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DIAGNOSTIC INSTRUMENTATION AND ANALYSIS LABORATORY

DIAGNOSTIC DEVELOPMENT AND SUPPORT OF MHD TEST FACILITIES

Technical Progress Report
for the period
July, August, September 1989

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

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DIAGNOSTIC DEVELOPMENT AND SUPPORT OF MHD TEST FACILITIES

Technical Progress Report
for the period
July, August, September 1989

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ABSTRACT

The Diagnostic Instrumentation and Analysis Laboratory (DIAL) at Mississippi State University (MSU) is developing diagnostic instruments for MHD power train data acquisition and for support of MHD component development test facilities. Microprocessor-controlled optical instruments, initially developed for HRSR support, are being refined, and new systems to measure temperatures and gas-seed-slag stream characteristics are being developed. To further data acquisition and analysis capabilities, the diagnostic systems are being interfaced with DIAL's computers. Technical support for the diagnostic needs of the national MHD research effort is being provided. DIAL personnel will also cooperate with government agencies and private industries to improve the transformation of research and development results into processes, products and services applicable to their needs.

STATEMENT OF WORK

Objective

Knowledge of many properties of the MHD operating system is required to find solutions to technological barriers. It is desirable to measure gas temperature, wall temperature, gas velocity, particle size, plasma conductivity, gas composition and other engineering parameters. Conventional instrumentation is of limited use in characterizing these properties, so new instrumentation is required. DIAL is developing intrusive and non-intrusive diagnostic instrumentation to characterize the MHD gas stream and provide direct instrumentation support to the various DOE MHD test facilities.

A number of the diagnostic systems already developed will be used for field measurements at the HRSR and MHD power train facilities. The amount of direct diagnostic support of the MHD engineering development test facilities will be as directed by the Department of Energy. Additional diagnostic systems will be developed to provide field-use instruments. Field tests for system refinements of these instrumentation systems will be conducted on the DIAL test stand and various DOE MHD test facilities.

A test stand has been constructed that can simulate the gas-slag-seed stream composition, temperature, and metal/fireside environmental conditions for the radiant furnace, superheater, and other MHD system components. The microprocessor-controlled diagnostic instruments developed by DIAL are being evaluated on the test stand. Measurements conducted on the test stand also provide useful data for the national MHD program.

Scope of Work

In order to meet the overall objective, the scope of work to be performed is outlined in the following tasks.

Task 1.0 Diagnostic Instrumentation Development

The following microprocessor-controlled diagnostic instrumentation will be developed for support of the MHD component engineering development. Field tests for system refinements will be conducted. Objectives for the specific instrumentation systems are:

A. Coherent Anti-Stokes Raman Spectroscopy System (CARS)
(measures local gas temperature and major species concentration)

A mobile CARS system will be constructed to allow point gas temperature measurements to be made at the MHD test facilities. By moving the focusing and collecting lenses in tandem a temperature profile can be obtained. A system with capabilities to measure a profile over some four feet will be designed, thus allowing profile measurements in the downstream test components at the Coal-Fired Flow Facility (CFFF). Such measurements will provide a useful characterization of the gas stream and important information for testing and further developing heat transfer computer models. The spatial and temporal variation of the gas temperature at the exit of the Component Development and Integration Facility (CDIF) channel will provide important information for MHD system scale-up.

B. Particle Size Distribution System (PSD)
(measures particle size distribution)

Efforts will be directed toward improving the present instrument with respect to performance and portability for field use. The emphasis on performance improvements will focus on expanding the range of particle velocities for which reliable measurements can be obtained. The improvement in portability will be achieved by developing or buying new hardware for the electronic system and computer and for the optical mounting system. Experimental measurements will be made on the DIAL test stand and at other MHD test sites. Efforts will be concentrated on development of a new ensemble averaging technique which can be used to make measurements of particle size distributions in high velocity flows (i.e., several hundred meters-per-second.) It is possible to use ensemble averaging of the photomultiplier signals without resolving them into pulses characterized by peak value, pulse width, etc. The measurement data is mathematically translated to a particle size distribution by a deconvolution procedure. Experiments will be conducted comparing the results from the ensemble averaging technique with those obtained with the present single-particle counter instrument. A practical instrument will be developed which can be taken to various MHD facilities for field measurements.

C. Potassium Emission/Absorption System (PE/AS)
(measures time-resolved temperature, K-atom density, and electron density)

The Potassium Emission/Absorption System has achieved the first stage of development as a time-resolved temperature measurement system and will shortly be available for field use. Efforts will be directed toward the next stage of development of the PE/AS for electron density measurements in or near the MHD channel. The method relies upon fitting the shape of the seed atom emission lines for a determination of neutral seed atom density. Knowledge of the seed atom density and the temperature allows for a statistical equilibrium calculation of the electron density. A laboratory burner capable of heavy seed loadings will be constructed and used for laboratory tests of the electron density measurements in conjunction with an independent method, such as microwave absorption, to verify the measurement method. Subsequently, the system will be field tested and made available as a channel diagnostic for support of the national MHD program. The PE/AS is a versatile spectroscopic instrument and other diagnostic techniques using the imaging abilities of the vidicon detector will be investigated.

D. Intrusive Multi-Probe System (IMPS)
(optical temperature probes)

Probe 1: Intrusive, Optical Fiber, Wide Range, Spatial Wall Temperature Probe.

Probe 2: Intrusive, Spatial, SLR, High Gas Temperature Probe.

The first year's efforts will be directed toward developing new concepts and techniques of using wide range, temperature sensitive, optical fiber probes to intrusively measure spatial temperatures of MHD interior walls and components. Also, effort will be directed toward investigating various optical techniques of resolving the signal from the miniature optics required for an intrusive spatial SLR gas temperature probe.

The second year's effort will be directed toward laboratory testing and field use evaluation of the intrusive, spatial, temperature measuring concepts and techniques developed during the first year.

E. Faraday Rotation System (FRS)
(measures electron density)

A Faraday Rotation System will be developed as an alternate method for measurement of electron density in an MHD channel. The measurement relies upon the rotation of polarization of light as it traverses a magnetic field. Optical access will be required through the MHD channel. Faraday rotation using far-infrared radiation and far-infrared interferometry are the primary methods for electron density measurements of combustion MHD plasmas. Faraday rotation has been suggested as best suited for in-situ measurements on the longer path lengths of all but the small research MHD channels.

Development of a Faraday rotation system will first entail choice of design criteria followed by selection of components and system assembly. The system will require custom design and construction for efficient transfer optics. The system will also require thorough testing on small scale systems and comparison measurements will need to be made. Longer wavelength laser lines will be used for measurements on small scale systems. After development only minor changes, if any, will be necessary for operation on the relatively shorter wavelength laser lines needed for larger scale systems. The system components have been chosen for "flat" performance throughout the far-infrared wavelengths.

F. Multi-Purpose Imaging System (MPIS)
(measures K-atom density and pressure profile)

Recently, a number of imaging methods have been developed which are directly applicable to the turbulent flows present in the MHD power plant. Techniques such as Rayleigh-Mie imaging, laser-induced fluorescence, and pressure gradient mapping yield essentially instantaneous two-dimensional profiles of number density, species concentration, and pressure, respectively. This information, either processed alone or in combination, can describe in some detail the inherent gas characteristics. An instrument will be developed which will permit the rapid determination of atom number density and either pressure or species concentration in the topping cycle region. The optical configuration of the instrument is novel and the desired profile is selected by alternately processing either the Rayleigh-Mie wavelength (532 nm) or a wavelength specific to the gas species electronic transition, or the 405 nm line of K for the determination of pressure by LIF. In this manner rapid profiles can be obtained and further processed to yield a wide variety of information. The particular emphasis will be the development of a K atom density and pressure profile instrument which will be a very useful channel diagnostic. Also consideration will be given to the possible application of this system for measurement of OH and measurement of the electron density profile.

Task 2.0. Test Stand Operations

The existing MHD/HRSR simulation test stand will be employed for support of diagnostic instrumentation development, shakedown, and evaluation. The test stand will be modified to simulate the MHD gas stream environment. This will further aid in the evaluation of the instruments before they are taken to the MHD engineering development test facilities. In particular, the test stand will be modified to burn a fuel oil/coal slurry which will more accurately simulate a coal fuel MHD combustor. Provisions for an increased flow rate of fuel-air mixture of approximately 40% will also be made.

The test stand control and data acquisition computer will be replaced with a new system that will enhance data collection and control as well as provide much needed memory and disc space.

Task 3.0. Technical Support for the National MHD Program

The Diagnostic Instrumentation and Analysis Laboratory will continue to provide field measurements at other national MHD facilities on an as-needed basis. The current mobile laboratory will be upgraded and an 18-wheeler type trailer will be equipped to operate as a field laboratory. As new diagnostic instruments are developed for the field they will be interfaced with the data acquisition system in the trailer.

The objective of this task is to provide diagnostic measurements and support to the national MHD program. Work will include attendance at quarterly meetings and review and input to technical reports.

The following systems are available for field measurements:

Sodium Line Reversal System (average gas temperature)

Multi-Color Pyrometer System (wall temperature and emissivity)

Two-Color Laser Transmissometer System (average particle size and particle number density)

Laser Doppler Velocimeter System (local velocity, velocity profile and turbulence level)

Gas Analysis System (gas composition, e.g., CO, CO_2, NO, etc.).

The following systems will be modified/constructed for field use and will be employed for field tests:

Coherent Anti-Stokes Raman Spectroscopy System (local gas temperature, temperature profile)

Particle Size Distribution System (particle size distribution)

Potassium Emission/Absorption System (time-resolved temperature, K-atom density, electron density)

Intrusive Multi-Probe System (optical temperature probes - wall and gas temperature)

Faraday Rotation System (electron density)

Multi-Purpose Imaging System (K-atom density, pressure profile).

DIAL has already started evaluation of the required instrumentation to control a complete MHD system. As part of the support of the national MHD program, this effort will be expanded to include an evaluation of dynamic characteristics of the complete MHD system when the bottoming cycle is integrated with the topping cycle. Instrumentation will be selected to control the MHD system.

Task 4.0. Project Management

The objective of this task is to provide the required management for accomplishment of the Statement of Work with the proposed resources management reporting as required by DOE Order 1332.1A and Contract Reporting Requirements.

Task 5.0. Technology Transfer

Technology transfer is a congressionally mandated objective of the federal government. Various enactments of Congress have the purpose of significantly improving the transformation of research and development results into processes, products, and services that can be applied to state and local government and private sector needs. To ensure the maximum benefits of PETC's and subsequently DIAL's investment in research and development, DIAL's personnel will cooperate with regional industries to demonstrate the technology for intrusive and non-intrusive diagnostic instrumentation developed for the characterization of MHD systems. However important, this task shall in no way interfere with the mainstream efforts of the MHD program.

DESCRIPTION OF FACILITIES

The combustion test stand is a computer-controlled simulation test facility available for the combustion of fuel oil at up to 800 lbm/hour of fuel and air. The air can be preheated to temperatures up to 1100 K (1520°F) by electrical resistance heaters. Downstream of the combustor are refractory-lined sections containing access ports on both sides and the top of each section.

The DIAL test facility has a Hewlett-Packard measurement and control system (HP-1000 minicomputer-based system) with real-time software, graphics, and extensive input-output (I/O) capability. DIAL is acquiring a Digital Equipment Corporation VAX 11/780 super-minicomputer, and the staff also has access to the MSU's Univac 1100/80 computer. Computer modeling hardware consists of a graphics terminal and hard copy unit connected to MSU's mainframe Univac 1100/80 computer.

The microprocessor development laboratory has two Diversified Technology development systems for developing software and firmware for special purpose microcomputers to be used in controlling diagnostic instruments, signal processing and signal analysis.

Complete laser facilities are available, including YAG and dye lasers, spectrometers and photometers, fiber optics, and other equipment. Discharge lamps, power supplies, vacuum systems, UV optics, monochromators, detectors and processing electronics are also available. In addition, the laboratory has several benchtop laboratory burners controlled by precision gas handling systems.

The department of Electrical Engineering at MSU has the facilities and staff for the design, development and construction of hybrid integrated circuits and printed circuit boards.

The following support facilities are available in DIAL: (1) Electronics Shop, (2) Machine Shop, (3) Instrument Shop, and (4) Gas Sampling and Analysis System.

Minicomputer Operations

The DEC Vax-11/780 system will continue to be used as the primary computer for modeling and large scale data analysis. The spectrum modeling and fitting, program development, and data transfer for the CARS project require the largest portion of the computer time. Other instrument development and refinement projects require continued modeling support; these projects include the Two Color Laser Transmissometer (TCLT), Multi-Color Pyrometer (MCP), Potassium Emission/Absorption System (PE/AS), and Particle Size Distribution System (PSD). Computer resources will be required for data analysis of Laser Doppler Velocimeter (LDV) experiments and for general combustion/heat transfer modeling efforts.

technical progress

Task 1. Instrumentation Development: R. L. Cook

A. Coherent Anti-Stokes Raman Spectroscopy System (CARS)

J. P. Singh and F. Y. Yueh

Work Performed

During this reporting period the mobile CARS instrument was further tested in the laboratory. The wider spectral line base width problem addressed in the last quarterly report was found to be due to water condensation on the dual intensified diode array (DIDA) detector head. A high flow of dry nitrogen was circulated through the detector and spectrometer enclosure to remove water vapor from the detector head. Then the N_2 CARS furnace data were collected with the mobile CARS instrument by using both the collinear and USED CARS phasematching geometries. The CARS signal was piped through an optical fiber to the detection system. The data acquisition/analysis system was then tested by transferring the data in the data acquisition computer to the data analysis computer through the computer network. These preliminary test results were satisfactory.

The CARS alignment experiment was conducted at the CFFF during the LMF4-R test. The mobile CARS system was assembled in the mobile laboratory. The pump and Stokes laser beams were first aligned according to the collinear phasematching geometry and directed to the diffuser via a hole in the wall of the trailer. The path of the laser beam was manipulated with a series of 90-degree turning prisms. A low wave pass (LWP) dichroic mirror to eliminate any collinear CARS generated before the diffuser was used to turn the laser beams to a 100-centimeter focal length lens which caused them to be focused inside the diffuser. A 60-centimeter focal length lens on the receiver side was used to recollimate the laser beams. The CARS signal was then separated from high intensity laser beams through a stack of filters and coupled to the optical fiber with a 100-millimeter focal length lens and a coupler mounted on a computer controlled x-y translator. The CARS signal passed through the optical fiber to the spectrometer through a coupler designed for maximum transfer of the CARS signal to the spectrometer.

The room temperature N_2 CARS signal was used to test the alignment of the laser beams. It can be recorded on an optical spectrometric multichannel analyzer (OSMA) by attenuating 10^4 times. The N_2 CARS spectra were also recorded while the combustor preheated. A typical fit from those data is shown in Figure 1.A.1. The temperature extracted from the CARS data is slightly lower than expected because of the contribution from the cold N_2 CARS signal generated between the lens and hot gas stream. A strong background emission from the diffuser has been observed in the N_2 CARS spectral region when coal is burned. This emission was so strong that the CARS signal was totally masked by it. The spectral characteristics of this background are shown in Figure 1.A.2. This background problem was solved by gating the OSMA detector. A CARS spectrum recorded with the OSMA in the gated mode is shown in Figure 1.A.3. Although a strong CARS signal was recorded in the gated mode, the data was not analyzed due to its poor spatial resolution. These spectra were mainly dominated by the cold N_2 signal generated between the lens and the diffuser. In order to improve the spatial resolution, USED CARS phasematching geometry was then tested. This technique did not improve the spatial resolution as expected due to poor laser beam quality close to the port. To preserve the quality of the laser beam, separation between the port and transmitter has been reduced from 60 to 40 feet by exiting the laser beams through the back of the trailer. This beam path has improved the beam quality at the port and reduced the beam wandering due to the vibration from the facility structure. CARS data in this beam path was not recorded due to the damage of the optical fiber. Since the fiber needs to be sent to the manufacturer for repair, the completion of the CARS alignment experiment will be delayed. The CARS alignment experiment will be continued in field tests during the November run at CFFF.

