ground state atoms, and, especially for seeded combustion systems, thermal emissions can be avoided. It is for these reasons that the excitation and detection wavelengths and levels of the potassium atoms shown in Figure 1 were chosen for investigation.

Rubidium, like the other alkali metals, is a rather common impurity in the potassium salts used as seed for MHD plasmas. From emission measurements taken on the DIAL test stand facility at Mississippi State University, which is used to simulate an MHD environment, it is estimated that the technical grade K_2SO_4 seed contains approximately two parts-per-thousand rubidium.⁴ This is a reasonable value considering that sea water contains 0.5 and the earth's crust 10 parts-per-thousand Rb relative to K.⁵ The seed also contains a substantial sodium impurity, but this species is not as useful as a surrogate because of its large abundance in coal. The very small amount of rubidium in coal guarantees that the

preponderance of the Rb comes from the seed and is therefore an indication of the potassium atom concentration.⁶

A spectroscopic advantage in the use of rubidium fluorescence is the large, 14.7 nm, separation of the 5P to 5S doublet caused by the increase in spin-orbit splitting for heavy metals. Even though the excited state $5P_{1/2}$ and $5P_{3/2}$ levels are widely spaced, the rapid collisional energy transfer found in atmospheric pressure flames results in both levels being populated, and hence fluorescing, when either one is excited by a laser. Therefore, it is possible to excite at one wavelength and observe at another, with the use of an interference filter in the collection optics, to discriminate against the laser scattering that might be a problem in a particle laden flow. Another possibility is to spectrally disperse the fluorescence and image the two emission wavelengths separately. If the collisional energy transfer between the excited states is rapid enough to establish thermal equilibrium between them, the intensities of the spectrally-resolved images will be related by their Boltzman populations and thus the local temperature. It should thus be possible to extract the temperature gradient along the laser excitation path from such images.

Experimental Apparatus

A block diagram of the fluorescence imaging system is shown in Figure 2. The excitation light was provided by an Nd:YAG pumped dye laser (Quanta-Ray DCR-1A and PDL-2) and an optional frequency doubler (Spectra Physics WEX). By using various dyes and doubling crystals, wavelengths of interest between 300 and 795 nm were generated at power levels ranging from 20 mJ (580 nm) to less than 1 mJ (810 nm doubled to 405 nm). The laser light was expanded by cylindrical lenses to excite a wide, thin section of the flame. Solution seeded CH_4/air and MAPP/ N_2O flames from slot and Meker burners provided the combustion sources.

For each excitation wavelength, fluorescence was searched for by using a small monochromator and photomultiplier tube (not shown in the diagram). Images of the detected fluorescence were taken by a gated, intensified, charge injection device camera (Xybion ISG). A 100-ns gate, synchronized to the laser Q-switch, was used to help in discriminating the fluorescence from background flame emission. The video output of the camera was sent to a computer (PC/AT clone) equipped with a frame grabber (DT 2851) that digitized, stored, processed, and displayed selected images.

Results

Since a three level excitation/detection scheme was desired, one photon transitions from the 4S ground state of the potassium atoms to high lying Np states (see Figure 1) were investigated. Laser wavelengths of 310.3 to 291.7 nm were used to excite levels with n values of 8-14, but no fluorescence could be detected at either the excitation wavelengths or in the 892.7 to 754.4 nm region corresponding to Np to 5S transitions. Emissions from the 5D, 5P and 6S levels, which could be populated by collisional transfer from the initially excited states, were also undetectable. Attempts to produce fluorescence by two photon transitions to high lying Ns and Nd states were also unsuccessful.

Two experiments that were successful provided some reasons for the lack of fluorescence detection. The first one, optogalvanic spectroscopy⁷, consisted of measuring the change of the electrical conductivity of the flame with a biased probe as the laser was tuned through various potassium resonances. Strong optogalvanic signals were observed at 310.2 and 303.5 nm. These results show that it is possible to excite the 8P and 9P levels of the potassium atoms in the flame, and that some of these excited atoms are ionized in the flame. The second experiment involved using 583.2 nm light to raise atoms from the thermally populated 4P level to the 5D level. When this was done, very weak fluorescence was detected at 404.5 nm, the 5P to 4S transition. The time evolution of this light pulse was indistinguishable from that of the laser; i.e., the rise and fall times were less than 10 nsec, indicating that the collisional processes of transfer from the 5D level and quenching of the 5P state are both rapid.

Fluorescence has also been detected by directly exciting the 5P level with 404.4 and 404.7 nm radiation and observing at the laser wavelength. The emitted light is relatively weak and has a short lifetime (<10 nsec), indicative of rapid quenching, but is suitable for imaging applications. Figure 3 shows a laser fluorescence image of a potassium seeded CH₄/air flame produced by excitation at 404.7 nm. The line through the flame region is true fluorescence since it disappears when the laser is tuned off resonance, whereas the Mie/Rayleigh scattered light from room air outside of the flame remains visible. The contrast in this image is poor primarily because of the low laser power available from doubling the already weak 809.4 nm output of the dye laser.

A one laser shot (10 nsec) fluorescence image of a rubidium seeded flame is shown in Figure 4. A 0.008 M RbCl solution was aspirated at a rate of 1.9×10^{-4} l/min to give a Rb mole fraction of 4.2×10^{-5} in the flame. This concentration, which produces an acceptable image, is comparable to that found in the DIAL test stand. The original eight bits-per-pixel (256 gray levels) digitized image has been reduced to twelve intensity levels for printing as can be seen in the gray scale at the bottom of the picture. It is clear that the Rb concentration is the highest in the center of the flame and tapers off toward the cooler edges. This light center section is about 1.2 times as intense as the darker area adjacent to it. The abrupt cut off at the top comes from the use of the fan shaped excitation beam. The spatial scale of this image can be set by comparison to the 3.8 cm diameter burner top which gives the bright laser scatter spots at the base of the flame.

Figure 5 shows another image of a 0.008 M RbCl seeded flame but now in the presence of 3 M K_2CO_3 . The use of a long wavelength pass filter in front of the camera and short gating time to discriminate against the intense thermal K emission is demonstrated in the right hand image of this figure where the laser has been tuned 0.3 nm off the Rb resonance. The potassium emission is visible, but is not intense enough to greatly interfere with the rubidium fluorescence (compare the left hand image where the laser is tuned to resonance). The sharp intensity change at the top of this image indicates the contrast obtainable between fluorescence and emission, and the Rb concentration profile is clearly visible.

Discussion

Taken together, the above results indicate that some process, probably collisional energy transfer, is destroying the excited states faster than they can radiate leading to vanishingly small fluorescence quantum efficiencies. Even though the radiative lifetimes of these states, 760 nsec for the 8P, 572 nsec for the 5D, and 133 nsec for the 5P,⁸ are long compared to the typical collision times of 3 nsec found in atmospheric pressure flames, very efficient processes must be invoked to explain such complete quenching of the fluorescence. For example, the first excited state of the OH molecule has a radiative lifetime of 700 nsec but still fluoresces brightly under flame conditions.

There is very little information in the literature on the dynamics of potassium excited states, but there are results for sodium atoms that are applicable to this study. T.F. Gallagher and his group have done consider-

able work on the lifetimes of the excited states of Na and have reported quenching cross sections (total removal rates) for collisions with a number of gases.⁹ In particular, they have found cross sections of 160 Å² for CO and 110 Å² for N₂ quenching of the 6S state of Na.¹⁰ These cross sections imply a lifetime of 0.1 nsec for this state under flame conditions. If similar cross sections hold for K excited states, which is not an unreasonable assumption, even the 5P level with its relatively short radiative lifetime will have a fluorescence quantum efficiency, the number of photons emitted divided by the number absorbed, of less than 0.001. It is also known that Na states higher in energy than the 7D, which is only 2249 cm⁻¹ below the Na ionization limit, are completely ionized at flame conditions.¹¹ The 8P level of K is only 2779.7 cm⁻¹ below the ionization limit and the 9P level is only 2067.7 cm⁻¹ away so it may be assumed that these and all higher levels of potassium are completely ionized and thus do not fluoresce in flames. This rapid ionization also explains the strong optogalvanic signals that were observed. The mechanism for quenching the 5D and 5P levels, which are 4834 and 10,308 cm⁻¹ below the ionization energy, is less clear, but both total loss of excitation energy and transfer of energy to other nearby atomic levels is known to be rapid for Na atoms of comparable energy.¹²

Conclusions

Due to the rapid collisional quenching of the upper states of the potassium atom, it is not possible to find a three level scheme that will allow excitation and detection at different wavelengths under combustion conditions. However, images of the potassium atom concentration in flames have been produced with 404.7 nm laser excitation and fluorescence detection. Increasing the laser power by mixing the 1064 nm fundamental of the Nd:YAG with 651 nm dye laser output to make the 405 nm light would allow brighter images to be taken. Computer subtraction of captured images can be used to discriminate against scattered light if necessary.

We have also successfully taken LIF images of flames seeded with small amounts of rubidium and large amounts of potassium. Since the Rb/K ratio used in this study is similar to that in technical grade potassium salts, it appears that rubidium fluorescence images will provide valuable information about MHD plasmas, such as the seed concentration profiles.

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Figure 1. Potassium energy levels.

Figure 2. Block diagram of fluorescence imaging experimental apparatus.

Figure 3. Fluorescence image of potassium in a flame using 405-nm excitation.

Figure 4. Fluorescence image of rubidium in a flame.

Figure 5. Fluorescence image of rubidium in a flame with a large potassium background emission.

Differential Absorption Laser Spectroscopy System

Introduction

Optical and laser remote-sensing techniques^{1,2} provide powerful tools for environmental monitoring. Differential absorption lidar^{3,4} (DIAL) is a mobile, laser-based system for obtaining a three-dimensional mapping of atmospheric pollutants. Differential optical absorption spectroscopy^{5,6} (DOAS) uses a classical light source to determine line-of-sight, average concentrations over an extended path.

The Differential Absorption Laser Spectroscopy (DALAS) system developed at MSU utilizes methodology and technology developed for differential absorption lidar and for differential optical absorption spectroscopy for environmental monitoring and applies it to diagnostics of combustion processes. A DALAS experiment is performed by comparing the transmission of two wavelengths through the sample. One wavelength is strongly absorbed by the species. The other wavelength is not absorbed or is just weakly absorbed by the species. Taking the ratio of the transmitted intensities of the two wavelengths "subtracts out" background effects (such as light scattering or absorption by other species) that are not associated with absorption by the species of interest. If the appropriate calibration experiments have been done or if the absorption coefficient of the species are known, then the absolute concentration of the species can be determined from Beer's law. Otherwise, if the value of the absorption coefficient of the species is not known, then only the relative concentration of the species can be determined. Furthermore, the DALAS system can provide time-resolved concentration measurements if concentration fluctuations are of interest.

Purpose of the Instrument

For practical combustion systems (coal-fired electric generating facilities, industrial burners, hazardous waste incinerators, etc.), DALAS has the capability of providing real time, line-of-sight, average species concentration (number density) determinations at the sub-parts-per-million level. DALAS is a general purpose technique that can be applied to a wide variety of species. A DALAS experiment is performed by comparing the transmission of two wavelengths through the sample. One wavelength corresponds to a strong absorption of the species of interest.

The other wavelength is a wavelength that the species only weakly absorbs. Both wavelengths follow the same path through the sample and are detected by the same photodiode detection system. Comparison of the two wavelengths "subtracts out" background effects (such as light scattering by particulates or background absorption) that are not associated with absorption by the species of interest. The concentration of the species is determined from Beer's law. Note if the species' absorption coefficient (whose value is a function of both temperature and pressure) is known, then absolute concentrations of the species can be determined; however, if the value of the species' absorption coefficient at the temperature and pressure of interest are not known, then only the time-dependent relative concentration of the species can be determined.

DALAS is limited to monitoring the absolute concentration of only one species at a time. In principle, DALAS can be used to obtain the relative concentration of two species by having one wavelength correspond to a wavelength that one of the species strongly absorbs and the second species does not strongly absorb, and the second wavelength to a wavelength the first species does not strongly absorb, but the second species does strongly absorb. Both transitions must be within the gain profile of a single laser dye. Furthermore, both transitions must involve either ground states or metastable states so that their relative intensity is an unambiguous indicator of the species' concentration.

Performance Requirements

The functions to be performed by the DALAS system include:

1. Generation of two visible (and if necessary, two ultraviolet) wavelengths under computer control;
2. Measurement of the DALAS signal intensity for both wavelengths, and graphically displaying them on a computer screen during the experiment;
3. Saving raw data for off-line determination of absolute concentration and for comparison with other system parameters in order to assist in efforts to optimize and control the combustion process.

Technical Approach

The differential absorption technique requires two lasers (or one laser with two output wavelengths) to determine the number density (concentration) of the species of interest in the sample.

In order to determine the concentration of the species we are interested in, we must know the total change in laser intensity that occurs when a laser beam passes through a known distance of this species. For low concentrations, the Beer-Lambert law best describes the exponential attenuation that occurs when a light beam passes through an absorbing medium:

$$I(\lambda, r) = I_0(\lambda) \exp[-\alpha(\lambda)r]. \quad (1)$$

Here we define $I_0(\lambda)$ to be the incident light intensity at wavelength λ ; $I(\lambda, r)$ is the light intensity at wavelength λ after it passes a distance r through the absorbing medium; and $\alpha(\lambda)$ is the wavelength-dependent absorption coefficient. If λ is fixed, α is a constant at constant temperature and pressure.

The Beer-Lambert law can be used by the DALAS system to determine species concentration when a laser beam passes through an absorbing medium. The light's intensity can be expressed as

$$I(\lambda, r) = S(\lambda, r) I_0(\lambda) \exp[-\int \alpha(\lambda) dr]. \quad (2)$$

Here $S(\lambda, r)$ is a system response parameter that is usually determined by the geometric configuration of the receiving system and by the quantum efficiency of the detection system at wavelength λ . Usually $\alpha(\lambda)$ consists of three parts:

$$\alpha(\lambda) = \alpha(\text{Mie}) + \alpha(\text{Rayleigh}) + \alpha(\text{absorption}). \quad (3)$$

$\alpha(\text{Mie})$ is the scattering constant for Mie scattering, which occurs when photons are elastically scattered from small particles or aerosols of a size comparable to the wavelength of the light. $\alpha(\text{Rayleigh})$ is the scattering constant for Rayleigh scattering, which occurs when photons are elastically

scattered from atoms or molecules. Both processes occur with no frequency change.

α (absorption) is the effective absorption constant contributed by all species in the sample that absorbs at wavelength λ :

$$\alpha(\text{absorption}) = \sum \alpha_i(\lambda) = \sum n_i \sigma_i(\lambda) \quad (4)$$

where $\alpha_i(\lambda)$ is the absorption coefficient of the i th component; n_i is the concentration of the i th species in the sample; and σ_i is the absorption cross section of the i th species.

Figure 6 shows a schematic of the DALAS apparatus. Two spatially identical laser pulses are directed into the flame or gas cell. One corresponds to strong absorption by one species (λ_a). The other one (reference wavelength λ_r) is not absorbed or just weakly absorbed by this species. These two signals are collected and processed. The two-wavelength laser output can be realized by two different lasers or by one laser with two-wavelength output.

For a DALAS measurement, we need to select λ_a to correspond to strong absorption by just one species. Usually we select λ_r to lie in the far wing of this absorption so that light with this wavelength is just weakly absorbed by this species. This means that the absorption cross section σ for λ_a is much bigger than that for λ_r . The off-resonance wavelength is used to eliminate Mie and Rayleigh scattering attenuation contributions, absorption by other species, and instrumental response parameters.⁷ Because the cross sections for Mie and Rayleigh scattering generally do not differ much over a small wavelength interval, the concentration of the absorbing species of interest can be determined by taking the ratio of the attenuations due to the two laser wavelengths. From Equation (2), we can get

$$\frac{I(\lambda_{a,r})}{I(\lambda_{r,r})} = \frac{S(\lambda_{a,r})I_0(\lambda_a)}{S(\lambda_{r,r})I_0(\lambda_r)} \exp \left[- \int \sum [\sigma_i(\lambda_a) - \sigma_i(\lambda_r)] n_i(r) dr \right] \quad (5)$$

Because one species dominates the absorption at wavelength λ_a , and because the scattering cross section is assumed to be almost constant in the region from λ_a to λ_r , we can obtain the concentration $n_i(r)$ by differentiating the above equation,

$$n_i(r) = \frac{1}{\Delta\sigma_i} \frac{d}{dr} \left[\ln \left(\frac{I(\lambda_r, r)}{I(\lambda_a, r)} \right) + \ln \left(\frac{S(\lambda_a, r)I(\lambda_a)}{S(\lambda_r, r)I(\lambda_r)} \right) \right]. \quad (6)$$

Integrating the above equation from r_1 to r_2 , we obtain

$$\int n_i(r) dr = \frac{1}{\Delta\sigma} \left[\ln \left(\frac{I(\lambda_r, r_2)I(\lambda_a, r_1)}{I(\lambda_a, r_2)I(\lambda_r, r_1)} \right) + \ln \left(\frac{S(\lambda_a, r_2)S(\lambda_r, r_1)}{S(\lambda_r, r_2)S(\lambda_a, r_1)} \right) \right]. \quad (7)$$

Usually the second term is zero because $S(\lambda_j, r_k)$ is approximately equal to $S(\lambda_j, r_m)$ for a small wavelength interval. If the system response parameters $S(\lambda, r)$ depend on wavelength, the second term is not zero. However, through careful system design, this term can at least be made very small. If we assume this term can be neglected, the average concentration of the species over the sample path length $\Delta r = r_2 - r_1$ can be expressed by

$$n_i = \frac{1}{\Delta r \Delta\sigma_i} \left[\ln \left(\frac{I(\lambda_r, r_2)}{I(\lambda_a, r_2)} \right) + \ln \left(\frac{I(\lambda_a, r_1)}{I(\lambda_r, r_1)} \right) \right]. \quad (8)$$

The value of the second logarithmic term in Equation (8) is determined by putting a laser power meter before the sample and measuring the laser power first at wavelength λ_a and then at wavelength λ_r . Although the values for both terms can fluctuate, the time averaged ratio $I(\lambda_r, r_1)/I(\lambda_a, r_1)$ is a constant for a given set of (λ_a, λ_r) wavelengths.¹¹ This ratio is determined by the relative position of λ_a and λ_r on the gain curve of the laser dye solution.

System Description

The DALAS system consists of three parts:

1. the pulsed dye laser system,
2. the sample system, and
3. the photodetector and signal processing system.

Tunable pulsed dye laser system. Either simultaneous or alternate two-wavelength dye laser operation can be used.^{2,8} Actually, the alternate mode of laser operation offers some important advantages such as simplification of the DALAS signal receiver and transmitter; doubling the energy available for each wavelength; and complete elimination of the competition for intensity between the two wavelengths.⁹

In the reasoning leading to Equation (8), the assumption is made that the scattering factors are equal for the two signals. This requires that the two laser beams are spatially and temporally identical and the optical paths are the same. But it would be difficult to exactly align two laser beams spatially and temporally if different laser sources are used to generate the two wavelengths. Even a small deviation from identical optical paths can cause a systematic error. The temporal requirement is often not fulfilled if one laser is used for both beams. But this shortcoming can be overcome by signal averaging. Signal averaging can also provide reliable statistics, and the short-time separation between sequential DALAS signals does not significantly reduce the accuracy.

Nenchev, et al., first used a rotating parallel plate in a dye laser oscillator so that a different laser wavelength can be obtained for each laser pulse.¹⁰ In their design, wavelength selection is obtained from a reflective interference wedge acting as a small-angle Fizeau interferometer. The lasing wavelength is dependent on where along the wedge the laser beam strikes. Commutation between the two wavelengths is achieved by rapidly, precisely, and repeatedly changing the tilt angle of the parallel plate so that the laser beam strikes where the wedge separation is wide enough to produce the desired wavelength. The adjustment of their parallel plate's position is critical. The basic design of Hung and Brechignac⁸ eliminates these drawbacks (see Figure 7). They also used a rotating, rectangular glass block to refract the dye laser beam, but to an independent wavelength selection system (grating mirror) instead of an interference wedge. The glass block is rotated 90° between laser pulses by a

stepper motor under computer control. The operation of this dye laser is not sensitive to the alignment of the dye laser beam and the block. This ruggedness is an important asset for field measurements. In our grazing-incidence dye laser system, Hung and Brechignac's design⁸ is adopted and modified.

By using a series of different dye solutions, the output dye laser wavelength can cover the spectral region from ultraviolet to near infrared. For our SO₂ experiments, Rhodamine 610 (Exciton) was the laser dye used. Because the energy efficiency of the grazing-incidence configuration is low, a first stage amplifier was constructed in order to obtain the relatively high power required for frequency doubling. Both laser dye solutions flow through 50 mm x 18 mm x 13 mm quartz dye cells (Spectra-Physics 002-0210) sealed by ethylene propylene O-rings (Parker 2-018). In order to attain maximum transmission, the cell was oriented at Brewster's angle. The high power laser pump beam causes a rapid change of the dye solution temperature. This changes the index of refraction of the dye, causing optical distortion and decomposing the dye. To solve this problem, a circulation system was used. The dye laser solution was pumped continuously through the dye laser circulation system by a pump (Micropump 120-415).

The pump source used was a Nd:YAG laser (Quanta-Ray DC R-2A-10). Its second harmonic output (wavelength 532 nm) was used. The specifications for our Nd:YAG laser are: up to 45 MW of 532 nm peak power; typically 20 mJ/pulse average 532-nm laser energy; 8 ns full-width-at-half-maximum (FWHM) nominal pulse duration; and 10 Hz repetition rate.

A 50-mm diameter beamsplitter (CVI Laser BS532.0-10-2025) was used to divide the Nd:YAG laser beam: 10% of the 532-nm input beam was reflected and focused to a narrow strip by a 60-mm focal length cylindrical lens (Melles Griot 01LCP021) mounted on a rotation stage (Newport RSA-2) that enables us to rotate the focused 532-nm pump beam for maximum dye laser power. Because the absorption coefficient of the active medium for the pump radiation is large, the pump beam is strongly attenuated. Dye lasing occurs in a thin layer directly behind the dye cell wall along the focal line of the cylindrical lens so the focal line must be adjusted to be near the wall and to be rotated to guarantee maximum dye laser output.

