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MASTER

2nd Quarterly Report on
THE EFFECT OF RAPID HEATING
RATE ON COAL NITROGEN AND SULFUR RELEASE

Contract No. DE-AC22-81PC-40273

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For the

U.S. Department of Energy
Pittsburgh Energy Technology Center
Pittsburgh, PA 15236

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FORWARD

This report summarizes technical progress accomplished during the first quarter of the investigation conducted for DOE under contract number DE-AC22-81PC-40273. The work period was September 19, 1981 to December 19, 1981. Work was accomplished under the supervision of Dr. A. B. Witte, program manager, Dr. N. Gat, Principal investigator, Mssrs. L. M. Cohen, and H. M. Bobitch, test conductors, Dr. J. A. Betts, diagnostics, and Mr. M. R. Denison, Analysis. Dr. J. D. Hickerson is the technical officer for DOE.

Other contributors to the program were Dr. W. L. Shackleford, Mssrs. F. L. Hetzel, and R. Yee. Miss V. Christian provided typing and art services.

SUMMARY

A laser pyrolysis technique is applied to the investigation of the effects of heating rate on release of coal-bound sulfur and nitrogen.

An experimental system characterization and calibration has been completed. A detailed documentation was prepared describing the 3-color pyrometer and the data analysis technique. The coal particle feed system has been calibrated to provide accurate mass flow rate at pre-selected particle velocities.

The first batch of samples submitted for chemical analysis will be used for the determination of kinetics parameters at a high heating rate ($\approx 10^6$ K/s). The coal used presently is a Montana Rosebud. Two other coals are available; one is ILL #6 (through EERC) which will need to be pulverized and the second is a Pitt. hv-A (through KVB).

In the course of this work it was confirmed that sieve and drag size distribution of coal differ significantly, and that particle shape effects may be significant in the modelling of particle dynamics.

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1. INTRODUCTION

Background and Objectives:

The objective of the program is to determine the effect of variation in heating rate on the release of fuel-bound nitrogen and sulfur in pulverized coal particles.

Information on fuel-bound nitrogen release in pyrolysis may have great value if it can be used to modify existing large-scale stationary coal burners, or assist in the design of retrofit burners, so as to reduce the proportion of fuel-bound nitrogen which is converted to NO_x rather than N_2 . Since burner design can affect the initial heating rate and since some recent evidence on fuel nitrogen conversion suggests that nitrogen retained in the char is more likely to emerge as N_2 in the flame zone, there is reason to believe that the heating rate parameter can be manipulated to reduce NO_x emission in coal combustion. If, for example, it were found that a low heating rate favors retention of nitrogen in the char, then a control strategy would be to heat the coal gradually through contact with a preheat zone in the burner, predicated on confirmation of the finding that the char catalyzes reduction to N_2 . Of course, an opposite finding in this investigation suggests its own control strategy. How heating rate plays a role in coal pyrolysis is discussed next.

The pyrolysis of coal can be modeled by multiple consecutive and/or parallel reactions. It is generally accepted that different reactions dominate at different ranges of the temperature. The heating rate determines the duration that the coal particle is subjected to a certain temperature range, and consequently, the dominating pyrolysis reactions. Therefore, particles heated at a low rate may undergo pyrolysis reactions different from those particles subjected to a high heating rate. As a result, the end products, the sulfur and nitrogen release, may differ.

The purpose of the present investigation, is to correlate the volatile yield using first order overall reactions, to determine the kinetics parameters, and to develop model for engineering purposes.

The technique employed here uses a high energy IR laser beam to heat coal particles in free flight. The experiment simulates heat fluxes and heating rates which pulverized coal particles experience in actual combustion systems.

The effort during the first quarter was directed mainly towards the application of the diagnostics to the measurements of the spectral radiance from the pyrolysis zone, and the modifications to the hardware. A simple analytical model describing the energy and mass balance was developed for a coal particle undergoing laser pyrolysis. The model helps qualitatively, to explain the laser pyrolysis phenomena. As more experimental data is made available, the model can be used as a quantitative tool. The above subjects were discussed in the first quarterly progress report (January 28, 1982), and in the presentation at the March 4, 1982, Contractor's Review meeting.

During the second quarter, system operation and test procedure were developed. A large number of experiments were performed in which the various measurements (particle temperature, laser parameters, etc.) were checked and analysed for consistency, correctness and reliability. The temperature measuring technique, using the 3-color pyrometer, was refined to provide more accurate values and a better spatial resolution. A data reduction scheme was developed to obtain the particle temperature and area as well as an error band for these quantities. The scheme is a non-linear least square curve fit to the 3-color emission spectrum. As a result of these developments, temperatures of a single or a few particles can be measured with an accuracy of better than 5 percent, typically 1 to 2 percent. The use of a redundant third channel in the pyrometer increases the credibility of the measurements. The complete documentation describing in detail the calibration and the operation of the 3-color pyrometer is given in Appendix A of this report.

Due to the high cost of the chemical analysis, no samples were analysed during the period of time in which the system was checked up. The first samples have been sent for analysis only recently upon completion of the various calibration and checkups.

Progress was also made on several other issues. These are briefly discussed in the following sections.

1. Particle Temperature History and Determination of Rate Constants

Coal particle temperature is measured as a function of position within the laser beam. The laser beam width is typically about eight millimeters and the pyrometer is presently set to a spatial resolution of about 1 mm in the direction of motion of the particles. Typical results are shown in Figure 1.

It can be shown that the particle final temperature is proportional to the product of the laser power density (I) and the particle diameter (D). The heating rate, on the other hand, is proportional to the ratio of these quantities (I/D). Thus, by keeping I and D constant, and changing the particle residence time in the beam (by changing its velocity), one can obtain pyrolysis data at various stations along a heating curve, as explained in Figure 2. This information is then used to determine the kinetics parameters at the given heating rate and final (asymptotic) temperature. The experiments are repeated at other levels of I and other values of D to yield the kinetics parameters for other heating rates.

2. Particle Feed Control

The particle feeder is of a fluidized bed type. The feeder was carefully calibrated both for the solids feed rate and the carrier gas (Argon) flow, both as a function of the fluidizing flow rate. Calibration curves are shown in Figure 3. In order to increase the particle velocity through the laser beam, a diluent stream of Ar is added to the carrier/solids flow in a specially designed feed nozzle shown in earlier reports.

Without the diluent stream, particle velocity changes between 10 to 35 cm/sec while the flow rate of coal varies over three orders of magnitude, from 0.2 to 800 mg/min. For 70 μ m particles, the above conditions correspond to between 7 to 7500 particles/cm³. When diluent is added, the velocity of the particles can be increased by at least two orders of magnitude, while controlling the particle number density at a desired level.

Figure 1. Particle Temperature as a Function of Position in the Laser Beam (Laser Total Power 1025 Watts, $d_p=70\mu\text{m}$):
 (a) reference conditions, I , d_p , and V_p , (b) higher particle velocity, I , d_p , $2.7 V_p$.

Figure 1. (Continued)

Figure 2. This figure shows how the time dependent kinetics data is obtained in the laser pyrolysis experiment; (a) shows typical particle temperature rise, and volatile yield during the heating process; by allowing a long residence time in the beam (low particle velocity) the asymptotic yield and ΔT are measured as in (b); by allowing a short residence time (high particle velocity) particles are collected at intermediate positions along the heating curve as in (c).

Figure 3. Calibration Curves for Fluidized Bed Coal Feeder, Carrier Gas and Solids Feed Rate

3. Particle Size Distribution

A comparison between the sieve size and the drag size of the coal was presented in the March 4, meeting, and shown here in Figure 4. The implication of these curves is important in the calculation of trajectories* in coal combustors. In the present and in other pyrolysis studies, these curves may indicate that not all the particles reach the same final temperature, and that some particles take longer time to heat up than others. The curves also imply that internal temperature gradients may be significant at extremely high heating rates.

The analysis of the pyrolysis of pulverized coal should take all of these factors into account. A statistical approach may be needed to account for particle sizes and shape distribution. A model, taking into account the internal temperature gradients should be used as well. However, this analysis is more complicated and will not be pursued at this point.

The experimental proof to the internal gradient effect was manifested by the "rocketing" effect of particles heated on one side only. These particles released gases preferentially from the heated side. When the particles were heated from two opposing directions, the "rocketing" effect disappeared.