The mobile CARS instrument was returned to MSU and reassembled inside the trailer. A series of tests to determine the best method for making CARS measurements in the CFFF diffuser was initiated. The planar BOXCARS phasematching geometry which can produce high spatial resolution was found to be suitable for N_2 CARS measurements in the field. Since CO_2 is also a major species inside the CFFF diffuser, it is possible to perform temperature

N_2 CARS spectrum at UTSI diffuser

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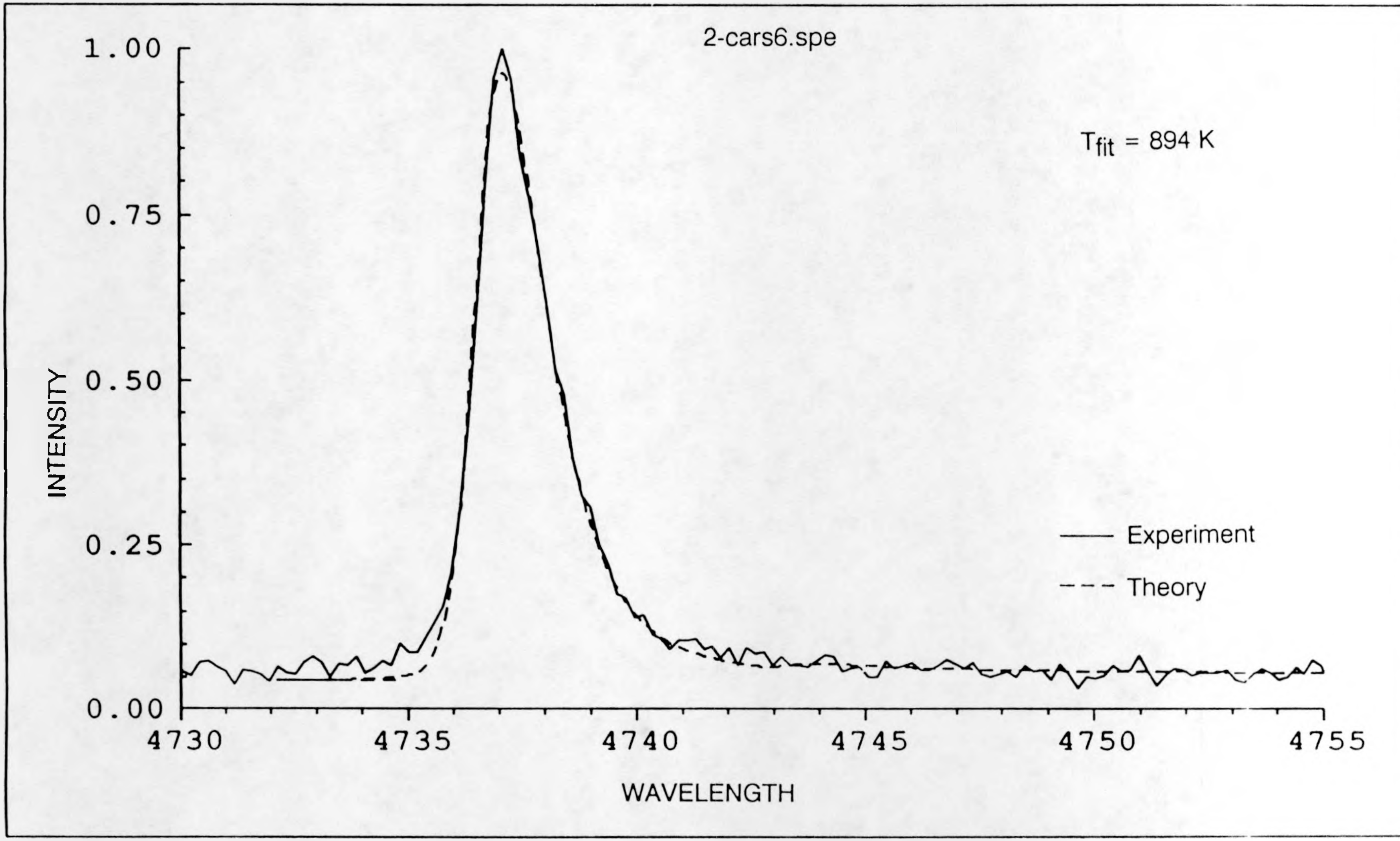

Figure 1.A.1. N_2 CARS spectrum recorded while the combustor preheated.

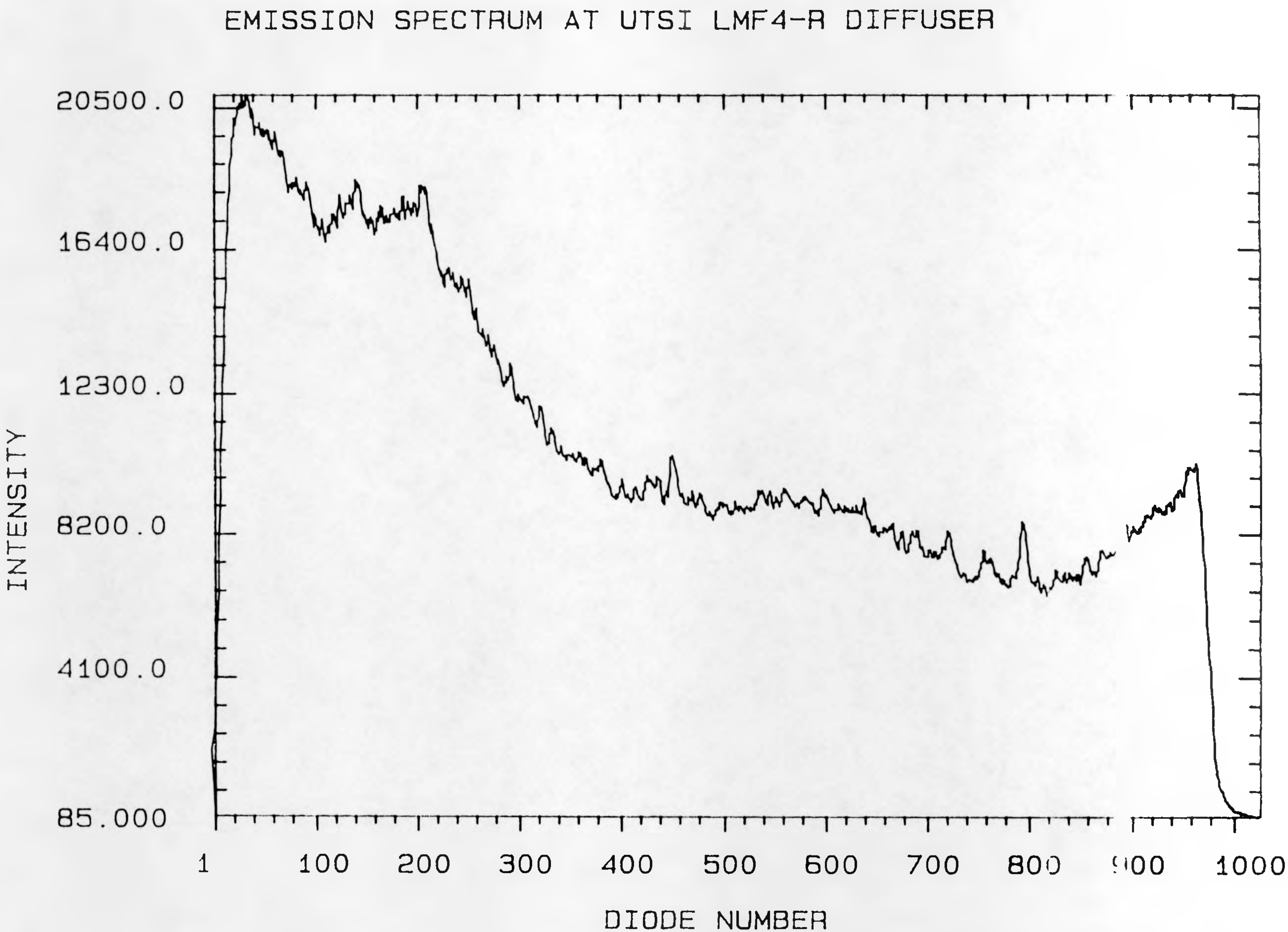

Figure 1.A.2. Emission spectrum of the diffuser from 4700 A to 4900 A with an attenuation of 400 times.

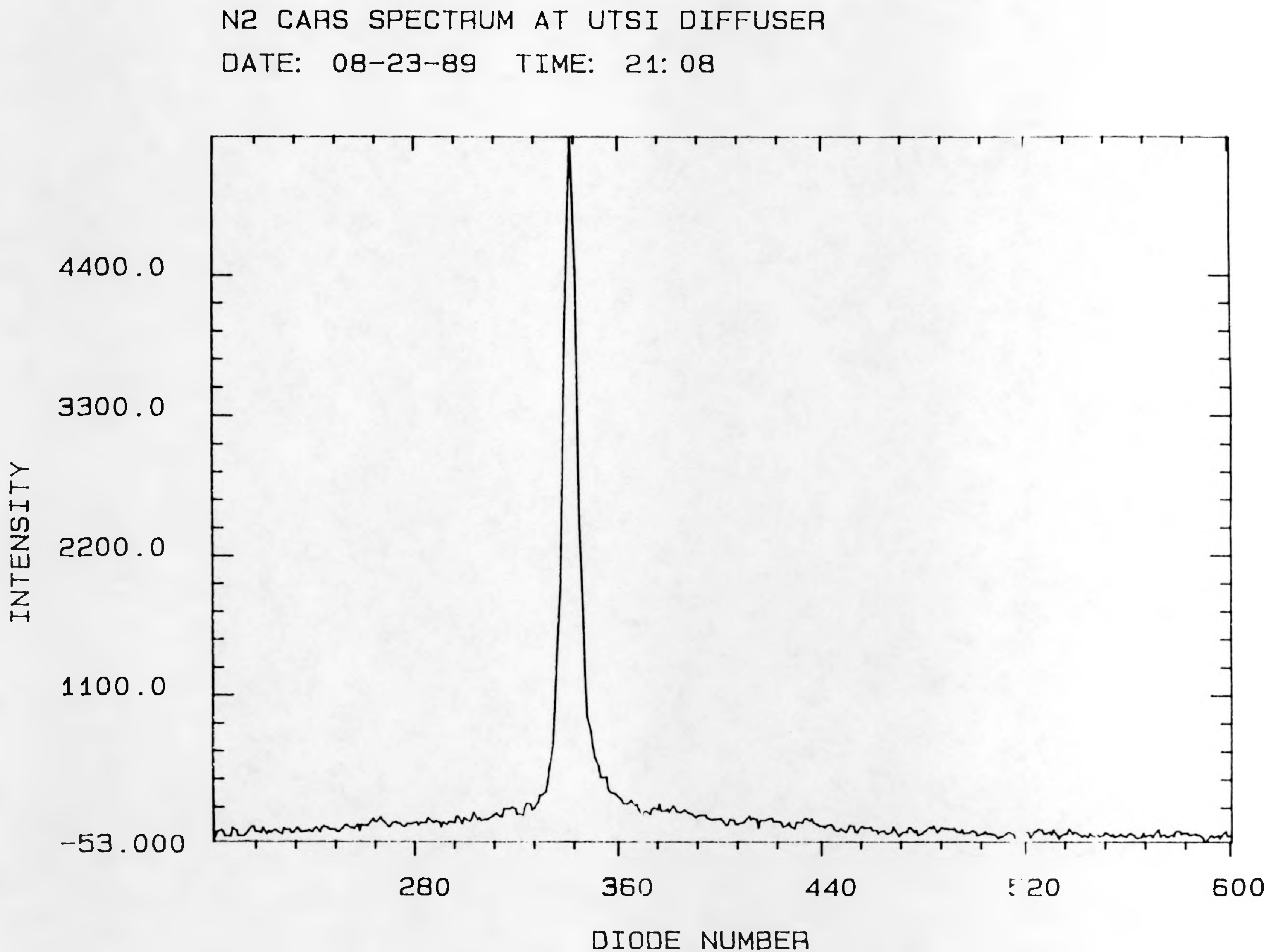

Figure 1.A.3. N_2 CARS spectrum recorded with the OSMA in the gated mode.

measurements using CO_2 CARS. A study on the feasibility of making CO_2 CARS measurements in the field using collinear CARS phasematching geometry is underway.

Upgrading the CARS data analysis software to provide a user-friendly interface began. A user guide for this software is also being written.

Conclusions

The mobile CARS system was tested in the laboratory; the preliminary test results were satisfactory. A CARS alignment experiment was performed during the LMF4-R test at the CFFF. A spatial resolution problem was encountered during those measurements. A solution to this resolution problem is being investigated and will be tested on the DIAL test stand.

Work Forecast

Work will concentrate on testing the mobile CARS system on the DIAL test stand. The CARS alignment experiment will continue during the next run at the CFFF in November. Upgrading the CARS data analysis software will also continue.

Nomenclature

CARS:	Coherent Anti-Stokes Raman Spectroscopy System (MSU's)
DIDA:	Dual-Intensified Diode Array
N_2:	Nitrogen
USED CARS:	Unstable-Resonator, Spatially-Enhanced Detection
CFFF:	Coal-Fired Flow Facility (at UTSI)
UTSI:	The University of Tennessee Space Institute, Tullahoma
LMF4-R:	Low Mass Flow Test Sequence Notation (CFFF)
LWP:	Low Wave Pass
OSMA:	Optical Spectromatic Multichannel Analyzer
MSU:	Mississippi State University
CO_2:	Carbon Dioxide
DIAL:	Diagnostic Instrumentation and Analysis Laboratory (at MSU)

B. Particle Size Distribution System (PSD)

J. D. Gassaway

Work Performed

Mechanical and Optical Development: Recent efforts have focused on designing suitable beam expanders for controlling the size of the sample volume for heavy loading conditions and on developing a folded configuration for the receiver function to implement the alignment functions within space constraints. The receiver design is finished and implemented while the beam expander design is still under consideration. The instrument will be used in low loading situations before the expanders are completed. The results of these efforts will be included in the final report on the instrument.

Signal Processor for Field Instrument: The designs have been documented using a commercial circuit capture program with netlist output compatible with an automated layout system operated by a vendor. The first boards have been received and others will be done as funds are available. This design will be fully described in the final report. In the meantime, modifications have been made to the prototype signal processor so that it can be used with the new optical and computer systems until the new processor is finished.

Computer Operating System for Field Instrument: This work has been finished to the point of having a useful system for operating the instrument and producing convenient data files. It takes advantage of a color display, hard disk storage, and other capabilities not available on the prototype computer. It is ready for use in the laboratory and field. It will be fully described in the final report.

Results from Simulator Program: Further results have been obtained with the simulator program to investigate effects of variation in the index of refraction and out of range conditions. All modes have been simulated and conditions of feasibility for operation investigated. These results have been published in a Ph.D. dissertation[1] and some of them will be presented in the final report on the instrument.

Modeling for the Ensemble Averaging Method (EAM): As described in previous reports,[2,3] the object of this approach is to make measurements under high velocity and loading conditions in which single particle scattering techniques are not feasible, regardless of the method used to implement the measurement and interpret the data. The study of this approach has been brought to the point of calculating a response matrix for a proposed configuration of such an instrument. The simulation includes the Mie scatter model and an optical model for the laser beam and optical receiver. The data reduction algorithm discussed in a previous report[2] was used to calculate distributions for simulated input distributions. Further efforts are needed to determine the feasibility of the method. The effort is stalled until resources and personnel are available.

Conclusions

The development of the field instrument is completed to the point that it can now be used in applications where the particle loading is low enough. The simulator program for the single particle counter instrument has been finished and used to explore various factors such as index of refraction and presence of out of range particles on the accuracy of the instrument. The preliminary design studies of the ensemble averaging instrument indicate the need for further study of methods for handling optical distortion and choosing the discretization intervals in calculating a response matrix.

Work Forecast

The optical system for the field instrument is now being used for establishing alignment routines. Calibration experiments will soon be underway. The instrument will be used with the modified prototype signal processor and new computer system and software within the next quarter for field operations. After a shakedown test in the field, measurements will be done on the DIAL test stand as soon as possible. No further work is planned on the ensemble averaging method until personnel and resources are available.

References

1. Samavi, S. 1989. Simulation of particle sizing system based on scattering from laser beams. Ph.D. Dissertation, Department of Electrical Engineering, Mississippi State University.

2. Gassaway, J. D. 1989. DIAL Quarterly Technical Progress Report. FE-15601-36.

3. Gassaway, J. D. 1989. DIAL Quarterly Technical Progress Report. FE-15601-37.

Nomenclature

PSD: Particle Size Distribution System (MSU's)
Ph.D.: Doctor of Philosophy
EAM: Ensemble Averaging Method
DIAL: Diagnostic Instrumentation and Analysis Laboratory (at MSU)
MSU: Mississippi State University

C. *Potassium Emission/Absorption System (PE/AS)*

L. E. Bauman

Work Performed

Lambda-Maximum Study: One method that has been suggested for monitoring MHD seed atom number density is the procedure of determining the density from the wavelength of maximum intensity of the self-reversed seed atom emission line.[1] This technique offers the possibility of rapid monitoring of the seed density through limited optical access with the use of recently available linear array detectors. Though relatively simple experimentally, the method requires knowledge of flow parameters and computational modeling.

The self-reversal of an emission line, or so-called center dip, arises as the radiant emission from the hot core flow is absorbed when passing through the cooler boundary layers, since the line width is narrower at lower temperatures. If the thermal profile of the flow is known across the line-of-sight optical path, then the wavelength of maximum intensity can be related to the seed atom density through modeling the shape of the emission-absorption line. A preliminary study has been completed for assessing the applicability of this method. The study was limited to parameters representative of DIAL's MHD test facility at the set of optical ports where the gas temperature is hottest.

The thermal model assumed is that of a symmetric flow of total width L, with a uniform hot core flow of temperature T_{core}, and exponential fall-off of temperature in the boundary region of width δ, to a wall temperature of T_{wall} as shown in Figure 1.C.1.