As shown in Figure 7, a commutation between two wavelengths in successive pulses is obtained by rotation of a parallel 25.4 mm x 38.1 mm x 12.7 mm (width x length x thickness) custom glass block (Optics For Research) under computer control by direct coupling of a stepper motor (NMB Technologies 17BB-H2552) and the shaft of the brass mount to which the glass block is glued. The glass block is made of BK7 glass and a single anti-reflection coating layer of magnesium fluoride is coated on both 25.4 mm x 12.7 mm faces and on both 38.1 mm x 12.7 mm faces. When the block is rotated by 90°, the separation¹³ of the laser beams for successive pulses can be determined by

$$h = \frac{2d \sin(\alpha_1 - \alpha_2)}{\cos(\alpha_2)} \quad (9)$$

where d is the thickness of the block; α_1 is the incident angle; α_2 is the refraction angle; and n is the refractive index of the block which is given by

$$n = \frac{\sin(\alpha_1)}{\sin(\alpha_2)} \quad (10)$$

A separation of 17 mm between the two laser beams can be achieved for a rotation angle $\beta = 2\alpha_1 = 90^\circ$.

A holographic diffraction grating (American Holographic 130.2400-D14V15) was used to select the dye laser wavelength. It is mounted vertically on a kinematic mirror mount manufactured by the DIAL machine shop. The horizontal axis of the grating's kinematic mirror mount was adjusted by a micrometer (Newport SM-05) and the vertical axis was adjusted by a fine screw (Newport AJS-2). The basic grating equation is

$$m\lambda = a [\sin\theta_1 + \sin\theta_2] \quad (11)$$

where m is the diffraction order; a is the groove spacing of grating; λ is the laser wavelength; θ_1 is the light's incidence angle; and θ_2 is the refraction angle. In the present case, $a = 1/2400 \text{ mm}^{-1} = 417 \text{ nm}$. When the 60-mm

wide, 40-mm tall, 2400-lines/mm grating was used at 87° incident angle, according to the grating equation, only first order diffraction could be obtained. This eliminated additional loss of light into other unwanted diffraction orders.

One end of the dye laser oscillator stage was composed of the diffraction grating and a tuning mirror. The double-stage tuning mirror consists of two aluminum mirrors M_1 and M_2 (25 mm $\times$ 102 mm) (Ealing 23-4195) mounted vertically one above the other so each of them can reflect the associated lower or upper laser beams produced by the rotation of the glass block (see Figure 7). Each tuning mirror was mounted on a kinematic mirror mount with a micrometer of 0.0001" (2.54×10^{-3} mm) resolution (Daedal 9531E) on one end controlling the horizontal displacement of the tuning mirror; the other end of the mirror mount pivots on a ball bearing. The center of the ball bearing was 88.6 ± 0.1 mm from the center of the micrometer. A fine screw (Newport AJS-2) was used to adjust the vertical tilt of each mirror mount plate. The dual-stage kinematic mirror mount was manufactured by the DIAL machine shop. The rotation of the tuning mirror was determined by the setting of the horizontal micrometer. The laser output wavelengths were determined by the orientations of mirrors M_1 and M_2 .

The automatic tuning of the end mirror system for wavelength scanning was designed and constructed by Mr. Charles Robinson, a DIAL electronics technician. This system consisted of two parts: a stepper motor with $1.8^\circ/\text{step}$ resolution was connected to the micrometer of the lower end mirror, and an electronic circuit to control the rotation speed and direction of the stepper motor. When the stepper motor was operating, the rotation of the stepper motor changed the tilt angle of the end mirror so the dye laser wavelength was changed. When the stepper motor rotated in one direction, the wavelength continuously increased; in the other direction, the wavelength continuously decreased. The rotation speed of the stepper motor could be adjusted almost continuously. A slow speed was preferred because we needed a high-resolution spectrum of SO_2 and the feed back response of the INRAD Autotracker II frequency doubling system was not fast enough to maintain frequency doubling at faster scan speeds.

A 4% reflective wedge prism (Melles Griot 02PRW005) was used as the output mirror forming the other end of the laser cavity and also providing output coupling. This reflector was mounted in a kinematic

mirror mount. Since the amplified spontaneous emission (ASE) background of the output was low,¹¹⁻¹⁴ the output could be used to drive an amplifier.

The operation of this dye laser was not complicated. When one wavelength was selected and diffracted by the grating on to one of the tuning mirrors, the laser beam was reflected by this mirror back on to the grating; and was then diffracted again by the grating at the same angle as the incident beam. This light beam was fed back into the dye cell. When the light oscillated in this cavity, part of it passed through the output mirror as the output beam.

The design of the DALAS dye laser oscillator (Figure 7) differs from the design of Hung and Brechignac⁷ in that there is no pinhole aperture between the dye cell and the glass block. Omission of the pinhole aperture makes the dye laser much easier to align, but at the expense of slightly increasing the bandwidth of the dye laser.

Because the efficiency of the grating-incidence configuration is low, a dye laser amplifier system is desirable (Figure 8). The output of the oscillator makes a single pass through the amplifier, and the output power is greatly increased.

With the beamsplitter tilted at about 45° to the pump beam, about 90% of the pump beam was sent to the amplifier stage. Three 90° prisms (ESCO Products I425250) were used to direct the pump beam to the first stage amplifier. This caused an optical delay so that the input signal from the oscillator comes a little earlier than the pump beam. This greatly reduced the Amplified Spontaneous Emission (ASE) background. The distance of the optical delay was determined experimentally. When the maximum dye laser output was achieved, the additional optical path length was 26 cm.¹¹

The same size and type of dye cell was used for the amplifier stage. The dye (Rhodamine 610) flowed with the help of the same type of dye pump system as the one used in the oscillator stage. A 150-mm focal length cylindrical lens (Melles Griot 01LCP166) was used to focus the pump laser beam and it was mounted on the same type of rotation stage as was used in the oscillator section. This cell was also inclined at Brewster's angle for maximum transmission.

A second stage amplifier section identical to the first stage amplifier section is being added to further increase the visible dye laser power in order to obtain higher tunable ultraviolet laser output power. The mirror in the first stage amplifier (Figure 8) is being replaced by a 50-mm diameter beamsplitter (CVI Laser BS532.0-50-2025) that reflects 50% of the 532-nm Nd:YAG laser beam. Thus, of the initial 532-nm Nd:YAG laser beam, 10% will be used to pump the oscillator, 45% will be used to pump the first stage amplifier, and 45% to pump the second stage amplifier.

The alignment of this dye laser is usually simple and relatively insensitive to pump laser focus and grating position. However, it is quite sensitive to the path through the dye cell as determined by the output mirror of the oscillator stage. After the laser is aligned, it is quite stable. For the dye laser system above, the wavelength for maximum dye laser energy output is around 600 nm, but SO₂ molecules strongly absorb near 300 nm so frequency-doubling was needed for the SO₂ experiments.

An Autotracker II Servo Tuning System (INRAD) was used as the frequency doubling system for the wavelength scanning experiments. This system senses the frequency doubled output of an angle-tuned crystal and adjusts the phase-match angle for maximum frequency doubled output. The frequency doubling crystal used was KDP-R6G (INRAD). A 300-mm focal length biconvex lens (Melles Griot 01LDX 2371066) was used to focus the dye laser beam on to the KDP crystal, because the ultraviolet output energy is directly proportional to the square of the input energy density. The crystal was slightly away from the focal point, because a very high energy density will damage the crystal.

Sample system. The sample system included four parts: a sample cell; a mechanical vacuum pump for pumping the gas from the sample cell; a pressure meter to measure the pressure in the cell; and gas supplied to the sample cell for detection. The sample cell was made of stainless steel, ultrahigh vacuum components (Nor-Cal): one tee and one four-way cross with 69.9-mm diameter Conflat-type ultrahigh vacuum flanges. Optical access was provided through two custom viewports (Insulator Seal Inc.) with ultraviolet-grade fused silica windows. This sample cell had three orifices: one was connected to a vacuum pump (Edwards EDM20); a pressure gauge (Baratron 122AA-00100AB) was connected to the second orifice of the cell, and the output of this pressure sensor was sent to a digital pressure meter (Edwards 1505); the third orifice of the cell was for the gas supply.

Detection system. The photodetector and amplifier circuits (Figures 9 and 10) were designed and constructed by Mr. Lee Gresham, a DIAL electronics technician. The silicon photodiode (Hamamatsu S1722-02) has a 4.1-mm diameter sensitive surface, with an effective area of 13.2 mm². The spectral response range is from 190 nm to 1100 nm (Figure 11). The peak spectral response wavelength is 960 nm. The typical radiant sensitivity is 0.5 amps/W. For an input wavelength of 300 nm, the typical radiant sensitivity is 0.07 amps/W.

The signal from the photodetector was sent on even-numbered laser pulses to one boxcar averager module and on odd-numbered laser pulses to the other boxcar averager module. Thus one boxcar averager monitored the on-resonance signal intensity and the other boxcar averager monitored the off-resonance signal intensity. The laser trigger was sent to a pulse generator (Berkeley Nucleonics 8010). The pulse generator sent a 5-V signal to trigger the photodetector. The boxcar averagers (Stanford Research System SR250) amplified and averaged the input signals and then sent the averaged output signals by way of an analog-to-digital board (Data Translation DT2805) to a computer (Dell 486D/33) that was used to collect the data. The DALAS data collection program was written by Mr. Ping-Rey Jang, a DIAL computer programmer. The data acquisition program plotted the signal intensities as a function of time on the computer screen during data collection, stored the data on a hard drive, controlled the stepper motor for the rectangular glass block in the dye laser's oscillator section, and reset the boxcar averager modules to zero after reading the values after a user-selected number of laser pulses. A copy of the data acquisition program is presented in Appendix A.

Development History

The DALAS project began in January, 1990. During calendar year 1990, construction, testing, and optimization were completed for the oscillator section of the two-wavelength dye laser. The bandwidth of the dye laser was narrowed from 3 nm FWHM to less than 0.010 nm FWHM. Construction of the first stage amplifier section of the dye laser was begun. Design of the photodetection system was initiated.

During calendar year 1991, testing and characterization of the dye laser (oscillator and first stage amplifier) at a single wavelength was completed. A computer program for data acquisition and computer-con-

trol of the glass block in the dye laser oscillator was completed and tested. An optical cell/vacuum system was designed, constructed, and leak testing began.

During calendar year 1992, custom viewports for the optical cell were purchased and testing of the optical cell completed. Two-wavelength dye laser operation was achieved. The DALAS and LOGS projects gained sole use of the Nd:YAG laser when the CARS project acquired a new laser. The DALAS (and LOGS) projects were moved into a new laboratory room so that they would be next to the laser rather than a room away as they had been previously. Construction of the photodetection system was completed, as was its testing and characterization using 532-nm light.

During 1993, the DALAS system was modified so that the spectrum of sulfur dioxide in the 300-nm region could be recorded in order to select on- and off-resonance wavelengths. From the laser excitation spectra recorded with a 0.020 FWHM bandwidth laser, the absorption coefficient of sulfur dioxide was obtained as a function of laser wavelength in the 300-nm region (see Appendix B). The dependence of the DALAS signal intensity as a function of SO₂ pressure was investigated. Construction of a second stage amplifier for the dye laser was begun in order to increase the ultraviolet laser power obtainable by frequency doubling the dye laser.

Current Status

Dye laser system. The dye laser bandwidth and tunability were characterized before applying the DALAS system to a species of interest.

Dye laser bandwidth. The DALAS dye laser's bandwidth was measured by directing the dye laser beam into a high-resolution, 1-m monochromator (SPEX 1704 with 2400-lines/mm grating) with a photomultiplier tube detector (EMI 9871KA). In order to protect the photomultiplier tube from damage, a diffuser (Kimwipes) was placed just before the monochromator's entrance slit in the path of the laser beam. An apparent FWHM bandwidth of 0.010 nm for the laser beam was obtained in the visible (see Figure 12). This bandwidth is the convolution of the real laser bandwidth and the monochromator's bandpass (0.004 nm). Because the laser bandwidth is comparable to the monochromator's bandpass, the observed lineshape profile is broader than the true lineshape profile. Hence the true bandwidth of this dye laser should be approximately half the observed laser bandwidth (i.e., approximately 0.005 nm

FWHM).¹¹ This bandwidth was confirmed using a Fabry-Perot etalon (Quanta Ray FPA-1) with a 1-cm⁻¹ free spectral range.¹¹

In a grazing-incidence configuration, the bandwidth of the oscillator is a function of the cavity length.¹¹ Reassembly of the dye laser following the move to a new laboratory room in 1992 increased the distance between the center of the dye cell and the center of the diffraction grating from 90 mm to 230 mm, which increased the apparent bandwidth in the visible to 0.020 nm.¹²

Dye laser tunability. One of the most important reasons to select a dye laser as the light source for the DALAS system is that it can supply continuously tunable wavelength output. It was therefore desirable to characterize the tunability of this dye laser system.

From the basic grating equation (Eq. 11), it is easy to obtain the tuning rate, which is defined as the rate of wavelength change with respect to the angle ϕ of rotation of the tuning mirror.

$$\frac{d\lambda}{d\phi} = a \cos\phi \quad (12)$$

In Figure 13, the tuning curve for the oscillator stage of the constructed dye laser is shown. This figure shows that the wavelength dependence on the tuning mirror tilt angle is nearly linear. This is due to the small changes in angle involved. The wavelength range of Figure 13 is from 594.5 to 607.5 nm, which, when frequency doubled, covers the strongest transitions of SO₂ near 300 nm. The tuning mirror's angle changes by 2.1° to cover this entire spectral region.

Other dye laser characteristics. Output power is an important parameter for a dye laser. About 10% of the power of the Nd:YAG pump beam is converted into dye laser power by the oscillator/first amplifier stage amplifier combination using Rhodamine 6G laser dye; this is a typical conversion efficiency for dye lasers. When 170 Mw of 532-nm Nd:YAG laser average power is used to pump the dye laser oscillator/amplifier, the average output power of the dye laser is 17.8 Mw at 565 nm.

Suppression of broadband amplified spontaneous emission (ASE) was verified by scanning the monochromator across the entire dye lasing

region and observing that the only detectable optical output from the dye laser is at the lasing wavelength. The spectral purity was good without any significant ASE background even at the extremes of the tuning range.

Photodetector linearity. The detector linearity is a very important factor to determine the dependability of the experimental results. The ultraviolet power meter (Scientech 360203–3198 sensor for 250 - 400 nm region with Scientech 36–5002T2 power indicator) was not sufficiently sensitive to calibrate the input ultraviolet power to the detector. Therefore, we used the Nd:YAG laser beam (532-nm output) as the power source. With the visible power meter (Scientech 360203–3200 sensor), the power of the Nd:YAG laser used was 100 Mw. Because the detector is very sensitive and the laser power is high, neutral density filters (Schott Glass) were required to decrease the laser power by six to seven orders of magnitude. Two neutral density filters, both with optical density 3.3, were used. By changing the optical density using a third neutral density filter, the input power to the detector was adjusted. The output of the detector was sent to the boxcar averager. Table I presents the data collected. The uncertainty of the detector signal intensity is one standard deviation.

Table I. Detector linearity data.

Laser Power (nW)	Detector Intensity (V)
0.08	0.27 ± 0.018
0.35	0.43 ± 0.004
0.50	0.57 ± 0.006
1.22	1.02 ± 0.009
2.65	1.89 ± 0.013
3.25	2.25 ± 0.027
4.50	2.92 ± 0.034
5.32	3.08 ± 0.049
6.48	3.12 ± 0.054

Figure 14 shows the relationship between laser power and the detector output signal at 532 nm. It indicates that when the laser power is between 0.5 and 4.5 Nw, the detector's linearity is good. But if the laser

power is over 5 Nw, the detector is saturated. The photodetector system has a nonlinear response to laser powers less than 0.5 Nw.

The photodetector has a sensitivity of 0.24 amps/W at 532 nm, and 0.07 amps/W at 300 nm (Figure 11). Because we lack a sufficiently sensitive ultraviolet power meter, we make the assumption that the linear region of this detector at 300 nm is between 1.7 and 15.4 Nw. Should the laser power exceed this range, the detected laser intensity can be brought back into range by placing an appropriate neutral density filter between the detector and the sample. When this detector was used with the DALAS dye laser to record the spectrum of SO₂, it was expected to be operating in the linear region.

Spectrum of SO₂. Between 285 and 315 nm, the absorption spectrum of SO₂ displays a series of well-defined peaks spaced about 2 nm apart.¹⁶ In order to choose the on- and off-resonance wavelengths, a complete high-resolution spectrum was desired. Previous reports^{16,17} present spectra at a resolution too low to be useful to this study. High-resolution studies^{18,19} of the 300 nm band either do not present spectra or only present a small portion of the spectrum. Therefore, it was necessary to record a high-resolution spectra of the 300-nm region.

Our dye laser system provides narrow bandwidth and also the capability of scanning the wavelength at a very slow speed (0.01 nm/second). These advantages permitted us to record a high-resolution spectrum of SO₂. The starting wavelengths were determined before recording the spectrum by directing the laser beam into a 1-m high-resolution monochromator. After the spectrum was recorded, the ending wavelength was similarly determined. According to Figure 14, there is effectively a linear relationship between wavelength and tuning angle so the wavelength can be determined for each intermediate point. Our visible dye laser system generated wavelengths from 594.5 to 607.5 nm. After passing the visible laser beam through a KDP frequency doubling crystal, the wavelengths range covered is from 297.25 to 303.75 nm. This region just covers the strongest transitions of the 290-nm system of SO₂. A bandpass glass filter (Corning 7-54) was used in front of the photodetector to block the visible dye laser and pass the ultraviolet radiation. For the spectra reported here, the glass block in the dye laser oscillator section was not rotated so that two-wavelength operation was not in effect for these scans. The wavelength was scanned by using a stepper motor to slowly, but

continuously rotate a micrometer that changed the tilt angle ϕ of one of the oscillator's end mirrors.

Transmission of light through an absorbing gas can be described by a form of the Beer–Lambert law

$$I(\lambda) = I_0(\lambda) \exp[-\sigma(\lambda)nr] \quad (13)$$

where $I_0(\lambda)$ and $I(\lambda)$ are the incident and transmitted intensities at wavelength λ ; $\sigma(\lambda)$ is the absorption cross section at wavelength λ ; n is the number density in molecules/unit volume; and r is the path length. An alternative formulation of Equation (13) is commonly used in which σn is replaced by αp , where p is the pressure and α is known as the absorption coefficient. The relation between α and σ (assuming ideal gas behavior) is

$$\alpha = \frac{\sigma}{kT}. \quad (14)$$

Usually α is expressed in units of $\text{atm}^{-1} \text{ cm}^{-1}$. If σ is expressed in m^2 , the numerical relationship at $T = 20^\circ\text{C}$ is

$$\alpha = 2.504 \times 10^{23} \sigma. \quad (15)$$

The disadvantage of using α is its strong temperature dependence.¹⁶

Because our experiments were performed around 20°C using the above relation, Equation (13) can be rearranged to be

$$\sigma(\lambda) = \frac{-\ln\left(\frac{I(\lambda)}{I_0(\lambda)}\right)}{(2.504 \times 10^{23} r p)}. \quad (16)$$

In our test system, the absorption cell length r was 43.0 ± 0.1 cm. When the SO_2 pressure was 1.24 ± 0.01 Torr, then the constants in Equation (16) become

$$\sigma(\lambda) = -5.69 \times 10^{-23} \ln[I(\lambda)/I_0(\lambda)]. \quad (17)$$

$I_0(\lambda)$ was obtained when all the gas inside the sample cell was pumped out and the laser scanned from 297.25 to 303.75 nm. When the sample cell was filled with pure SO₂ at 1.24 Torr and the dye laser scanned over the same wavelength interval at the same speed, $I(\lambda)$ was obtained. The observed spectrum was very "noisy". Some of the "noise" was due to rotational-vibrational-electronic transitions of SO₂ and some was due to the shot-to-shot laser power fluctuations. The main features of the spectra were reproducible, but the "noise" was not. Therefore, the spectrum was signal averaged by averaging together the intensity readings of ten consecutive wavelength intervals. In the future, it will be desirable to modify the scanning system so that it is computer controlled, enabling several laser pulses to be averaged together at a single wavelength.

By applying Equation (17) to each pair of data points [$I(\lambda)$, $I_0(\lambda)$], the SO₂ absorption cross section profile was obtained (Figure 15). The resulting measurements of the SO₂ absorption coefficient as a function of wavelength are presented in Appendix B.

The values of the absorption coefficients measured in replicate experiments agreed to within 20%. The major reasons causing different results in replicate experiments are fluctuations of the Nd:YAG laser power; fluctuations of the room and hence the sample temperature; and the reduced precision when using a pressure sensor to measure pressures at the end of its range.

There have been several previous reports about the absorption spectrum of SO₂. Thompson et al.²⁰ measured the SO₂ spectrum from 185 to 330 nm. Although no information was given concerning the resolution used in these measurements, the absence of the detailed structured features in their results indicates the data were obtained at significantly lower resolution than the present results. Thompson and coworkers²¹ measured the room temperature spectrum of SO₂ over the range 296.2 to 301.1 nm using a tunable dye laser with a spectral resolution of 0.02 nm. Brassington¹⁶ also used a frequency doubled dye laser, with a bandwidth of 0.05 nm, to measure the room temperature spectrum of SO₂ from 290 to 317 nm. Comparing his work with our experiment results, it is not hard to find that the absorption cross sections near 300 nm are almost the same.

For the absorption peak around 298 nm, there is about 5% difference for the absorption cross sections. For the absorption peak around 302 nm, the difference for SO₂ absorption cross sections is about 10%. There is a lot of rotational structure in the absorption cross sections in Figure 15. But we do not find such pronounced rotational structure in the figures of Brassington; the reason is the difference in resolution in the two studies. Warneck et al.²² measured the spectrum of SO₂ at room temperature over the range 185 to 315 nm at a resolution of 0.1 nm. It was later shown²³⁻²⁵ that the results from Warneck and coworkers have a systematic error of 0.3 nm in the wavelength calibration. Wu and Judge²⁵ measured the SO₂ spectrum over the range 208 to 228 nm and 299 to 340 nm at 294 K and a resolution of 0.06 nm. Hearn and Jones²⁶ measured the SO₂ spectrum over the range 228 to 339 nm at 300 K with a resolution of 0.06 nm. McGee and Burris²⁷ measured the SO₂ absorption cross section between 300 and 320.4 nm at 295 and 210 K; they also reported the absorption cross section in this wavelength interval in a table. Comparison of the values in this table with our values reveals that there exist some differences at the peaks and in the valleys which are almost certainly related to the resolution. In the wavelengths corresponding to the strong absorption, their experimental results are 10% higher than the present results. This is probably because of the temperature difference and detector sensitivity.