* and hence burning patterns

DRAG SIZE DISTRIBUTION OF DRIED SIFTED
MONTANA ROSEBUD COAL

$$\rho = 1.35 \text{ gm/cm}^3$$

Figure 4. Comparison between Sieve Size and Drag Size Distribution

PLANS FOR NEXT STUDY PERIOD

The next study period will be dedicated to the gathering of experimental data. The coal samples will be analyzed before and after passing through the laser beam. By adjusting the particle velocity through the fixed size beam, the kinetics are "frozen" at various stages along the particle heating curve. The information thus obtained is time-dependent pyrolysis data. This data together with the measured temperature history will provide the required kinetics rate parameters.

APPENDIX A

CONTENTS

- (1) Data Reduction Scheme for 3-Color Pyrometer, dated 4 February 1982.
- (2) Statistical Error Estimate for the Temperature and Area Measured by the 3- λ Pyrometer, dated 30 March 1982.
- (3) Documentation of 3-Color Pyrometer, dated 12 April 1982.

DEFENSE AND SPACE SYSTEMS GROUP

ONE SPACE PARK - REDONDO BEACH - CALIFORNIA 90278

INTEROFFICE CORRESPONDENCE

TO: J. A. Betts

cc: H. M. Bobitch
L. M. Cohen
A. B. Witte

82.K513.6-52
DATE: 4 February 1982

SUBJECT: Data Reduction Scheme for
3-Color Pyrometer

FROM: N. Gat
BLDG. R1 MAIL STA. 1028 EXT. 61694

I have tried a simple least squares approach to determine the temperature and the area of the radiating coal particles. It seems to work quite well in a couple of numerical examples I have tried. To be convinced that it always works we may have to program it on a computer since the manual work is extensive. I think it is worth trying.

Nahum Gat

NG:vc

OPTIMIZATION TECHNIQUE FOR THE DETERMINATION OF THE TEMPERATURE AND THE AREA OF A RADIATING SURFACE USING A THREE-COLOR PYROMETER

1. BASICS

The emissive power of a black body follows Plank's spectral distribution

$$I_b(\lambda, T) = \frac{2 \pi C_1}{\lambda^5 (e^{C_2/\lambda T} - 1)} \quad \frac{\text{(power)}}{\text{(area), (unit wave length)}} \quad (1)$$

A coal particle of area A and emissivity ϵ emits radiation given by,

$$I(\lambda, T) = \epsilon I_b(\lambda, T) A \quad \text{Power/(unit wave length)}. \quad (2)$$

Each one of the pyrometer detectors can "see" a portion of the radiation given in (2), depending on $S_F(\lambda)$ the spectral response of the filter in front of it.

$$I_D(T) = \int_0^\infty I(\lambda, T) \cdot S_F(\lambda) d\lambda, \quad \text{(Power)} \quad (3)$$

In addition to the spectral response of the filter, the detector has a spectral response, $S_D(\lambda)$, and an electrical circuit which converts the power to an electrical signal (e.g. voltage). These effects and the geometrical factor are given by a calibration constant, C, which is specific to a given detector/electrical-circuit/filter combination.

Thus

$$v = C I_D(T) = C \epsilon A \int_0^{\infty} \frac{2 \pi C_1 S_F(\lambda)}{\lambda^5 (e^{C_2/\lambda T} - 1)} d\lambda \quad (\text{volts}) \quad (4)$$

where C has units of volt/power.

2. THE LEAST SQUARES TECHNIQUE

Equation (4) gives the expected voltage given by each detector as a function of the body temperature, T , and its surface area, A . In an actual experiment, three voltages V_1 , V_2 , and V_3 are observed, and the problem is to find the most probable values of T and A which could produce these voltages.

The first step is to write the sum of the deviation between the observed and the expected voltages:

$$\sum_{n=1}^3 \Delta_n^2 = \sum_{n=1}^3 (V_n - v_n)^2 \quad (5)$$

The goal is, thus, to find T and A for which $\sum_1^3 \Delta_n^2$ is minimized. This can be expressed by equating the two partial derivatives to zero;

$$\frac{\partial}{\partial A} \sum_1^3 \Delta_n^2 = 0 \quad (6)$$

and

$$\frac{\partial}{\partial T} \sum_1^3 \Delta_n^2 = 0. \quad (7)$$

Explicitly, equations (6) and (7) can be written as follows:

$$\sum_{n=1}^3 \left[\left(V_n - C_n \epsilon A \int_0^{\infty} I_b(\lambda, T) S_{F,n}(\lambda) d\lambda \right) \right. \\ \left. C_n \int_0^{\infty} I_b(\lambda, T) S_{F,n}(\lambda) d\lambda \right] = 0 \quad (8)$$

and

$$\sum_{n=1}^3 \left[\left(V_n - C_n \epsilon A \int_0^{\infty} I_b(\lambda, T) S_{F,n}(\lambda) d\lambda \right) \right. \\ \left. C_n \frac{\partial}{\partial T} \int_0^{\infty} I_b(\lambda, T) S_{F,n}(\lambda) d\lambda \right] = 0 \quad (9)$$

where the subscript n is added to designate the corresponding values of each detector.

$S_{F,n}(\lambda)$ is not a function of temperature, and the differentiation in equation (9) can be performed to yield

$$\frac{\partial}{\partial T} \int_0^{\infty} I_b(\lambda, T) S_{F,n}(\lambda) d\lambda = \int_0^{\infty} \frac{2 \pi C_1 C_2 e^{C_2/\lambda T} S_{F,n}(\lambda) d\lambda}{\lambda^5 (e^{C_2/\lambda T} - 1)^2 \lambda T^2} \quad (10)$$

Equations (8) and (9) are sufficient to determine the two unknown A , and T . The problem in solving these equations is that no closed form solution can be obtained for T . The two equations can be rewritten, though, to yield the value of A as follows:

$$A = \frac{\sum_{n=1}^3 v_n c_n \int_0^{\infty} I_b(\lambda, T) S_{F,n}(\lambda) d\lambda}{\epsilon \sum_{n=1}^3 \left[c_n \int_0^{\infty} I_b(\lambda, T) S_{F,n}(\lambda) d\lambda \right]^2} \quad (11)$$

$$A = \frac{\sum_{n=1}^3 v_n c_n \int_0^{\infty} \frac{\partial I_b(\lambda, T)}{\partial T} S_{F,n}(\lambda) d\lambda}{\sum_{n=1}^3 c_n^2 \int_0^{\infty} I_b(\lambda, T) S_{F,n}(\lambda) d\lambda \int_0^{\infty} \frac{\partial I_b(\lambda, T)}{\partial T} S_{F,n}(\lambda) d\lambda} \quad (12)$$

In a simplified nomenclature, these equations can be rewritten as

$$A = \frac{\sum_{n=1}^3 v_n \dot{v}_n}{\sum_{n=1}^3 v_n^2}, \quad (11a)$$

and

$$A = \frac{\sum_{n=1}^3 v_n \frac{\partial v_n}{\partial T}}{\sum_{n=1}^3 \left(\frac{\partial v_n}{\partial T} \right) v_n}. \quad (12a)$$

To solve equations (11a) and (12a), we need to figure the expected detector voltage v_n and the variation of that voltage with the surface temperature. Using filters with a given "window", the technique to obtain the required values is time consuming. A simplified approach is shown later.

To prove that the two equations above are not identical, the right hand side of both equations are equated to each other. After some manipulation, the final equation obtained is

$$\begin{aligned} & (v_1 v_2' - v_1' v_2)(V_1 v_2 - V_2 v_1) + (v_1 v_3' - v_1' v_3)(V_1 v_3 - V_3 v_1) + \\ & (v_2 v_3' - v_2' v_3)(V_2 v_3 - V_3 v_2) = 0 \end{aligned} \quad (12b)$$

where

$$v' = \frac{\partial v}{\partial T}$$

Equation (12b) is a complicated function of temperature and cannot be easily solved.

3. SOLUTION TECHNIQUE

Equations (11) and (12) cannot be solved explicitly for T and A. Thus the simplest way -- not the most elegant, though -- is to determine the unknown by trial and error. That is done by choosing a temperature, performing the required integration numerically and obtaining the values A_1 and A_2 from equations (11) and (12), respectively. The quantity $\epsilon = A_1 - A_2$ is then plotted versus the temperature. The accompanying numerical example shows that in the range of temperatures of practical interest there is only one solution to the problem. Therefore, the value of ϵ can either be positive for temperatures higher than the true temperature and negative for lower temperatures or vice versa. In other words, $\epsilon = 0$ exists for only one temperature and ϵ is positive on one side of the curve and negative on the other.