Equation (1) gives the functional form of the model thermal profile where the fall-off exponent is denoted as γ and the position coordinate is x.

$$T(x) = \begin{cases} T_{wall} + (T_{core} - T_{wall})(x/\delta)^{\frac{1}{\gamma}} & 0 < x < \delta \\ T_{core}, & \delta < x < L-\delta \\ T_{wall} + (T_{core} - T_{wall}(L-x)/\delta)^{\frac{1}{\gamma}}, & L-\delta < x < L. \end{cases} \qquad (1)$$

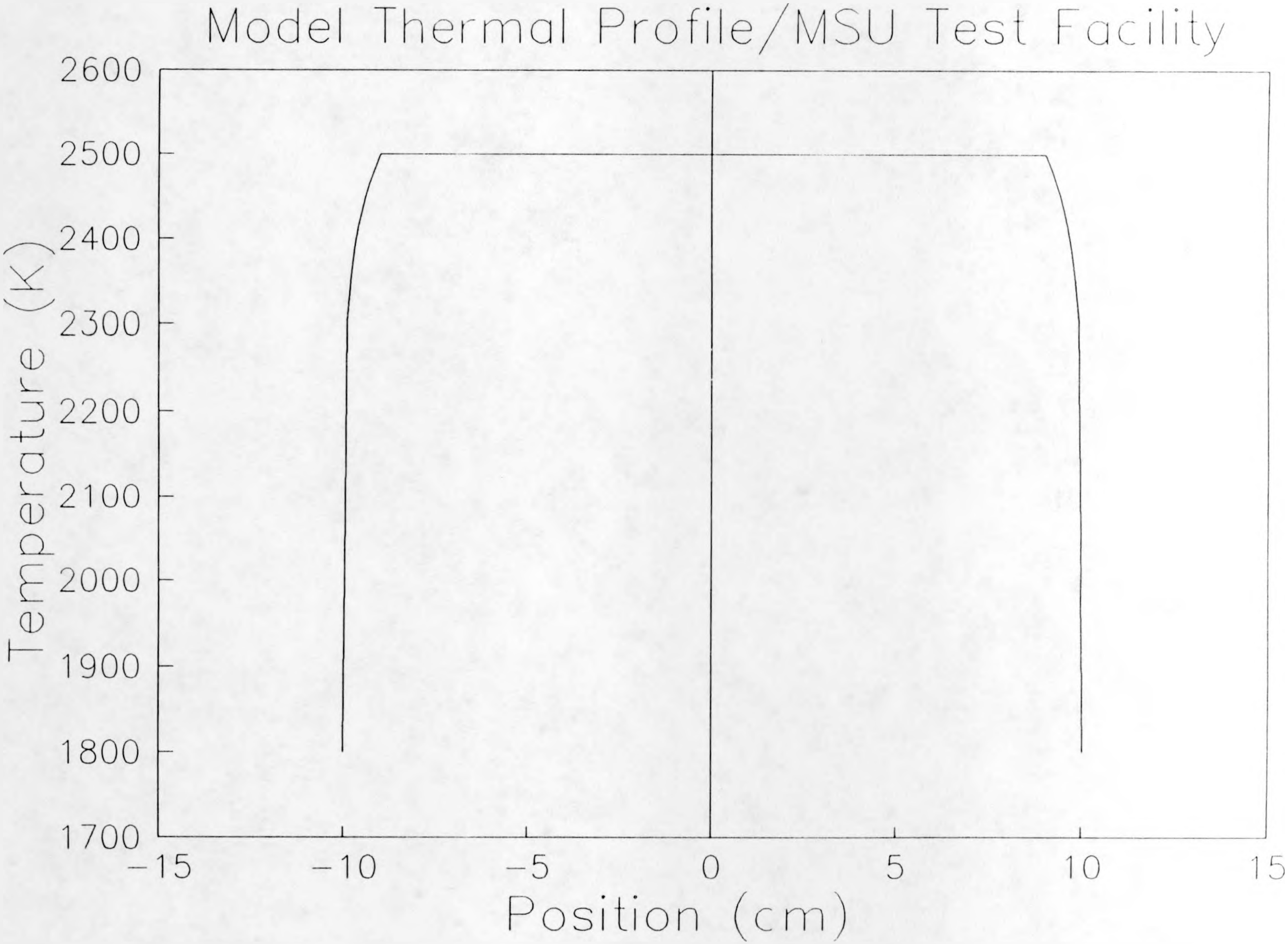

Figure 1.C.1. Thermal profile assumed for model study.

Equation (2) gives the radiant transfer equation across the line-of-sight, where I_λ is the radiant emittance emerging from the flow; α_λ is absorption coefficient of the seed atoms; and $B_\lambda(T_x)$ is the blackbody function for the gas temperature at position x. The absorption coefficient, accurately modeled by a Voigt profile for all but the far wings of the line, depends upon gas pressure, mole fraction of seed atoms, gas constituents, and on position x through dependence on temperature. Chemical equilibrium effects that cause a slow variation of seed atom density in the flow boundary layer were ignored.

$$I_\lambda = e^{-\tau_L} \int_0^L \alpha_\lambda(x) B_\lambda(T_x) e^{\tau_x} dx \quad \text{and} \quad \tau_x = \int_0^x \alpha_\lambda(x')dx' \qquad (2)$$

The assumed thermal profile was taken roughly from previous coherent anti-Stokes Raman spectroscopic measurements of temperature and is given in Table 1.C.1.[2] Also given in the table were the ranges of parameters used for studying the uncertainty of the measurement. Only clean flow conditions were considered to avoid complexities of particle emission-absorption and scattering; previous modeling work predicted a negligible effect of particles on the emission profiles for all but the far wings.[3] The flow width was taken to be 20 centimeters and a pressure of 1.1 atmospheres was assumed. The wavelength of maximum intensity, λ_{max}, was calculated for seed atom mole fractions varying from 0.0001 to 0.004.

For the model values, λ_{max} varied from 766.31 to 765.29 nanometers for seed atom mole fractions of 0.0001 to 0.004, respectively. These wavelengths are not in the far wings where deviations from the Voigt profile would be important. The wavelength is most sensitive to seed atom density at the lower loadings as shown in Figure 1.C.2. The variation is nearly linear for mole fractions above 0.002. In this range, to determine the mole fraction within 10% would require an instrument capable of resolving 0.04 nanometers.

Any discussion of applying this technique would be premature without discussing the errors involved in lack of accurate knowledge in the model parameters or fluctuations in these parameters during an experiment. The method appears to be most sensitive to variations in pressure as shown in Figure 1.C.3. At a seed atom mole fraction of 0.003, λ_{max} is 765.55, 765.45, and 765.35 nanometers, for pressures of 1.0, 1.1, and 1.2 atmospheres, respectively. Or

Table 1.C.1. Thermal profile model values used in lambda-maximum study.

Parameter	Symbol	Value	Minimum	Maximum
Mole Fraction Seed Atom	N_K		0.0001	0.004
Core Temperature (K)	T_{core}	2500	2400	2600
Wall Temperature (K)	T_{wall}	1800	1700	2000
Boundary Layer Width (cm)	δ	1	0.5	3.0
Boundary Layer Exponent	γ	10	7	10
Gas Pressure (atm.)	P	1.1	1.0	1.2

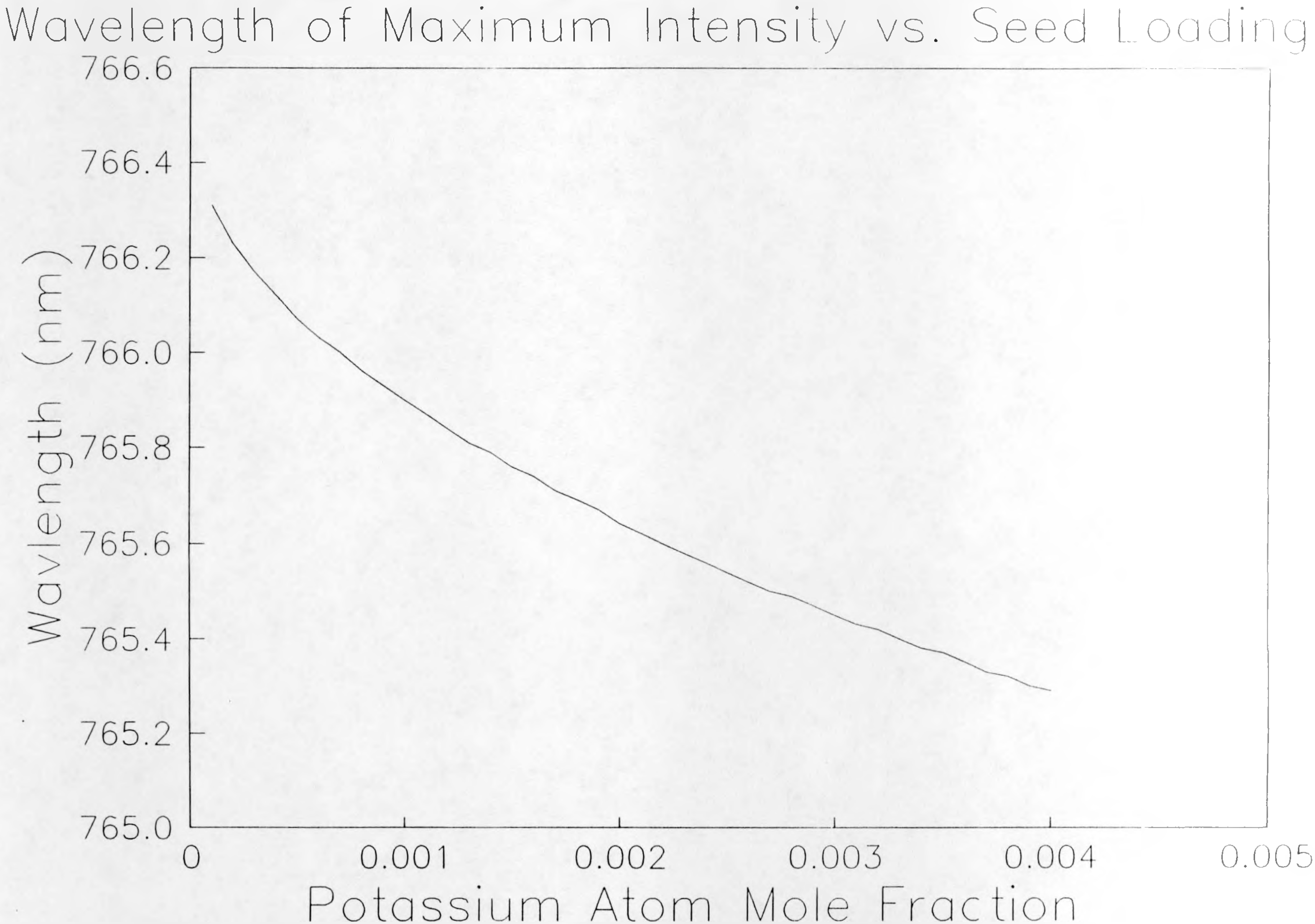

Figure 1.C.2. Wavelength of maximum intensity for self-reversed lines versus seed atom density for values given in Table 1.C.1.

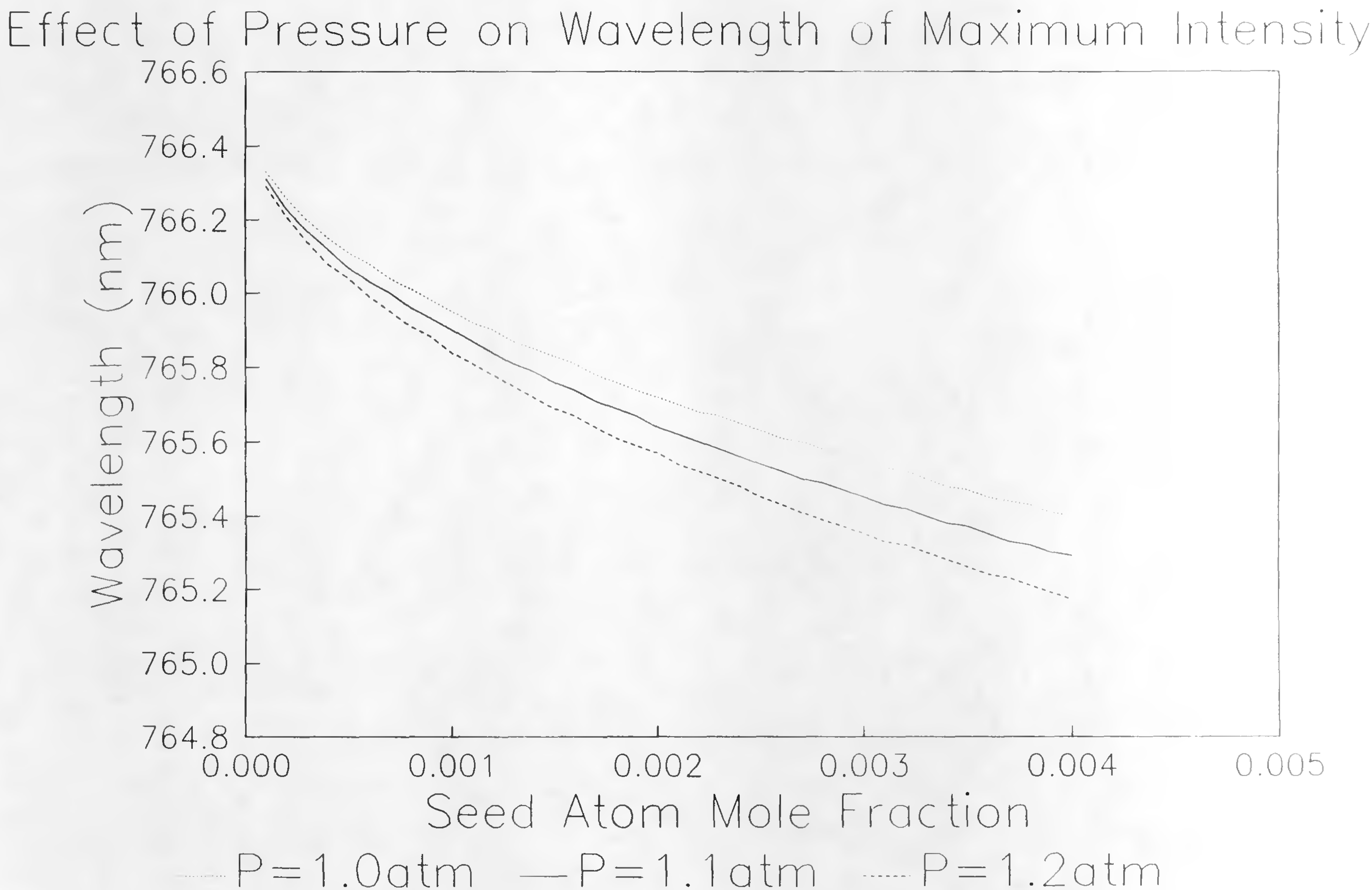

Figure 1.C.3. Wavelength of maximum intensity for self-reversed lines versus seed atom density for gas pressure of 1.0, 1.1, and 1.2 atm.

alternatively, a λ_{max} of 765.40 nanometers corresponds to mole fractions of 0.0027, 0.0033, and 0.0040 for pressures of 1.0, 1.1, and 1.2 atmospheres, respectively. This amounts to about a 20% change in λ_{max} for a 9% change in pressure. Clearly, pressure must be fairly well determined for this technique to provide accurate answers. Pressure is fairly easily measured and it is certainly reasonable to expect to know the gas pressure within 5%. Simultaneous measurements of pressure and λ_{max} would be advisable.

The method is relatively insensitive to variations in wall temperature or core temperature as shown for changes of 100 K in Figures 1.C.4. and 1.C.5. Changes in the boundary layer fall-off exponent from 10 to 7, the range expected for a boundary layer flow, produced very little change in the relationship between λ_{max} and seed atom density. The boundary layer width, a parameter difficult to determine except through sophisticated diagnostic techniques, does appear to appreciably affect the method as shown in Figure 1.C.6 for widths of 0.5, 1.0, 1.5, and 2.0 centimeters. These fairly large variations in δ were chosen to reflect the general lack of knowledge of this parameter. The boundary layer width is expected to be affected by an optical port, particularly one with purge gas.

From these results, the combined inaccuracy in determination of seed atom number density from error in flow parameters would be expected to be less than 20% on the DIAL facility. Results would be different for other facilities primarily because of the different path lengths. The uncertainty in determining λ_{max} would most likely lead to uncertainty in seed atom number density on this order also. A concurrent measure of gas pressure can reduce its contribution to the uncertainty. A good measure of the combined uncertainty could be found through the square root of the sum of the squares of the individual uncertainties.

A complete lineshape fit of scanned emission profiles for representative flows at the specific facility and measurement position with known gas pressure may provide a close enough measure of these model parameters to allow accurate use of this method. For example, a lineshape fit of a profile from a CFFF diffuser port yielded the following values and uncertainties: $T_{core} = 2584 \pm 14$ K, $T_{wall} = 1620 \pm 440$ K, $\delta = 1.6 \pm 0.4$ centimeters, and $\gamma = 9.2 \pm 6.0$. Without accurate knowledge of the model parameters the technique would still provide a relative measurement of seed atom density.

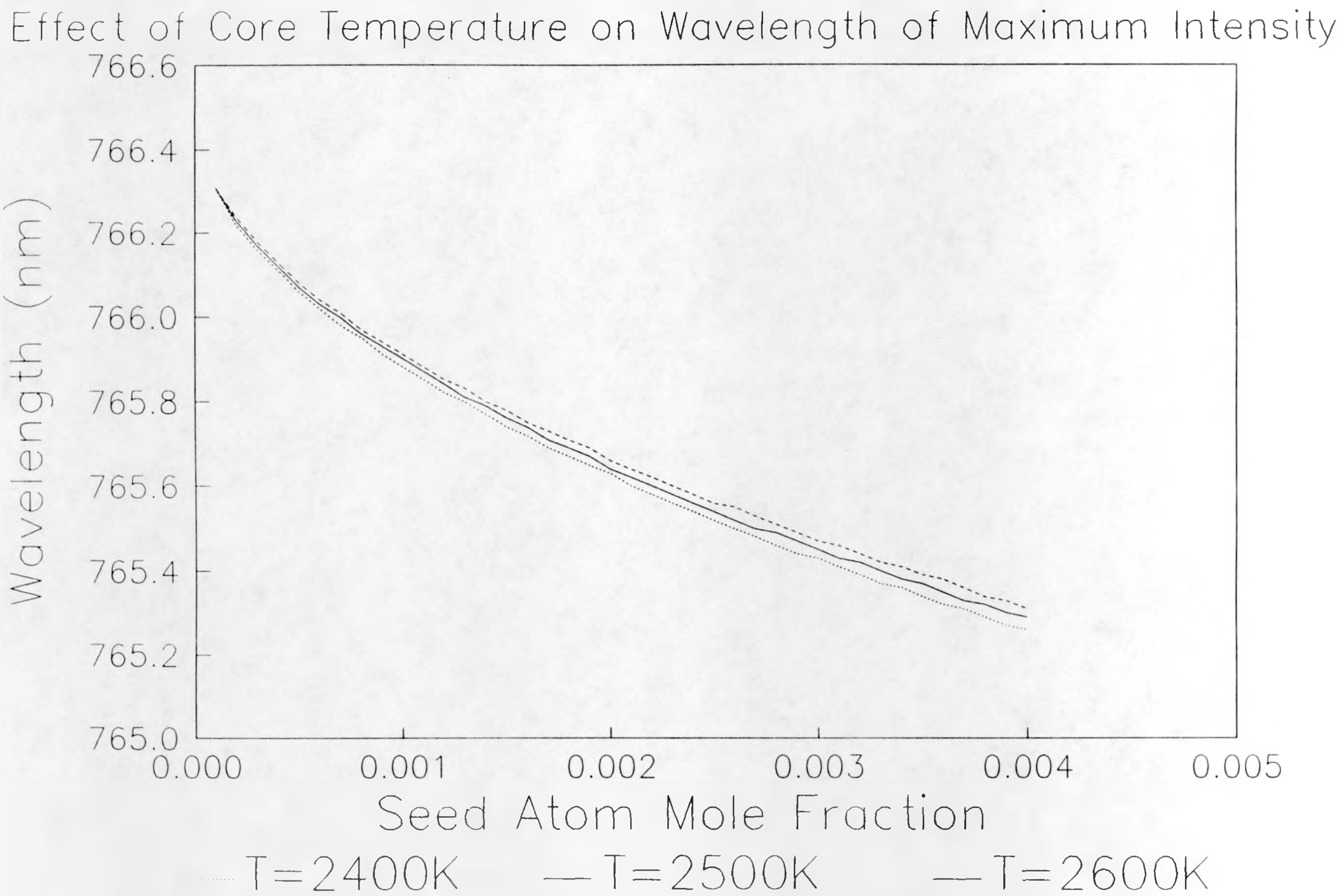

Figure 1.C.4. Wavelength of maximum intensity for self-reversed lines versus seed atom density for core gas temperature of 2400, 2500, and 2600 K.