Because the absorption cross section of SO₂ is very sensitive to many parameters such as temperature and resolution, many previous reports show a significant variation in the reported absorption cross sections.^{16,22,25-27} Some of the results are more than 20% different even for nearly identical experimental conditions.^{16,20} It is difficult to say which one is correct. Many factors can influence the result such as uncertainty in pressure meter calibration and cell length measurement, detector linearity, and monochromator calibration. However, it is clear that the results reported here are comparable to those reported by other investigators. The technology and methodology developed for these SO₂ measurements can be directly applied to determination of the absorption cross section for other species of interest with a comparable level of accuracy.

Because the strongest transition occurs near 300 nm, we selected the on-resonance wavelength in this region. The interval between the on- and off-resonance wavelength should be as small as practical. The on-resonance wavelength selected for SO₂ is 300.04 nm because of the large absorption cross section. The off-resonance wavelength selected is

299.89 nm because of the small absorption cross section and because it is not far from the selected on-resonance wavelength.

By changing the SO₂ pressure in the sample cell and keeping other experimental conditions constant when the dye laser wavelength is 300.04 nm, the data in Table II was obtained. When the dye laser wavelength is 299.89 nm, the data in Table III is obtained. In both cases, the uncertainty in the DALAS signal intensity corresponds to one standard deviation.

Table II. DALAS signal intensity *vs.* SO₂ pressure at 300.04 nm.

Pressure (Torr)	Signal (V)
0.00	2.54 ± 0.02
0.10	2.18 ± 0.02
0.20	1.86 ± 0.04
0.52	1.03 ± 0.05
0.82	0.60 ± 0.03
1.07	0.37 ± 0.01
1.45	0.19 ± 0.02

Table III. DALAS signal intensity *vs.* SO₂ pressure at 299.89 nm.

Pressure (Torr)	Signal (V)
0.00	2.40 ± 0.03
0.30	2.16 ± 0.05
0.40	2.08 ± 0.06
0.72	1.85 ± 0.01
1.36	1.44 ± 0.06
2.44	0.95 ± 0.02
3.25	0.68 ± 0.03
4.37	0.45 ± 0.02
5.40	0.28 ± 0.01

Figure 16 is a plot of the transmitted laser intensity of SO₂ at 300.04 nm *vs.* SO₂ pressure. When the pressure is above 1.2 Torr, the signal is very small. Figure 17 is a plot of the transmitted laser intensity of SO₂ at 299.89 nm *vs.* SO₂ pressure. When the pressure of SO₂ is above 4 Torr, there is still relatively high signal intensity.

From the above data, we obtain Figures 18 and 19. Figure 18 is the SO₂ absorption cross section at 300.04 nm as a function of SO₂ pressure. Figure 19 is the SO₂ absorption cross section at 299.89 nm as a function of SO₂ pressure. For Figures 18 and 19, there is about a 16% difference in the absorption cross sections when the pressures change from low to high.

Further improvements of the DALAS system are required to provide the necessary detection sensitivity. Rather than monitoring gas nonintrusively, it will be necessary to extract a sample of the gas stream, then flow the sample through a multiple pass cell (alias White cell²⁸) before returning the gases to the gas stream. It is clear from the Beer-Lambert law (Eq. 13) that increasing the path length will significantly reduce the minimum detectable concentration. Completion of the second amplifier stage will significantly increase the visible dye laser power and hence the ultraviolet dye laser power. This will help compensate for the laser power losses caused by losses due to the mirror surfaces not being 100% reflective. The DALAS data acquisition program will be changed to permit display of the ratio of the two continuously monitored intensities during data acquisition.

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Nomenclature

BK7	a type of borosilicate glass
cm ⁻¹	reciprocal centimeters (wavenumber)
DALAS	differential absorption laser spectroscopy
DIAL	differential absorption lidar (laser radar)
DOAS	differential optical absorption spectroscopy
FWHM	full-width-at-half-maximum
I(λ ,r)	intensity at wavelength λ for sample length r
KDP	potassium dihydrogen phosphate
mg	milligrams
mJ	millijoules
MW	megawatts
Mw	milliwatts
Nd:YAG	neodymium:yttrium aluminum garnate
n _i (r)	number density (concentration) of ith species for sample length r
nm	nanometers
ns	nanoseconds
Nw	nanowatts

r	path length
$S(\lambda, r)$	system response parameter
SO_2	sulfur dioxide
a	absorption coefficient
λ_a	on-resonance (absorption) wavelength
λ_r	off-resonance (reference) wavelength
$\sigma(\lambda)$	absorption cross section at wavelength λ

Figure 6. Schematic of a DALAS system.

Figure 7. Dye laser cavity for producing two-wavelength output on alternating laser pulses.

Figure 8. Schematic diagram of the amplifier stage.

Figure 9. Photodetector circuit (unless otherwise indicated, Microfarad capacitances are used).

Figure 10. Photodetector amplifier circuit (unless otherwise indicated, Microfarad capacitances are used).

Figure 11. Spectral response of the photodetector (adapted from Hamamatsu catalog).

Figure 12. Lineshape of the DALAS dye laser observed through a 1-m monochromator.

*Figure 13. Plot of dye laser wavelength vs. mirror tuning angle θ
Rhodamine 610 dye solution.*

Figure 14. Photodetector output vs. input laser power.

Figure 15. Absorption cross section of SO₂ in the region of 297.5 to 303.75 nm.

Figure 16. Plot of the transmitted laser intensity of SO_2 at 300.04 nm vs. SO_2 pressure.

Figure 17. Plot of the transmitted laser intensity of SO₂ at 299.89 nm vs. SO₂ pressure.

Figure 18. Absorption cross section of SO_2 at 300.04 nm vs. SO_2 pressure.

Figure 19. Absorption cross section of SO_2 at 299.89 nm vs. SO_2 pressure.

Laser Optogalvanic Spectroscopy System

Instrument Purpose and Development History

The Laser Optogalvanic Spectroscopy system (LOGS) is a general purpose system for identifying atomic and molecular plasma species and for measuring average temperature. This system is capable of working even when high particulate flow severely limits transmission of optical beams across high-temperature gas flows. Because LOGS uses electrical rather than optical detection, this technique alleviates the problem associated with monitoring weak absorption or weak fluorescence in the presence of a strong optical background signal. Hence, LOGS can identify species present and characterize their temperatures even under conditions where techniques employing optical detection fail.

In a LOGS experiment, a pulsed dye laser is tuned into resonance with a transition of a species in a plasma, temporarily increasing the excited state concentration of that species. Because the energy necessary for ionization is less for an excited electronic state than for the ground state, the rate of ionization temporarily increases. This process can be monitored as a transient (tens of microseconds) voltage change if a high-voltage electrode (relative to ground) is inserted into the plasma. By scanning the wavelength of a tunable dye laser and recording the LOGS signal as a function of laser wavelength, the optogalvanic spectrum (which is analogous to an absorption spectrum) is obtained. The temperature of the species can be ascertained by the standard technique of ratioing the intensities of different transitions and taking into account their different transition probabilities. Only the response of the plasma in the vicinity of the electrode is probed. For studies of practical combustion systems, only optical access from one side of the gas stream is required since the electrode and laser beam can be introduced through the same optical port. If a short electrode is mounted on an insulated linear motion feedthrough, a segment-wise measurement of the temperature across the combustion channel can be obtained.

Since the project began in January 1990, we have assembled a LOGS apparatus; and have observed atomic LOGS transitions in bench-top flames both from atoms in their ground state and from atoms in excited electronic states. The effect of corrosion of the electrode on the LOGS signal intensity has been extensively studied.

Introduction

Whenever the wavelength of a laser coincides with the absorption of an atomic (or molecular) species in a plasma (such as a flame or a gas discharge), the rate of ionization of the species momentarily increases either (1) due to laser-assisted electron impact ionization

where M^* is an electronically excited atom or molecule and M^{**} is a highly excited atom or molecule; or (2) due to multiphoton ionization

The first case is often referred to by analytical chemists as laser-enhanced ionization (LEI) spectroscopy, and the second case as direct laser ionization (DLI) spectroscopy. For both cases, the change in the ionization rate can be monitored as a transient voltage change if a high-voltage electrode (relative to ground) is inserted into the plasma. This optogalvanic effect (OGE) signal can be used to identify and characterize species, and also to investigate plasma processes. Because the detection is electrical rather than optical, OGE alleviates problems associated with monitoring weak absorption or weak fluorescence in the presence of a strong optical background signal. Extensive research has been done on the use of LEI for quantitative analysis of trace elements in bench-top flames.¹⁻⁷ Using this technique, sub- $\mu\text{g/L}$ -level concentrations of trace elements can be measured.

The feasibility of using OGE as a diagnostic of flame processes has long been recognized.⁸ To date OGE has been used in bench-top flames to measure ion mobilities in flames,⁹⁻¹¹ soot formation,^{10,12} diffusion coefficients,¹³ bulk ionization rates,¹⁴ flame temperatures,^{15,16} flow velocity,¹⁷ and species concentration profiles.^{12,18-29}

Purpose of the Instrument

For practical combustion systems (coal-fired electric generating facilities, industrial burners, hazardous waste incinerators, etc.), laser optogalvanic spectroscopy (LOGS) has the capability of becoming a general

purpose, *in situ* technique for qualitative identification of atomic and molecular species, for monitoring relative species abundances, and for measurement of average temperature under conditions where techniques using optical detection fail due to particle-induced light scattering or due to the system being optically thick. Scanning the laser wavelength produces an optogalvanic spectrum that is analogous to an absorption spectrum. Identification and characterization of atomic and molecular species can be obtained from the LOGS spectrum using standard spectroscopic techniques. The temperature of a species can be ascertained from the LOGS spectrum by the standard technique of ratioing the intensities of different transitions and taking into account their different transition probabilities. Only the response of the plasma in the vicinity of the electrode is probed. If a short electrode is mounted on an insulated linear motion feedthrough, a segment-wise measurement of relative species abundance and of temperature across the combustion channel can be obtained. Moreover, optical access from only one side of the gas stream is required as compared with the two to four optical ports required by other laser-based techniques; this is important because there is often limited optical access to many practical combustion systems.

Performance Requirements

The functions performed by the LOGS system are to include:

1. Scan the dye laser's wavelength under computer control;
2. Measure and graphically display on computer screen during the experiment the LOGS signal intensity and the laser power normalization photodetector signal intensity;
3. Save raw data for off-line detailed analysis;
4. Determine the relative abundance of different species present in the LOGS spectrum;
5. Determine the temperature of molecular species present in the LOGS spectrum.

Technical Approach

Laser Optogalvanic Spectroscopy system (LOGS) is a general purpose system for identifying atomic and molecular plasma species and for measuring average temperature. Scanning the wavelength of a tunable

dye laser and recording the LOGS signal produces a LOGS spectrum that is analogous to an absorption spectrum. Both identification of species and measurement of temperature are based upon analysis of the LOGS spectrum, but the analysis procedure is significantly different for the two functions.

Atomic species can be identified by the standard spectroscopic analysis method³⁰ of comparing the observed wavelength of a transition with the wavelengths of known atomic species as listed in a standard compendium.³¹ Confirmation of a tentative identification is obtained by verifying the presence in the spectrum of other transitions of the designated atomic species.

Identification of molecular species is attempted by comparison of the wavelength of the center of a vibrational band with transition wavelengths listed in standard compendia.^{32,33} If that approach is unsuccessful, then if the rotational structure is well resolved, rotational analysis³⁴⁻³⁶ of a vibrational-electronic (vibronic) band can be performed. The rotational constant(s) (B and for polyatomic molecules, also A and C) are dependent on the moments of inertia of the molecule:

$$B = \frac{h}{8\pi^2 c I} \quad (3)$$

where h is Planck's constant (6.626×10^{-34} J sec); c is the speed of light; and I, the moment of inertia, is calculated from

$$I = \sum m_i r_i^2 \quad (4)$$

where r_i is the perpendicular distance of mass m_i of the i th atom from the molecular axis coordinate system.³⁴⁻³⁶ For polyatomic molecules, the rotational constants A and C are similarly defined. Knowledge of the value of the rotational constant(s) enable estimation of the reduced mass and hence the molecular weight. Estimation of the molecular weight is essential for identification of the species.

If the rotational structure is not well-resolved, then the reduced mass μ can be estimated from the vibrational frequency ω by assuming a value for the vibrational spring constant k (Eq. 5).

$$\mu = \frac{4\pi^2 k}{\omega^2} \quad (5)$$

An estimate of the value of the spring constant k can be obtained from analogous molecules or from Badger's rule,³⁴ which is

$$k \approx \frac{1.86}{(R_e - d_{ij})^3} \quad (6)$$

where k has units of 10^5 dynes/cm; R_e is the equilibrium internuclear distance (in Å); and d_{ij} is a constant (in Å) that is different for each type of molecule.³⁴

The temperature can be ascertained by the standard technique of ratioing the intensities of different transitions and taking into account their different transition probabilities. The intensity of a transition observed in absorption is given by

$$I_{vJ} = R \nu |\langle \Psi' | \mu | \Psi \rangle|^2 |\langle v' | v'' \rangle|^2 A_J g_J \exp\left(\frac{-E_{vJ}}{k_B T}\right) \quad (7)$$

where I_{vJ} is the intensity; R is the instrumental response or detection sensitivity, which in general can be wavelength dependent; ν is the frequency of the transition (in Hz); $|\langle \Psi' | \mu | \Psi \rangle|^2$ is the electric dipole electronic transition probability; $|\langle v' | v'' \rangle|^2$ is the Franck-Condon vibrational overlap probability; A_J is the rotational line strength;^{34,36-40} g_J is the statistical weight;³⁴⁻³⁶ k_B is Boltzmann's constant (1.38×10^{-23} J/K); T is the temperature (in Kelvin); and E_{vJ} is the total energy (electronic plus vibrational plus rotational) of the lower energy level.³⁴⁻³⁶

If the rotational structure is well resolved, then the temperature can be obtained from ratioing the intensities of isolated, unoverlapped rotational-vibrational-electronic (ro-vibronic) transitions. In this case, the electronic transition probabilities and the Franck-Condon vibrational overlap factors are the same for the two transitions. The instrumental response R is assumed to be constant same over the vibronic band. Hence if the intensities (I_1 and I_2) of two unoverlapped ro-vibronic transitions of

the same vibronic band are measured, the temperature can be calculated from

$$T = \frac{(E_2 - E_1)}{k_B \ln \frac{(I_1 \nu_2 A_{J2} g_{J2})}{(I_2 \nu_1 A_{J1} g_{J1})}} \quad (8)$$

where E_p is the total energy (electronic plus vibrational plus rotational) of the lower energy level that the p th ro-vibronic transition starts from; I_p is the measured intensity of the p th ro-vibronic transition; ν_p is the frequency (energy) of the p th ro-vibronic transition; A_{Jp} is the rotational line strength of the p th ro-vibronic transition; and g_{Jp} is the statistical weight of the p th ro-vibronic transition. The values of the A_{Jp} rotational line strengths are calculated from knowledge of the rotational quantum number(s) of the lower energy state by simple analytical formulae^{34,36,37,40} in the case of diatomic molecules and of (near) symmetric top polyatomic molecules, and are obtained from tables^{38,39} for asymmetric top molecules. The g_J values depend on the value of the rotational quantum number(s) and of the total nuclear spin quantum number. There are simple analytical formulae for calculation of g_J .^{34,36}

If the rotational structure is not well resolved, the temperature can be ascertained by ratioing the integrated intensity of two different vibronic bands. In this case, temperature is given by

$$T = \frac{(E_2 - E_1)}{k_B \ln \frac{(I_1 |\langle \mu_2 \rangle|^2 |\langle \nu_2' | \nu_2'' \rangle|^2)}{(I_2 |\langle \mu_1 \rangle|^2 |\langle \nu_1' | \nu_1'' \rangle|^2)}} \quad (9)$$

where $|\langle \nu_p' | \nu_p'' \rangle|^2$ is the Franck-Condon vibrational overlap probability for the p th vibronic transition; and $|\langle \mu_p \rangle|^2$ is the electric dipole electronic transition probability. If the upper and lower electronic states are the same for both vibronic transitions, then the ratio of electric dipole electronic transition probabilities is unity, simplifying the equation. The Franck-Condon factors are obtained from the literature when available.

Otherwise, for diatomic molecules, they can be calculated using the standard computer programs⁴¹ for computing Franck-Condon factors from vibrational constants.

System Description

The experimental apparatus (shown in Figure 20) has been described in detail elsewhere.⁴² A 10-Hz Nd:YAG laser (Quanta-Ray DCR-2A-10) is used to pump a tunable dye laser (Quanta-Ray PDL1). Kiton Red 620 (Exciton) in methanol or ethanol is typically used as the dye solution.

The dye laser beam passes into a plasma. For the bench-top experiments performed to develop the technique, the plasma was a pre-mixed methane/air flame of a 25-cm long, 1.6-cm wide single slot burner head⁵⁴ that was constructed by DIAL's machine shop. In order to decrease flame turbulence and hence increase flame stability, a stainless steel 20 mesh wire cloth (Small Parts, Inc. C-CX-20-A) is secured across the top of the burner. To prevent the flame spreading passed the ends of the burner, nitrogen gas is introduced at the ends of the burner. The burner is equipped with a stainless steel pneumatic nebulizer (Spraying Systems, Inc. 1/4 JNIA air atomizer nozzle) which draws an aqueous sample solution from a magnetically stirred 5-gallon container (Nalgene 2320-0050) and aspirates an aerosol of small droplets mixed with fuel (methane) and oxidant (air) into the flame. The aqueous sample solution has been made with a concentration of 10 mg/L sodium chloride and 10 mg/L potassium sulfate. The concentrations of sodium chloride and potassium sulfate were chosen so that the LOGS signal is a linear function of Na and of K concentrations.⁴³ Another magnetically stirred 5-gallon container is used to receive the sample solution that is not entrained in the gas stream by the nebulizer.

Aqueous sodium chloride was introduced into the flame because the bright orange color of the Na D lines serves as a sensitive visual diagnostic of whether or not the solution was being efficiently aspirated into the flame. The dark red potassium D lines are difficult to see. The electrode corrosion experiments were performed with the wavelength of the dye laser fixed at the peak of the K 578.2 nm transition. The peak of the LOGS transition was determined by manually scanning the wavelength of the dye laser and displaying the LOGS signal intensity on an oscilloscope (Tektronix 475A).

Commercial grade methane (Airco), compressed ambient air, and dry nitrogen (Airco) are used. Since the gas streams of practical combustion systems typically contain many contaminants and particles, it was felt that these "poor" quality gases would better approximate practical combustion conditions than would higher purity gases. The flow rate of each gas is controlled and adjusted by a two-stage gas regulator on the gas cylinder followed by a single-stage gas regulator in series with a 150 mm flowmeter.

The dye laser beam irradiates the flame parallel to and approximately 5 mm below the 1.6-mm diameter, 178-mm long, 2% thoriated tungsten welding rod electrode. Care is taken so that the dye laser beam does not irradiate the electrode: during preliminary studies, the dye laser beam irradiated the electrode; wavelength scans of the dye laser produced a reproducible LOGS spectrum with molecular ro-vibronic transitions, which were tentatively assigned as originating from a tungsten oxide. The height between the electrode and the burner can be varied by a use of an XYZ translation stage (Newport 460-XYZ). The electrode is mounted by a set screw into a 12.7-mm thick aluminum block to which high voltage from a constant-current power supply (Kepco BHK 1000-0.2M) is attached. The burner, the electrode, and the XYZ translation stage are surrounded by mesh screen to minimize the effect of air drafts on the flame stability.

A power resistor limits the current to 20 Ma. Most of the experiments reported in this report used -960 V as the electrode voltage; some experiments were performed with an electrode voltage of -500 V to observe the effect of electrode voltage. The burner head serves as the anode and is earth grounded. The LOGS signal is amplified by a modified version of the circuit of Havrilla and Green⁴⁴ (see Figure 21). The modification consists of changing the resistance in order to obtain waveforms that better reproduce the incoming LOGS signal: 11.4 k Ω is used for resistor R₁; and 1 M Ω was used for R₂. The amplified LOGS signal is integrated by a boxcar averager module (Stanford Research Systems SR250), which averages together the LOGS signals of one hundred laser pulses. The averaged output of the boxcar averager is digitized (Data Translation DT 2805) and stored on a PC-compatible computer (Dell 486D/33) every ten seconds during the experiment. The LOGS data acquisition program DYESCAN (Appendix C) also plots the LOGS signal intensity and the photodetector signal intensity on the computer screen during the experiment. Furthermore, it is capable of scanning the dye laser's wavelength during data acquisition. The LOGS data acquisition

program DYESCAN was written in C computer language by Mr. Ping-Rey Jang of DIAL.

Before entering the flame, a portion of the dye laser beam is reflected by an uncoated microscope slide beamsplitter, through a 4.3 OD neutral density filter (Schott Glass), and onto a photodiode (see Figure 22). The output of the photodiode for one hundred laser pulses is integrated by a boxcar averager module (Stanford Research Systems SR250) and stored on a PC-compatible computer for off-line laser power normalization of the OGE signal intensity. Since the response of the photodiode circuit is nonlinear with laser intensity, laser intensity is calculated. The equation used is the best-fit equation obtained by a multi-equation least squares fitting program (Jandel Scientific TableCurve 3.1) for a fit of photodiode voltage *vs.* laser power calibration data. The photodiode response is frequently calibrated and the most recent calibration curve used for normalization. The LOGS signal is normalized off-line by dividing the LOGS signal intensity (in V) by the calculated laser power (in Mw). Since the dye laser power is a slowly varying function of time, plots of the normalized signal *vs.* time are qualitatively similar to plots of the raw LOGS signal intensity *vs.* time.