To save computing time, the numerical integration can be performed for each filter in advance, and tabulated as a function of temperature. The computer can store the data and interpolate to obtain intermediate values if needed.

4. NUMERICAL EXAMPLE

For simplicity let's assume that each filter has an ideal step function spectral response, i.e.

$$S_{F,n}(\lambda) = \begin{cases} 0 & (0 < \lambda < \lambda_{n,1}) \\ 1 & (\lambda_{n,1} \leq \lambda \leq \lambda_{n,2}) \\ 0 & (\lambda_{n,2} < \lambda < \infty) \end{cases} \quad (13)$$

In that case the integrals in equations (11) and (12) can be solved explicitly.

$$I_D = \int_0^{\infty} I_b(\lambda, T) S_{F,n}(\lambda) d\lambda = \int_{\lambda_1}^{\lambda_2} I_b(\lambda, T) d\lambda =$$

$$(F_{\lambda_2 T} - F_{\lambda_1 T}) \sigma T^4 = \Delta F_{\lambda_1 T \rightarrow \lambda_2 T} \sigma T^4 \quad (14)$$

where the value of $\Delta F_{\lambda_1 T \rightarrow \lambda_2 T}$ can be obtained from tables or figures. The second integral is obtained as follows:

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$$\int_0^{\infty} \frac{\partial I_b(\lambda, T)}{\partial T} S_{F,n}(\lambda) d\lambda = \int_{\lambda_1}^{\lambda_2} \frac{2 \pi C_1 C_2 e^{C_2/\lambda T}}{\lambda^5 (e^{C_2/\lambda T} - 1)^2 \lambda T^2} d\lambda, \quad (15)$$

Modifying the integration variable and integrating by parts yields:

$$\begin{aligned} T^3 \int_{\lambda_1 T}^{\lambda_2 T} \frac{2 \pi C_1 C_2 e^{C_2/\lambda T} d(\lambda T)}{(\lambda T)^2 (e^{C_2/\lambda T} - 1)^2 (\lambda T)^4} &= T^3 \left[\frac{2 \pi C_1}{(e^{C_2/\lambda T} - 1) (\lambda T)^4} \right]_{\lambda_1 T}^{\lambda_2 T} + \\ &4 \int_{\lambda_1 T}^{\lambda_2 T} \frac{2 \pi C_1 d(\lambda T)}{(e^{C_2/\lambda T} - 1) (\lambda T)^5} \Bigg] = T^3 \left[z(\lambda T) \right]_{\lambda_1 T}^{\lambda_2 T} + 4 \sigma \Delta F_{\lambda_1 T \rightarrow \lambda_2 T} = \\ &= \sigma T^3 \left[\frac{\Delta(z\lambda T)}{\sigma} + 4 \Delta F \right] \end{aligned} \quad (16)$$

where

$$z = \frac{2 \pi C_1}{(e^{C_2/\lambda T} - 1) (\lambda T)^5} = \frac{I_b(\lambda, T)}{T^5}$$

z is a function of the variable (λT) only. For clarity, the functions ΔF and $\frac{1}{\sigma} \Delta(z\lambda T)$ are shown schematically in Figure 1, for three ideal filters.

The filters are 0.8 to 0.82 μm , 0.9 to 0.92 μm , and 1.10 to 1.12 μm .

Using equations (14) and (16), in equations (11) and (12), respectively, the solution becomes:

$$A = \frac{\sum_{n=1}^3 V_n C_n \Delta F_n}{\epsilon \sigma T^4 \sum_{n=1}^3 (C_n \Delta F_n)^2}, \quad (17)$$

$$A = \frac{\sum_{n=1}^3 V_n C_n \left[\frac{1}{\sigma} \Delta (z\lambda T)_n + 4 \Delta F_n \right]}{\epsilon \sigma T^4 \sum_{n=1}^3 C_n^2 \Delta F_n \left[\frac{1}{\sigma} \Delta (z\lambda T)_n + 4 \Delta F_n \right]}. \quad (18)$$

For the purpose of our numerical example, we assume a surface temperature of 5000°R and an area of 1 ft². Equations (4), (14) and Figure 1 are used to obtain the detector output (assuming all the detectors are equal, and that they have a flat spectral response and that the calibration constants are all $C_n = 10^{-4}$ volts/BTU/hr).

$$v_{0.8} = 1.035 \text{ volts,}$$

$$v_{0.9} = 1.170 \text{ volts,}$$

$$v_{1.1} = 1.215 \text{ volts.}$$

To demonstrate the solution technique, we assume that during an experiment, the three detectors gave the following reading,

$$V_{0.8} = 1.0 \text{ volt,}$$

$$V_{0.9} = 1.3 \text{ volts,}$$

$$V_{1.1} = 1.4 \text{ volts}$$

Using equations (17) and (18) and Figure 1, we calculate the values of $\epsilon = A_1 - A_2$ for assumed temperatures in the range 3000 to 6500°R. The results are shown in Figure 2.

If more than one solution is found in the range of interest (e.g. there could be two or three temperatures for which $\epsilon = 0$), then the corresponding T and A should be plugged into equation (5) to obtain the absolute minima (and the local minimas).

Figure 1

$$\epsilon = A_1 - A_2$$

Σ

+ .01

461510

0.0

1000

2000

3000

5000

10000

$T (^{\circ}R)$

- .01

- .02

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ONE SPACE PARK - REDONDO BEACH - CALIFORNIA 90278

INTEROFFICE CORRESPONDENCE

TO: J. A. Betts

CC: H. M. Bobitch
L. M. Cohen
A. B. Witte

82.K513.6-56
DATE: 30 March 1982

SUBJECT: Statistical Error Estimate for the
Temperature and the Area Measured
with the 3- λ Pyrometer.

FROM: N. Gat

BLDG.

MAIL STA.

EXT.

R1

1028

61694

The enclosed simplified analysis may be appropriate for estimating the errors involved in the calculation of temperature and area by the non-linear curve-fitting technique which was described in an earlier IOC.

Statistical Error Analysis for the Temperature and the Area Obtained by the Least Squares Technique

Ref. 1: Data Reduction Scheme for 3-Color Pyrometer,
N. Gat, IOC #82.K513.6-52, Feb. 4, 1982.

General

Curve fitting of experimental data, by the "least-squares" technique, can be applied for optimizing the parameters of a general functional relationship such as $y = f(x; A, B)$ where y = dependent variable, x = independent variable, and A and B are parameters. In general the following statistical parameters are used to describe the quality of the curve-fit:

$$S_y = \pm \sqrt{\frac{\sum_{i=1}^N (y_i - \bar{y})^2}{N-1}}, \quad (1)$$

$$S_{y \cdot x} = \pm \sqrt{\frac{\sum_{i=1}^N (y_i - y_{ic})^2}{N-2}}, \quad (2)$$

$$r = \sqrt{1 - \frac{S_{y \cdot x}^2}{S_y^2}} \quad (3)$$

Where S_y is the standard deviation of the dependent variable, $S_{y \cdot x}$ is the standard error of estimate of the same variable, and r is a correlation coefficient. When $r=1$, a perfect fit exists (i.e. for each point $y_i = y_{ic}$), when $r = 0$, a poor fit exists (i.e. $y_{ic} = \bar{y}$). See sketch 1.

SKETCH 1: Nomenclature in the Curve Fitting Statistics. y_i are measured points, y_{ci} are computed points.

SKETCH 2: Detector's voltage dependence upon wavelength for given parameters. Variations in the parameters T and A will produce an error in the output which corresponds to the standard Error of Estimate, assuming that the errors are normally distributed.

The correlation coefficient describes the correlation between the dependent and the independent variables.

3-λ Pyrometer Data Reduction

In our case (Ref. 1) the measured quantity, or the dependent variable, is the detector's voltage. The independent variable is the wavelength, and the parameters A and B are the temperature and area of the emitting surface. The functional relationship, shown in sketch 2, is given by

$$v = v(\lambda; T, A). \quad (4)$$

A direct application of the statistical analysis gives therefore, a correlation between the detector output and the wavelength for the parameters which were found in the curve-fit analysis. We still do not have an idea about the "goodness" of the parameters (temperature and area).