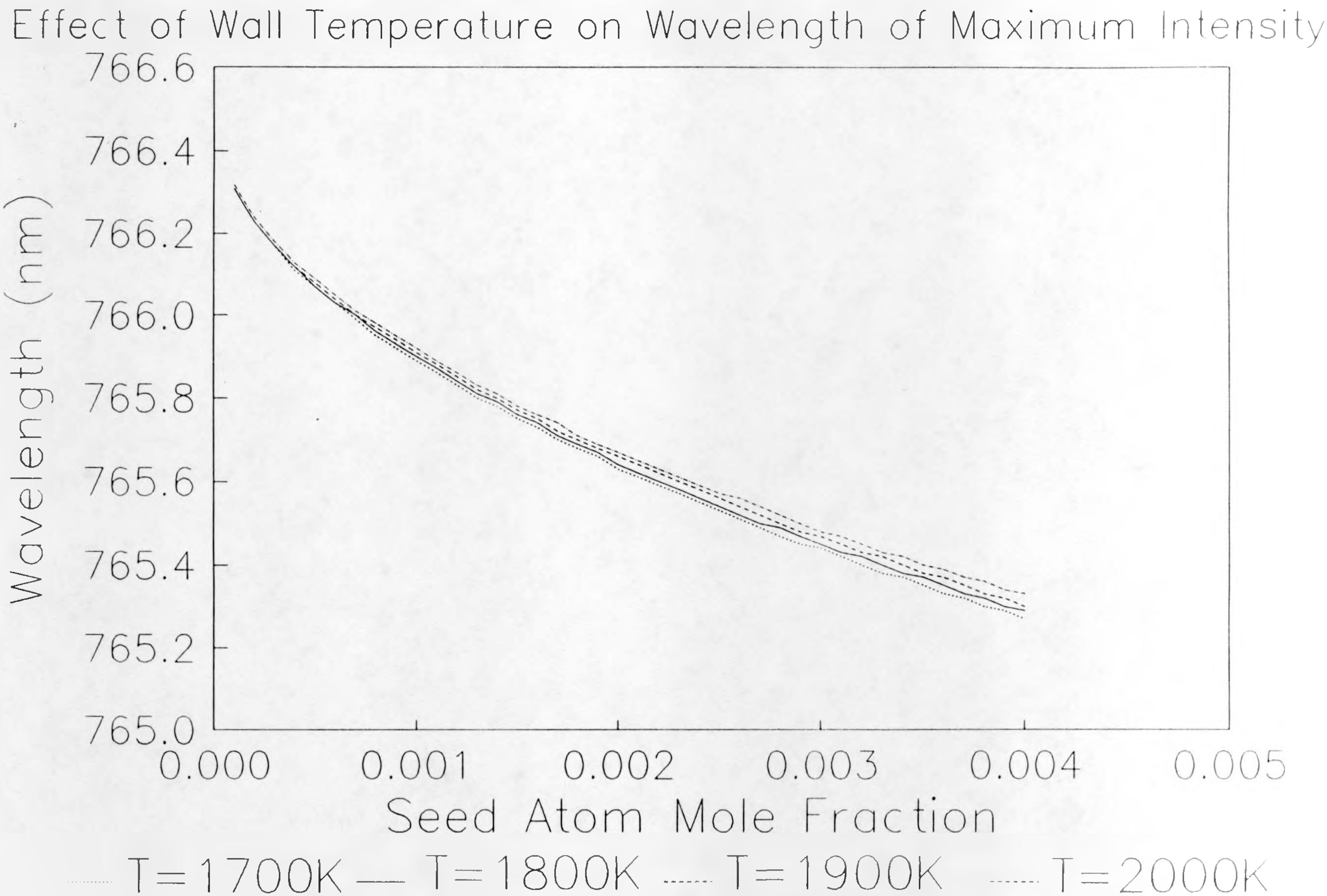

Figure 1.C.5. Wavelength of maximum intensity for self-reversed lines versus seed atom density for wall gas temperature of 1700, 1800, 1900 and 2000 K.

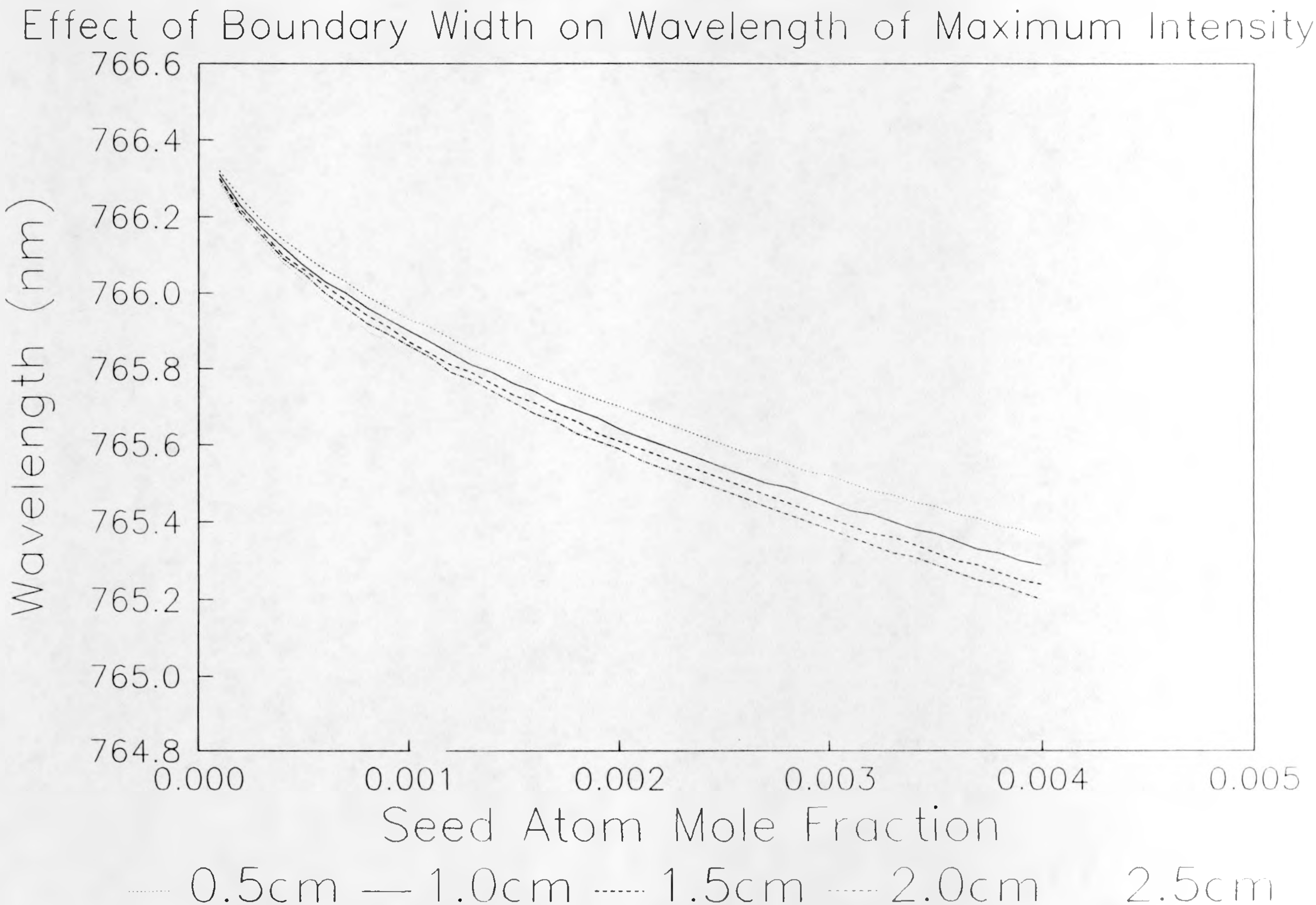

Figure 1.C.6. Wavelength of maximum intensity for self-reversed lines versus seed atom density for boundary layer widths of 0.5, 1.0, 1.5, and 2.0 and 2.5 cm.

The advantage of this intensity maximum technique is that it requires an emission signal only; the necessary information could be obtained through limited optical access -- a single, small fiber optic port to an MHD facility. Fiber optic input to a monochromator with a linear array detector then could provide fast time response for monitoring seed atom density. The SLR systems use 0.6-meter monochromators and with a 1200-groove-per-millimeter grating the dispersion at the slit plane is approximately 0.11 nanometers-per-millimeter. A linear array detector with elements of width 25 microns would provide a resolution of 0.04 nanometer. The instrument resolution function would depend upon the slit setting and could be as low as 0.04 nanometer. Photodiode array detectors have a response that peaks in the near infrared and therefore is well-matched to the potassium D-line emission. These detectors can be sampled at megahertz frequencies, thereby providing rapid time response. A 512 element array with a sampling rate of 5 megahertz could with appropriate electronics provide a frame of data every 100 microseconds. Computer speed for determination of λ_{max} and data storage would limit the time response but could conceivably be in the hundreds of microseconds. In essence, such a system could provide a sub-millisecond, real-time monitor of seed atom density.

In conclusion, the technique appears promising enough to suggest expenditures of equipment and development time to produce such a system. Further modeling work to simulate conditions on the Department of Energy's CFFF and CDIF facilities will need to be done. Fiber optic ports already exist in the CDIF MHD channel that would permit immediate use of such a system for seed atom density monitoring.

Field Tests: During this quarter, the Potassium Emission/Absorption System was in Butte, Montana at the CDIF to support the coal-fired combustor tests. For these tests, the channel was in place and seed was injected. Measurements were made at the middle set of ports of the diffuser where the optical path across the flow is approximately 12 inches. Rectangular box-type recesses on both sides open into the 3-inch diameter circular ports. On each side, the optical window is mounted at the end of the port, recessed about 24 inches from the flow, with a pressure-driven shutter and two sets of nitrogen purge lines intended to keep the window clean and the access open.

Potassium Emission Absorption System configurations chosen for these tests included: lamp, chopper and optics mounted on rails attached to the diffuser; a collimated beam using 20-centimeter focal length achromatic doublet lenses; fiber optic transmission to the detector-side system; 600-groove-per-millimeter grating in the 0.32-meter monochromator; slit width of 40 microns; the 766.5-nanometer line positioned at vidicon channel 316; and 20-amp lamp current for an effective reference lamp temperature of 2550 K.

The major problem encountered in testing was that of keeping the optical ports open and the windows clean. Nitrogen purge lines contained traces of oil that splashed on the windows and collected slag/ash particles. This was noticed during the early tests, when apparently problems with the coal flow hampered the tests, and was partially ameliorated through filters before the successful tests on August 10 and 16, 1989. The problem of slag/seed build up on the port entrances was noticed on August 10, when ultimately the light path was blocked entirely after two hours of testing. Presumably the square recess between the diffuser wall and circular port provided a good base for the build up of slag. Redesign of the optical ports/purges will be necessary before the Potassium Emission/Absorption System can be used effectively for long term tests.

Preliminary results from the 89-CFC-15 test on August 10, 1989 are presented in Figures 1.C.7. and 1.C.8. In these figures the hatched regions show the plus or minus one standard deviation limits surrounding the line of average values. Key items in the test notes that aid in analysis of this data include:

13:14:29	Coal-Fired Combustor (CFC) ignition
13:18:29	Seed flow initiated
13:58:00	Inverter on-line
14:00:02	Starting magnet, gradual power up
14:15:25	Magnet at 4000 Amps
14:16:50	Increasing seed flow
14:19:50	Begin increasing magnet and inverter
14:26:54	Magnet at full power (2.92 Tesla)
14:54:00	Seed system in manual
15:10:00	Seed flow steadily dropping, trying to restore
15:15:00	Seed system in auto

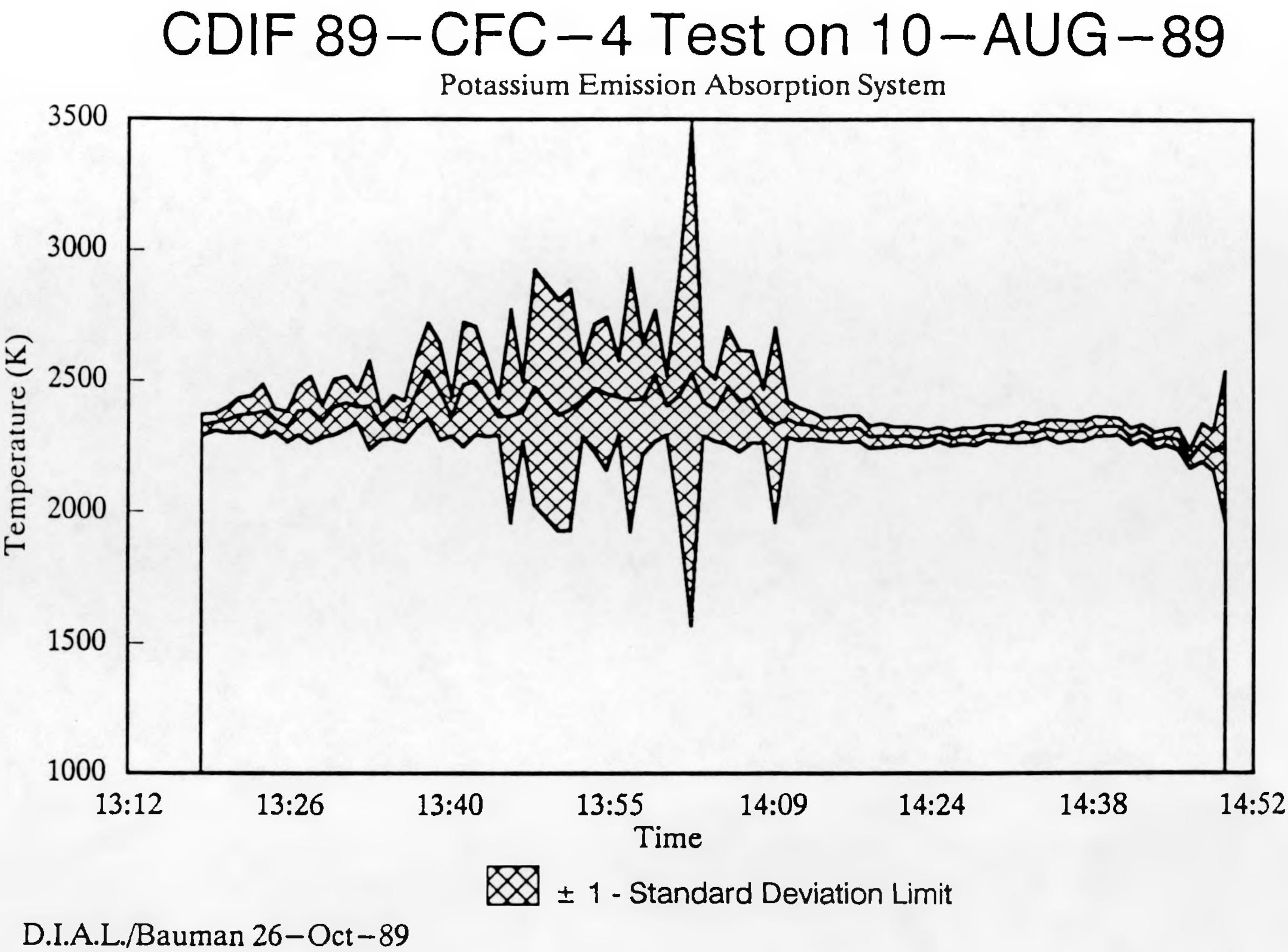

Figure 1.C.7. Temperature versus time for the CDIF 89-CFC-15 test.