Development History

The LOGS project began in January 1990 mostly utilizing available equipment. During calendar year 1990, a LOGS system was assembled and tested. The LOGS signals of atomic species in their ground electronic states (sodium 589.0 and 589.6 nm transitions) and of atomic species in excited states (potassium 581.3 and 583.2 nm transitions) were observed. Figure 23 shows a portion of the LOGS spectrum of 10 mg/L potassium sulfate recorded by scanning the dye laser wavelength. A photodiode circuit for normalizing the dye laser power fluctuations was designed and tested. Investigation of the effect of electrode corrosion on the LOGS signal intensity began. The system, for introduction of aqueous solutions into the burner, was modified in order to permit multihour experiments monitoring the effects of electrode corrosion.

During calendar year 1991, the first phase of the corrosion studies were completed. An electrode assembly for studies of the LOGS signal intensity on the DIAL combustion test stand was designed and constructed. The rate of progress was substantially slowed by the need for laser repairs and by questions about the reliability of the data acquisition system.

During calendar year 1992, the reliability of the data acquisition system was verified after the delay generator had been repaired by the manufacturer. An improved design of the electrode assembly was employed. During the early part of the year, the rate of progress was substantially slowed by large Nd:YAG laser power fluctuations, which were discovered to be associated with the transportation of the laser beam from the Nd:YAG laser into the next room where the LOGS system was located; these large laser power fluctuations caused the LOGS results to be of uncertain reliability. This problem was overcome when the CARS project, which shared the Nd:YAG laser with the LOGS and DALAS projects, obtained a new Nd:YAG laser, and the LOGS and DALAS projects obtained sole use of the old Nd:YAG laser. The laser and the LOGS and DALAS systems were moved into a new laboratory room so that the laser could be next to the systems. The reliability of the LOGS system was reverified after the move to the new laboratory room.

During 1993, an extensive study of the effect of corrosion on LOGS signal intensity was completed and submitted for publication.

Current Status

After numerous instrumentation delays, investigation of the effect of electrode corrosion on the LOGS signal intensity as a function of time, electrode voltage, and position in near-stoichiometric flames has been completed. Immersion of the tungsten LOGS electrode into the flame produces an oxide coating on the electrode. The various oxides of tungsten can be identified by their characteristic colors.⁴⁵ There were blue, brown, and yellow coatings on the electrodes. The blue coating was presumably W_2O_5 and the brown coating WO_2 . The yellow coating was presumably WO_3 , which is the ultimate product of oxidation. These oxide coatings are expected to have less electrical conductivity than the metal. Hence their presence can be expected to affect the LOGS signal intensity.

The effects of electrode corrosion in a near stoichiometric flame were investigated under a variety of conditions: different electrode voltages (-500 V and -960 V); and the electrode positioned 10 mm and 15 mm above the burner head.

In one set of experiments,⁴² it was observed that the electrode diameter increased from 1.500 ± 0.001 mm initially to 1.662 ± 0.009 mm after six hours and to 2.154 ± 0.048 mm after a total of fourteen hours.

Because of the statistical nature of these experiments, the oxide coating thickness is probably different in each individual experiment, but the overall trend is unambiguous. Clearly the thickness of the oxide coating can relatively quickly become a significant fraction of the initial diameter of the electrode.

The basic structure of a premixed flame consists of three zones: the inner zone, the interconal zone, and the outer zone. The inner zone is the primary reaction zone which for cylindrical burners (such as Bunsen burners) forms a roughly conical surface and is only a few tenths of a mm thick. The outer zone is the outer diffusion flame. The interconal zone is above the inner zone and below the outer diffusion flame. Among the three zones of the flame, the interconal zone is that portion of the reacting zone in which most of the chemical reactions take place and the temperature is the highest.^{46,47} For most practical combustion systems, the gas flow regions that can usually be most easily optically accessed correspond more closely to the outer diffusion region of the flame rather than either the inner zone or the interconal zone. At 10 mm, the electrodes were in the outer zone just outside the boundary region between the interconal and outer zones for this near stoichiometric flame. By observation, at 15 mm the electrodes remained visually outside the flame, but still contacted the flame; this situation is in effect similar to the standard electrode configuration for LEI. Although the electrode was in the outer zone at both distances, the flame temperature at 15 mm is expected to be less than at 10 mm.⁴⁶ Therefore, the experimental conditions chosen were expected to correspond to different temperatures and hence to different rates of oxide coating formation.

Figure 24 shows a plot of LOGS signal intensity (V) *vs.* dye laser power (mW) for a -960 V electrode (aqueous solution consists of 10 mg/L sodium chloride and 10 mg/L potassium sulfate; data recorded at 10 mm above the burner indicated by •; data recorded at 15 mm indicated by ▲). The 95% confidence intervals for the LOGS signal intensity are comparable to or smaller than the symbols. At 15 mm above the burner, the LOGS signal intensity is linear with increasing dye laser power in the 0 to 8.5-mW range. The lines shown in the figure were obtained from linear least squares fits. Note that near 8.5 mW there is a sudden bend in the curve. After the bend, the slope is 51% of the slope before the bend. The bend is attributed to the onset of optical saturation.⁵⁵ In order to operate in a region where the LOGS signal is linear with dye laser power, it is therefore necessary to use dye laser powers significantly below about 8.5

mW for -960 V electrodes at 15 mm. At 10 mm above the burner, the LOGS signal intensity is linear with increasing dye laser power in the 0 to 4.1-mW range. In this case, the bend occurs between 4.1 and 6.4 mW; again, laser powers less than the bend must be used to ensure a linear LOGS response. At a given dye laser power, the LOGS signal intensity at 10 mm is about twice that at 15 mm. The percentage difference between 10 and 15 mm decreases with increasing dye laser power.

Figure 25 shows a plot of LOGS signal intensity *vs.* dye laser power for a -500 V electrode (aqueous solution consists of 10 mg/L sodium chloride and 10 mg/L potassium sulfate; data recorded at 10 mm above the burner indicated by •; data recorded at 15 mm indicated by ▲). Again, symbols are comparable to or larger than the 95% confidence intervals. At 10 mm, the LOGS signal intensity at -500 V is about 45% of that at -960 V for a given dye laser power. The LOGS signal intensity of a -500 V electrode positioned 15 mm above the burner of the near-stoichiometric flame is almost indistinguishable from that shown in Figure 24 for a -960 V electrode at 15 mm except that for a -500 V electrode at 15 mm, the onset of optical saturation occurs near 5.8 mW. Again, the lines shown correspond to linear least squares fits. The slopes before the bend are similar at 15 mm for both electrode voltages as are the slopes after the bend for both electrode voltages. For a -500 V electrode at 10 mm, the bend occurs near 9.6 mW. At a given dye laser power, the LOGS signal intensity at 10 mm is about 80% of that at 15 mm. In contrast, the -960 V LOGS response at 10 mm is about twice that at 15 mm (Figure 24). Thus, the LOGS signal intensity is a sensitive function of electrode position, of electrode voltage, and of dye laser power. Consequently, caution must be used when comparing absolute LOGS signal intensities recorded under different experimental conditions. The percentage differences between 10 and 15 mm decreases with increasing dye laser power. The effect of the LOGS signal's laser power dependence on the change in the LOGS signal intensity is discussed below.

For all the experiments reported here, the maximum difference ΔP between the maximum dye laser power $P_{\max}$ recorded during a six-hour experiment and the minimum dye laser power $P_{\min}$ recorded for the same experiment was 1.1 mW; most ΔP were 0.75 mW or less. The standard deviation of the dye laser power during a six-hour experiment was typically less than 0.20 mW. Hence for a given experiment, changes in the dye laser power were very small. Because during each experiment, dye laser power changes were small and because the dye laser powers used

correspond to linear regions in the dye laser power *vs.* LOGS signal intensity response curve, the LOGS signal intensity was linear with dye laser power. Therefore, the LOGS signal intensity can be normalized by dividing the LOGS signal intensity (V) by the dye laser power (mW). Consequently, the figures of LOGS signal intensity *vs.* time presented in this paper are normalized to take into account the effect of dye laser power fluctuations on the LOGS signal intensity.

Figure 26 shows a plot of normalized LOGS signal intensity *vs.* time for a -960 V electrode positioned 10 mm above the burner (dye laser power was 8.8 mW ($\sigma = 0.17$ mW, maximum range 8.2 to 9.2 mW); Student's *t* value for control data for this experiment is 1.96). The averaged LOGS signal from the boxcar averager module is inverted before being sent to the computer; thus, up in Figures 26 (and in Figures 27-29) corresponds to a LOGS signal decrease. The sharp spike that occurred just before three hours is attributed to a perturbation of the sample delivery system by the need in this experiment to refill the sample container at that time. The dye laser power used (8.8 mW) places the LOGS signal on the verge of optical saturation; therefore, some caution must be exercised in interpreting the results. The valid data sets obtained at 10 mm for both electrode voltages are qualitatively similar to Figure 26--persistent decreases in normalized LOGS signal intensity with increasing time. The average normalized LOGS signal intensity during the last ten minutes of this six hour experiment is 41% smaller than the average normalized LOGS signal during the first ten minutes of the experiment.

A new test electrode was used for each experiment. To insure that the observed changes in LOGS signal intensity were not due to changes in the experimental conditions, a control electrode was used. The control electrode was mounted in the same aluminum block and at the same height as the test electrode. A dielectric was mounted between the aluminum block and the translation stage so that the position of the electrodes could be adjusted without turning off the constant-current power supply. The distance between the two electrodes was 25 mm, which was significantly wider than the width of the flame. The XYZ translation stage was used to reproducibly insert the desired electrode into the flame. The LOGS signals of the control electrode and photodiode signals were collected for ten minutes at the beginning of the experiment and again at the end of the experiment. The means and standard deviations of the normalized LOGS signal intensity of the reference electrode before and after the experiment were *t*-tested to verify these values are equal.

Experiments for which the reference electrode data did not meet the t-test criteria were not used in the analysis.

Figure 27 shows a plot of normalized LOGS signal intensity *vs.* time for an electrode at -500 V irradiated by a 4.8-mW dye laser with conditions otherwise identical to those of Figure 26. Dye laser power was 4.8 mW ($\sigma = 0.14$ mW, maximum range 4.4 to 5.2 mW); Student's *t* value for the control data for this experiment is 0.45. It is obvious that there are significant differences between Figures 26 and 27. There is a smaller, but still significant (17%) decrease in the normalized LOGS signal intensity in Figure 27. Thus reducing the electrode voltage by about a factor of two reduced the resulting net change in normalized LOGS signal intensity by slightly more than a factor of two.

In the case of Figure 27, the decrease follows a period of almost three hours when the LOGS intensity was roughly constant. This initiation period may be due to the time required for an appreciable oxide coating to form over most of the electrode's surface. The role of the different tungsten oxides in changing the LOGS signal intensity is unknown. Since the electrode in the flame was orange hot, it was rather difficult to visually judge the extent of oxide formation. Variation in this initiation time from one experiment to the next was observed. Initiation times ranged from a few minutes up to several hours. Clearly the duration of the initiation period strongly affects the net change observed over a six-hour period. Since initiation periods were observed for all the experimental conditions studied, the duration of the initiation period cannot be related to the voltage, dye laser power, or electrode position, and must therefore be related to the details of the electrode's surface and/or to the details of the flame. A factor that could have contributed to variation in the initiation period is variation in the nebulizer performance. The salts tended to precipitate out in the nebulizer. After several experiments, the nebulizer had to be disassembled and cleaned out. After reassembly, the setting of the nebulizer was slightly different than it had been; thus, the cleaning process tended to alter the size distribution of aqueous sample nebulized into the flame. This would make the flame conditions (temperature, droplet size, absolute concentration of the alkali atoms, etc.) that pertained to one experiment different from the flame conditions that pertained to a different experiment. Technology is commercially available that enables researchers to have significantly better control of experimental conditions than the apparatus used in this study. However, the amount of control and reproducibility possible with the apparatus used is comparable to or

better than that of large-scale practical combustion systems. Thus the variability observed in the present study may more closely correspond to practical combustion systems than to laboratory systems.

The LOGS signal intensity is a sensitive function of the experimental conditions. Since experimental conditions were frequently changed between one experiment and the next experiment to be performed, the laser beam-electrode distance and/or the nebulizer performance might have been slightly different between one experiment and an "identical" experiment at a later time. Since measurements are made with a control electrode at the beginning and again at the end of the experiments and the averages of the two measurements t-tested to verify that the experimental conditions had not significantly changed during the course of the six-hour experiment, the validity of the results of each individual experiment has been established, but it is prudent to restrict comparisons of different experiments to qualitative and relative (percentage change) comparisons. As noted above, replicate measurements for each of the experimental conditions were made; and that for a given set of experimental conditions, replicate data sets were qualitatively and quantitatively similar. Thus, the reliability of the data is ensured.

So far we have considered LOGS signals from the outer zone just outside the interconal zone of the flame, where the temperature and the number of reactive species are still relatively high. Now let us examine the effect of electrode corrosion in a region of the outer zone of the flame that is expected to be "colder" and less reactive. Figure 28 shows the results for a -960 V electrode positioned 15 mm above the burner for a near-stoichiometric flame. The dye laser power was 4.85 mW ($\sigma = 0.09$ mW, maximum range 4.6 to 5.1 mW); Student's t value for the reference/control data for this experiment is 1.59. The overall change in the normalized LOGS signal intensity is 43%, which is comparable to that observed at 10 mm. In this experiment, the initiation period was about 45 minutes. After the initiation period, the net change (24%) of the normalized LOGS signal intensity with time (over a three hour period) in Figure 28 is equal to the net change (25%) of the normalized LOGS signal intensity with time (over the first three hours) in Figure 26 where the electrode is at 10 mm above the burner. It thus appears that once the electrode's "resistance" to oxide formation has been overcome that the average rate of oxide formation is independent on whether or not there was an initiation period.

The effect of electrode voltage on the LOGS sensitivity does not play a simple role in the magnitude of the corrosion-induced LOGS changes observed. At 10 mm the LOGS sensitivity at -500 V is about half that at -960 V (see Figures 25 and 26). Thus, one is tempted to attribute the fact that the corrosion-induced LOGS signal change at -500 V is half that at -960 V to the differences in the LOGS sensitivity at the two voltages. However, at 15 mm the LOGS sensitivity at -500 V is slightly greater than at -960 V, while the corrosion-induced LOGS signal change at -500 V is again half that at -960 V. Thus, the effect of LOGS sensitivity on the corrosion-induced LOGS signal change is not clear.

Examination of the figures shows one important difference between the change in the LOGS signal intensity at 10 mm and at 15 mm. At 10 mm (Figures 26 and 27), the LOGS signal intensity is still decreasing after six hours. In contrast at 15 mm (Figure 28), there appears to be a plateau. This is physically reasonable since one expects the rate of change of the LOGS signal intensity with time to slow as a sufficiently thick oxide coating forms on the electrode's surface. Thus at 15 mm (Figure 28), the flame conditions are such as to apparently bring the LOGS signal intensity to a steady state after about three hours. However at 10 mm (Figures 26 and 27), the flame conditions are such that the LOGS signal intensity is still decreasing after six hours. Hence the data suggest (but do not prove) that after a sufficiently long period of time, the LOGS signal intensity becomes nearly independent of time. This behavior can be expected to persist only as long as the oxide coating on the electrode is not disturbed.

During preliminary experiments⁴² of up to 14 hours, building vibrations or wind currents produced by the overhead air conditioner occasionally induced part of the oxide coating to fall. Most of the oxide coating that fell off was yellow and hence presumably WO_3 . Neither the blue coating (presumably W_2O_5) nor the brown coating (presumably WO_2) readily came off the electrode. When the coating fell off, there was a very large, positive spike in the normalized LOGS signal intensity, which corresponds to a LOGS voltage decrease since the averaged LOGS signal from the boxcar average module is inverted. Following the spike, the normalized LOGS signal intensity was larger than it had been just prior to the spike. In some of these preliminary experiments, multi-spikes occurred as the cycle of the coating building up and falling off recurred. This type of behavior can be expected to occur in practical combustion systems due to the facility vibrating and/or due to sporadic acoustic shockwaves in the combustor. Thus, although a general qualitative

description of the results can be given, local experimental conditions can have significant consequences quantitatively.

In summary, we have found that LOGS signal intensity is a sensitive function of electrode voltage, of dye laser power, and of position in the flame. Moreover, the observed onset of optical saturation is a function of electrode voltage and electrode position in the flame.

The normalized signal intensity of a tungsten electrode changes by approximately 40 - 50% over a six-hour period for -960 V electrodes for near-stoichiometric flames. We interpret the change in terms of the formation of an oxide coating on the electrode. The oxide coating acts as an insulator coating on the electrode, reducing the voltage experienced by the ions in the flame and hence reducing the LOGS signal detected. On the other hand, for electrodes at -500 V in near stoichiometric flames, there is less than one half of the change at -960 V. Thus, there is a significant voltage dependence for the change of the LOGS signal intensity.

In some, but not all the experiments, an initiation period was observed. During the initiation period (which ranges from a few minutes up to several hours), the normalized LOGS signal intensity does not change. We attribute the initiation period to the time required to form an appreciable oxide coating over most of the surface of the electrode. Variations from experiment to experiment in the nebulizer performance (and hence the flame temperature and the rate of oxide formation) may have also contributed to variation in the duration of the initiation period.

During some of the first corrosion study experiments, very large LOGS signal spikes were observed when the oxide coating suddenly fell off the electrode during the course of the experiment. Subsequent work revealed that the overhead air conditioner had induced the coating to fall off. However, the phenomena of the coating falling off and generating large LOGS signals can be expected to occur in practical combustion facilities, where the induction can be caused by facility vibrations or acoustic shockwaves in the gas channel.

Because of electrode corrosion, reliable measurements of the relative concentration of a species cannot be obtained by monitoring the LOGS signal intensity at a fixed wavelength. However, we believe that reliable results can be obtained even with a corroded electrode by scanning the laser wavelength and recording the resulting LOGS spectrum. If two

(or more) replicate LOGS spectra are recorded within a short time, then the LOGS background should be approximately the same for all. By comparing the relative intensities of the transitions of these spectra, it will be possible to establish consistency and hence reliability. In this manner, temperatures and the abundance of a given atomic or molecular species relative to other species present in a given LOGS spectrum can be determined in practical combustion systems. If only periodic monitoring is required, the use of gate valves would enable the LOGS probe to be inserted for a measurement and then extracted; this would substantially reduce the rate of formation of the oxide coating. The use of platinum^{19,52} or iridium⁵³ electrodes would be an expensive, but effective way of increasing the useful lifetime of the electrode. A more cost effective method to prolong the life of the electrode would be to use a water-cooled stainless steel electrode.⁵⁶ It would be worthwhile to investigate the effect of particles on the LOGS signal intensity; this is important given the prevalence of ash particles present in coal-fired combustion. Using the method of Beiting and Singh,⁵⁴ it is possible to introduce fly ash into a bench-top flame; thus a bench-top study is readily feasible.

The LOGS system has now reached the stage where it is ready for testing on the DIAL test stand as preliminary to its field testing on a practical combustion system. As described in the Introduction, LOGS signals can be generated either by laser-enhanced electron impact ionization or by multiphoton ionization. It would be beneficial to compare the two production mechanisms, first in the DIAL test stand and then in a practical combustion system to determine which mechanism should in general be utilized.

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Nomenclature

ARO	after receive order
B	rotational constant
CFFF	Coal-Fired Flow Facility
DEC	Digital Equipment Corporation
DLI	direct laser ionization
h	Planck's constant
k	vibrational spring constant
k_B	Boltzmann's constant
LEI	laser-enhanced ionization
LOGS	laser optogalvanic spectroscopy
m W	milliwatt
Nd:YAG	neodymium:yttrium aluminum garnet
NIM	nuclear instrumentation module
nm	nanometer
OGE	optogalvanic effect
R	instrumental response
R_e	equilibrium internuclear distance
ro-vibronic	rotational-vibrational-electronic
UTSI	University of Tennessee Space Institute
vibronic	vibrational-electronic
μg	microgram
ω	vibrational frequency

Figure 20. Schematic of the Laser Optogalvanic Spectroscopy (LOGS) system.

Figure 21. LOGS amplifier circuit, which is a modified version of the design of Havrilla and Green.⁴⁴

Figure 22. LOGS photodiode circuit.

*Figure 23. LOGS spectrum of the potassium 581.3-nm transition.
The spectrum extends from 581.0 to 581.5 nm.*

Figure 24. Plot of LOGS signal intensity (V) vs. dye laser power (mW) for K 578.238-nm transition detected by a -960 V electrode.

Figure 25. Plot of LOGS signal intensity (V) vs. dye laser power (mW) for K 578.238-nm transition detected by a -500 V electrode.

Figure 26. Plot of normalized LOGS signal intensity (V/mW) for K 578.238-nm transition vs. time (hours) detected by a -960 V electrode positioned 10 mm above burner under near-stoichiometric ($\phi = 1.06$) conditions.

Figure 27. Plot of normalized LOGS signal intensity (V/mW) for K 578.238-nm transition vs. time (hours) detected by a -500 V electrode positioned 10 mm above burner under near-stoichiometric ($\phi = 1.06$) conditions.

Figure 28. Plot of normalized LOGS signal intensity (V/mW) for K 578.238-nm transition vs. time (hours) detected by a -960 V electrode positioned 15 mm above burner under near-stoichiometric ($\phi = 1.06$) conditions.

Figure 29. Plot of normalized LOGS signal intensity (V/mW) for K 578.238-nm transition vs. time (hours) detected by a -500 V electrode positioned 15 mm above burner under near-stoichiometric ($\phi = 1.06$) conditions.

Cross Correlation System

Purpose

The Cross-Correlation system (CCS) is a robust method of measuring the velocity of a gas stream as it flows in a duct, channel, or pipe. The cross-correlation technique differs from the LDV described earlier in that it provides less detailed information about the flow, but is simpler in application, more robust, and can be employed in situations where optical access is limited.

Theory

In MHD applications, the gas is hot enough to emit light. The turbulent nature of the flow means that the intensity of this light fluctuates as a function of time. This can be observed in the MSU DIAL combustion test stand, the CFFF at UTSI, or the CDIF in Butte, Montana. If an observer looks in an optical port at the hot gas, (s)he will see a flickering, pulsating source of light.

These fluctuations are carried downstream by the gas flow. Therefore, if one measures the light intensity versus time at two different locations, one downstream of the other, one would find that the fluctuations at the downstream location will lag behind those at the upstream location. This lag time is the time it takes the fluctuations to travel from one location to another and is equal to the distance between the two measurement points divided by the velocity at which the fluctuations are convected.