Since we are interested in the effect of temperature and area on the dependent variable, voltage, and since the wavelengths of the detectors are fixed, we may write

$$v_{\lambda} = v_{\lambda}(T, A). \quad (5)$$

Therefore

$$dv_{\lambda} = \left(\frac{\partial v_{\lambda}}{\partial T} \right)_A dT + \left(\frac{\partial v_{\lambda}}{\partial A} \right)_T dA. \quad (6)$$

The source of error in the voltage is now expressed in terms of the influence coefficients (the partial derivatives). In the worst case, when the error is due to only one of the parameters

we may write

$$\Delta V_{\lambda} = \left(\frac{\partial V}{\partial T} \right)_A \Delta T, \quad (7)$$

or

$$\Delta V_{\lambda} = \left(\frac{\partial V}{\partial A} \right)_T \Delta A. \quad (8)$$

From which we get

$$\Delta T = \pm \Delta V_{\lambda} \frac{1}{\left(\frac{\partial V_{\lambda}}{\partial T} \right)_A} \quad (9)$$

and

$$\Delta A = \pm \Delta V_{\lambda} \frac{1}{\left(\frac{\partial V_{\lambda}}{\partial A} \right)_T} \quad (10)$$

The error in the dependent variable, ΔV , can be taken as the value of $S_{y \cdot x}$ which is the standard error of estimate for the voltage.

Hence,

$$\Delta V = \pm \sqrt{\frac{\sum_{n=1}^N (V_n - v_n)^2}{n-2}} \quad (11)$$

And the derivatives in equations 9 and 10 are given in Reference 1.

Numerical Example

This example follows that given in Reference 1. The three filters were assumed to be ideal, and the calculated and measured voltages were as follows

wave length	theoretically expected voltage	measured voltage
0.8 -0.82	1.035	1.0
0.9 -0.92	1.170	1.3
1.10-1.12	1.215	1.4

The surface was 1 ft² at 5000°R.

Using equation 2 (or 11) we get the standard error of voltage estimate;

$$\Delta V = \pm \sqrt{\frac{(1.0-1.035)^2 + (1.3-1.170)^2 + (1.4-1.215)^2}{1}} = \pm 0.2288v$$

Using Figure 1 in Reference 1 we get the derivatives in equations 9, and 10 as follows.

$$\left(\frac{\partial V}{\partial T}\right)_A = \sigma T^3 A C_n \epsilon \left[\frac{1}{\sigma} \Delta(z\lambda T) + 4\Delta F \right],$$

and

$$\left(\frac{\partial V}{\partial A}\right)_T = \sigma T^4 \Delta F C_n \epsilon.$$

The table below summarizes the data obtained from Figure 1.

wave length	ΔF	$\frac{1}{\sigma} \Delta(z\lambda T)$	$\frac{\partial v}{\partial T} (\frac{\text{volts}}{^{\circ}\text{R}})$	$\frac{\partial v}{\partial A} (\frac{\text{volts}}{\text{ft}^2})$
.8-.82	.0108	.0254	14.83×10^{-4}	1.168
.9-.92	.0120	.0204	14.79×10^{-4}	1.298
1.1-1.12	.0132	.0088	13.32×10^{-4}	1.427

Using equation (9) and (10), the error in the temperature and in the area is easily obtained. To be conservative the error is calculated on the basis of the worst wavelength.

$$\Delta T = \frac{0.2288}{13.32 \times 10^{-4}} = \pm 171^{\circ}\text{R} = \pm 95\text{K}$$

and

$$\Delta A = \frac{0.2288}{1.168} = \pm 0.195 \text{ ft}^2.$$

To summarize, the errors in the parameters that could produce the corresponding error in the detector's output are $\pm \frac{171}{5000} 100 = \pm 3.42\%$ in the temperature, and $\pm \frac{0.195}{1.0} 100 = \pm 19.5\%$ in the area.

TRW

DEFENSE AND SPACE SYSTEMS GROUP

ONE SPACE PARK - REDWOOD BEACH - CALIFORNIA 90278

INTEROFFICE CORRESPONDENCE

82.K311-1-027

TO: N. Gat R1/1028

CC: see below

DATE: April 12, 1982

SUBJECT: DOCUMENTATION OF 3-COLOR PYROMETER

FROM: J. Betts

BLDG.

MAIL STA.

EXT.

R1

1196

61453

Attached is a document reviewing the use, calibration and status of the 3-color pyrometer. Let me know if any additions or corrections are needed to make this document complete.

JB/cmt

cc: H. Bobitch R1/1044
L. Cohen R1/1028
C. McCully 01/1151
W. Shackelford R1/1184
A. Witte R1/1032

CALIBRATION AND STATUS OF 3-COLOR PYROMETER

Description of the Pyrometer

A schematic drawing showing the current configuration of the three color pyrometer used in the coal heating experiments is shown in figure 1. Light from the source is collected by a 140 mm focal length, 34 mm diameter achromatic focussing lens (Rolyn Catalog number 20.0275) which forms a 1:1 image of the observed scene at the limiting aperture of the system. The light is then chopped to allow phase sensitive detection and then passes through a 1 mm by 4 mm slit at the focal point of the lens which serves as the limiting aperture of the system. A 31 mm focal length, 17.8 mm diameter achromatic lens (Rolyn Catalog number 20.0080) then collimates the collected light. Approximately 1/3 of the collimated light is directed into the 1.1 micron channel with the first beam splitter, another 1/3 of the collimated light is directed into the 0.95 micron channel with a second beam splitter while the remaining 1/3 of the collimated light passes into the 0.8 micron channel. Each channel consists of a bandpass filter, focussing lens and silicon photodiode detector. The detectors are positioned so that they are all the same distance from the aperture. Care was taken that the detectors were positioned so that no beam clipping occurred (see the section on previous problems for a discussion of problems encountered with beam clipping). The filters were positioned so the maximum signal was obtained from the 1.1 micron channel (the lowest signal channel) to make the ratios from the different signal channels closer to 1. The detectors used were Centronix, OSI-5K single element hybrid silicon photodiodes with a 5 mm² active area. Preamplifiers, resistors and capacitors are mounted around the central photodiode so that direct conversion of light signal to voltage is obtained with no further amplification. The response of these detectors is shown in figure 2 in which lines are drawn at the three wavelengths used with the pyrometer. The x's in this figure show the actual response for each pyrometer channel as determined from the calibration. This includes optical system losses, filter transmissions and detector response. Note that the detector response drops dramatically at 1.1 micron, illustrating why the signal in this channel is always lowest in test runs. A data sheet on the detectors is attached (figure 3) for reference. The normalized transmission of the three interference filters used in the pyrometer is shown in Figure 4. The maximum transmissions for the 0.8, 0.95 and 1.1 micron filters are 58.3%, 53.5% and 42.7% respectively. The integral of the filter transmission for each channel times the blackbody function was calculated numerically using a computer.

program. Table 1 shows the numerical values of this integral in units of watts/cm² ster.

Table 1. Blackbody Temperature versus Integral of Blackbody Function times Filter Transmission.

Temperature (K)	Beff= BB(wavelength, Temperature)*S(wavelength)		
	0.80 microns	0.95 microns	1.1 microns
1000	5.81(-6)	4.20(-5)	1.17(-4)
1100	2.96(-5)	1.66(-4)	5.60(-4)
1200	1.15(-4)	5.22(-4)	1.51(-3)
1300	3.62(-4)	1.38(-3)	3.48(-3)
1400	9.69(-4)	3.16(-3)	7.13(-3)
1500	2.27(-3)	6.49(-3)	1.33(-2)
1600	4.79(-3)	1.22(-2)	2.29(-2)
1700	9.26(-3)	2.12(-2)	3.70(-2)
1800	1.66(-2)	3.48(-2)	5.67(-2)
1900	2.81(-2)	5.42(-2)	8.31(-2)
2000	4.50(-2)	8.07(-2)	1.17(-1)
2100	6.89(-2)	1.16(-1)	1.60(-1)
2200	1.01(-1)	1.61(-1)	2.13(-1)
2300	1.45(-1)	2.17(-1)	2.75(-1)
2400	2.00(-1)	2.85(-1)	3.49(-1)
2500	2.70(-1)	3.67(-1)	4.35(-1)
2600	3.56(-1)	4.63(-1)	5.32(-1)
2700	4.59(-1)	5.75(-1)	6.42(-1)
2800	5.82(-1)	7.03(-1)	7.64(-1)
2900	7.26(-1)	8.47(-1)	8.99(-1)
3000	8.93(-1)	1.01	1.05

Use of the Pyrometer

When the pyrometer is used it should be aligned so that the source whose temperature is to be measured is 28 cm (2 times the focal length of the collecting lens) from the collecting lens. The field of view of the pyrometer in this focal plane was measured by moving a tungsten filament light bulb with a 1 mm pinhole in front of it across the field of view of the pyrometer and looking for a drop in the intensity as the source passed out of the field of view of the instrument. A 2-axis stage was used to accurately measure the position where an intensity drop occurred. The drop in

intensity as the source passed out of the field of view of the instrument was very sharp. The measurement yielded a field of view of 1 mm as the source was scanned vertically and 3.5 mm as the source was scanned horizontally.