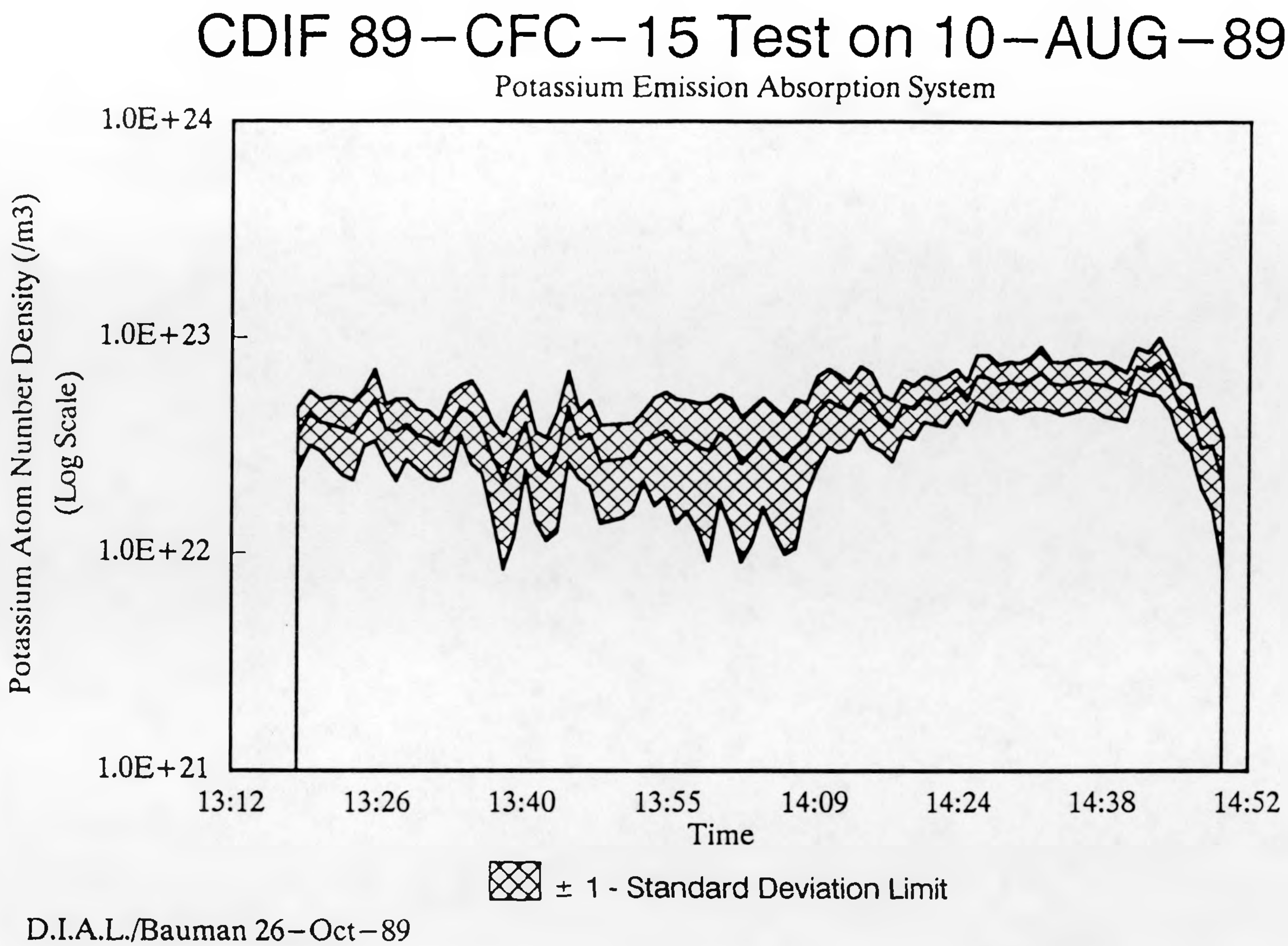

Figure 1.C.8. Potassium seed atom number density versus time for the CDIF 89-CFC-15 test.

The PE/AS results show large fluctuations in temperature, root mean square deviations as high as 450 K, around 13:50 that decrease to less than 50 K upon powering on the magnet and inverter. For reference, instrumental uncertainty on a stable laboratory flame is about 15 K. The seed atom density appears to slowly decrease from about $(4 \pm 1) \times 10^{16}$ cm^{-3} at 13:20 to $(3 \pm 1) \times 10^{16}$ cm^{-3} at 14:08. After powering the magnet the seed atom density increases to almost 8×10^{16} cm^{-3} at just before 14:45, at which point the seed atom density drops rapidly to about $(2 \pm 1) \times 10^{16}$ cm^{-3} at 14:51. Measurements after this point were suspect because of the low light transmission due to dirty windows and slag blockage of the ports. By 15:00, light transmission was totally extinguished. The seed atom density measurements seem to match well with the test notes concerning seed feed.

The measurement of seed atom density depends upon a difference in optical depth at two distinct wavelengths and hence is unaffected by changes in light transmission as long as some signal is received; a lower light transmission may increase the noise in the data but does not affect the accuracy. No appreciable increase in standard deviation was recorded for the test and the variation in seed atom number density throughout the almost two hours of PE/AS data is most certainly real. On the other hand, the temperature measurement is affected by changes in light transmission on the lamp-side only, though not as badly as a single wavelength line reversal measurement. A decrease in reference signal due to dirty windows would cause the measured gas temperature to increase, so that the decrease in measured temperature after 13:45 is also certainly real and may be underestimated due to dirty windows or slag buildup in the lamp-side port.

The reduction in potassium emission fluctuations upon powering of the magnet is striking and most likely represents actual changes in the flow properties but could be due to a reduction in vibrations of the optical mounts affecting the transmission of the lamp signal.

On the 16th of August, again about two hours of PE/AS data was obtained before the light transmission was extinguished. Figures 1.C.9. and 1.C.10. show the results. Important times noted in the test notes are:

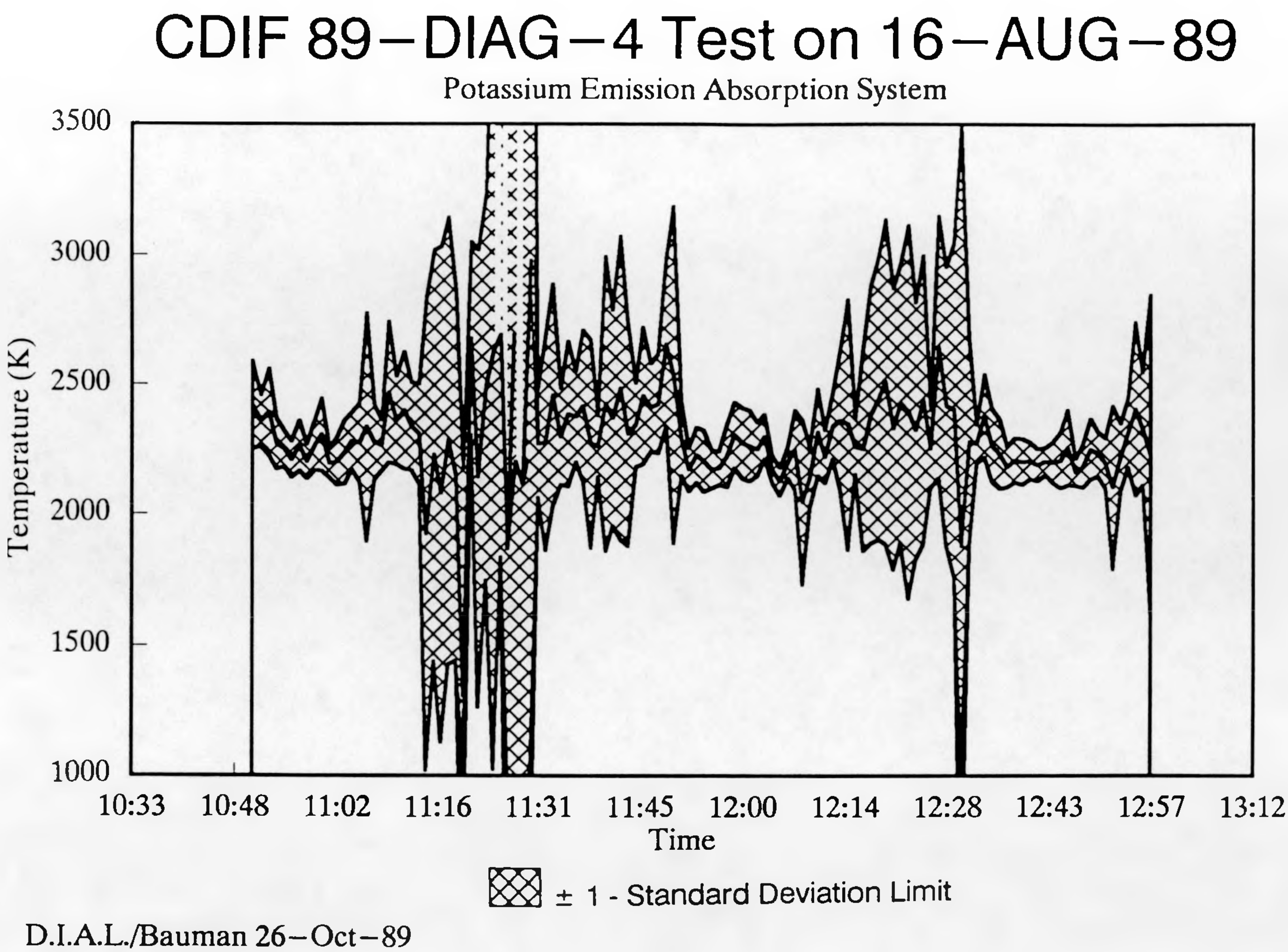

Figure 1.C.9. Temperature versus time for the CDIF 89-CFC-16 test.

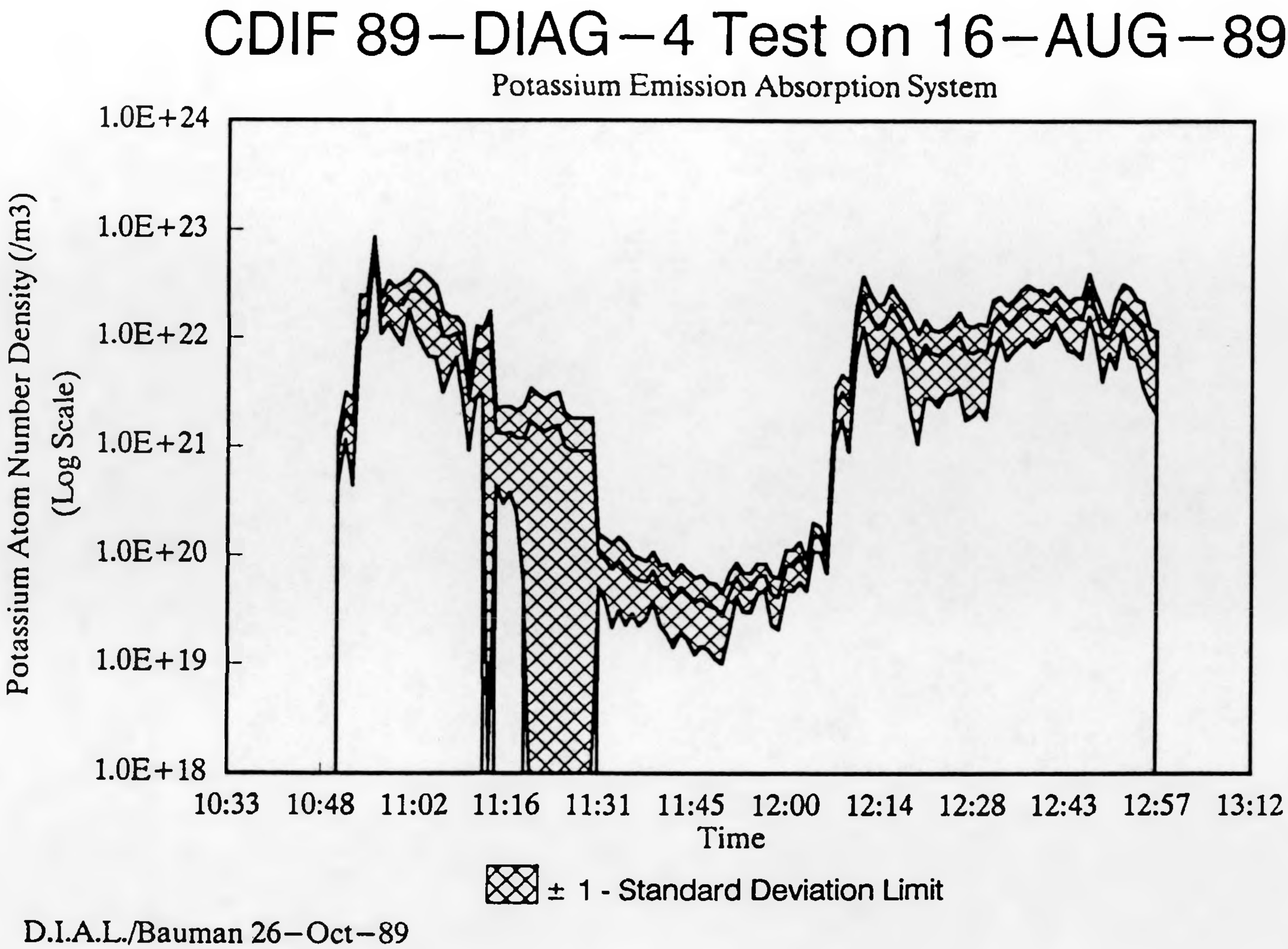

Figure 1.C.10. Potassium seed atom number density versus time for the CDIF 89-CFC-16 test.

10:46:15	CFC ignited
10:53:40	Initiating seed flow to combustor
10:59:11	Attempting to increase seed flow to 2%
11:07:00	Seed flow at 2%, start to reduce to 1.7%
11:24:00	Secured seed flow, could not keep steady
12:06:00	Seed flow to combustor started
12:22:42	Magnet powered up, gradual increase
12:38:50	Magnet @ 2.92 Tesla and 5000 volt on inverter

Reduced light transmission because of slag blockage of the ports is the cause for the very large uncertainty limits.

Scanning System for Potassium Far-Wing Line Profiles: Computer control of the wavelength drive of an Instruments SA model HRS-2 0.6-meter monochromator is complete. The system will be used for far wing scans of the potassium D-line in order to investigate functional forms to model the profile.

The system consists of a focussing lens, a filter wheel, order separating filter, monochromator with wavelength drive controller, photomultiplier tube detector with amplifier/discriminator and photometer, and computer. The computer, through digital output, steps the wavelength drive and filter wheel, and using an analog-to-digital converter brings in the detector signal. A neutral density filter is inserted during the scans in the region of the intense line centers in order to avoid damaging the detector when it is set sensitive enough to study the weaker wings. A neutral density filter of 2.0 was chosen which provides a factor of 100 reduction in intensity. A study of the instrument response function revealed problems with overlapping orders at wavelengths above 760 nanometers, and an order separating filter was added to alleviate this problem.

The instrument response function was determined using a tungsten strip lamp at three different temperatures and a blackbody source. The functions agree well with each other and the scanning system is now ready for experiments which are scheduled on the DIAL MHD test facility during October.

Conclusions

The PE/AS continues to be used effectively for field testing. Work is proceeding to study the far wings of the potassium D-line. This study will hopefully extend the usable wavelength range for the two-wavelength determination of seed atom density to the wings.

Work Forecast

Experiments on the DIAL test facility to obtain potassium D-line far wing profiles are scheduled for October of 1989; analysis and, if necessary, further tests will follow.

References

1. Balashov, N. A.; Vasil'eva, I. A.; Gaponov, I. M.; et. al. 1974. *Teplofiz. Vys. Temp.* 12:2:417-424.
2. Beiting, E. J. 1986. *Appl. Opt.* 25:10:1687.
3. Bauman, L. E. 1989. In *Proceedings of the 27th Symposium on Engineering Aspects of Magnetohydrodynamics.* 8.3-1.

Nomenclature

PEAS: Potassium Emission Absorption System (MSU's)
MHD: Magnetohydrodynamics
DIAL: Diagnostic Instrumentation and Analysis Laboratory (at MSU)
MSU: Mississippi State University
CFFF: Coal-Fired Flow Facility (at UTSI)
SLR: Sodium Line Reversal System
CDIF: Component Development and Integration Facility (in Butte, Montana)
89-CFC-15: Test sequence notation at CDIF

D. Intrusive Multi-Probe System (IMPS)

L. R. Hester

Work Performed

The special test section that was designed for calibration and operational verification of the intrusive sensors was installed on the DIAL test stand. Wall surface temperature measurements were made in the special section using the Intrusive Lightpipe Sensor and the Multicolor Pyrometer System for comparison purposes. The lightpipe sensor yielded surface temperatures approximately 150°F lower than the MCP system. This difference can be attributed to the surface temperature being at the lower end of the operating range of the MCP heads. The two measurements should match higher in the operating range of the MCP heads. More tests will be conducted when a higher temperature in the test section can be achieved.

The Intrusive Lightpipe Sensor and its support system were transported to the CFFF and furnace wall temperatures were measured during the LMF4-R test. A total of thirty-five insertions were made for wall surface temperature measurements. Twenty-one insertions were made at penetration 2225 on level three and fourteen at penetration 2231 on level four. No problems were encountered during any of the insertions and all measurements were considered successful. The addition of a closed sheath to the sensor for the initial insertion provided a means of accurately determining the sensor's position relative to the wall surface. In this manner the wall surface position can be identified as the facility's operating conditions change.

The automatic controls for the air drive positioning mechanism for the intrusive support system were completed. Work was started on the hardware and software to interface the PC computer to the air drive mechanism.

Conclusions

It can be concluded from the furnace wall surface temperature measurements made during the LMF4-R test at the CFFF, that the intrusive lightpipe sensor can operate in gas streams with considerably higher temperatures than originally thought possible. The lightpipe sensor was inserted a distance of approximately

50 inches through the gas stream. The sensor could be held in position for a measurement time of 15 seconds without the support tube exceeding its critical temperature.

Work Forecast

More calibration and operational verification tests will be conducted in the special test section of the DIAL test stand. The tests will also compare the operational characteristics of the Intrusive Lightpipe Sensor and the Multicolor Pyrometers.

All of the materials were received for the intrusive SLR sensor optics holder. Before the new holder is constructed, new construction techniques will be studied to obtain the tolerances required to maintain the proper optics alignment while the system is subjected to excessive vibrations.

The overall development of the total intrusive support system and the sensors will be accelerated to be ready for field testing at CFFF during future runs.

Nomenclature

DIAL: Diagnostic Instrumentation and Analysis Laboratory (at MSU)
MSU: Mississippi State University
MCP: Multi-Color Pyrometer System
CFFF: Coal-Fired Flow Facility (at UTSI)
UTSI: The University of Tennessee Space Institute (Tullahoma)
LMF4-R: Low Mass Flow Test Sequence Notation (at CFFF)
SLR: Sodium Line Reversal System

E. Faraday Rotation System (FRS)

L. E. Bauman

Work Performed

The system is essentially assembled with the exception of minor optical additions or changes depending upon the laser wavelength chosen for operation on a particular flame/plasma. Weakly ionized, seeded flames are only available for testing in the laboratory and so require use of a long wavelength laser line to produce a measurable angle of rotation. The angle is directly proportional to electron number density, optical path length in the plasma, magnetic induction, and the square of the laser wavelength. Attempts to operate the laser on long wavelength methanol lines were unsuccessful; with receipt of the methyl fluoride laser gas, lasing was easily achieved on the 496.1 micron line. Preliminary testing of the system with this wavelength on seeded flames demonstrated measurements of rotation angles between one and three degrees.

Work on improving the laser stability has reduced drift of the laser power to one to two percent over the time frame for experiments. However, laser stability does require a warm-up time of over two hours.