This technique for measuring the gas velocity is called the cross-correlation technique after the signal processing algorithm used to compare two measured signals and identify the lag time. The *cross-correlation function* of two measured signals $x(t)$ and $y(t)$ is defined by first computing a mean and variance of each signal,

mean of $x(t)$;

$$\bar{x} = \frac{1}{T} \int_0^T x(t) dt$$

mean of $y(t)$;

$$\bar{y} = \frac{1}{T} \int_0^T y(t) dt$$

variance of $x(t)$;

$$\sigma_x^2 = \frac{1}{T} \int_0^T (x(t) - \bar{x})^2 dt$$

variance of $y(t)$;

$$\sigma_y^2 = \frac{1}{T} \int_0^T (y(t) - \bar{y})^2 dt$$

where T is the sampling period. Then the normalized cross-correlation function is computed from the formula

$$\rho_{xy}(\tau) = \frac{\frac{1}{T-\tau} \int_0^{T-\tau} (x(t) - \bar{x})(y(t+\tau) - \bar{y}) dt}{\sigma_x \cdot \sigma_y}.$$

If the fluctuations in the signal $x(t)$ are exactly matched by fluctuations in the signal $y(t)$ after a time delay τ' , then the normalized cross-correlation function will reach a maximum value of one at $\tau = \tau'$.

In practice, the fluctuations do not travel downstream without changing. This means that the normalized cross-correlation function will have a peak at some value less than one. However, as long as a peak in the cross-correlation function can be clearly identified, then the location of this peak identifies the lag time and a mean velocity can be found.

Figure 30 shows a detector setup of the CCS as it was employed on the DIAL combustion test stand. Two optical ports one foot apart were used. Here, monochromators were used to select a particular wavelength of the emitted light and photomultiplier tubes were used as detectors. Typically, the results did not depend on the wavelength selected and the light intensity would be so great that the photomultiplier tubes would

have to be operated at relatively low voltages to avoid damaging the tubes. Figure 31 shows a pair of typical signals that were measured with this setup. Figure 32 illustrates some cross correlation functions that were computed from measured light intensity signals with this arrangement. Since the peak occurs at about 0.02 seconds, then the fluctuations travel at a mean velocity of roughly 50 feet/second, or about 16 meters/second.

Figure 33 shows the results of a direct comparison of the velocity as measured by the CCS with the centerline velocity measured by the LDV system at the same station. The flow rates of air and fuel through the combustor were varied to produce a range of velocities. Clearly, the velocity measured by the CCS is correlated very closely with the centerline velocity, but it is slightly lower. This should be expected since the velocity is highest at the centerline, and is less at other locations across the diameter. This indicates that the cross-correlation method measures an average velocity, and will not be useful if the velocity profile is highly skewed or nonuniform.

Figure 34 shows the some results of testing the CCS at the CFFF facility at UTSI. The data were taken on November 16, 1990 during test LMF4-V. Optical receiving assemblies that were in place for the SLR were used to collect light from the vertical radiant furnace and then optical fibers carried this light to the detectors, which were located in the mobile instrumentation laboratory.

For the data of Figure 34, the receiving optics were located at penetrations 2236 and 2218, which are both on the center of the south wall of the vertical radiant furnace. One penetration is on the second level and the other is on the third level. If this separation is taken to be 12.5 feet (3.82 m), then the propagation delay of 0.21 seconds corresponds to a velocity of 59.7 feet/second (18.1 m/s).

Conclusions

Cross-correlation is a method of measuring gas velocity. It is best suited to situations where the gas is flowing in a pipe or duct with a fairly uniform velocity profile, and the method yields an average gas velocity.

However, the method is quite robust and can be used in situations where LDV measurements would be impossible. All that is required is to collect some light emitted by the gas at each measurement location. Thus,

an extremely small penetration could be used. Extreme cleanliness is not required of the optical windows. As long as they pass some light, that should be good enough. Finally, the only pieces of equipment that must be mounted on the facility are two lenses to focus the light into the ends of two optical fibers. If desired, this assembly could be made very compact and thus could be used in very confined spaces.

The implementation described here uses the light emitted by the gas as the measured signal which is subjected to cross-correlation analysis. If one wanted to apply the method to a cooler gas flow that did not emit light, then one would have to identify some other fluctuating variable that could be measured at two locations, and a similar analysis applied.

Figure 30. Typical setup of the Cross-Correlation System on the DIAL combustion test stand.

Figure 31. Typical photomultiplier signals measured on the DIAL combustion test stand.

Figure 32. Cross-correlation functions computed from signals measured on the DIAL combustion test stand. The two signals were measured at locations one foot apart.

Figure 33. Comparison of the velocity measured by the cross-correlation method with the velocity at the centerline of the combustion test stand as measured by laser Doppler velocimetry.

Cross-Correlation Function
Ports 2206 and 2218, no seed

Figure 34. Cross-correlation function computed from data taken at CFFF during test LMF4-V.

Visible/Infrared Emission Spectroscopy System

Recording wavelength-resolved emission spectra and correcting them for instrumental response provides a means of obtaining information on the relative absorption/emission intensities of atomic and molecular species present in high-temperature gas streams and on the relative emissivity of components of interest such as tubes, walls, the gas stream, etc., by comparing the observed spectrum with that of a blackbody radiation source. Temperatures and emissivity values are obtained by least squares fitting the corrected emission spectra to the Planck blackbody function.

The Visible/Infrared Emission Spectroscopy system (VIES) was developed in order to assist the CFFF's efforts to characterize ceramic tubes for use in an MHD high temperature air heater (HTAH). The emissivity values are essential for reliable heat transfer calculations. Since September 1989, the VIES system has been used in eight tests at CFFF in order to develop the VIES system and make temperature and emissivity determinations on HTAH ceramic tubes positioned in the gas stream in CFFF's vertical radiant furnace.

The VIES system consists of a moderately high-resolution monochromator (0.5-m) with four diffraction gratings (one each for the 200 - 650 nm, 650 - 2000 nm, 1050 - 3200 nm, and 2000 - 5200 nm regions); a silicon photodetector for the visible (200 - 1200 nm) region; a lead selenide photodetector for the infrared (1150 - 4800 nm) region; an optical chopper; calcium fluoride optics for imaging onto the monochromator's entrance slit; a sapphire port window; and a PC-compatible computer for control of the monochromator's wavelength and for data acquisition and analysis.

In the temperature range 1200 to 1700 K, the reproducibility of the VIES system is ± 15 K for temperature and ± 0.02 for emissivity; the accuracy is ± 20 K for temperature and ± 0.09 for emissivity. At lower temperatures down to approximately 1000 K, accurate temperatures can be obtained, but the uncertainty in the emissivity value significantly increases. Temperatures above 1700 K were not monitored, but the VIES system is expected to provide accurate temperatures and emissivities at these higher temperatures.

A complete review of the VIES system can be found in Topical Report No. 15.

Optical Access Devices

Modern technologies need sophisticated control and monitoring instrumentation. Advanced optical diagnostic methods can fulfill a large part of this need. Over the years a significant amount of support has been provided to develop optical and laser-based spectroscopy techniques to measure and characterize various physical parameters in combustion and other similar systems. Often, such state-of-the-art techniques provide the only practical and accurate method for obtaining measurements of physical properties such as gas temperature profiles or velocity profiles. These nonintrusive methods offer advantages over standard intrusive methods. They are nonperturbing and usually provide a rapid response with wide sensitivity.

As part of the U.S. Department of Energy's national MHD development program, DIAL has developed and used a number of advanced optical techniques and instrumentation systems for characterization of various parameters in MHD system components. These instruments, which are generally nonintrusive, are designed to measure those parameters such as gas stream temperatures, flow fields, turbulence levels, particulate characteristics, gas composition, etc., which are of importance in the characterization and ultimate design of an MHD power plant. An important element of this program involves field measurements; hence, the instrumentation systems are designed to operate in the industrial-like environment of large-scale facilities.

A salient characteristic of nonintrusive optical techniques is the need for optical access to the gas stream. In some cases, it is possible to manually knock out any slag build-up and to manually clean the optical windows. This, however, requires that someone be available to regularly monitor and clean the optical ports. This clearly is not feasible for continuous long-term operation of the instrumentation system. Moreover, in many cases, because of safety or facility considerations, access to the optical port is not possible once the facility is in operation. For these reasons we have designed and tested two devices, a remote window changing mechanism and a slag ram, to alleviate this serious limitation of optical access.

These two devices for maintaining optical access are described in detail in Topical Report No. 7.

TEST STAND OPERATIONS

Combustion Test Stand

Design History

DIAL's combustion test stand was originally designed for metal sample corrosion/erosion studies. It consisted of all cold-walled, water-cooled test sections. Combustion air was supplied from an air compressor and preheated to 1113 K via electrical resistance heaters. Fuel oil number one was pumped to the combustor with a Cummins diesel fuel pump, and a stepping motor attached to the throttle mechanism on the pump was used for controlling the fuel flow rate. Each test section was fully instrumented for collection of thermal and flow data. The fuel and air systems were also well instrumented and controlled from a Hewlett Packard Model 1000 process control computer. The exhaust stream from the combustion test stand was processed through a water spray, a venturi scrubber, and a filter box before going to the stack. The water cooling system was a closed system with a water tank, pump, and forced air fluid coolers.

The cold-walled test stand did not produce high enough temperatures to adequately simulate the down-stream conditions of an MHD generator. So the test sections near the combustor were replaced with refractory-lined sections which raised the maximum combustion temperature to approximately 2300 K. These test sections were designed with optical access to the gas stream. They vary in length, including one, two, and four feet, and have both optics and intrusive probe ports. These sections can be installed in the test train to provide ports at any location along the approximately 30-foot test stand length.

After the metal corrosion/erosion tests were completed, the purpose of this project was the development of nonintrusive diagnostic measurement techniques. The test stand was then used mainly to simulate various combustion gas streams. A slurry injection system was added to inject seed and flyash so that coal combustion could be simulated. Various particulates have been slurried with fuel oil and successfully injected into the combustor in parallel with the main fuel flow.

Data monitoring is now provided with a Hewlett Packard A400 computer and HP3852 data acquisition system. Data is stored on a nine-track tape for later review or for use in thermal modeling.

Specifications

The most significant specifications for DIAL's combustion test stand are listed below:

FUEL	Diesel #1 - 0 to 60 lb/hr Coal slurry - 0 to 20 lb/hr
OXIDIZER	Air - 0 to 720 lb/hr
SOLIDS INJECTION	Fly ash, etc. - 0 to 6 lb/hr
COOLING SYSTEM	Closed water system with heat exchangers
OPTICAL PATH LENGTH	8 to 24 in.
OPERATING TEMPERATURE	1000 to 2300 K
AIR PREHEAT	0 to 1100 K

The system was designed to run for extended periods of time. The longest test completed was a 100-hour metal lifetime test. For instrument development, long runs are not normally necessary and short test runs became the rule. A new combustor was designed to use cold air instead of the normally preheated air. It uses a propane igniter and eliminates about two hours of preheat and one hour of cool down from each test run. This combustor made the short test run more practical. It can also be used with preheated air.

Figure 35 is a block diagram of the test stand system. It shows all of the major components of the facility with the exception of the computer system.

fly ash, seed, etc

fuel

Figure 35. Test stand schematic.

TECHNICAL SUPPORT
for
NATIONAL MHD PROGRAM

Field Trips - National

The Diagnostic Instrumentation and Analysis Laboratory provided technical support for DOE's national MHD research and development program by participating in numerous test runs at facilities around the country. These test runs are noted below. Prior to 1986, details of test runs were reported in Quarterly Technical Progress Reports. Beginning in 1986, individual Data Reports were compiled for each test run.

1982

Facility: CFFF
Location: UTSL, Tullahoma, TN
Date: May 1982
Instrument(s): SLR, TCP

Facility: CDIF
Location: Butte, MT
Date: June 1982
Instrument(s): SLR

Facility: CFFF
Location: UTSL, Tullahoma, TN
Date: June 1982
Instrument(s): SLR

Facility: CDIF
Location: Butte, MT
Date: October 14, 1982
Instrument(s): SLR

Facility: CFFF
Location: UTSL, Tullahoma, TN
Date: May, August, October 1982
Instrument(s): Listed as operational SLR, TCP, ONO, SCLT

Facility: CFFF
Location: UTSL, Tullahoma, TN
Date: August and September 1982
Instrument(s): Not specified

Facility: CDIF
Location: Butte, MT
Date: May 1982
Instrument(s): SLR

Facility: CDIF
Location: Butte, MT
Date: April, May, June, October 1982
Instrument(s): Listed as operational SLR, TCP, SCLT

Facility: CFFF
Location: UTSI, Tullahoma, TN
Date: April, May, June, August, October 1982
Instrument(s): Listed as operational SLR, TCP, SCLT

1983

Facility: Avco Everett Research Laboratory
Location: Everett, MA
Date: August 22, 1983
Instrument(s): LDV

Facility: CFFF
Location: UTSI, Tullahoma, TN
Date: April, May, June 1983
Instrument(s): Not specified

Facility: CFFF
Location: UTSI, Tullahoma, TN
Date: April, May, June, July, August, September 1983
Instrument(s): Listed as field ready SLR, TCP, ONO, TCLT, LDV

Facility: Avco Combustor Facility
Location: Everett, MA
Date: August 1983
Instrument(s): Not specified

Facility: CFFF
Location: UTSI, Tullahoma, TN
Date: July 15, 20; August 10, 18; September 8, 15, 22, 1983
Instrument(s): TCP, SLR

1984

Facility: AMPEL
Location:
Date: March 1984
Instrument(s): Not specified

Facility: CFFF
Location: UTSL, Tullahoma, TN
Date: October, November, December 1984
Instrument(s): Not specified

Facility: Argonne National Laboratory
Location: Argonne, IL
Date: October, November, December 1984
Instrument(s): Not specified

Facility: Avco Everett Research Laboratory
Location: Everett, MA
Date: October, November, December 1984
Instrument(s): Not specified

Facility: CFFF
Location: UTSL, Tullahoma, TN
Date: January 1984
Instrument(s): Not specified

Facility: Avco Everett Research Laboratory
Location: Everett, MA
Date: August 1984
Instrument(s): Not specified

Facility: Argonne National Laboratory
Location: Argonne, IL
Date: January, August, September 1984
Instrument(s): Not specified

Facility: CFFF
Location: UTSL, Tullahoma, TN
Date: April, May, September 1984
Instrument(s): Not specified

1985

Facility: CFFF
Location: UTSI, Tullahoma, TN
Date: December 11, 1985
Instrument(s): SLRS, MCP, TCLT, LDV

Facility: CFFF
Location: UTSI, Tullahoma, TN
Date: November 4, 1985
Instrument(s): SLRS, MCP, TCLT, LDV

Facility: CFFF
Location: UTSI, Tullahoma, TN
Date: January, April, September 1985
Instrument(s): SLR, TCLT, MCP

1986

Facility: Argonne National Laboratory
Location: Argonne, IL
Date: April 7 - 18, 1986
Instrument(s): SLRS, MCP, TCLT
Report: *Diagnostic Measurements at Argonne National Laboratory SOIL 43 - SOIL 48*

Facility: CFFF
Location: UTSI, Tullahoma, TN
Date: April 29, 1986
Instrument(s): MCP, SLRS
Report: *Data Report LMF4-G*

Facility: CFFF
Location: UTSI, Tullahoma, TN
Date: June 5, 1986
Instrument(s): MCP, SLRS, TCLT, LDV
Report: *Data Report LMF4-H*

Facility: CFFF
Location: UTSI, Tullahoma, TN
Date: August 18 - 23, 1986

Instrument(s): MCP, SLRS
Report: *Data Report LMF4-I*

1987

Facility: CFFF
Location: UTSI, Tullahoma, TN
Date: August 24 - September 5, 1987
Instrument(s): MCP, SLRS, TCLT, LDV, PEAS, PSD, IMPS
Report: *Data Report LMF4-K*

Facility: Argonne National Laboratory
Location: Argonne, IL
Date: July 14 - 20, 1987
Instrument(s): MCP, SLRS, TCLT
Report: *Diagnostic Measurements at Argonne National Laboratory SOIL 55 - SOIL 57*

1988

Facility: CFFF
Location: UTSI, Tullahoma, TN
Date: February 17 - 19, 1988
Instrument(s): MCP, SLRS
Report: *Data Report LMF4-M, Vol. 8, No. 1*

Facility: CFFF
Location: UTSI, Tullahoma, TN
Date: April 26 - May 8, 1988
Instrument(s): MCP, SLRS, TCLT, LDV, IMPS
Report: *Data Report LMF4-N, Vol. 8, No. 2*

Facility: CFFF
Location: UTSI, Tullahoma, TN
Date: August 15 - September 2, 1988
Instrument(s): MCP, SLRS, TCLT, LDV, IMPS
Report: *Data Report LMF4-O, Vol. 8, No. 3*

Facility: CFFF
Location: UTSI, Tullahoma, TN
Date: November 8 - 12, 1988

Instrument(s): MCP, IMPS, TCLT, CARS
Report: *Data Report LMF4-P, Vol. 8, No. 4*

1989

Facility: CFFF
Location: UTSI, Tullahoma, TN
Date: May 29 - June 1, 1989
Instrument(s): IMPS, MCP, TCP, PEAS, TCLT
Report: *Data Report LMF4-Q, Vol. 9, No. 1*

Facility: CFFF
Location: UTSI, Tullahoma, TN
Date: August 17 - 30, 1989
Instrument(s): SLR, TCLT, TCP, AT, CARS, IMPS, IWD
Report: *Data Report LMF4-R, Vol 9, No. 2*

Facility: CFFF
Location: UTSI, Tullahoma, TN
Date: November 29 - December 7, 1989
Instrument(s): LDV, TCLT, CARS, IWD, PSD
Report: *Data Report LMF4-S, Vol. 9, No. 3*

1990

Facility: CFFF
Location: UTSI, Tullahoma, TN
Date: May 29 - June 12, 1990
Instrument(s): IMPS, LDV, CARS, PSD
Report: *Data Report LMF4-T, Vol. 10, No. 1*

Facility: CFFF
Location: UTSI, Tullahoma, TN
Date: July 30 - August 13, 1990
Instrument(s): IMPS, MCP, TCLT, PSD
Report: *Data Report LMF4-U, Vol. 10, No. 2*

Facility: CFFF
Location: UTSI, Tullahoma, TN
Date: November 6 - 16, 1990

Instrument(s): CARS, IMPS, MCP, SLR, TCLT, CCS, PSD, VIES
Report: *Data Report LMF4-V*

1991

Facility: CFFF
Location: UTSI, Tullahoma, TN
Date: May 6 - 11, 1991
Instrument(s): CARS, IMPS, TCLT, PSD, VIES
Report: *Data Report LMF4-W, Vol. 11, No. 1*

Facility: CFFF
Location: UTSI, Tullahoma, TN
Date: August 25 - 29, 1991
Instrument(s): PEAS, TCLT, PSD
Report: *Data Report LMF5-B, Vol. 11, No. 2*

Facility: CFFF
Location: UTSI, Tullahoma, TN
Date: September 23 - 25, 1991
Instrument(s): IMPS, MCP, PEAS, TCLT, PSD, VIES
Report: *Data Report LMF5-C*

Facility: CFFF
Location: UTSI, Tullahoma, TN
Date: November 18 - 24, 1991
Instrument(s): CARS, IMPS, LDV, MCP, PEAS, TCLT, PSD, VIES
Report: *Data Report LMF5-D, Vol. 11, No. 4*

1992

Facility: CFFF
Location: UTSI, Tullahoma, TN
Date: April 23 - 30, 1992
Instrument(s): CARS, LDV, MCP, PEAS, TCLT, FTIR, PSD, RaP, VIES
Report: *Data Report LMF5-E, Vol. 12, No. 4*

Facility: CDIF
Location: Butte, MT
Date: June 10 - 17, 1992

Instrument(s): PEAS
 Report: *Data Report CDIF 92-COMB-3-7, Vol. 12, No. 4*

Facility: CDIF
 Location: Butte, MT
 Date: August 14 - 26, 1992
 Instrument(s): CARS, LDV, MCP, PEAS, TCLT, PSD, RaP, SiDA, VIES
 Report: *Data Report LMF5-F, Vol. 12, No. 5*

Facility: Arthur Kill Generating Station, Consolidated Edison
 Company of New York, Inc.
 Location: Staten Island, NY
 Date: August 19, 1992
 Instrument(s): MCP, PaP, SiDA
 Report: *Pyrometric Measurements at the Arthur Kill Generating Station*

Facility: CFFF
 Location: UTSI, Tullahoma, TN
 Date: September 29 - October 9, 1992
 Instrument(s): CARS, LDV, MCP, PEAS, SLRS, TCLT, SiDa
 Report: *Data Report LMF5-G, Vol. 12, No. 6*

Facility: CDIF
 Location: Butte, MT
 Date: February 5, 1992
 Instrument(s): PEAS
 Report: *Data Report CDIF 92-RJRM-3, Vol. 12 No. 1*

Facility: CDIF
 Location: Butte, MT
 Date: February 7, 1992
 Instrument(s): PEAS
 Report: *Data Report CDIF 92-RJRM-4, Vol. 12, No. 2*

Facility: CDIF
 Location: Butte, MT
 Date: February 11, 1992
 Instrument(s): PEAS
 Report: *Data Report CDIF 92-RJRM-5, Vol. 12, No. 3*

1993

Facility: CFFF
Location: UTSI, Tullahoma, TN
Dates: April 20 - 26, 1993
Instrument(s): SiDA, MCP, PEAS, TCLT
Report: *Data Report LMF5-H, Vol. 13, No. 1*

Facility: CFFF
Location: UTSI, Tullahoma, TN
Date: July 8 - 18, 1993
Instrument(s): SiDa, LDV, MCP, TCLT
Report: *Data Report LMF5-I, Vol. 13 No. 2*

Field Trips - International

Facility: MHD Facility at the Shanghai Power Equipment
Research Institute (SPERI)
Location: Peoples Republic of China
Date: June 4 - 6, 1985
Instrument(s): LDV, ONO, MCP, TCLT, SLR

TECHNOLOGY TRANSFER

Commonwealth Edison's Joliet, Illinois Station

Name of Facility: Commonwealth Edison Station No. 9 - Unit 6, Joliet, Illinois.