When the pyrometer is used, care must be taken that light from sources other than that to be measured (i.e. room light) does not enter the system in a location in front of the chopper. A background measurement showed a detectable signal when the lockin amplifiers were set for a sensitivity of 10 microvolts full scale. This signal disappeared when the aperture of the system was blocked. The spectrum of the fluorescent lights in the room where the experiments were conducted showed little or no radiation at wavelengths longer than 0.7 microns. Thus the source of this signal may have been something other than room lights. For applications where low signals are expected it may be desirable to place a chopper close to the source to be measured to eliminate any stray light signals between the chopper and the detectors. It may also be desirable to position a nonreflecting black background behind the source whose temperature is to be measured to insure that light from distances farther than the focal plane of the pyrometer does not enter the instrument.* The arc jet which runs the HF/DF laser in Building 67 was turned on while the pyrometer was running. No detectable noise from this source was apparent in the detector signal.

Calibration of Radiometer

The pyrometer was calibrated in the configuration shown in Figure 1 with both the Blackbody and Eppley lamp sources. The system was carefully aligned and the beam splitters were positioned for optimum signal in the 0.95 and 1.1 micron channels. The calibrations were checked for consistency by comparing ratios of calibration constants calculated from the voltage ratios and the known source irradiance. A summary of the calibration ratios is shown in Table 2.

Table 2. Summary of Calibration Ratios

<u>Aperture</u>	<u>c1/c2</u>	<u>c1/c3</u>	<u>c2/c3</u>
.2	2.24	12.4	5.55
.1	2.21	12.4	5.61
.05	2.05	11.7	5.67
.025	2.14	12.5	5.86
Eppley	2.08	11.4	5.46

Note that there is good agreement between constants determined with different blackbody aperture sizes. This was not the case with the previous pyrometer configuration that is described in a later section. Also note that the calibration ratios determined with the Eppley lamp are somewhat lower than those determined with the Blackbody.

The effect of these deviations on temperature were checked by using an average of the calibration constants as the fixed calibration constant and then calculating the blackbody temperature for each aperture using the voltage signals obtained. The details of this temperature calculation are presented in the next section. The spread in temperatures was 25 K which is an acceptable error limit. The recommended calibration constant ratios are then $c1/c2 = 2.14$, $c1/c3 = 12.1$ and $c2/c3 = 5.63$. These ratios were converted into absolute numbers for calibrations constants $c1$, $c2$, and $c3$ of 5.141(6), 2.407(6) and 4.107(5) mv/watt respectively.

Data Reduction

Temperatures are determined from the voltages measured for each channel, the calibration constants and the integrals $Beff(T)$ which were tabulated for each channel in Table 1. The measured voltage in each channel, V_n can be expressed as

$$V_n = A \epsilon c_n Beff(T)$$

where A is the emitting area of the source, ϵ is the source emissivity, and c_n is the calibration constant for the n th channel. The emitting area and emissivity can be eliminated by taking ratios of voltages and determining temperature by fitting these voltage ratios to the ratios of calibration constants and blackbody integrals. A listing of a computer

program (TEMPTR) that will calculate temperatures from the measured voltages is attached as figure 5. This program runs on both the CDC time share system and on the MINC minicomputer located in building 67. The program requires transmissions of the interference filters used for each channel as inputs. In the CDC program these are read as Tapes 1 through 3 whereas in the MINC program the values are there as default values. The program requires as input the ranges of the lockin amplifiers for each channel in units of millivolts full scale. The program then converts the actual numerical readings from the lockin into absolute voltages in units of millivolts. The MINC computer is programmed to collect the raw data (voltages) and to then calculate the temperatures using the computer program. Only ratios of calibration constants are important in this program. Thus, the default values of calibration constants in the MINC program are not absolute but are normalized to give the recommended calibration ratios.

If the product of the area times emissivity is desired, a least squares fit program to fit voltages to both A and T is required. Two techniques for performing a least squares fit of voltage data obtained from the 3-color pyrometer to a Blackbody function to obtain the area and temperature for emitting coal particles have been implemented on the CDC computer. The first technique (Program LSTSQ) uses an approach outlined by N. Gat (IOC's 82.K513.6-52 and 82.K513.6-56) for determining area and temperature and the statistical errors in each. A listing of this program is included as figure 6. The second technique (Program DERIV) uses a conventional non-linear least squares computer subroutine using a gradient-expansion algorithm which minimizes the function

$$\chi^2 = \sum \left\{ \frac{1}{2\sigma_i} [V_i - V(\lambda_i)]^2 \right\}$$

where the V_i 's are observed values of the voltage from the three channels of the pyrometer, the $V(\lambda_i)$'s are expected values of voltage calculated from the integral of the blackbody function over the spectral bandwidth for each channel and the σ_i 's are statistical weights. Statistical uncertainties in each parameter are obtained from an error matrix generated by the program. A listing of this program is included as figure 7. Inputs to both programs include a subroutine which calculates the voltage function and its derivatives with respect to area and temperature.

The two programs were run for identical conditions to compare calculated areas, temperatures and statistical errors. Table 3 shows a comparison of the product of area times emissivity and temperature calculated for several standard

cases (Blackbody and Eppley lamp sources).

Table 3. Comparison of LSTSQ, DERIV and TEMPTR Computer Program Results for Calculation of Temperature and Area of an Emitting Source

SOURCE	PARAMETER	LSTSQ	DERIV	TEMPTR
BB, .025" (.635 mm) aperture	A (CM2) T (K)	(3.17±.12)E-3 1514±7	(3.17±.015)E-3 1513±1	1513±2
BB, .05" (1.27 mm) aperture	A (CM2) T (K)	(1.39±.05)E-2 1482±7	(1.42±.007)E-2 1481±1	1480±2
BB, .1" (2.54 mm) aperture	A (CM2) T (K)	(2.04±.14)E-2 1529 12	(2.08±.32)E-2 1527 22	1505±37
BB, .2" (5.08 mm) aperture	A (CM2) T (K)	(2.92±.24)E-2 1535±15	(2.98±.59)E-2 1533±29	1504±47
Eppley 35 amps	A (CM2) T (K)	(6.87±.54)E-3 2917±51	(6.91±.60)E-3 2916±43	2796±138
Eppley 20 amps	A (CM2) T (K)	(6.29±.33)E-3 1807±13	(6.29±.46)E-3 1806±14	1783±31

The calibration constants were obtained from calibration of the pyrometer with the blackbody with the 0.025 inch hole (3.167 (-3) cm² area). Thus, the first set of data in Table 3 should give the best correction. Note that the two programs give almost identical fits for area and temperature. However, the statistical errors are somewhat different although there is no obvious trend. It is most likely that the errors computed with DERIV (the standard least squares program) are more appropriate as several assumptions were made for the error analysis in LSTSQ. Also included in Table 3 are temperatures calculated using the three two-color temperatures (determined from voltage ratios). Note that these temperatures differ somewhat from those calculated the the least squares programs

and have higher standard deviations (especially those for the Eppley lamp). This will be discussed further below. Errors in the calculated areas are in general larger than errors in the calculated temperatures. This follows from the functional dependence of the voltage on area and temperature.

The LSTSQ and DERIV computer programs were compared for computing time required for running a single case and found to take almost identical times (.203 versus .204 seconds). DERIV used slightly less disk than LSTSQ. DERIV has a slight edge in its statistical analysis but otherwise the two programs are equivalent. Cindy McCully uses the fitting subroutine for the least squares fit in DERIV (LSSQ) in Dale Hook's small signal gain program and thus already has the subroutine in the MINC computer. Thus she feels it will be faster to program the MINC for Least Squares fitting of the pyrometer data using this program because less typing will be required. Thus, the DERIV program will be used in the MINC for data processing.