Efficient methods for angle measurements are still under investigation. Currently data sets of average laser power versus grid polarizer orientation are stored and transferred to the VAX for determination of the Faraday rotation angle through use of a 'canned' fitting routine. It is planned to eventually have the FRS control and data collection computer perform this analysis so that the system will be stand-alone for field operation. Currently an LSI/11-23 computer is being used for control and data collection. This computer is old and increasingly difficult to boot up because of the disk drive and must be replaced.

Conclusions

Development of the system hardware is essentially complete.

Work Forecast

Laboratory tests on seeded flames have begun and will continue with various salt solutions.

F. *Multi-Purpose Imaging System (MPIS)*

R. Lengel and J. S. Lindner

Work Performed

A large amount of time was spent developing additional image processing capabilities. This work involved linking a number of routines in a coherent manner. Intensity histograms and line graphs can now be plotted on the printer. These plots will allow numerical evaluation of any image which will aid in the determination of image structure and in the optimization of the given experimental configuration. Some previously captured image files were uploaded to the departmental computer and printed using the laser printer. This process yields an extremely high quality image and will be used for critical work.

Artifacts were observed in the output display from the charge injection device (CID) camera. Long-term observation revealed that the output has reached a steady state with two lines -- one vertical and one horizontal. Each of these lines is about one pixel element wide. The two lines do not prohibit the collection of meaningful data but must be accounted for in image analysis. Discussions with the manufacturers were inconclusive as to the cause of these lines.

Conclusions

Additional image processing capabilities have been developed. Some degradation of the output from the CID camera was observed but appears to have attained a steady state.

Work Forecast

More incident laser power at 405 nanometers is required in order to image K atoms.[1] Future efforts will therefore be directed towards the selection of appropriate optics and integration of these optics into the experimental configuration.

References

1. Lindner, J. S., and Lengel, R. K. 1989. DIAL Quarterly Technical Progress Report FE-15601-37:55.

Nomenclature

MPIS: Multi-Purpose Imaging System (MSU's)
CID: Charge Injection Device
K: Potassium
DIAL: Diagnostic Instrumentation and Analysis Laboratory (at MSU)
MSU: Mississippi State University

Task 2. Test Stand Operations: J. A. Etheridge

A. Test Stand Modifications: The test section designed for the Intrusive Probe and the Multicolor Pyrometer was installed in the test stand.

B. Computer Control Up-grade: Software for the new test stand control computer was given the majority of effort during this quarter. A site visit by a representative from Bradley Ward, Inc., who developed the software, provided a better understanding of the PMIS software. Approximately one month was needed for getting the PMIS part of the software ready. Additional software was written in FORTRAN to take care of special cases such as data logging. The primary data acquisition software resides in an HP 3852 and was written in BASIC. Calibration of all data acquisition sensors was also completed.

The new software was tested during a test run that was for testing a technique for detecting water leaking into a gas stream. The new computer will be used for all test runs in the future and is considered to be complete except for on-line graphics which is to be added later.

C. Test Stand Runs: One test run was completed during this quarter. The purpose of this test was to investigate a technique for detecting water leaking into the gas stream.

Nomenclature

PMIS: Process Management Information System
FORTRAN: FORmula TRANslation (a computer language)
HP: Hewlett Packard
BASIC: Beginners All-purpose Symbolic Instruction Code (a computer language)

Task 3. Technical Support for National MHD Program: R. D. Benton

A. Field Measurements

Work Performed

The PE/AS temperature measurement system, the LDV velocity measuring system, and the Gas Analysis System were taken to the CDIF during this quarter. DIAL's instruments were set up to make velocity, temperature, and gas measurements on the triple port wall of the CDIF diffuser; however, the ports could not be kept clear. This hampered reliable measurements of velocity and temperature and only intermittent measurements were possible.

The GAS measurements were continued by clearing slag blockage with purge gas pressure. However, this method of clearing the slag blockage fails after about two hours of run time. The new remote window changing apparatus has been installed at the CDIF and is functioning properly.

Gas Analysis Tests at the CDIF (Green): The Gas Analysis System was operated at the CDIF during eight tests this quarter. These tests were 89-CFC-13, 89-CFC-14, 89-REST-1, 89-DIAG-10, 89-DIAG-11, AND 89-DIAG-12.

The Gas Analysis System, shown in Figure 3.A.1, consists of an MSU-designed, water-cooled gas sample extraction pipe which extracts and cools a gas sample. The gas is then passed through a heat transfer coil and a knockout pot to condense the combustion water. The sample is then pumped by an Air Dimensions, Inc., Gas Sampling Pump, Model 19340T, to an ice bath where further water condensation occurs. As a final step to remove moisture from the gas, it is passed through a cylinder of Drierite and then a 2-micron particle filter. After exiting the particle filter, the gas is distributed to the four gas analyzers and the gas chromatograph for analysis.

Test 89-CFC-13 was of insufficient duration to gather meaningful data. Test 89-CFC-14 also yielded little data due to sample pipe plugging. For 89-CFC-13 and 89-CFC-14 the gas sampling pipe was located at the farthest downstream east port. At this location, the water from the quench ring was washing particles into the pipe and plugging the sample line. In an attempt

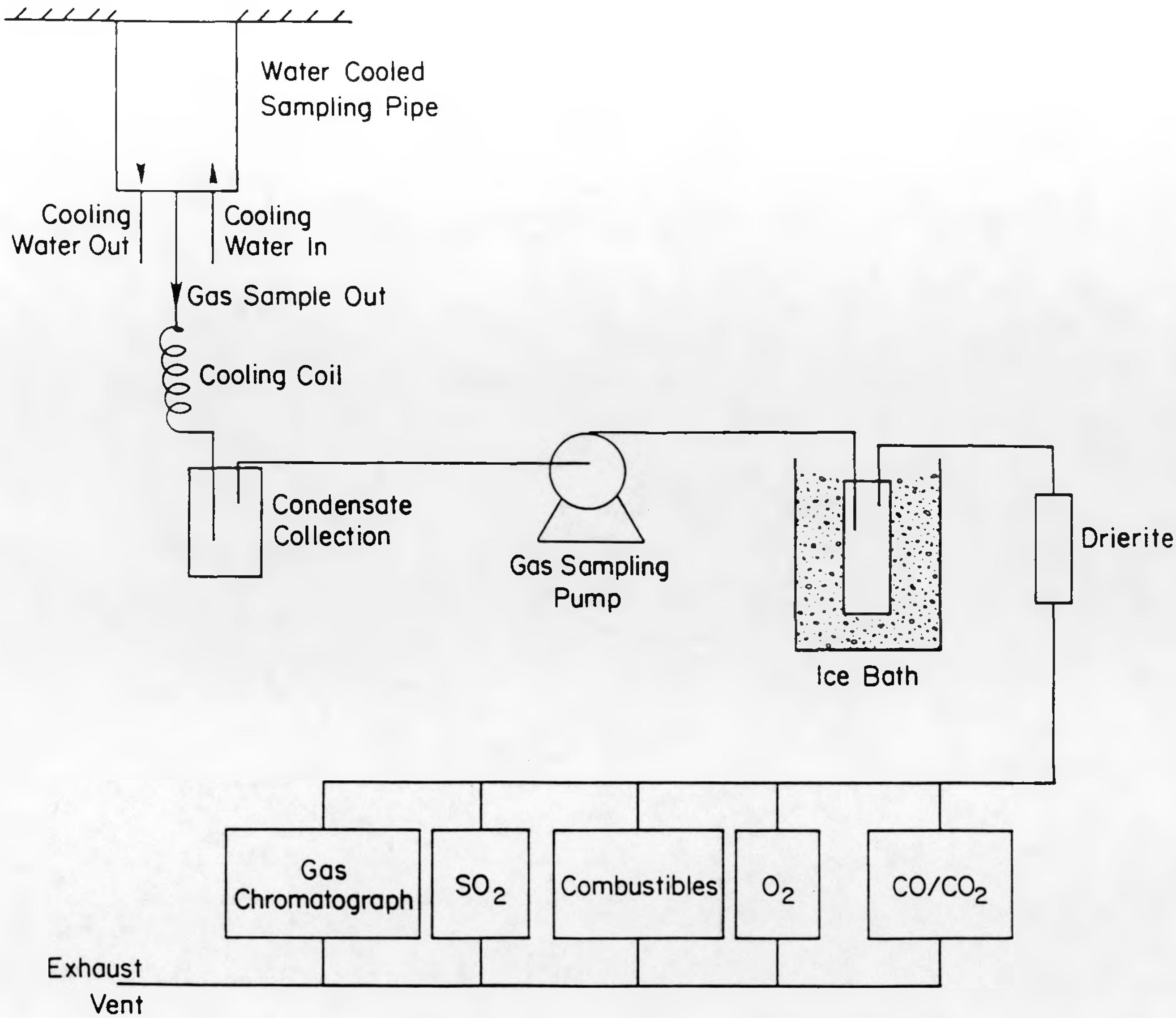

Figure 3.A.1. Gas Analysis System layout.

to prevent sample line plugging, the gas sampling pipe was moved to the farthest downstream west port for test 89-CFC-15. Unfortunately, the sample line plugged again and no reportable data were collected.

Data collected during test 89-REST-1 consisted of CO, CO_2, O_2, and combustibles. The gas sample for this test was extracted at the farthest upstream port on the east side of the triple port diffuser section. At this location sample line plugging was not a problem and 33 minutes of data were collected before the end of the pipe slagged over. Typical data from this test is reported in Table 3.A.1.

Table 3.A.1. Typical gas data for 89-REST-1 at CDIF.

Specie	Concentration (%)
O_2	0.15
CO	7.36
CO_2	41.77
Combustibles	2.98

Test 89-DIAG-10 resulted in the collection of a total of 54 minutes of gas data from the farthest upstream port. Typical data is presented in Table 3.A.2. Sample line plugging was not a problem until the end of the sampling pipe slagged over.

Table 3.A.2. Typical gas data for 89-DIAG-10 at CDIF.

Specie	Concentration (%)
O_2	0.14
CO	8.70
CO_2	43.12
Combustibles	3.78

Gas data were also collected during 89-DIAG-11 and 89-DIAG-12. The gas sample was extracted from the farthest upstream port on the east side of the triple port diffuser section for these runs. Slagging over of the end of the sampling pipe was still observed. Typical data from these test are presented in Tables 3.A.3. and 3.A.4.

Table 3.A.3. Typical gas data for 89-DIAG-11 at CDIF.

Specie	Concentration (%)
O_2	0.36
CO	9.38
CO_2	42.85
Combustibles	3.84

Table 3.A.4. Typical gas data for 89-DIAG-12 at CDIF.

Specie	Concentration (%)
O_2	0.12
CO	8.96
CO_2	43.77
Combustibles	4.42

The Gas Analysis System also contains an SO_2 analyzer which was used for test 89-DIAG-12. The SO_2 data collected indicated a concentration far less than expected; since the analyzer was calibrated and operated at a much higher, full scale setting, the data could not be distinguished from noise.

Velocity Measurements at the CDIF Diffuser Exit (Srikantaiah and Wilson): The Laser Doppler Velocimeter (LDV) was set up at the west side upstream (first) port of the diffuser exit in single component backscatter configuration. The gas stream width is 12 inches at this location. Considerable difficulty was experienced in obtaining velocity measurements due to port/window slagging. Also, the LDV detector (photomultiplier) quit working when the magnet was turned on. This was noted for the first time. Fiber optics were not used at this time to remote the PMT as it was feared the signal strength would have been considerably reduced, especially in the backscatter mode. (Single mode fiber optics were, however, used to transmit the laser beam thus remoting the laser equipment.) Additional shielding for the PMT or fiber optics will be tried to receive the signal in the next runs. Only a couple of data points, one at the centerline and one at three inches west from the centerline, were obtained when the magnet was off. The maximum velocity recorded at the centerline was about 600 meters-per-second and at three inches west about 450 meters-per-second. Note that these results are based on only a few samples measured. The velocity histogram had very few points, and as such, no conclusions should be drawn about the flow characteristics. The measurements should be repeated. The port/window slagging and photomultiplier problems must also be corrected.

PE/AS Field Tests at the CDIF (Karim and Bauman): The Potassium Emission/Absorption System was in Butte, Montana at the CDIF to support the coal-fired combustor tests. For these tests, the channel was in place and seed was injected. Measurements were made at the middle set of ports of the diffuser where the optical path across the flow is approximately 12 inches. Rectangular box-type recesses on both sides open into the 3-inch diameter circular ports. On each side, the optical window is mounted at the end of the port, recessed about 24 inches from the flow, with a pressure-driven shutter and two sets of nitrogen purge lines intended to keep the window clean and the access open.

Potassium Emission/Absorption System configurations chosen for these tests included: lamp, chopper and optics mounted on rails attached to the diffuser; a collimated beam using 20-centimeter focal length achromatic doublet lenses; fiber optic transmission to the detector-side system; 600 groove-per-millimeter grating in the 0.32-meter monochromator; slit width of 40 microns; the 766.5-nanometer line positioned at vidicon channel 316; and 20-amp lamp current for an effective reference lamp temperature of 2550 K.

The major problem encountered in testing was that of keeping the optical ports open and the windows clean. Nitrogen purge lines contained traces of oil that splashed on the windows and collected slag/ash particles. This was noticed during the early tests, when apparently problems with the coal flow hampered the tests, and was partially ameliorated through filters before the successful tests on August 10 and 16, 1989. The problem of slag/seed build up on the port entrances was noticed on August 10, when ultimately the light path was blocked entirely after two hours of testing. Presumably the square recess between the diffuser wall and circular port provided a good base for the build up of slag. Redesign of the optical ports/purges will be necessary before the Potassium Emission/Absorption system can be used effectively for long term tests.

Preliminary results from the 89-CFC-15 test on August 10, 1989 are presented in Figures 3.A.2. and 3.A.3. In these figures the hatched regions show the one standard deviation uncertainty limit surrounding the line of average values. Key items in the test notes that aid in analysis of this data include:

13:14:29 Coal-Fired Combustor (CFC) ignition
13:18:29 Seed flow initiated
13:58:00 Inverter on-line
14:00:02 Starting magnet, gradual power up
14:15:25 Magnet at 4000 Amps
14:16:50 Increasing seed flow
14:19:50 Begin increasing magnet and inverter
14:26:54 Magnet at full power (2.92 Tesla)
14:54:00 Seed system in manual
15:10:00 Seed flow steadily dropping, trying to restore
15:15:00 Seed system in auto

The PE/AS results show large fluctuations in temperature, root mean square deviations as high as 450 K, around 13:50 that decrease to less than 50 K upon powering on the magnet and inverter. For reference, instrumental uncertainty on a stable laboratory flame is about 15 K. The seed atom density appears to slowly decrease from about $(4 \pm 1) \times 10^{16}$ cm^{-3} at 13:20 to $(3 \pm 1) \times 10^{16}$ cm^{-3} at 14:08. After powering the magnet the seed atom density increases to almost 8×10^{16} cm^{-3} at just before 14:45, at which point the seed atom density drops rapidly to about $(2 \pm 1) \times 10^{16}$ cm^{-3} at 14:51. Measurements after this point were suspect because of the low light transmission due to dirty windows and slag blockage of the ports. By 15:00, light transmission was totally extinguished. The seed atom density measurements seem to match well with the test notes concerning seed feed.

The measurement of seed atom density depends upon a difference in optical depth at two distinct wavelengths and hence is unaffected by changes in light transmission as long as some signal is received; a lower light transmission

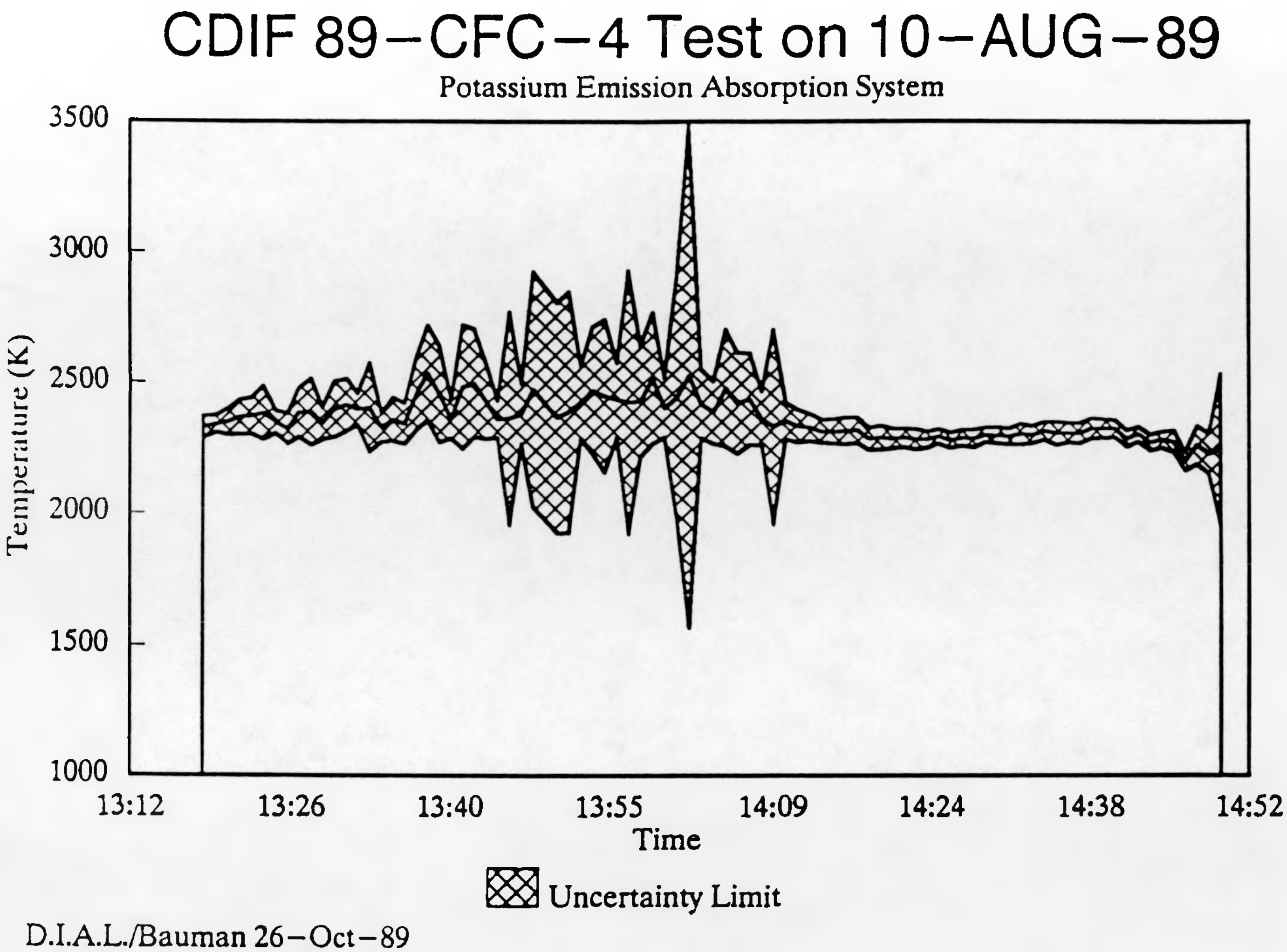

Figure 3.A.2. Temperature versus time for the CDIF 89-CFC-15 test.