Date of Activity: May 19, 1980.

Instrument Used: Two-Color Pyrometer.

Furnace wall temperature measurements were made in a large coal-fired boiler using the Two-Color Pyrometer System (TCP). Measurements were made to:

- (a) utilize the newly developed instrument system in an industrial environment;
- (b) estimate the distance the optical system could penetrate combustion gasses to measure a furnace slag wall temperature; and
- (c) obtain furnace wall temperatures and emissivities.

The Commonwealth Edison boiler is a coal-fired cyclone, reheat boiler manufactured by Babcock and Wilcox (B & W).

The distance of penetration by the instrument through the coal-fired combustion gases to the furnace slag wall was about eight feet. The values measured for slag wall temperatures were within the expected range of 2200 to 2600°F. The TCP and the associated computer system performed satisfactorily in the industrial environment.

Report: Written by L.E. Bauman and M. Shackelford, July 1980.

Stennis Space Center, Mississippi

Name of Facility: Stennis Space Center, Mississippi.

Dates of Activity: June 27 - 30, 1988.

Instrument Used: Potassium Emission/Absorption Spectrometer.

The PE/AS instrument, along with a telescope, were used as an emission spectrometer to collect time resolved spectra of the plume of a small hydrogen/oxygen rocket motor. These tests were designed to find appropriate diagnostic techniques for monitoring the firings of the Space Shuttle Main Engines carried out at the Stennis Space Center. As a result of this field trip, Sverdrup Technology now routinely uses a system similar to the PE/AS for such measurements.

Report: *Demonstration of Atomic Emission Spectroscopy for Optical Plume Anomaly Detection* by L.E. Bauman and R.K. Lengel, July 29, 1988.

Uncle Ben's, Inc., Greenville, Mississippi

Name of Facility: Uncle Ben's, Inc., Greenville, Mississippi.

Dates of Activity: October 9 - 10, 1991; January 21, 1992; January 30 - 31, 1992.

Instruments Used: Infrared Pyrometer System, Gas Analysis System, Pitot Probe Gas Velocity Measurement System, Visible/Infrared Emission Spectroscopy System.

We made three trips to visit the Greenville, Mississippi facility of Uncle Ben's, Inc. The purpose of these trips was to apply DIAL's diagnostic instruments to make a series of measurements on the boiler at this plant, which uses waste rice hulls as a fuel to provide process steam to the rest of the plant.

The first trip was to discuss the situation with the plant personnel and to decide what measurements would be beneficial. The second trip was to inspect the boiler plant in detail and decide how our instruments could be interfaced to the plant. The final trip was devoted to the actual measurements.

Reports: *Investigation of the Combustion Characteristics of a Rice Hull Burner System, Preliminary Report* by R. Kumar, C.W. Bouchillon, R.A. Green, D.L. Monts, and O.P. Norton, February 12, 1992.

Investigation of the Combustion Characteristics of a Rice Hull Burner System, Preliminary Report, Part 2 by R. Arun Kumar, C.W. Bouchillon, R.A. Green, D.L. Monts, and O.P. Norton, February 25, 1992.

Consolidated Edison, Staten Island, New York

Name of Facility: Arthur Kill Generating Station, Consolidated Edison Company of New York, Inc., Staten Island, NY.

Date of Activity: July 23 - 24, 1992.

Instruments Used: Multi-Color Pyrometer System (MCP), Silicon Diode Array System (SiDA), Ratio Pyrometer (RaP).

Arthur Kill Generating Station was using two boilers in their generation of electricity--a Combustion Engineering boiler and a Babcock and Wilcox (B & W) boiler. They were experiencing some failures in the refractory around the burner shrouds in the B & W boiler and were concerned about hot spots on boiler tubes in each boiler contributing to premature tube failure. DIAL utilized its various instruments to measure the temperature of the boiler walls, boiler tubes, and burner shrouds in each of the two boilers at Arthur Kill. Several wall areas were measured to allow comparison of temperatures within the boiler to evaluate the degree of uneven heating present inside the boiler.

Report: *Pyrometric Measurements at the Arthur Kill Generating Station, Consolidated Edison Company of New York, Inc. Staten Island, New York* by C. W. Bouchillon, R. D. Benton, and Robert A. Green, August 19, 1992.

APPENDICES

APPENDIX A

DALAS Data Acquisition Program

```

/* dalas.h -- include file for dalas.c */
#include <stdio.h> /* Include Microsoft Standard I/O file */
#include <stdlib.h> /* Include Microsoft Standard Library file */
#include <string.h> /* Include Microsoft String Manipulation file */
#include <time.h> /* Include Microsoft Time routines */
#include <ctype.h> /* Include Microsoft character conversion routines */
#include <graph.h> /* Include Microsoft Graphic routines */
#include <bios.h> /* Include Microsoft BIOS routines */
#include <io.h> /* Include Microsoft L-level File Handle & I/O routines */
#include <math.h> /* Include Microsoft Math Library */
#include <pclerrs.h> /* Include PCLAB error codes for Microsoft C */
#include <pcldefs.h> /* Include PCLAB function declarations for Microsoft C */

#define TRUE (~0)
#define FALSE 0
#define NUMBER_OF_CONVERSIONS 2
#define MAX_NO_OF_CHANNEL 8 /* Maximum Number Of scanning Channels */
#define unlimited 3
#define lo(f) ((f) & 0xff)
#define hi(f) (lo(f) >> 8)
/* function keys */
#define f5key 0x3f00
#define esckey 0x011b
/* cursor positioning keys */
#define upkey 0x4800
#define downkey 0x5000
#define leftkey 0x4b00
#define rightkey 0x4d00
#define pgupkey 0x4900
#define pgdnkey 0x5100
#define homekey 0x4700
#define endkey 0x4f00
#define LF '\012'
#define CR '\015'
#define ESC '\033'
#define BS '\010'
#define BEEP printf("\007")
#define port_select 1 /* DT-707 output port selection */
#define mask0 1 /* 01*/
#define high0 3 /* 11*/
#define low0 2 /* 10*/
#define mask1 2 /* 10*/
#define high1 2 /* 10*/
#define low1 0 /* 00*/
#define mask_move 4 /* 100 */
#define pause0 0 /* 000 */
#define pause1 4 /* 100 */
#define highest 4096 /* DT-2805 highest digital count */
#define lowest 0 /* DT-2805 lowest digital count */
#define radix 10

extern display_chart(int w_trigger, int page_length, int no_of_ch, int funid,
                    float start_wave, float end_wave, float a_point);
extern show_value(int count, int page_length, int no_of_ch, short *array,
                 int vmax, int vmin);

static unsigned int lookkey(void);

```



```

static char getkey(int *k);
static void moveit(unsigned int no_steps);
static void voltrng(void);

FILE *dfptr;
short analog_array[MAX_NO_OF_CHANNEL];
unsigned int digital_value, no_steps;
unsigned int digital_value0, digital_valuel;
int ch, got_file;
unsigned int high_delay, low_delay, delay;
int number_of_channel, w_trigger, n_samples, count, ptrcount;
int page_length, page_no, xtick, decimal, sign;
int last_page, first_page; /* last page, first page flags */
int vmax, vmin;           /* Display scaling */
/* no of sample in a file=(file length-67)/(5*number_of_channel+2) */
long file_length, no_of_sample;
double no_page;
char line[81], buffer[10], *p;
char date_buffer[9], time_buffer[9], q[80];
float clock_frequency, start_wave, end_wave, a_point;

```

```

/* dalas.c with entering trial delay count, clock freq*/
#include "dalas.h" /* Include user defined values & MSC libraries */
main ()
{
    /* Variable types Declaration */
    short adv, error, gain, s_channel, l_channel, channel;

    int i, j, k, timing_source;
    int savefile, funid, timeout_period;
    long page_offset; /* offset for previous page file pointer */
    long last_offset; /* offset for last page */
    long print_offset; /* offset for printing */
    long l, start_sample_no, end_sample_no;
    float voltage;
    time_t sstart, pstart, long_time;
    struct tm *newtime;

    /* Initialize variables to default */
    error = 0; /* Initialize error to zero */
    gain = 1; /* set gain code to 1 */
    s_channel=0; /* Start channel no. */
    l_channel=1; /* End channel no. */
    channel=0; /* First scanning channel # */
    timing_source=2; /* External trigger Internal clock */
    digital_value0= pause0;
    digital_value1= pause1;
    clock_frequency=400; /* 40 Internal clock in Hz=(number_of_channel +2)/.1 */
    printf("Enter trial delay count: ");
    scanf("%u", &delay);
    printf("\tEnter Internal Clock Frequency = ");
    scanf("%f", &clock_frequency);
    high_delay=low_delay=delay;
    page_no=1; /* Initial page no. */
ppp:
    count=1; /* Counter for no. of samples in the whole scan */
    ptrcount=1; /* Counter for no. of samples on the screen */
    savefile=FALSE; /* Initial file saving flag */
    _setvideomode(_DEFAULTMODE);
    /* User select desired function */
    printf("\n\n\n\n\t1. Charting with data logging to file.\n");
    printf("\t2. Charting without data logging to file.\n");
    printf("\t3. Chart previous logged data file.\n");
    printf("\t4. Print data file to printer.\n");
    printf("\t5. Quit.\n");
    printf("\tSelect(1..5):");
    while ((funid=getche()) < 49 || (funid > 53))
        BEEP;
    funid=funid-48;
    switch(funid)
    {
        case 1: /* User input data filespec */
            got_file=FALSE;
            ch=3;
            while (!got_file && ch != ESC)
                getfile(funid);
            if (ch == ESC)
            {
                _setvideomode(_DEFAULTMODE);
                goto ppp; /* exit(0); */
            }
            savefile=TRUE;
            break;
    }
}

```

```

case 2:
    savefile=FALSE;
    break;
case 3:
    got_file=FALSE;
    ch=3;
    while (!got_file && ch != ESC)
        getfile(funid);
    if (ch == ESC)
    {
        _setvideomode(_DEFAULTMODE);
        goto ppp; /* exit(0); */
    }
    page_length=pagelen();
    voltrng();
    display_chart(w_trigger,page_length,number_of_channel,funid,
        start_wave, end_wave, a_point);
    _settextposition(2,5);
    _outtext("Display : ");
    _outtext(line);
    _settextposition(1,70);
    _outtext("Page:");
    _settextposition(2,40);
    _outtext("Sample Started at = ");
    _outtext(date_buffer);
    _outtext(" ");
    _outtext(time_buffer);
    _settextcolor(15);
    file_length=filelength(fileno(dfptr));
    no_of_sample=(file_length-67)/(5*number_of_channel+2);
    if (floor((double)(no_of_sample-1)/(double)(page_length-1)) ==
        (double)(no_of_sample-1)/(double)(page_length-1))
        no_page=(double)(no_of_sample-1)/(double)(page_length-1);
    else
        no_page=floor((double)(no_of_sample-1)/(double)(page_length-1))+
            (double)1;
    if (no_page == (double) 1)
    {
        last_page=TRUE;
        first_page=TRUE;
    }
    else
    {
        last_page=FALSE;
        first_page=TRUE;
    }
    last_offset=((int)no_page-1)*(page_length-1)*(number_of_channel*5+2)+66;
    show_a_page();
    for(;;)
    {
        p=itoa(page_no, buffer, radix);
        _settextposition(1,76);
        _outtext(" ");
        _settextposition(1,76);
        _outtext(p);
        while(!kbhit());
        getkey(&ch); /* get key in keyboard buffer */
        _settextposition(25,55);
        _outtext(" ");
        switch(ch)
        {
            case pgupkey : /* Pageup display previous page */

```

```

    if (first_page)
    {
        BEEP;
        _settextposition(25,55);
        _outtext("First Page !!");
        break;
    }
    else
    {
        page_offset=(page_no-2)*(page_length-1)*(number_of_channel*
        5+2)+66;
        j=fseek(dfptr,page_offset,SEEK_SET);
        if (j)
            printf("Fseek Failed");
        page_no--;
        if (page_no == 1)
            first_page=TRUE;
        last_page=FALSE;
        show_a_page();
        break;
    }
    case pgdnkey : /* Pagedown display next page */
    if (last_page)
    {
        BEEP;
        _settextposition(25,55);
        _outtext("Last Page !!");
        break;
    }
    else
    {
        page_no++;
        if (page_no == (int)no_page)
            last_page=TRUE;
        first_page=FALSE;
        show_a_page();
        break;
    }
    case homekey : /* Home display the first page */
    if (first_page)
    {
        BEEP;
        _settextposition(25,55);
        _outtext("First Page !!");
        break;
    }
    else
    {
        j=fseek(dfptr,66L,SEEK_SET);
        if (j)
            printf("Fseek Failed");
        page_no=1;
        first_page=TRUE;
        if (no_page == 1L)
            last_page=TRUE;
        else
            last_page=FALSE;
        show_a_page();
        break;
    }
    case endkey : /* Pageup display the last page */
    if (last_page)

```

```

        {
            BEEP;
            _settextposition(25,55);
            _outtext("Last Page !!");
            break;
        }
        else
        {
            j=fseek(dfptr,last_offset,SEEK_SET);
            if (j)
                printf("Fseek Failed");
            page_no=no_page;
            last_page=TRUE;
            if (page_no != 1)
                first_page=FALSE;
            show_a_page();
            break;
        }
        case esckey :    /* Exit */
            _setvideomode(_DEFAULTMODE);
            goto ppp; /* exit(0); */
        default :
            break;
    }
}
_settextposition(25,55);
_outtext("Done! Any key = Exit");
BEEP;
while(!kbhit());
ch=getch();
_setvideomode(_DEFAULTMODE);
goto ppp; /* exit(0); */
case 4:
    got_file=FALSE;
    ch=3;
    while (!got_file && ch != ESC)
        getfile(funid);
    if (ch == ESC)
    {
        _setvideomode(_DEFAULTMODE);
        goto ppp; /* exit(0); */
    }
    file_length=filelength(fileno(dfptr));
    no_of_sample=(file_length-67)/(5*number_of_channel+2);
    _setvideomode(_DEFAULTMODE);
    printf("File:%s on %s %s", line, date_buffer, time_buffer);
    printf("Scan %d channel(s), %d waited trigger/sample, %ld samples\n",
        number_of_channel, w_trigger, no_of_sample);
    printf("Scanning: %9fA -- %9fA %9fA/Sample\n",
        start_wave, end_wave, a_point);
    start_sample_no=0L;
    end_sample_no=-1L;
    while ((start_sample_no < 1L) || (start_sample_no > no_of_sample) ||
        (end_sample_no < 1L) || (end_sample_no > no_of_sample) ||
        (start_sample_no > end_sample_no))
    {
        BEEP;
        printf("Start sample no.= ");
        scanf("%ld",&start_sample_no);
        printf("End sample no.= ");
        scanf("%ld",&end_sample_no);
    }
}

```

```

printf("Printing ...");
fprintf(stdprn,"File:%s On %s %s\n", line, date_buffer, time_buffer);
fprintf(stdprn,"Scan %d channel(s), %d waited trigger/sample, %ld
samples\n",
        number_of_channel, w_trigger, no_of_sample);
fprintf(stdprn,"Scanning: %9fA -- %9fA %9fA/Sample\n",
        start_wave, end_wave,
        a_point);
fprintf(stdprn,"Print from %ld to %ld\n",start_sample_no,end_sample_no);
print_offset=(start_sample_no-1L)*(number_of_channel*5+2)+66;
j=fseek(dfptr,print_offset,SEEK_SET);
if (j)
    printf("Fseek Failed");
for (l=start_sample_no; l <= end_sample_no; l++)
{
    for (i=0; i < number_of_channel; i++)
    {
        fscanf(dfptr,"%d",&analog_array[i]);
        fprintf(stdprn,"%4d ",analog_array[i]);
    }
    fprintf(stdprn,"\n");
}
flushall();
printf("Done! Any key = Exit");
BEEP;
while(!kbhit());
ch=getch();
_setvideomode(_DEFAULTMODE);
goto ppp; /* exit(0); */
case 5:
    _setvideomode(_DEFAULTMODE);
    _exit(0);
default:
    break;
}
/* User input measurement parameters */
number_of_channel=2;
printf("\n\tEnter No. of pair-waited-trigger(s)/sample (Min.= 1 pair) = ");
scanf("%d",&w_trigger);
w_trigger=w_trigger*2;
voltrng();
start_wave=0;
end_wave=start_wave;
printf("\tEnter No. of samples (0 = unlimited) = ");
scanf("%d",&n_samples);
page_length=pagelen();
if (n_samples == 0)
    n_samples=unlimited;
else{
    if (floor((double)n_samples/(double)(page_length-1)) ==
        ((double)n_samples/(double)(page_length-1)))
        no_page=(double)n_samples/(double)(page_length-1);
    else
        no_page=floor((double)n_samples/(double)(page_length-1))+(double)1;
}
printf("\nPress ESC key to quit or ANY other key to continue...");
ch=getch();
if (ch == ESC) goto ppp; /* exit(0); */
no_steps=6; /* It was 3 steps for 1/4 revolution; */
a_point=0;
/* Save measurement parameters into file */
if (savefile)

```

```

fprintf(dfptr, "%d %5d %5d %9.3f %9.3f %9.3f %3.0f\n", number_of_channel,
        w_trigger, n_samples, start_wave, end_wave, a_point,
        clock_frequency);

```

```

/* display chart recorder */

```

```

display_chart(w_trigger, page_length, number_of_channel, funid, start_wave,
             end_wave, a_point);

```

```

initialize();          /* Initialize the PCLAB subroutines */

```

```

error = setup_adc(timing_source, s_channel, l_channel, gain);

```

```

if (error != 0)

```

```

    printf("setup_adc ERROR=%d", error);

```

```

error = set_clock_frequency(&clock_frequency);

```

```

if (error != 0)

```

```

    printf("set_clock_frequency ERROR=%d", error);

```

```

ch=3;

```

```

flushall();

```

```

_strdate(date_buffer);

```

```

_strtime(time_buffer);

```

```

_settextposition(2,5);

```

```

if (savefile)

```

```

{

```

```

    fprintf(dfptr, "%s %s\n", date_buffer, time_buffer);

```

```

    _outtext("Data saved as ");

```

```

    _outtext(line);

```

```

}

```

```

else

```

```

    _outtext("Data not saved");

```

```

_settextposition(1,70);

```

```

_outtext("Page:");

```

```

_settextposition(2,40);

```

```

_outtext("Sample Started at = ");

```

```

_outtext(date_buffer);

```

```

_outtext(" ");

```

```

_outtext(time_buffer);

```

```

_settextcolor(15);

```

```

p=itoa(page_no, buffer, radix);

```

```

_settextposition(1,76);

```

```

_outtext(p);

```

```

enable_for_output(port_select);

```

```

output_digital_value(port_select, mask_move, digital_value0);

```

```

error = adc_on_trigger(s_channel, gain, &adv);

```

```

if (error != 0)

```

```

    printf("adc_on_trigger1 ERROR=%d", error);

```

```

hold_reset();

```

```

for(;;)

```

```

{

```

```

    for (i = 1; i <= w_trigger-1; i++)

```

```

    {

```

```

        adc_on_trigger(s_channel, gain, &adv);

```

```

    if (error != 0)

```

```

        printf("adc_on_trigger2 ERROR=%d", error);

```

```

        moveit(no_steps);          /* Move 1/4 revolution */

```

```

    }

```

```

    disable_system_clock();

```

```

    error = adc_series(number_of_channel, analog_array);

```

```

    if (error != 0)

```

```

        printf("adc_series ERROR=%d", error);

```

```

    enable_system_clock();

```

```

    show_value(ptrcount, page_length, number_of_channel, analog_array, vmax, vmin);

```

```

    if (savefile)

```

```

    {

```

```

        15601-52-Final

```

```

    for (k=0; k < number_of_channel; k++)
        fprintf(dfptr,"%4d ",analog_array[k]);
    fprintf(dfptr,"\n");
}
if (n_samples != unlimited)
{
    count++;
    /* increase the sampling counter */
    if (count > n_samples) break;
}
ptrcount++;
if (ptrcount > page_length) /*Re-initialize the display counter, xlabels */
{
    ptrcount=1;
    show_value(ptrcount,page_length,number_of_channel,analog_array,vmax,vmin);
    ptrcount=2;
    page_no++;
    p=itoa(page_no, buffer, radix);
    _settextposition(1,76);
    _outtext(p);
}
if (lookkey())
{
    getkey(&ch);    /* get key in keyboard buffer */
    switch(ch)
    {
        case f5key :
            _settextposition(25,55);
            _outtext("Hold! Any key = Resume");
            while(!kbhit());
            ch=getch();
            _settextposition(25,55);
            _outtext(" ");
            break;
        case esckey :
            terminate();
            if (savefile)
                fclose(dfptr);
            _setvideomode(_DEFAULTMODE);
            goto ppp; /* exit(0); */
        default:
            break;
    }
}
moveit(no_steps);    /* Move 1/4 revolution */
hold_reset();
}
moveit(no_steps);    /* Move 1/4 revolution */
hold_reset();
if (savefile)
    fclose(dfptr);
terminate();
_settextposition(25,55);
_outtext("Done! Any key = Exit");
BEEP;
while(!kbhit());
ch=getch();
_setvideomode(_DEFAULTMODE);
goto ppp; /* exit(0); */
}

hold_reset()
{