Looking at the data in Table 3, there is a discrepancy between the A's calculated using the Blackbody with the largest aperture and the Eppley lamp, both of which should have filled the field of view of the pyrometer. This can be partially explained by the fact that tungsten has a spectral emissivity much less than one whereas the spectral emissivity of the Blackbody source is one by definition. From the Handbook of Chemistry and Physics, the spectral emissivity of tungsten at 0.65 microns and 2900 K is 0.420 while at 1800 K it is 0.442. The Handbook also indicates that the emissivity of tungsten is decreasing with wavelength (e.g. 0.456 at 0.467 microns compared to 0.420 at 0.65 microns) which may make our assumption of constant emissivity for tungsten invalid. Using the tungsten emissivities at 0.65 microns brings the area of the tungsten filament at 35 amperes up to 0.0164 cm² and that at 20 amps to 0.0142 cm². These areas are still approximately a factor of 2 smaller than the areas found with the large aperture blackbody. We can calculate the tungsten emissivity at 35 amps from the known spectral radiance of the Eppley lamp compared to the equivalent Blackbody irradiance at the Eppley lamp temperature. The effective Eppley lamp temperature is 2950 K. Comparing the Eppley irradiances with the Blackbody irradiances at that temperature gives (0.8 microns) = 0.170, (0.95 microns) = 0.184 and (1.1 microns) = 0.182. This indicates that the effective irradiance of the Eppley lamp is approximately 0.185. Using this number gives an area of 0.037 cm² which is somewhat larger than that calculated for the large aperture blackbody but still within the error limits. Both numbers are consistent with the experimental

measurement of Henry Bobitch which gave an estimated field of view of 1 mm by 3.5 mm or 0.035 cm² with a resolution of a few tenths of a millimeter. Using the measurements with the 0.1 inch and 0.2 inch Blackbody apertures, an estimate of the field of view dimensions of the pyrometer can be made. This gives dimensions of 0.8 mm by 3.6 mm which agrees very well with the experimental measurement.

Statement of Prior Problems

The pyrometer configuration described in the preceding sections was finalized after problems were found with prior configurations. The original pyrometer configuration is shown as figure 8. It differs from the present configuration in that the collecting lens is a 4-inch diameter f/1.5 glass biconvex lens which was apertured down to approximately 0.56 inch and neither the collecting or collimating lenses were achromatic. In addition, a 1 mm aperture was placed before the chopper wheel as well as the 1 mm by 4 mm slit located after the chopper. The light was focussed at the 1 mm aperture. Also, the filters were located so the separate channels were in a different configuration. The detectors and their collecting lenses also were not located so that equal paths from the apertures to the detectors applied. The description of problems below apply to this original configuration and changes were made in the pyrometer to correct for the original problems.

Tests 20 and 22 which were run on February 17, 1982, showed severe discrepancies in data collection. Whereas the data from Test 20, which was taken when the flame was in the incandescent mode gave reasonable temperatures of near 2000 K and reasonable standard deviations, the data in Test 22 showed a systematic scatter in the 3 two-color temperatures. In these tests, the temperatures calculated using the 0.8 micron and 0.95 micron channels were always high, on the order of 2500 K, the temperatures with the 0.8 micron and 1.1 micron channels were intermediate, on the order of 2200 K while the temperatures determined with the 0.95 micron and 1.1 micron channels were low, on the order of 1700 K. This test was performed with the coal in the non-incandescent mode where some of the luminescent coal stream may have been at the edge of or out of the field of view of the pyrometer. This data indicated that there were still problems with the pyrometer for run conditions where the field of view of the instrument was not filled properly. Consequently, the elements of the pyrometer were reviewed to determine the major cause of these problems.

Tests to Locate Problems

The first test conducted to test the performance of the pyrometer was a new calibration using both Blackbody and Eppley lamp sources. This was used as a check to determine if any changes had occurred in the calibration. The most interesting result occurred using the blackbody source with different apertures. A summary of this data is presented in Table 4 for the pyrometer configuration shown in figure 9.

Table 4. Ratios of Signal Intensities From Different Channels for Configuration in Figure 9

<u>Aperture (inches)</u>	<u>V1/V2*</u>	<u>V1/V3*</u>	<u>V2/V3*</u>
0.2	.385	3.80	9.86
0.1	.400	3.93	9.82
0.05#	.313	3.91	12.5
0.05\$	.381	3.91	10.2
0.025	.317	3.92	12.3
0.0125	.306	4.05	13.2

*V1 is the voltage from the 0.8 micron channel

*V2 is the voltage from the 0.95 micron channel

*V3 is the voltage from the 1.1 micron channel

not realigned from larger aperture

\$ realigned for maximum signal

Note that there is a monotonic decrease in the ratio of V1/V2 from 0.4 to 0.3 as the aperture size is reduced from 0.2 inches to 0.0125 inches, and a monotonic increase in V2/V3 from 9.8 to 13.2 for the same reduction in aperture size. These changes are of the order of 30% and introduce an unacceptably large error in the calibration factor. However, the ratios V1/V3 remained nearly constant with hole size and alignment. Another revealing fact was that the alignment of the pyrometer became more critical for smaller aperture sizes. The instrument was first aligned with the largest Blackbody aperture. Note that

for the 0.05 inch aperture size that there are two ratios, the first for the same alignment as with the large aperture and the second for when the instrument was realigned for maximum signal. Note the large changes in the ratios of $V1/V2$ from 0.31 to 0.38 and in $V2/V3$ from 12.5 to 10.2 depending on the instrument alignment.

Because of the different ways the ratios from the various channels changed with aperture size, the filters were interchanged to determine if a systematic trend could be detected. Thus the .8 micron and .95 micron filters were interchanged to give the configuration shown in Figure 10. Again, the ratios of the various channels were compared with different Blackbody apertures. These results are presented in Table 5.

Table 5. Ratios of Signal Intensities with Filters Interchanged

Aperture(inches)	$V1/V2$	$V1/V3$	$V2/V3$
.4	.295	2.26	7.67
.2	.294	2.25	7.64
.1	.262	2.03	7.74
.05	.282	2.20	7.78
.025	.351	2.81	8.01
.0125	.395	3.14	7.95

Note that there is a systematic decrease in the ratio $V1/V2$ from 3.95 to 2.95, a decrease in the ratio $V1/V3$ from 3.14 to 2.26 and a decrease in the ratio $V2/V3$ from 7.95 to 7.67. The percent change in the ratios of $V1/V2$ and $V1/V3$ was much larger than the percent change in the ratio of $V2/V3$. This suggested that a problem could exist in the alignment of the straight channel, i.e., the one remaining after the two other channels are split from the main beam. This was checked visually by looking at the image of the source at the entrance of the various detectors. It was found that the straight channel was misaligned so that it was clipping a portion of the entering beam, resulting in lower observed signals and also changing the signal depending on where the source was in the field of view of the instrument. This was corrected in the final pyrometer configuration which was described in the first

paragraph of this memo.

Implications

Coal tests were run with the pyrometer in the configuration shown in figure 1. Data was collected on the MINC computer and reduced using the LSTSQ computer program which calculates the average of the three two-color temperatures. In all of these tests, temperatures of a reasonable order of magnitude and acceptable standard deviations were obtained. Thus, it appears that the pyrometer is performing properly for temperature measurements and that the temperature data obtained with it can be trusted.

Selected data points were reduced using both least squares programs. The temperatures calculated with these programs and with the TEMPTR program were compared for this test data. Table 6 shows this comparison for a set of randomly selected points from coal test 28 which was run on 28 February, 1982.

Table 6. Areas and Temperatures From Test 28 Data

TEMPTR	LSTSQ		DERIV	
T(K)	AREA(cm ²)	T(K)	AREA(cm ²)	T(K)
2260±83	(4.02±.13)E-5	2193±10	(4.02±.17)E-5	2194±16
2249±74	(4.53±.11)E-5	2187±7	(4.54±.18)E-5	2188±15
2313±44	(4.20±.05)E-5	2276±4	(4.22±.16)E-5	2276±15
2392±256	(2.49±.48)E-5	2186±55	(2.48±.31)E-5	2185±46
2190±42	(3.96±.46)E-5	2222±34	(3.96±.33)E-5	2223±31
2251±44	(6.18±.06)E-5	2214±3	(6.15±.24)E-5	2214±14
2192±19	(6.54±.57)E-5	2206±25	(6.57±.43)E-5	2205±25
2116±163	(8.31±.14)E-5	1987±39	(8.29±.83)E-5	1986±30
1991±72	(9.23±.49)E-5	1932±12	(9.13±.44)E-5	1933±14

Note that errors in area are of the order of 5 to 10% whereas errors in the temperatures are smaller, of the order of 1 to 2%. Both least squares programs calculate smaller temperature deviations than obtained from standard deviations in the TEMPTR program. Generally, the temperatures predicted by the least

squares programs agree within the error bars with those obtained from the TEMPTR program. Note that the particle diameters obtained were of the order of 40 to 80 microns indicating that the instrument could be observing single particles. For this data, the lowest temperatures which were obtained after the coal left the laser beam showed larger areas.