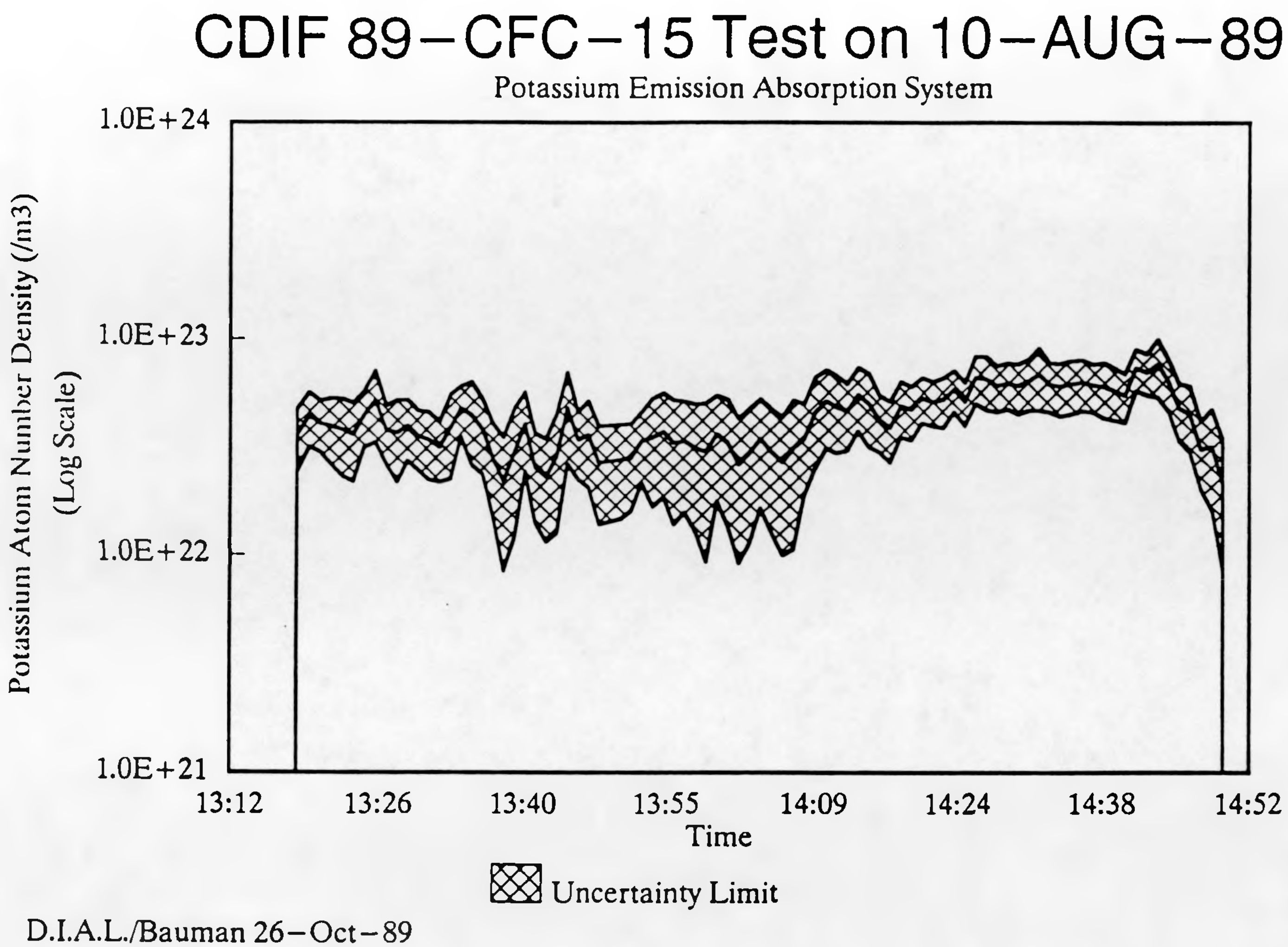

Figure 3.A.3. Potassium seed atom number density versus time for the CDIF 89-CFC-15 test.

may increase the noise in the data but does not affect the accuracy. No appreciable increase in standard deviation was recorded for the test and the variation in seed atom number density throughout the almost two hours of PE/AS data is most certainly real. On the other hand, the temperature measurement is affected by changes in light transmission on the lamp-side only, though not as badly as a single wavelength line reversal measurement. A decrease in reference signal due to dirty windows would cause the measured gas temperature to increase, so that the decrease in measured temperature after 13:45 is also certainly real and may be underestimated due to dirty windows or slag buildup in the lamp-side port.

The reduction in potassium emission fluctuations upon powering of the magnet is striking and most likely represents actual changes in the flow properties but could be due to a reduction in vibrations of the optical mounts affecting the transmission of the lamp signal.

On the 16th of August, again about two hours of PE/AS data was obtained before the light transmission was extinguished. Figures 3.A.4. and 3.A.5. show the results. Reduced light transmission because of slag blockage of the ports is the cause for the very large uncertainty limits. Important times noted in the test notes are:

10:46:15 CFC ignited
10:53:40 Initiating seed flow to combustor
10:59:11 Attempting to increase seed flow to 2%
11:07:00 Seed flow at 2%, start to reduce to 1.7%
11:24:00 Secured seed flow, could not keep steady
12:06:00 Seed flow to combustor started
12:22:42 Magnet powered up, gradual increase
12:38:50 Magnet @ 2.92 Tesla and 5000 Volt on inverter

LMF4-R test at the CFFF: The LMF4-R test at the CFFF was supported with the SLR, MCP, TCLT, and IMPS systems. All of these instruments performed satisfactorily. Since an extensive amount of data was produced by these measurements, a separate data report was prepared (Diagnostic Instrumentation and Analysis Laboratory Data Report, Vol. 9, No. 2, available on request).

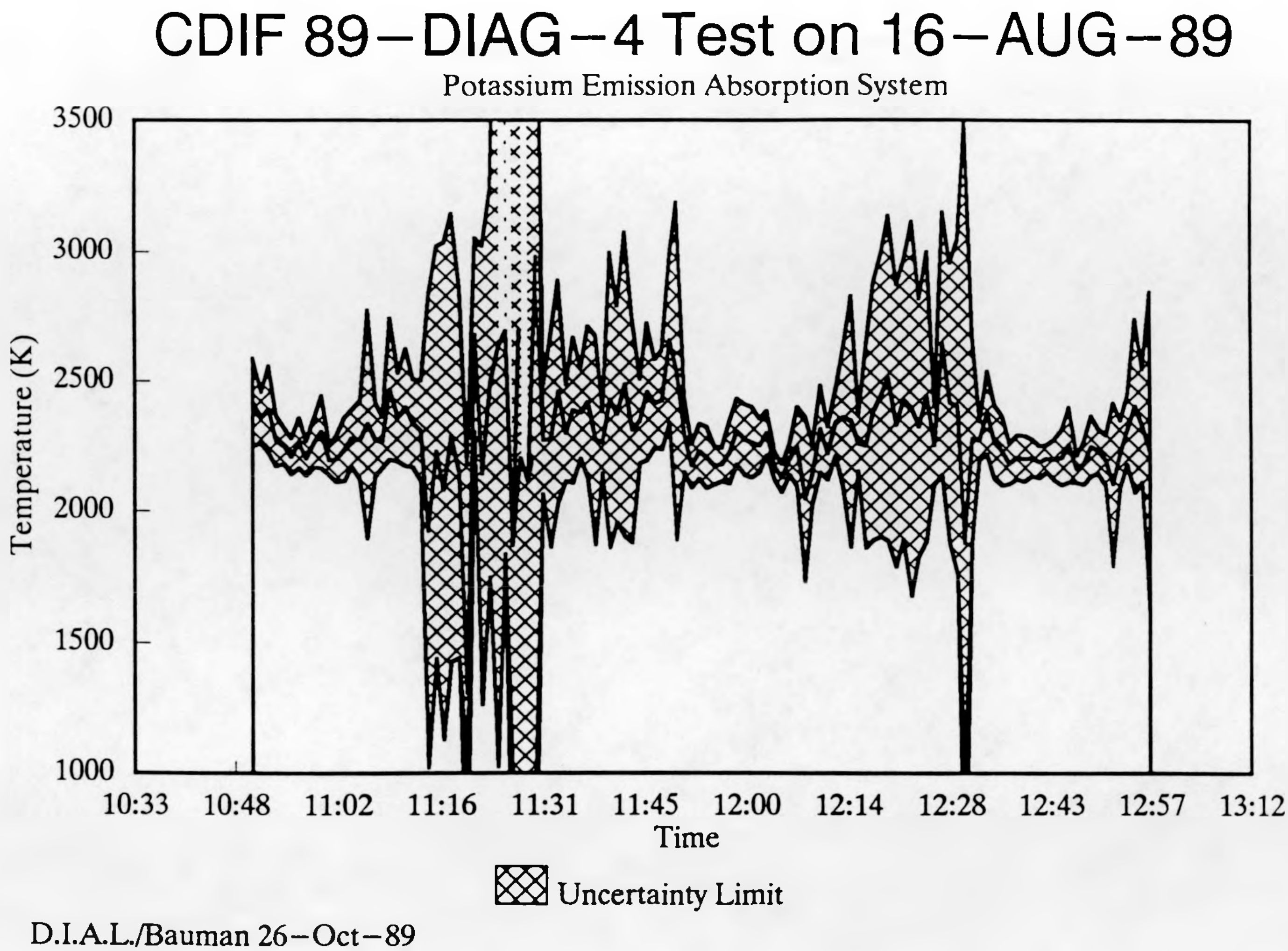

Figure 3.A.4. Temperature versus time for the CDIF 89-CFC-16 test.

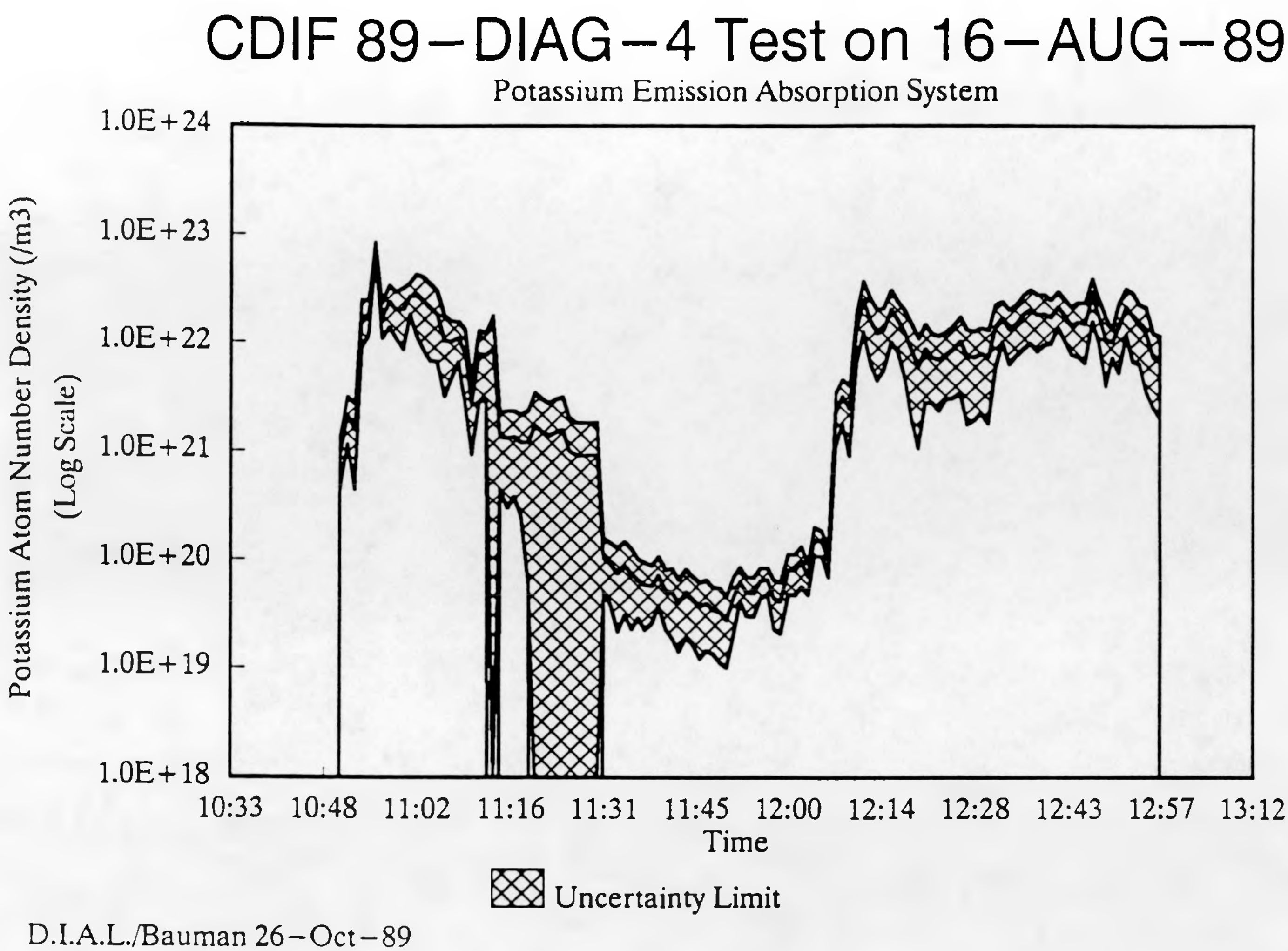

Figure 3.A.5. Potassium seed atom number density versus time for the CDIF 89-CFC-16 test.

Conclusions

Successful measurements at the CDIF on a sustained basis will not be possible until a method of maintaining clear optical access is developed. The measurements which were made were found to be in agreement with calculated data.

Work Forecast

A slag clearing device will be designed and tested to help in the continuing effort to get sustained measurements at the CDIF.

Nomenclature

PE/AS: Potassium Emission/Absorption System (MSU's)
LDV: Laser Doppler Velocimeter System (MSU's)
CDIF: Component Development and Integration Facility (in Butte, Montana)
DIAL: Diagnostic Instrumentation and Analysis Laboratory (at MSU)
GAS: Gas Analysis System (MSU's)
89-CFC-13,14,15: Test Run Designations at CDIF
89-REST-1: Test Run Designations at CDIF
89-DIAG-10,11,12: Test Run Designations at CDIF
MSU: Mississippi State University
CO: Carbon Monoxide
CO_2: Carbon Dioxide
O_2: Oxygen
SO_2: Sulfur Dioxide
PMT: Photo Multiplier Tube
CFC: Coal-Fired Combustor (at CDIF)
LMF4-R: Low Mass Flow Test Sequence Notation (at CFFF)
CFFF: Coal-Fired Flow Facility (at UTSI)
UTSI: The University of Tennessee Space Institute (Tullahoma)
SLR: Sodium Line Reversal System (MSU's)
MCP: Multi-Color Pyrometer System (MSU's)
TCLT: Two-Color Laser Transmissometer System (MSU's)
IMPS: Intrusive Multi-Probe System (MSU's)

B. Field Tests/Instrument Modifications

Worked Performed

Experiments were conducted with the CARS system (see section 1.A of this report), and an IR water detector system during this test.

Infrared Water Detector (IWD) Test for LMF4-R at the CFFF (Kalasinsky, Zhang, and Cook): Water absorbs infrared radiation at a number of wavelengths, but those located near 1.4, 1.9, and 2.7 microns hold the greatest potential for diagnostic purposes in a combustion stream. The radiation emitted from the walls of a combustion facility provide sufficient intensities of infrared light in these regions to allow simple absorption measurements to be made at a single viewing port. The selection of the optimum region for making the necessary measurements depends upon factors such as the amount of water normally in the combustion stream, the minimum amount of excess water which must be detected, and the inherent absorption strengths of water at the wavelengths under consideration. For comparison, the absorption at 2.7 microns is approximately ten times more intense than that at 1.9 microns, and the latter was chosen for the initial tests.

Because the wall can be treated as a blackbody, the emitted intensity from the wall at any given wavelength in the region of interest will depend upon the temperature of the wall. The signal detected at 1.9 microns will depend upon the wall temperature and the amount of water vapor between the wall and the detector. It is necessary, therefore, to monitor temperature fluctuations by measuring the infrared emission of the wall at a nearby wavelength. To accomplish this in the initial tests and evaluation, a system as shown in Figure 3.B.1. was configured. The wall emission was split into two paths by a cold mirror which reflects wavelengths shorter than approximately 2.5 microns and transmits longer wavelengths. The long wavelength component was directed into an appropriate pyrometer such as that in the Multi-Color Pyrometer (MCP) system for monitoring temperature variations. For the tests conducted during LMF4-R, temperature variations were available from TCP and MCP measurements at nearby ports. The short wavelengths were focused onto the entrance slit of a mini-monochromator. The monochromator allowed wavelengths to be selected before being sent to the liquid nitrogen-cooled indium antimonide (InSb) detector.