```



```

    unsigned int k;
    unsigned int digital_value;

/* Send sample HOLD signal Bit 0 & 1 in port 1 */
    digital_value=low0;
    output_digital_value(port_select, mask0, digital_value);
    digital_value=high0;
    output_digital_value(port_select, mask0, digital_value);
    for (k=1;k <= delay;k++);
    digital_value=low0;
    output_digital_value(port_select, mask0, digital_value);

/* Send sample RESET signal Bit 1 & 2 in port 1 */
    digital_value=high1;
    output_digital_value(port_select, mask1, digital_value);
    digital_value=low1;
    output_digital_value(port_select, mask1, digital_value);
    for (k=1;k <= delay;k++);
    digital_value=high1;
    output_digital_value(port_select, mask1, digital_value);
}
void voltrng()
{
    int got_vrng;
    got_vrng=FALSE;
    while(!got_vrng){
        printf("\n\tEnter Max. Voltage (-10 .. +10 volts) = ");
        scanf("%d",&vmax);
        printf("\tEnter Min. Voltage (-10 .. +10 volts) = ");
        scanf("%d",&vmin);
        if ((abs(vmax) <=10) && (abs(vmin) <=10) && (vmax != vmin))
            got_vrng=TRUE;
        else BEEP;
    }
    vmax=(vmax+10)*204.8;
    vmin=(vmin+10)*204.8;
}
/* Move the dye laser accordingly */
void moveit(unsigned int no_steps)
{
    unsigned int i,k;
    for(i=1; i <= no_steps; i++){
        output_digital_value(port_select, mask_move, digital_value1);
        for (k=1;k <= high_delay;k++);
        output_digital_value(port_select, mask_move, digital_value0);
        for (k=1;k <= low_delay;k++);
    }
}
/* Enter Data Filename */
getfile(int funid)
{
    int i;
    float clock_hz;

    flushall(); /* Clear keyboard input */
    i=0;
    printf("\n\tEnter Data Filename (EX:C:\\DT\\TEST.DAT): ");
    ch = getche();
    while( (ch != EOF) && (ch != LF) && (ch != CR) && (i < 81) )
    {
        if( ch == ESC ) return ch; /* Exit on ESC key */
        else if( ch == BS )
            15601-52-Final
    }
}

```

```

        {
            /* Back space on the back space key */
            if( i > 0 )
            {
                i--;
                printf(" \010");
            }
            else
                printf(" ");
        }
        else
        {
            /* Save the character in the line buffer */
            line[i++] = ( char )ch;
        }
        ch = getche();
    }
    line[i] = 0;
    dfptry = fopen( &line[0], "r");
    switch(funid)
    {
        case 1:
            fclose(dfptry);
            if(dfptry != NULL)
            {
                BEEP;
                printf("\n\tFile existed !! Overwrite? (Y/N): ");
                fflush();
                /* Clear keyboard input */
                ch = getch();
                /* Allow the user to continue or not. */
                while( (ch != 'Y') && (ch != 'y') && (ch != 'N') && (ch != 'n'))
                {
                    /* Screen out invalid keys, check for ESC.*/
                    if( ch == ESC ) break;
                    BEEP;
                    ch = getch();
                }
                /*
                 * If the user does not want to continue, then go back and get
                 * another file name.
                 */
                if( (ch == 'N') || (ch == 'n') )    got_file = FALSE;
                else    got_file = TRUE;
            }
            else    got_file = TRUE;
            if( got_file )
            {
                dfptry = fopen(&line[0], "w");
                if( dfptry == NULL )
                {
                    BEEP;
                    printf("\n\tINVALID FILE NAME");
                    got_file = FALSE;
                }
            }
            if( !got_file )    printf("\n\tTRY AGAIN!");
            break;
        case 3:
        case 4:
            if(dfptry == NULL)
            {
                printf("\n\tFile NOT found. TRY AGAIN!");
                got_file=FALSE;
                break;
            }
            else
            {
                15601-52-Final
            }
    }

```

```

        fscanf(dfptr,"%d %d %d %9f %9f %9f %3f", &number_of_channel, &w_trigger,
            &n_samples, &start_wave, &end_wave, &a_point, &clock_hz);
        fscanf(dfptr,"%s %s", date_buffer, time_buffer);
        if (clock_hz != clock_frequency)
        {
            printf("\n\tINVALID Data File.  TRY AGAIN!");
            got_file=FALSE;
            fclose(dfptr);
            break;
        }
        else
        {
            got_file=TRUE;
            break;
        }
    }
    default:
        printf("\n\t Something wrong !!");
        break;
    }
}

unsigned int lookkey(void)
{
    return _bios_keybrd(_KEYBRD_READY);
}

char getkey(int *k)
{
    char c;
    while(1) {
        *k = _bios_keybrd(_KEYBRD_READ);    /* use QuickC function */
        if ((c=lo(*k)) == 3) {                /* check for Ctrl-c */
            printf("Abort program (Y/N) ?");
            *k = _bios_keybrd(_KEYBRD_READ);    /* check response */
            if ((*k == 0x1559) || (*k == 0x1579))
            {
                _setvideomode(_DEFAULTMODE);
                exit(0);                /* terminate */
            }
        }
        else break;
    }
    return c;
}

/* User select display page length */
int pagelen()
{
    int ch,page_length;
    page_length=0;
    ch=3;
    printf("\n\tPage Scale (S=120, M=300, L=600)= ");
    ch=getche();
    ch=toupper(ch);
    while (ch != 'S' && ch != 'M' && ch != 'L')
    {
        printf("\n\tTry again!");
        printf("\n\tPage Scale (S=120, M=300, L=600)= ");
        ch=getche();
        ch=toupper(ch);
    }
}

```

```

switch(ch)
{
    case 'S': /* Small Sacle */
        page_length=121;
        break;
    case 'M': /* Medium Sacle */
        page_length=301;
        break;
    case 'L': /* Large Sacle */
        page_length=601;
        break;
    default:
        break;
}
return page_length;
}
show_a_page()
{
    int i;
    if (last_page)
    {
        ptrcount=1;
        while(!feof(dfptr))
        {
            for (i=0; i < number_of_channel; i++)
                fscanf(dfptr,"%d",&analog_array[i]);
            show_value(ptrcount,page_length,number_of_channel,analog_array,
                vmax,vmin);
            ptrcount++;
        }
    }
    else
        for (ptrcount=1; ptrcount < page_length; ptrcount++)
        {
            for (i=0; i < number_of_channel; i++)
                fscanf(dfptr,"%d",&analog_array[i]);
            show_value(ptrcount,page_length,number_of_channel,analog_array,
                vmax,vmin);
        }
}

```

```

/* display.c --- Display function for dalas.c compiled with /FPi87 switch*/
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
#include <graph.h>
int xpos[7]={5, 18, 30, 43, 55, 68, 80};
int xposd1[7]={3, 16, 28, 41, 53, 66, 75};
display_chart(int w_trigger, int page_length, int no_of_ch, int funid,
              float start_wave, float end_wave, float a_point)
{
    int ch,i,xtick,ytick,radix,decimal,sign;
    char buffer[80], ylegend[10],xlegend[20], funstr[80], *p, q[80];
    float xlabel;
    struct videoconfig config;

    radix=10;
    if (funid != 3)
        strcpy(funstr,"ESC:Exit  F5:Pause");
    else
        strcpy(funstr,"ESC:Exit  PgUp  PgDn  Home  End");
    strcpy(ylegend,"INTENSITY");
    if (start_wave == end_wave)
        strcpy(xlegend,"Count (x)");
    else
        strcpy(xlegend,"Wavelength A");
    _setvideomode(_ERESCOLOR);
    _getvideoconfig(&config);
    _setcolor(13);
    _setlogorg(0,config.numypixels-1);
    _rectangle(_GBORDER, 39,-315,639,-34);
/* Y-axis ticks */
    for (ytick=1; ytick<=21;ytick++)
    {
        _moveto(39,-35-((ytick-1)*14));
        _lineto(36,-35-((ytick-1)*14));
    }
/* X-axis ticks */
    for (xtick=1; xtick<=7;xtick++)
    {
        _moveto(39+((xtick-1)*100),-34);
        _lineto(39+((xtick-1)*100),-29);
        if (start_wave == end_wave) {
            _settextposition(24,xpos[xtick-1]);
            p = itoa(xtick-1, buffer, radix);
            _outtext(p);
        }
        else {
            xlabel=start_wave+a_point*(float)(page_length-1)/6*(xtick-1);
            p=fcvt(xlabel, 1, &decimal, &sign);
            strcpy(q,"");
            strncat(q,p,decimal);
            strcat(q,".");
            strcat(q,&p[decimal]);
            _settextposition(24,xposd1[xtick-1]);
            _outtext(q);
        }
        _setcolor(15);
        for (i=1; i < 10; i++)
        {
            _moveto(39+(xtick-1)*100+i*10,-34);
            _lineto(39+(xtick-1)*100+i*10,-33);
        }
    }
}

```

```

    _setcolor(13);
}
_settextcolor(14);
/* Y-axis legend */
for (i=0; i<=9; i++)
{
    _settextposition(9+i,3);
    ch=ylegend[i];
    p=&ch;
    _outtext(p);
}
/* X axis legend */
if (start_wave == end_wave) {
    _settextcolor(12);
    strcpy(buffer,"Scanning at:");
    p=fcvt(start_wave, 3, &decimal, &sign);
    strcpy(q,"");
    strncat(q,p,decimal);
    strcat(q,".");
    strcat(q,&p[decimal]);
    strcat(q," A");
    strcat(buffer,q);
    _settextposition(1,40);
    _outtext(buffer);
    p = itoa((page_length-1)/6, buffer, radix);
    strcat(xlegend,p);
    strcat(xlegend,"");
}
_settextcolor(14);
_settextposition(25,44-strlen(xlegend)/2);
_outtext(xlegend);

/* Display Function key's funtion */
_settextcolor(10);
_settextposition(25,3);
_outtext(funstr);
/* Data legend */
for (i=0; i < no_of_ch; i++)
{
    _setcolor(10+i);
    _moveto(32+i*64,-343);
    _lineto(48+i*64,-343);
    _settextcolor(10+i);
    _settextposition(1,8+i*8);
    _outtext("Ch.");
    p = itoa(i, buffer, radix);
    _outtext(p);
}
_settextcolor(12);
}

```

```

/* showval.c --- show a value onto screen for dalas.c compiled with /FPi87*/
#include <graph.h>
#include <stdio.h>
show_value(int count, int page_length, int no_of_ch, short *array,
           int vmax, int vmin)
{
    int i, nxval, ch, xval, yval;
    float xfac;

    xfac=(float)600/(float)(page_length-1);
    xval=39+((float)(count-1)*xfac);
/* Turn chart recorder pen bar off */
    if ((count > 1) && (count < page_length)) {
        _setcolor(0);
        _moveto(xval,-314);
        _lineto(xval,-35);
    }
    if ((count == 1) || (count == page_length)) {
        _setcolor(13);
        _moveto(xval,-314);
        _lineto(xval,-35);
    }

    for (i=0; i < no_of_ch; i++)
    {
        if ((array[i] <= vmax) && (array[i] >= vmin)){
            yval=(float)-35-(float)280*(array[i]-vmin)/(vmax-vmin);
            _setcolor(10+i);
            _setpixel(xval,yval);
        }
    }
/* Turn chart recorder pen bar on */
    if (count < page_length)
    {
        nxval=39+((float)count*xfac);
        _setcolor(11);
        _moveto (nxval,-314);
        _lineto (nxval,-35);
    }
}

```

APPENDIX B

SO₂ Absorption Coefficient as a Function of Wavelength for the 297.25 to 300.75-nm Region

λ (nm)	$\sigma(10^{-23} \text{ m}^2)$
297.25	1.66
297.27	2.04
297.29	1.62
297.31	1.29
297.33	1.43
297.35	1.34
297.37	1.42
297.39	1.80
297.41	1.45
297.43	1.80
297.45	1.53
297.47	1.50
297.49	1.22
297.51	1.24
297.53	1.35
297.55	1.38
297.57	1.33
297.59	1.57
297.61	1.56
297.63	1.41
297.65	1.39
297.67	1.25
297.69	1.20
297.71	1.34
297.73	1.62
297.75	1.67
297.77	1.60
297.79	1.78
297.81	1.67
297.83	1.43
297.85	1.68
297.87	1.61
297.89	1.89
297.91	2.09
297.93	1.91
297.95	2.85
297.97	3.04
297.99	4.08
298.01	5.07
298.03	5.76
298.05	6.29
298.07	6.78
298.09	7.62
298.11	8.30
298.13	9.51
298.15	9.73
298.17	9.84
298.19	10.07
298.21	9.32
298.23	9.75

λ (nm)	$\sigma(10^{-23} \text{ m}^2)$
298.25	8.91
298.27	8.94
298.29	8.49
298.31	8.02
298.33	8.54
298.35	8.88
298.37	8.09
298.39	7.74
298.41	7.95
298.43	7.47
298.45	8.10
298.47	7.45
298.49	7.14
298.51	7.02
298.53	6.91
298.55	6.11
298.57	6.50
298.59	6.32
298.61	6.24
298.63	4.95
298.65	4.60
298.67	4.25
298.69	3.68
298.71	3.94
298.73	3.61
298.75	3.58
298.77	3.28
298.79	2.98
298.81	2.91
298.83	2.82
298.85	2.60
298.87	1.75
298.89	1.91
298.91	2.28
298.93	2.28
298.95	1.70
298.97	2.14
298.99	2.20
299.01	1.90
299.03	1.91
299.05	1.67
299.07	1.72
299.09	1.40
299.11	1.36
299.13	1.56
299.15	1.89
299.17	1.98
299.19	1.60
299.21	1.60
299.23	1.48

λ (nm)	$\sigma(10^{-23} \text{ m}^2)$
299.25	1.49
299.27	2.01
299.29	1.94
299.31	1.63
299.33	1.59
299.35	1.53
299.37	1.44
299.39	1.47
299.41	1.56
299.43	2.11
299.45	2.12
299.47	1.81
299.49	1.77
299.51	1.78
299.53	1.74
299.55	1.53
299.57	1.58
299.59	1.43
299.61	1.65
299.63	1.98
299.65	1.64
299.67	1.55
299.69	1.55
299.71	1.57
299.73	1.52
299.75	1.82
299.77	1.86
299.79	1.76
299.81	1.59
299.83	2.10
299.85	2.21
299.87	2.35
299.89	2.62
299.91	5.00
299.93	6.70
299.95	8.51
299.97	10.69
299.99	11.69
300.01	12.44
300.03	12.49
300.05	12.20
300.07	11.88
300.09	11.72
300.11	11.34
300.13	11.05
300.15	9.33
300.17	9.36
300.19	9.77
300.21	10.20
300.23	9.18

λ (nm)	$\sigma(10^{-23} \text{ m}^2)$
300.25	8.64
300.27	8.09
300.29	8.06
300.31	7.02
300.33	6.74
300.35	6.12
300.37	6.69
300.39	6.24
300.41	5.63
300.43	5.41
300.45	4.46
300.47	4.19
300.49	4.44
300.51	4.12
300.53	4.46
300.55	3.95
300.57	3.69
300.59	3.02
300.61	3.08
300.63	2.62
300.65	2.80
300.67	2.64
300.69	2.77
300.71	2.62
300.73	2.69
300.75	2.08
300.77	1.85
300.79	1.84
300.81	2.41
300.83	1.83
300.85	2.19
300.87	2.08
300.89	1.78
300.91	2.06
300.93	1.79
300.95	1.65
300.97	1.79
300.99	1.64
301.01	1.78
301.03	1.88
301.05	1.46
301.07	1.61
301.09	1.40
301.11	1.42
301.13	1.15
301.15	1.27
301.17	1.32
301.19	1.08
301.21	1.12
301.23	1.10

λ (nm)	$\sigma(10^{-23} \text{ m}^2)$
301.25	1.00
301.27	1.06
301.29	0.89
301.31	0.91
301.33	1.02
301.35	1.17
301.37	0.96
301.39	1.17
301.41	1.04
301.43	1.02
301.45	1.00
301.47	0.96
301.49	0.71
301.51	1.32
301.53	1.32
301.55	1.44
301.57	1.48
301.59	1.51
301.61	1.29
301.63	1.63
301.65	2.22
301.67	3.33
301.69	3.79
301.71	4.69
301.73	5.71
301.75	5.49
301.77	5.66
301.79	7.63
301.81	8.09
301.83	9.30
301.85	8.71
301.87	8.88
301.89	9.32
301.91	9.37
301.93	10.13
301.95	10.30
301.97	10.21
301.99	9.51
302.01	9.33
302.03	9.15
302.05	9.01
302.07	8.57
302.09	8.36
302.11	7.25
302.13	8.40
302.15	7.80
302.17	7.26
302.19	6.96
302.21	6.93
302.23	6.80

λ (nm)	$\sigma(10^{-23} \text{ m}^2)$
302.25	7.35
302.27	6.73
302.29	6.36
302.31	5.38
302.33	5.00
302.35	4.97
302.37	5.41
302.39	3.43
302.41	3.76
302.43	3.43
302.45	3.02
302.47	3.97
302.49	3.41
302.51	2.79
302.53	1.86
302.55	3.13
302.57	2.18
302.59	1.89
302.61	2.44
302.63	1.52
302.65	2.06
302.67	2.05
302.69	1.57
302.71	2.34
302.73	2.30
302.75	1.58
302.77	1.95
302.79	1.81
302.81	1.27
302.83	1.60
302.85	1.54
302.87	1.35
302.89	1.32
302.91	1.43
302.93	1.23
302.95	1.52
302.97	1.18
302.99	1.15
303.01	1.38
303.03	1.50
303.05	1.66
303.07	1.27
303.09	1.43
303.11	1.34
303.13	1.48
303.15	1.73
303.17	1.20
303.19	1.14
303.21	1.32
303.23	1.62

λ (nm)	$\sigma (10^{-23} \text{ m}^2)$
303.25	1.03
303.27	1.01
303.29	1.30
303.31	1.15
303.33	0.92
303.35	1.26
303.37	1.17
303.39	1.35
303.41	1.30
303.43	1.14
303.45	1.04
303.47	1.55
303.49	1.22
303.51	0.99
303.53	0.85
303.55	1.15
303.57	1.44
303.59	1.78
303.61	1.57
303.63	1.66
303.65	2.00
303.67	2.17
303.69	2.51
303.71	3.51
303.73	3.58
303.75	3.62

APPENDIX C

LOGS Data Acquisition Program

```

    savefile=FALSE;
    break;
case 3:
    got_file=FALSE;
    ch=3;
    while (!got_file && ch != ESC)
        getfile(funid);
    if (ch == ESC)
    {
        _setvideomode(_DEFAULTMODE);
        goto ppp; /* exit(0); */
    }
    page_length=pagelen();
    voltrng();
    display_chart(w_trigger,page_length,number_of_channel,funid,
                 start_wave, end_wave, a_point);
    _settextposition(2,5);
    _outtext("Display : ");
    _outtext(line);
    _settextposition(1,70);
    _outtext("Page:");
    _settextposition(2,40);
    _outtext("Sample Started at = ");
    _outtext(date_buffer);
    _outtext(" ");
    _outtext(time_buffer);
    _settextcolor(15);
    file_length=filelength(fileno(dfptr));
    no_of_sample=(file_length-67)/(5*number_of_channel+2);
    if (floor((double)(no_of_sample-1)/(double)(page_length-1)) ==
        (double)(no_of_sample-1)/(double)(page_length-1))
        no_page=(double)(no_of_sample-1)/(double)(page_length-1);
    else
        no_page=floor((double)(no_of_sample-1)/(double)(page_length-1))+
            (double)1;
    if (no_page == (double) 1)
    {
        last_page=TRUE;
        first_page=TRUE;
    }
    else
    {
        last_page=FALSE;
        first_page=TRUE;
    }
    last_offset=((int)no_page-1)*(page_length-1)*(number_of_channel*5+2)+65;
    /* 65=35+30 */
    show_a_page();
    for(;;)
    {
        p=itoa(page_no, buffer, radix);
        _settextposition(1,76);
        _outtext(" ");
        _settextposition(1,76);
        _outtext(p);
        while(!kbhit());
        getkey(&ch); /* get key in keyboard buffer */
        _settextposition(25,55);
        _outtext(" ");
        switch(ch)
        {
            case pgupkey : /* Pageup display previous page */

```

```

if (first_page)
{
    BEEP;
    _settextposition(25,55);
    _outtext("First Page !!");
    break;
}
else
{
    page_offset=(page_no-2)*(page_length-1)*(number_of_channel*
        5+2)+65;
    j=fseek(dfptr,page_offset,SEEK_SET);
    if (j)
        printf("Fseek Failed");
    page_no--;
    if (page_no == 1)
        first_page=TRUE;
    last_page=FALSE;
    show_a_page();
    break;
}
case pgdnkey : /* Pagedown display next page */
if (last_page)
{
    BEEP;
    _settextposition(25,55);
    _outtext("Last Page !!");
    break;
}
else
{
    page_no++;
    if (page_no == (int)no_page)
        last_page=TRUE;
    first_page=FALSE;
    show_a_page();
    break;
}
case homekey : /* Home display the first page */
if (first_page)
{
    BEEP;
    _settextposition(25,55);
    _outtext("First Page !!");
    break;
}
else
{
    j=fseek(dfptr,65L,SEEK_SET);
    if (j)
        printf("Fseek Failed");
    page_no=1;
    first_page=TRUE;
    if (no_page == 1L)
        last_page=TRUE;
    else
        last_page=FALSE;
    show_a_page();
    break;
}
case endkey : /* Pageup display the last page */
if (last_page)

```

```

        {
            BEEP;
            _settextposition(25,55);
            _outtext("Last Page !!");
            break;
        }
        else
        {
            j=fseek(dfptr,last_offset,SEEK_SET);
            if (j)
                printf("Fseek Failed");
            page_no=no_page;
            last_page=TRUE;
            if (page_no != 1)
                first_page=FALSE;
            show_a_page();
            break;
        }
        case esckey : /* Exit */
            _setvideomode(_DEFAULTMODE);
            goto ppp; /* exit(0); */
        default :
            break;
    }
}
_settextposition(25,55);
_outtext("Done! Any key = Exit");
BEEP;
while(!kbhit());
ch=getch();
_setvideomode(_DEFAULTMODE);
goto ppp; /* exit(0); */
case 4:
    got_file=FALSE;
    ch=3;
    while (!got_file && ch != ESC)
        getfile(funid);
    if (ch == ESC)
    {
        _setvideomode(_DEFAULTMODE);
        goto ppp; /* exit(0); */
    }
    file_length=filelength(fileno(dfptr));
    no_of_sample=(file_length-67)/(5*number_of_channel+2);
    _setvideomode(_DEFAULTMODE);
    printf("File:%s on %s %s", line, date_buffer, time_buffer);
    printf("Scan %d channel(s), %d waited trigger/sample, %ld samples\n",
        number_of_channel, w_trigger, no_of_sample);
    printf("Scanning: %9fA -- %9fA %9fA/Sample\n",start_wave, end_wave,
a_point);
    start_sample_no=0L;
    end_sample_no=-1L;
    while ((start_sample_no < 1L) || (start_sample_no > no_of_sample) ||
        (end_sample_no < 1L) || (end_sample_no > no_of_sample) ||
        (start_sample_no > end_sample_no))
    {
        BEEP;
        printf("Start sample no.= ");
        scanf("%ld",&start_sample_no);
        printf("End sample no.= ");
        scanf("%ld",&end_sample_no);
    }
}