Data using the previous pyrometer configuration is probably good except for those tests where the field of view of the instrument was not filled. The new configuration and calibration should give us more confidence in the measurements made with this instrument.

34mm diameter
140mm focal length
achromatic lens

17.8mm diameter
31mm focal length
achromatic lens

SLIT
(1mm x 4mm)

.8μ
interference
filter

.95μ
interference
filter

1.1μ
interference
filter

silicon detectors

Figure 1. Current Pyrometer Configuration

Figure 2. Wavelength Response of Silicon Photodiodes.
(x's mark relative responses of the three
channels on the pyrometer)

ELECTRO OPTICS INFORMATION SHEET

Silicon Photodiode with integrated amplifier

SERIES OSI 5

Centronic Photodetectors type OSI 5 are specifically designed to simplify the difficulties normally associated with opto-electronic interfaces. They provide a simple solution to many of the problems encountered in the measurement and control of light.

The OSI 5 consists of a CENTRONIC high efficiency silicon photodiode combined with a high gain low noise amplifier in a TO.5 package. It is designed particularly for use where accurate measurements are needed of low light levels, and medium speed variation in such light levels. Its small size and excellent temperature coefficients make it ideally suited for use under adverse conditions.

Of particular note is the simplicity with which an OSI 5 may be used. Any supply voltage between $\pm 2.5V$ and $\pm 18V$ may be used. A single output line gives a voltage with respect to earth (Pin 1) proportional to the input light level, up to a maximum only slightly less than the power rail. Correction for dark level output is not normally required due to its extremely low value. The output may be short circuited to ground or either power rail without risk of damage. Changes in ambient temperature also cause only minimal variation in signal level, typically $150\mu V/^{\circ}C$.

The OSI 5 Series offers a broad spectral range with devices optimised for I.R., blue or U.V. sensitivity.

APPLICATIONS INCLUDE

- Light intensity measurements
- Light fluctuation detection
- Optical spectroscopy
- Pollution monitoring
- Alarm systems
- Optical shaft encoders
- Automated inspection and control
- Flow monitoring

SPECIAL FEATURES OF THE CENTRONIC OSI 5 SERIES

- Very high responsivity
- Broad spectral range
- Low noise
- Linear response
- TTL compatible
- Excellent power supply noise rejection
- Excellent temperature characteristics
- Rugged construction
- TO.5 encapsulation
- Low output impedance
- Short Circuit proof
- Simple to use

MECHANICAL SPECIFICATION

TO.5 can with 4 leads

Gold-Plated leads:

Active light sensitive area:

1/2" length

5 mm²

ABSOLUTE MAXIMUM RATINGS

Supply Voltage:

± 18 V.

Output Short Circuit Duration:

Indefinite

Storage Temperature:

-65°C to 100°C

Operating Temperature:

0°C to 70°C

1. Earth
2. Output
3. V+
4. V- (Connected to can)

ELECTRICAL SPECIFICATION — All at $V_s \pm 15V$ and 25°C unless otherwise stated.

Parameter	Conditions	Min.	Typ.	Max.	Units
O/P Dark Level			+20	+60	mV
O/P Saturation Level		-9	-12		V
O/P Resistance ¹	$R_L \geq 2K\Omega$		75		Ω
O/P Short Circuit Current			6		mA
O/P Noise Voltage			1	3	mV rms
Responsivity	253nm OSI 5J	15	30		$mV/\mu W^{-1}cm^2$
"	425nm OSI 5K	30	60		"
"	950nm OSI 5L	180	220		"
"	1065nm OSI 5L	100	150		"
Supply voltage (V+)		2.5	15	18	V
Supply voltage (V-)		-2.5	-15	-18	V
Supply current	$R_L = \infty$		0.5	1.3	mA
Supply Voltage Rejection Ratio		150	50		$\mu V/V$
Bandwidth	Upper 3dB point	3	5		kHz
Rise Time ²	$C_L = 0$		30	50	$\mu sec.$
Fall Time ²	$C_L = 0$		30	50	$\mu sec.$
Dark Level Temperature Coefficient	$20^\circ C \leq t_A \leq 50^\circ C$		150	500	$\mu V/^\circ C$

Notes.

1. At 5KHz. Drops to 0.01 at D.C.
2. Time for output signal to reach 90% of true reading after application of a step change in light intensity.

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604.107.12 2011.10.10

4x10⁻¹² watts
10⁻¹⁰ watts

Type No.	Optimised Response	Active Area mm ²	Typical Rise Time μ s	Typical Output Noise mV rms	Typical NEP (Noise Equivalent Power)		Minimum Responsivity (mV/ μ W/cm ²)				
					at Wavelength nm	W. Hz ⁻¹	Wavelength nm				
							250	430	630	900	1064
OSI-5J	UV	5	30	1	250	4×10^{-11}	15	60	—	—	—
OSI-5K	General Purpose	5	30	1	900	2×10^{-12}	—	30	160	250	—
OSI-5L	1064nm	5	30	1	1064	4×10^{-12}	—	—	—	220	130

Basic Circuits and Packages (all dimensions in mm) Dimension* refers to distance between window and active area.

Figure 3. (continued)

10 (T05)

Figure 4. Normalized Transmission Curves for Interference Filters Used in Pyrometer


```

PROGRAM TEMPTR(INPUT,OUTPUT,TAPE1,TAPE2,TAPE3)
COMMON/SLIT/XLANDA,S,NPTS,STEP
C THIS PROGRAM TAKES VOLTAGE READINGS FROM A THREE COLOR PYROMETER
C AND CALCULATES THE THREE TWO COLOR TEMPERATURES ASSUMING
C THE SOURCE OF INTEREST IS RADIATING AS A BLACK BODY
C THE INPUT TAPES CORRESPOND TO THE SPECTRAL RESPONSE OF
C THE INTERFERENCE FILTERS FOR EACH CHANNEL OF THE PYROMETER
C AND CONTAIN A TABLE OF WAVELENGTHS AND TRANSMISSIONS.
COMMON/CAL/CALIB
COMMON/CONST/CON1,CON2
DIMENSION XLANDA(3,14),S(3,14)
C XLANDA IS THE WAVELENGTH AND S THE TRANSMISSION OF THE
C INTERFERENCE FILTER. PROGRAM IS CURRENTLY DIMENSIONED
C FOR 14 DATA POINTS.
H=6.62517E-27
C=2.997928E10
XK=1.38046E-16
CON1=2.*H*C**2*1.E-7
CON2=H*C/XK
DISPLAY *WHAT ARE CALIBRATION CONSTANTS C12,C13,C23*
C CALIBRATION CONSTANTS ARE RATIOS OF CALIBRATION
C CONSTANTS DETERMINED AGAINST STANDARD SOURCE.
ACCEPT CALIB1,CALIB2,CALIB3
DISPLAY *RANGE ON LOCKIN IN MV FULL SCALE*
ACCEPT COR1,COR2,COR3
DO 110 ICH=1,3
110 REWIND ICH
NPTS=14
STEP=.002
DO 20 I=1,NPTS
READ(1,15) XLANDA(1,I),S(1,I)
READ(2,15) XLANDA(2,I),S(2,I)
READ(3,15) XLANDA(3,I),S(3,I)
15 FORMAT(2F6.4)
XLANDA(1,I)=XLANDA(1,I)*1.E-4
XLANDA(2,I)=XLANDA(2,I)*1.E-4
XLANDA(3,I)=XLANDA(3,I)*1.E-4
20 CONTINUE
30 DISPLAY *WHAT ARE V1, V2, V3*
C V1, V2, V3 ARE VOLTAGES FOR THE THREE RADIOMETER CHANNELS
ACCEPT V1,V2,V3
V1OV2 = V1/V2*COR1/COR2
V1OV3 = V1/V3*COR1/COR3
V2OV3 = V2/V3*COR2/COR3
IF(V1.EQ.0.) GO TO 400
CALIB=CALIB1
CALL TEST(1,2,V1OV2,TEMP)
TEMP1=TEMP