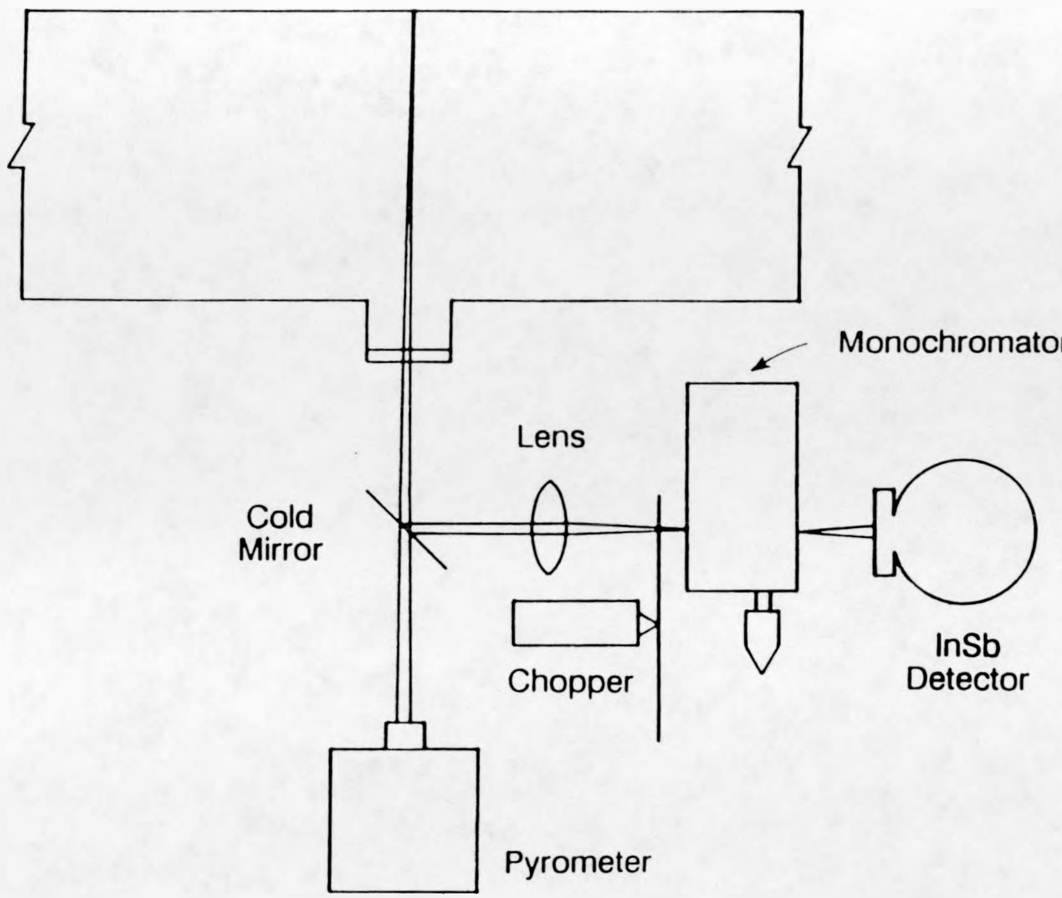

Figure 3.B.1. Infrared Water Detector for the LMF4-R test run at the CFFF.

A chopper was positioned between the lens and monochromator to modulate the signal and provide an AC signal to the amplifier system. Results were recorded on a strip chart. A monochromator response curve was obtained using a calibrated blackbody source.

The extent of absorption of radiation at 1.9 microns by water produced by normal combustion is significant, and preliminary tests at the combustion facility were compared to tests using a laboratory blackbody source to verify the background water level. In tests conducted at penetration 2207 with one, two, and three gallons-per-minute of excess water added to the combustion stream, the signal at 1.9 microns decreased as it would for either a drop in temperature or additional absorption by water. Figure 3.B.2. shows the data recorded at 1.9 microns, while pyrometer data are indicated in Figure 3.B.3. It is not apparent from these figures that a change in water concentration can be distinguished from a change in temperature; however, Figure 3.B.2. does show features which coincided with the opening of a port. With additional air in the combustion stream, some secondary combustion is indicated by the momentary rises in the baseline signal. Either of two possibilities can account for the observed effect: (1) emission of infrared radiation at 1.9 microns by newly formed water vapor, or (2) an increase in the temperature of the gas stream. Since other diagnostic systems did not record increases in temperature, it has been concluded that the former explanation is appropriate; this explanation suggests other experiments which may be useful in the future for detecting water.

A more revealing result regarding the presence of water was obtained during the second group of experiments. In these experiments, the monochromator was scanned while the water was being added, but the wavelength scan was begun only after the signal stabilized after dropping. In this way the temperature of the "source" stabilized before the scan, and the effects of temperature changes and water absorption could be separated. Figure 3.B.4. indicates the variations in the spectra obtained when one, two, three, and four gallons-per-minute of additional water vapor were injected. Marked on the figure are the differences between the intensities at 1.9 microns and 1.65 microns; the latter wavelength would not be absorbed by the water vapor and can be used as a reference point. On a relative scale, there is increasing absorption at 1.9 microns with increasing

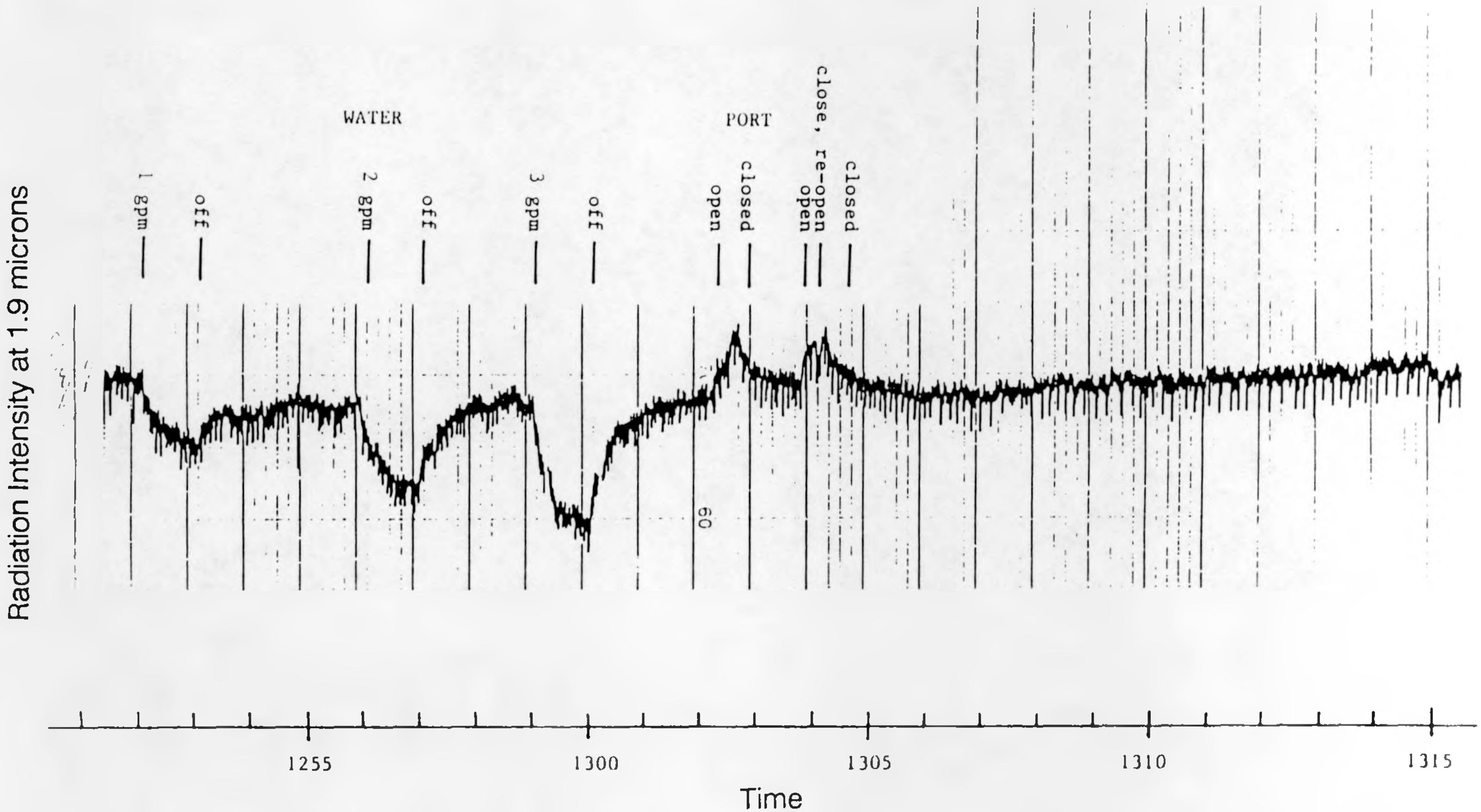

Figure 3.B.2. Variation in radiation intensity at 1.9 microns as different water flow rates are injected in the CFFF furnace.

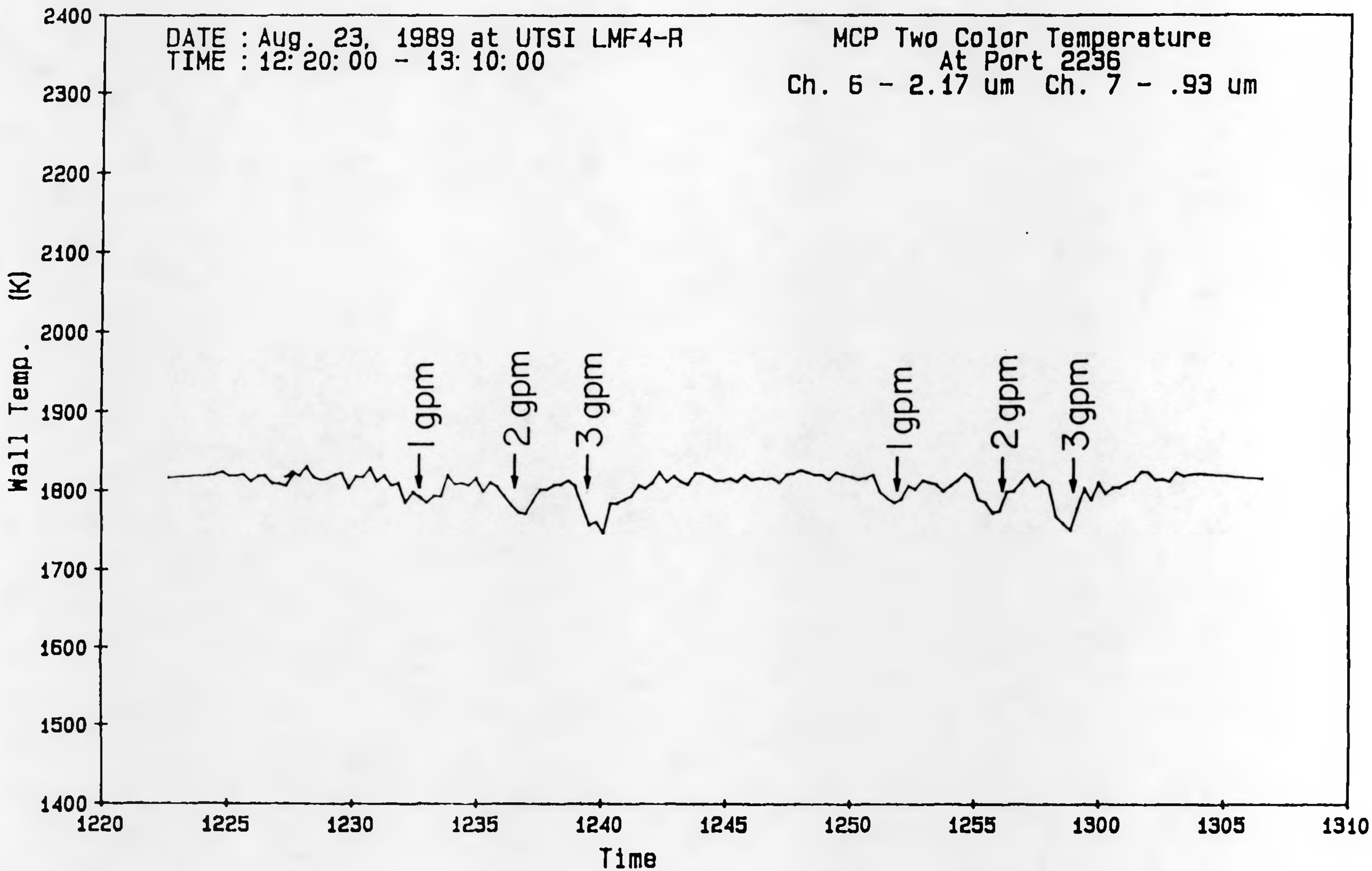

Figure 3.B.3. Variation in CFFF wall temperature as different water flow rates are injected in the furnace.

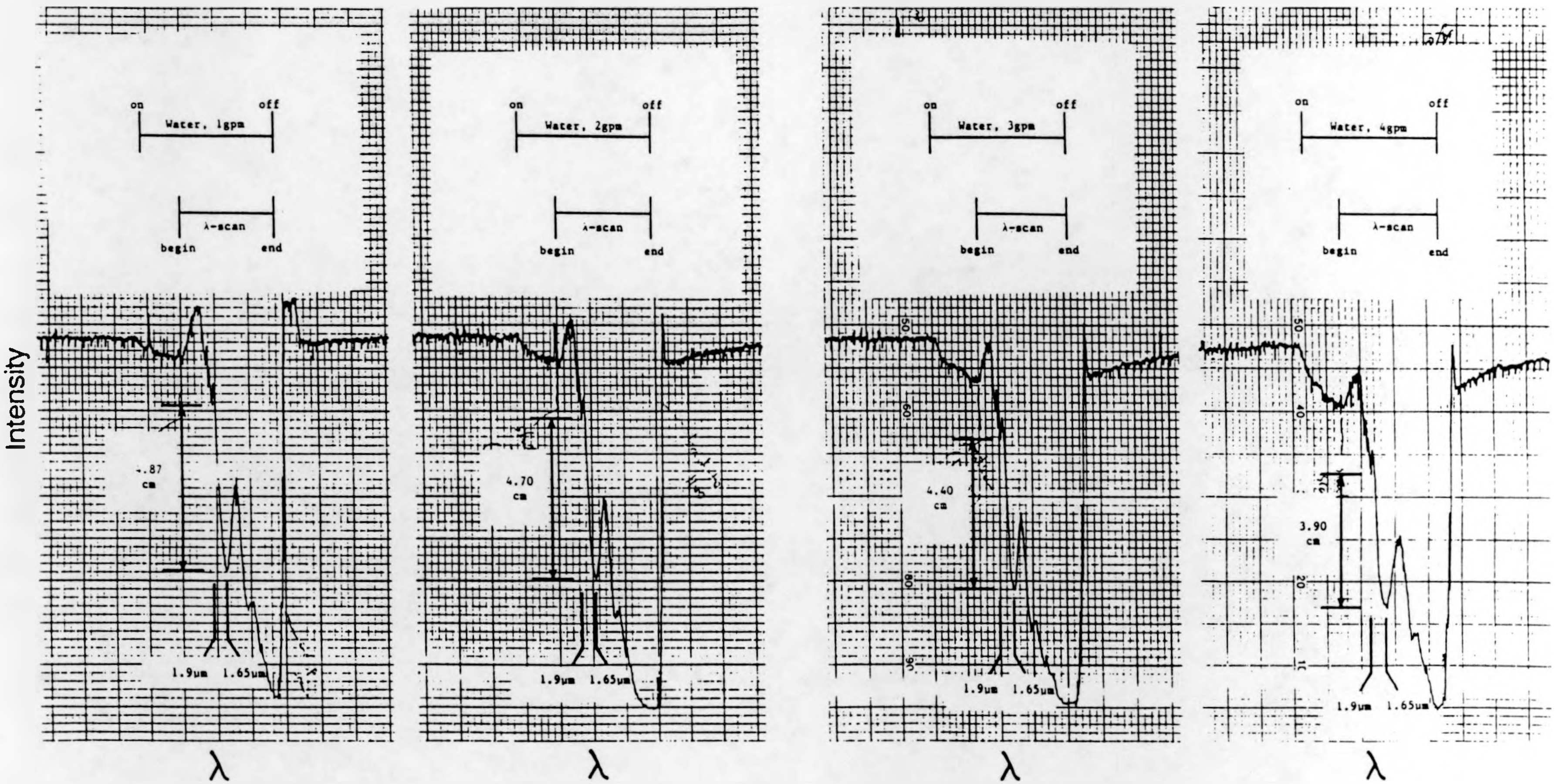

Figure 3.B.4. Strip chart recordings of radiation measured in the 1.65 - 1.9 micron range as water is being injected in the CFFF furnace.

excess water concentration. If the data were stored in a computer, a series of ratioed spectra would show this fact more clearly. In the future, this capability will exist.

Future experiments include installing a computer-controlled stepper motor on the monochromator scan drive and a computer interface for the lock-in amplifier. A set of experiments identical to those attempted during LMF4-R will be conducted with the 3.82-micron pyrometer in place. Emission experiments will be conducted with a window opposite the window through which data are collected (in the same region of the combustion stream as before). A set of experiments identical to those attempted during LMF4-R will be conducted in a cooler region of the downstream system, and absorption experiments using a laboratory blackbody source will conducted at penetrations in a cooler region.

Conclusions

Measurements at the CFFF during the LMF4-R test were successful.

Work Forecast

The LMF4-S test at the CFFF is scheduled for November, 1989. We will be making measurements during this test.

Nomenclature

CARS: Coherent Anti-Stokes Raman Spectroscopy System (MSU's)
IR: Infrared
IWD: Infrared Water Detector
LMF4-R: Low Mass Flow Test Run Notation (at CFFF)
CFFF: Coal-Fired Flow Facility (at UTSI)
MCP: Multi-Color Pyrometer (MSU's)
TCP: Two-Color Pyrometer (MSU's)
InSb: Indium Antimonide
AC: Alternating Current

C. Mobile Instrument Laboratory

The mobile instrument laboratory is essentially completed and is in routine operation.

Task 4. Project Management

This is an ongoing task considered up to date with the submission of this report.

Task 5. Technology Transfer

Preliminary discussions of a proprietary nature were held with Dow Chemical for a new project.