```



```

printf("Printing ...");
fprintf(stdprn,"File:%s On %s %s\n", line, date_buffer, time_buffer);
fprintf(stdprn,"Scan %d channel(s), %d waited trigger/sample, %ld
samples\n",
        number_of_channel, w_trigger, no_of_sample);
fprintf(stdprn,"Scanning: %9fA -- %9fA %9fA/Sample\n",start_wave,
end_wave,
        a_point);
fprintf(stdprn,"Print from %ld to %ld\n",start_sample_no,end_sample_no);
print_offset=(start_sample_no-1L)*(number_of_channel*5+2)+65;
j=fseek(dfptr,print_offset,SEEK_SET);
if (j)
    printf("Fseek Failed");
for (l=start_sample_no; l <= end_sample_no; l++)
{
    for (i=0; i < number_of_channel; i++)
    {
        fscanf(dfptr,"%d",&analog_array[i]);
        fprintf(stdprn,"%4d ",analog_array[i]);
    }
    fprintf(stdprn,"\n");
}
flushall();
printf("Done! Any key = Exit");
BEEP;
while(!kbhit());
ch=getch();
_setvideomode(_DEFAULTMODE);
goto ppp; /* exit(0); */
/* case 5: */
case 5:
    _setvideomode(_DEFAULTMODE);
    exit(0);
default:
    break;
}
/* User input measurement parameters */
printf("\n\tEnter No. of scanning channel (Max.= 8 channels) = ");
scanf("%d",&number_of_channel);
l_channel=number_of_channel-1; /* Last channel no. */
printf("\n\tEnter No. of trigger(s) for each sampling (Min.= 1 trigger) = ");
scanf("%d",&w_trigger);
voltrng();
printf("\tDisable Dye Laser (Y/N)?");
ch=getche();
ch=toupper(ch);
if (ch == 'Y'){
    printf("\n\tEnter Scanning order (3rd .. 6th) = ");
    scanf("%d", &scan_order);
    cur_pos=read_cur_pos(scan_order);
    printf("\n\tEnter fixed scanning wavelength (in xxxx.xxx A) = ");
    scanf("%f", &start_wave);
    end_wave=start_wave;
    printf("\tEnter No. of samples (0 = unlimited) = ");
    scanf("%d",&n_samples);
    page_length=pagelen();
    if (n_samples == 0)
        n_samples=unlimited;
    else {
        if (floor((double)n_samples/(double)(page_length-1)) ==
            ((double)n_samples/(double)(page_length-1)))
            no_page=(double)n_samples/(double)(page_length-1);

```

```

        else
            no_page=floor((double)n_samples/(double)(page_length-1))+(double)1;
            printf("\nThe whole scan will takes %.0f page(s)",no_page); */
    }
}
else {
    start_wave=0;
    end_wave=start_wave;
    printf("\n\tEnter Scanning order (3rd .. 6th) = ");
    scanf("%d", &scan_order);
    printf("\tEnter Steps/point = ");
    scanf("%u",&steps_point);
    a_point=first_order/scan_order*steps_point;
    while (start_wave == end_wave) {
        BEEP;
        printf("\tEnter Starting wave length (in xxxx.x A) = ");
        scanf("%f", &start_wave);
        printf("\tEnter Ending wave length (in xxxx.x A) = ");
        scanf("%f", &end_wave);
    }
    n_samples=(int)((long int)(fabs(end_wave - start_wave)*1000.0+.5)/
        1000.0/a_point*10.0+.5)/10.0+1;
    cur_pos=read_cur_pos(scan_order);
    page_length=pagelen();
}
printf("\nPress ESC key to quit or ANY other key to continue...");
ch=getch();
if (ch == ESC) goto ppp; /* exit(0); */
/* move the Dye Laser to start_wave */
isitbusy();
no_steps=(unsigned int)((long int)(fabs(start_wave - cur_pos)*1000.0+.5)/
    1000.0/first_order*scan_order+.5);
move_start=TRUE;
moveit(no_steps);
monodial=start_wave*scan_order;
cur_pos=start_wave;
/* Save measurement parameters into file */
if (savefile)
    fprintf(dfptr, "%d %5d %5d %9.3f %9.3f %9.3f %2.0f\n",number_of_channel,
        w_trigger, n_samples, start_wave, end_wave, a_point,
        clock_frequency);

/* display chart recorder */
display_chart(w_trigger,page_length,number_of_channel,funid,start_wave,
    end_wave, a_point);

/* seed for random number generator */
time(&long_time);
newtime=localtime(&long_time);
srand(newtime->tm_sec);

initialize(); /* Initialize the PCLAB subroutines */
error = setup_adc(timing_source, s_channel,l_channel, gain);
error = set_clock_frequency(&clock_frequency);
ch=3;
flushall();
_strdate(date_buffer);
_strtime(time_buffer);
/* disable system clock(); */
_settextposition(2,5);
if (savefile)
{

```

```

    fprintf(dfptr,"%s %s\n",date_buffer,time_buffer);
    _outtext("Data saved as ");
    _outtext(line);
}
else
    _outtext("Data not saved");
    _settextposition(1,70);
    _outtext("Page:");
    _settextposition(2,40);
    _outtext("Sample Started at = ");
    _outtext(date_buffer);
    _outtext(" ");
    _outtext(time_buffer);
    _settextcolor(15);
    p=itoa(page_no, buffer, radix);
    _settextposition(1,76);
    _outtext(p);
/* hold_reset(); */
for(;;)
{
    for (i = 1; i <= w_trigger-1; i++)
    {
        adc_on_trigger(s_channel, gain, &adv);
        voltage=(float)adv*20/4096-10;
/*         printf("adv=%d   %.3f\n",adv,voltage);
*/
    }
    hold_reset();
    isitbusy();
    error = adc_series(number_of_channel,analog_array);
/*     rand_no(highest,lowest,number_of_channel,analog_array); */
    show_value(ptrcount,page_length,number_of_channel,analog_array,vmax,vmin);
    if (savefile)
    {
        for (k=0; k < number_of_channel; k++)
            fprintf(dfptr,"%4d ",analog_array[k]);
        fprintf(dfptr,"\n");
    }
    if (n_samples != unlimited)
    {
        count++; /* increase the sampling counter */
        if (count > n_samples) break;
    }
/* move to next position */
    if(start_wave != end_wave){
        move_start=FALSE;
        moveit(steps_point);
    }
    ptrcount++;
    if (ptrcount > page_length) /*Re-initialize the display counter, xlabels */
    {
        if (start_wave != end_wave) {
/*             _clearscreen(_GVIEWPORT); */
            _setcolor(15);
            for (xtick=1; xtick<=7;xtick++){
                xlabel=start_wave+a_point*(float)(page_length-1)*page_no+
                    a_point*(float)(page_length-1)/6*(xtick-1);
                p=fcvt(xlabel, 1, &decimal, &sign);
                strcpy(q,"");
                strncat(q,p,decimal);
                strcat(q,".");
                strcat(q,&p[decimal]);

```

```

        _settextposition(24,xposd[xtick-1]);
        _outtext(q);
    }
    _setcolor(13);
}
ptrcount=1;
show_value(ptrcount,page_length,number_of_channel,analog_array,vmax,vmin);
ptrcount=2;
page_no++;
p=itoa(page_no, buffer, radix);
_settextposition(1,76);
_outtext(p);
}
if (lookkey())
{
    getkey(&ch);    /* get key in keyboard buffer */
    switch(ch)
    {
        /* refresh the screen disabled */
/* case f1key :
        _clearscreen(_GVIEWPORT);
        _setcolor(15);
        moveto(39,-175);
        _lineto(639,-175);
        ptrcount = 1;
        page_no++;
        p=itoa(page_no, buffer, radix);
        _settextposition(1,76);
        _outtext(p);
        BEEP;
        break;
*/
        case f5key :
            _settextposition(25,55);
            _outtext("Hold! Any key = Resume");
            while(!kbhit());
            ch=getch();
            _settextposition(25,55);
            _outtext("                ");
            break;
        case esckey :
            terminate();
            write_monodial();
/* enable_system_clock(); */
            if (savefile)
                fclose(dfptr);
            _setvideomode(_DEFAULTMODE);
            goto ppp; /* exit(0); */
        default:
            break;
    }
}
}
if (savefile)
    fclose(dfptr);
/* enable_system_clock(); */
terminate();
write_monodial();
_settextposition(25,55);
_outtext("Done! Any key = Exit");
BEEP;
while(!kbhit());
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```

```

    ch=getch();
    _setvideomode( DEFAULTMODE);
    goto ppp; /* exit(0); */
}

hold_reset()
{
    unsigned int digital_value, k;

    enable_for_output(port_select);
/* Send sample HOLD signal Bit 0 & 1 in port 1 */
    digital_value=low0;
    output_digital_value(port_select, mask0, digital_value);
    digital_value=high0;
    output_digital_value(port_select, mask0, digital_value);
    for (k=1;k <= delay;k++);
    digital_value=low0;
    output_digital_value(port_select, mask0, digital_value);

/* Send sample RESET signal Bit 1 & 2 in port 1 */
    digital_value=high1;
    output_digital_value(port_select, mask1, digital_value);
    digital_value=low1;
    output_digital_value(port_select, mask1, digital_value);
    for (k=1;k <= delay;k++);
    digital_value=high1;
    output_digital_value(port_select, mask1, digital_value);
}

void voltrng()
{
    int got_vrng;
    got_vrng=FALSE;
    while(!got_vrng){
        printf("\n\tEnter Max. Voltage (-10 .. +10 volts) = ");
        scanf("%d",&vmax);
        printf("\tEnter Min. Voltage (-10 .. +10 volts) = ");
        scanf("%d",&vmin);
        if ((abs(vmax) <=10) && (abs(vmin) <=10) && (vmax != vmin))
            got_vrng=TRUE;
        else BEEP;
    }
    vmax=(vmax+10)*204.8;
    vmin=(vmin+10)*204.8;
}

void isitbusy()
{
    unsigned int digital_value;
    enable_for_input(port_select);
    for(;;) {
        input_digital_value(port_select, mask_busy, &digital_value);
        if(digital_value == 0x0000)
            break;
    }
}

/* Move the dye laser accordingly */
void moveit(unsigned int no_steps)
{
    unsigned int i, k, turn, reminder, digital_value1, digital_value0;
    int direction;
    turn=no_steps/255;
    reminder=no_steps % 255;
    if(move_start){
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```

```

    if (start_wave > cur_pos) {
        digital_value1=increase+255;
        digital_value0=increase+remainder;
        direction=1;
    }
    else if (start_wave < cur_pos) {
        digital_value1=decrease+255;
        digital_value0=decrease+remainder;
        direction=-1;
    }
}
else {
    if (start_wave < end_wave) {
        digital_value1=increase+255;
        digital_value0=increase+remainder;
        direction=1;
    }
    else if (start_wave > end_wave) {
        digital_value1=decrease+255;
        digital_value0=decrease+remainder;
        direction=-1;
    }
}
for(i=1; i<=turn; i++){
    enable_for_output(port_select);
    output_digital_value(port_select, mask_move, digital_value1);
    output_digital_value(port_select, mask_ndr, ndr_low);
    output_digital_value(port_select, mask_ndr, ndr_high);
    monodial=(long int)(monodial*1000.0+.5)/1000.0+first_order*255*direction;
    isitbusy();
}
enable_for_output(port_select);
output_digital_value(port_select, mask_move, digital_value0);
output_digital_value(port_select, mask_ndr, ndr_low);
output_digital_value(port_select, mask_ndr, ndr_high);
monodial=(long int)(monodial*1000.0+.5)/1000.0+first_order*remainder*
    direction;
}
/* Enter Data Filename */
getfile(int funid)
{
    int i;
    float clock_hz;

    flushall(); /* Clear keyboard input */
    i=0;
    printf("\n\tEnter Data Filename (EX:C:\\DT\\TEST.DAT): ");
    ch = getche();
    while( (ch != EOF) && (ch != LF) && (ch != CR) && (i < 81) )
    {
        if( ch == ESC ) return ch; /* Exit on ESC key */
        else if( ch == BS )
        {
            /* Back space on the back space key */
            if( i > 0 )
            {
                i--;
                printf(" \010");
            }
            else
                printf(" ");
        }
        else
        {
            /* Save the character in the line buffer */

```

```

        line[i++] = ( char )ch;
    }
    ch = getche();
}
line[i] = 0;
dfp_ptr = fopen( &line[0], "r");
switch(funid)
{
case 1:
    fclose(dfp_ptr);
    if(dfp_ptr != NULL)
    {
        BEEP;
        printf("\n\tFile existed !! Overwrite? (Y/N): ");
        fflush(); /* Clear keyboard input */
        ch = getch(); /* Allow the user to continue or not. */
        while( (ch != 'Y') && (ch != 'y') && (ch != 'N') && (ch != 'n'))
        { /* Screen out invalid keys, check for ESC.*/
            if( ch == ESC ) break;
            BEEP;
            ch = getch();
        }
        /*
        If the user does not want to continue, then go back and get
        another file name.
        */
        if( (ch == 'N') || (ch == 'n') ) got_file = FALSE;
        else got_file = TRUE;
    }
    else got_file = TRUE;
    if( got_file )
    {
        dfp_ptr = fopen(&line[0], "w");
        if( dfp_ptr == NULL )
        {
            BEEP;
            printf("\n\tINVALID FILE NAME");
            got_file = FALSE;
        }
    }
    if( !got_file ) printf("\n\tTRY AGAIN!");
    break;
case 3:
case 4:
    if(dfp_ptr == NULL)
    {
        printf("\n\tFile NOT found. TRY AGAIN!");
        got_file=FALSE;
        break;
    }
    else
    {
        fscanf(dfp_ptr,"%d %d %d %9f %9f %9f %2f", &number_of_channel, &w_trigger,
            &n_samples, &start_wave, &end_wave, &a_point, &clock_hz);
        fscanf(dfp_ptr,"%s %s", date_buffer, time_buffer);
        if (clock_hz != clock_frequency)
        {
            printf("\n\tINVALID Data File. TRY AGAIN!");
            got_file=FALSE;
            fclose(dfp_ptr);
            break;
        }
    }
}

```

```

        else
        {
            got_file=TRUE;
            break;
        }
    }
default:
    printf("\n\t Something wrong !!");
    break;
}

}

unsigned int lookkey(void)
{
    return _bios_keybrd(_KEYBRD_READY);
}

char getkey(int *k)
{
    char c;
    while(1) {
        *k = _bios_keybrd(_KEYBRD_READ);    /* use QuickC function */
        if ((c=lo(*k)) == 3) {                /* check for Ctrl-c */
            printf("Abort program (Y/N) ?");
            *k = _bios_keybrd(_KEYBRD_READ);    /* check response */
            if ((*k == 0x1559) || (*k == 0x1579))
            {
                _setvideomode(_DEFAULTMODE);
                exit(0);                        /* terminate */
            }
        } else break;
    }
    return c;
}

/* User select display page length */
int pagelen()
{
    int ch, page_length;
    page_length=0;
    ch=3;
    printf("\n\tPage Scale (S=120, M=300, L=600)= ");
    ch=getche();
    ch=toupper(ch);
    while (ch != 'S' && ch != 'M' && ch != 'L')
    {
        printf("\n\tTry again!");
        printf("\n\tPage Scale (S=120, M=300, L=600)= ");
        ch=getche();
        ch=toupper(ch);
    }
    switch(ch)
    {
        case 'S':    /* Small Sacle */
            page_length=121;
            break;
        case 'M':    /* Medium Sacle */
            page_length=301;
            break;
        case 'L':    /* Large Sacle */
            page_length=601;
    }
}
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```



```

        break;
    default:
        break;
    }
    return page_length;
}
show_a_page()
{
    int i;
    if (start_wave != end_wave) {
/*      _clearscreen(_GVIEWPORT);  */
        _setcolor(15);
        for (xtick=1; xtick<=7;xtick++){
            xlabel=start_wave+a_point*(float)(page_length-1)*(page_no-1)+
                a_point*(float)(page_length-1)/6*(xtick-1);
            p=fcvt(xlabel, 1, &decimal, &sign);
            strcpy(q, "");
            strncat(q, p, decimal);
            strcat(q, ".");
            strcat(q, &p[decimal]);
            _settextposition(24, xposd[xtick-1]);
            _outtext(q);
        }
        _setcolor(13);
    }
    if (last_page)
    {
        ptrcount=1;
        while(!feof(dfptr))
        {
            for (i=0; i < number_of_channel; i++)
                fscanf(dfptr, "%d", &analog_array[i]);
            show_value(ptrcount, page_length, number_of_channel, analog_array,
                vmax, vmin);
            ptrcount++;
        }
    }
    else
        for (ptrcount=1; ptrcount < page_length; ptrcount++)
        {
            for (i=0; i < number_of_channel; i++)
                fscanf(dfptr, "%d", &analog_array[i]);
            show_value(ptrcount, page_length, number_of_channel, analog_array,
                vmax, vmin);
        }
}
float read_cur_pos(int scan_order)
{
    pfptr=fopen("monodial.dat", "r");
    if (pfptr == NULL){
        printf("\tEnter Monochromator dial's reading (in xxxxx.xx) = ");
        scanf("%9f", &monodial);
        cur_pos=monodial/scale_order;
        pfptr=fopen("monodial.dat", "w");
        fprintf(pfptr, "%9.2f", monodial);
    }
    else {
        fscanf(pfptr, "%9f", &monodial);
        printf("\tCurrent Monochromator dial's reading = %.2f Change it (Y/N)?",
            monodial);
        ch=getche();
        ch=toupper(ch);
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    }
}

```

```

    if (ch == 'Y'){
        fclose(pfp_ptr);
        printf("\n\tInitial position = ");
        scanf("%9f",&monodial);
        pfp_ptr=fopen("monodial.dat", "w");
        fprintf(pfp_ptr, "%9.2f", monodial);
    }
}
fclose(pfp_ptr);
cur_pos=(long int) (monodial*1000.0+.5)/1000.0/scan_order;
return cur_pos;
}
write_monodial()
{
    pfp_ptr=fopen("monodial.dat", "w");
    fprintf(pfp_ptr, "%9.2f", monodial);
    fclose(pfp_ptr);
}

```

```

/* DYESCAN.H -- include file for DYESCAN.C */
#include <stdio.h>      /* Include Microsoft Standard I/O file */
#include <stdlib.h>     /* Include Microsoft Standard Library file */
#include <string.h>     /* Include Microsoft String Manipulation file */
#include <time.h>       /* Include Microsoft Time routines */
#include <ctype.h>      /* Include Microsoft character conversion routines */
#include <graph.h>     /* Include Microsoft Graphic routines */
#include <bios.h>      /* Include Microsoft BIOS routines */
#include <io.h>        /* Include Microsoft L-level File Handle & I/O routines */
#include <math.h>      /* Include Microsoft Math Library */
#include <pclerrs.h>   /* Include PCLAB error codes for Microsoft C */
#include <pcldefs.h>  /* Include PCLAB function declarations for Microsoft C */

#define TRUE (~0)
#define FALSE 0
#define NUMBER_OF_CONVERSIONS 2
#define MAX_NO_OF_CHANNEL 8      /* Maximum Number Of scanning Channels */
#define unlimited 3
#define lo(f) ((f) & 0xff)
#define hi(f) (lo(f) >> 8)
/* function keys */
#define f1key      0x3b00
#define f2key      0x3c00
#define f3key      0x3d00
#define f4key      0x3e00
#define f5key      0x3f00
#define f6key      0x4000
#define f7key      0x4100
#define f8key      0x4200
#define f9key      0x4300
#define f10key     0x4400
#define esckey     0x011b
/* cursor positioning keys */
#define upkey      0x4800
#define downkey    0x5000
#define leftkey    0x4b00
#define rightkey   0x4d00
#define pgupkey    0x4900
#define pgdnkey    0x5100
#define homekey    0x4700
#define endkey     0x4f00
#define LF         '\012'
#define CR         '\015'
#define ESC        '\033'
#define BS         '\010'
#define BEEP       printf("\007")
#define port_select -1 /* DT-707 output port seletion: Port 0 & 1 selected */
#define mask0 0x0100 /* 01*/
#define high0 0x0300 /* 11*/
#define low0 0x0200 /* 10*/
#define mask1 0x0200 /* 10*/
#define high1 0x0200 /* 10*/
#define low1 0x0000 /* 00*/
#define mask_busy 0x0800
#define mask_move 0xf0ff
#define mask_ndr 0x1000 /* New Data Ready mask */
#define increase 0x3f00
#define decrease 0x1f00
#define ndr_low 0x0000 /* for sending a pulse to */
#define ndr_high 0x1000 /* new data ready line */
/* #define delay 10 */
#define highest 4096 /* DT-2805 highest digital count */

```

```

#define lowest 0          /* DT-2805 lowest digital count */
#define radix 10
#define first_order 0.12

extern display_chart(int w_trigger, int page_length, int no_of_ch, int funid,
                    float start_wave, float end_wave, float a_point);
extern rand_no(int maxno, int minno, int no_of_ch, short *array);
extern show_value(int count, int page_length, int no_of_ch, short *array,
                 int vmax, int vmin);

static unsigned int lookkey(void);
static char getkey(int *k);
static float read_cur_pos(int scan_order);
static void isitbusy(void);
static void moveit(unsigned int no_steps);
static void voltrng(void);

FILE *dfptr, *pfptr;
short analog_array[MAX_NO_OF_CHANNEL];
unsigned int digital_value, no_steps, steps_point;
int ch, got_file, move_start;
unsigned int delay;
int number_of_channel, w_trigger, n_samples, int_n_samples, count, ptrcount;
int page_length, page_no, scan_order, xtick, decimal, sign;
int last_page, first_page; /* last page, first page flags */
int xposd[7]={3, 16, 28, 41, 53, 66, 75};
int vmax, vmin;           /* Display scaling */
/* no of sample in a file=(file length-37)/(5*number_of_channel+2) */
long file_length, no_of_sample;
double no_page;
char line[81], buffer[10], *p;
char date_buffer[9], time_buffer[9], q[80];
float clock_frequency, start_wave, end_wave, a_point, cur_pos, monodial;
float xlabel;

```