```

Figure 5. Computer Program for Determining Temperature From Voltage Ratios

```

CALIB = CALIB2
CALL TEST(1,3,V10V3,TEMP)
TEMP2=TEMP
CALIB = CALIB3
CALL TEST(2,3,V20V3,TEMP)
TEMP3=TEMP
TAVE=(TEMP1+TEMP2+TEMP3)/3.
C  CALCULATE AVERAGE TEMPERATURE USING THREE TWO COLOR
C  TEMPERATURES
DT1=TAVE-TEMP1
DT2=TAVE-TEMP2
DT3=TAVE-TEMP3
SD=SQRT(DT1**2 +DT2**2 +DT3**2)/2.
C  CALCULATE STANDARD DEVIATION
PRINT 100,TAVE,SD
100 FORMAT(1X,*TEMPERATURE = *F9.2,*      DEVIATION =*F9.2//)
PRINT 200
200 FORMAT(1X,*TEMPERATURE*,11X,*DEVIATION*)
PRINT 300, TEMP1,DT1
PRINT 300, TEMP2,DT2
PRINT 300, TEMP3,DT3
300 FORMAT(1X,F10.4,10X,F10.4)
  DISPLAY * *
  DISPLAY * *
  GO TO 30
400 STOP
  END
FUNCTION BEFF(N,TEMP)
C  THIS SUBROUTINE CALCULATES THE EFFECTIVE BLACKBODY
C  FUNCTION FOR EACH CHANNEL. BEFF IS THE INTEGRAL
C  OF THE BLACKBODY FUNCTION TIMES THE INTERFERENCE
C  FILTER FUNCTION OVER WAVELENGTH.
COMMON/SLIT/XLANDA,S,NPTS,STEP
COMMON/CONST/CON1,CON2
DIMENSION XLANDA(3,14),S(3,14)
BEFF=0.0
DO 60 J=1,NPTS
51 EXPON=CON2/(XLANDA(N,J)*TEMP)
  BWAVE = CON1/(XLANDA(N,J)**5*(EXP(CON2/(XLANDA(N,J)*TEMP))-1.))
  BEFF1=BWAVE*S(N,J)
  IF((J.EQ.1).OR.(J.EQ.NPTS)) BEFF1=BEFF1/2.
  BEFF = BEFF + BEFF1*2.E-7
60 CONTINUE
61 RETURN
  END
SUBROUTINE TEST(NCA,NCB,SIG,TEMP)
C  THIS SUBROUTINE DOES A BINARY FIT TO DETERMINE
C  TEMPERATURE. AS SET UP IT CALCULATES A
C  TEMPERATURE BETWEEN 2000 AND 4000 DEGREES.
C  HIGHER OR LOWER TEMPERATURES CAN BE DETERMINED
C  BY EITHER INCREASING STEP OR CHANGING TEMP.

```

Figure 5. (continued)

```

COMMON/CAL/CALIB
TEMP=2500.
STEP = 750.
10  B1=BEFF(NCA,TEMP)
    B2=BEFF(NCB,TEMP)
    VOLT =CALIB*B1/B2
    IF(SIG.LE.VOLT) GO TO 20
    TEMP = TEMP + STEP
    STEP = STEP/2.
    IF (STEP.LE.1.) GO TO 50
    GO TO 10
20  TEMP = TEMP - STEP
    STEP = STEP/2.
    IF(STEP.LT.1.) GO TO 50
    GO TO 10
50  RETURN
    END

```

Figure 5. (continued)

```

PROGRAM LSTSQ (INPUT,OUTPUT,TAPE1,TAPE2,TAPE3)
C   THE INPUT TAPES CORRESPOND TO THE SPECTRAL RESPONSE OF
C   THE INTERFERENCE FILTERS FOR EACH CHANNEL OF THE PYROMETER
C   AND CONTAIN A TABLE OF WAVELENGTHS AND TRANSMISSIONS.
COMMON/SLIT/XLANDA,S ,NPTS,STEP
COMMON/CAL/CALIB
COMMON/CONST/CON1,CON2
DIMENSION XLANDA(3,14),S(3,14),CALIB(3),DVWRTA(3),DVWRIT(3)
C   XLANDA IS THE WAVELENGTH AND S IS THE TRANSMISSION OF THE
C   INTERFERENCE FILTER. PROGRAM IS DIMENSIONED FOR
C   14 DATA POINTS.
DIMENSION VOLTC(3),SIG(3)
C   THIS PROGRAM USES A SIMPLE LEAST SQUARES APPROACH
C   TO DETERMINE THE TEMPERATURE AND THE AREA OF RADIATING
C   COAL PARTICLES USING AN APPROACH DEVELOPED
C   BY NARUM GATT. A LINEAR SEARCH METHOD IS USED TO
C   FIND THE SOLUTION OF AN EQUATION INVOLVING THE
C   INTEGRAL OF THE BLACKBODY FUNCTION OVER EACH
C   FILTER CHANNEL AND THE DERIVATIVES OF THE SAME
C   INTEGRAL.
H=6.62517E-27
C=2.997928E10
XK=1.38046E-16
CON1=2.*H*C**2*1.E-7
CON2=H*C/XK
C   BASELINE CALIBRATION CONSTANTS FOR CHANNEL1 EQUALS .8 MICRONS
C   CHANNEL 2 EQUALS .95 MICRONS AND CHANNEL 3 EQUALS 1.1 MICRONS
C   ARE INCLUDED IN THIS PROGRAM.
CALIB(1)=8.182E5
CALIB(2)=3.831E5
CALIB(3)=6.536E4
DISPLAY *IF BASELINE CALIBRATION CONSTANTS APPLICABLE*
DISPLAY *ENTER 1, OTHERWISE ENTER 0*
ACCEPT ICAL
IF (ICAL.EQ.1) GO TO 45
DISPLAY *WHAT ARE CALIBRATION CONSTANTS C12,C13,C23*
C   CALIBRATION CONSTANTS ARE IN UNITS OF MV/WATT
ACCEPT CALIB(1),CALIB(2),CALIB(3)
45 DISPLAY *RANGE ON LOCKIN IN MV FULL SCALE*
ACCEPT COR1, COR2, COR3
DO 110 ICH=1,3
110 REWIND ICH
NPTS=14
STEP=.002
DO 20 I=1,NPTS
READ(1,15) XLANDA(1,I),S(1,I)
READ(2,15) XLANDA(2,I),S(2,I)

```

Figure 6. Computer Program for Least Squares Fit to Temperature and Area

```

      READ(3,15) XLANDA(3,1),S(3,1)
15  FORMAT(2F6.4)
      XLANDA(1,1)=XLANDA(1,1)*1.E-4
      XLANDA(2,1)=XLANDA(2,1)*1.E-4
      XLANDA(3,1)=XLANDA(3,1)*1.E-4
20  CONTINUE
30  DISPLAY *WHAT ARE V1, V2, V3*
C    V1,V2, V3 ARE VOLTAGES FOR THE THREE PYROMETER CHANNELS
      ACCEPT SIG(1), SIG(2), SIG(3)
      IF (SIG(1).EQ.0.) GO TO 400
C    PROGRAM CAN BE STOPPED BY SETTING V1 TO 0
      SIG(1)=COR1*SIG(1)
      SIG(2)= COR2*SIG(2)
      SIG(3)= COR3*SIG(3)
      CALL TEST(SIG,A,TEMP,VOLTC)
      DISPLAY * *
      PRINT 100, A,TEMP
C    A IS THE EMITTING AREA OF THE COAL PARTICLES AND TEMP IS
C    THE TEMPERATURE OF THE EMITTING PARTICLES
100  FORMAT(1X,*AREA = * E10.4,3X,*TEMPERATURE = * F10.1)
      RADIUS =(1.E04)* SQRT(A/3.14159)
      DIAM = 2.*RADIUS
      PRINT 101, DIAM
101  FORMAT(1X,*PARTICLE DIAMETER = *F10.1,* MICRONS*)
C    CALCULATE THE CORRELATION COEFFICIENT TO DETERMINE THE
C    GOODNESS OF THE FIT
      SUM = 0.0
      DO 120 II=1,3
120  SUM = SUM + SIG(II)
      ANEAN=SUM/3.
      SUM1=SUM2=0.
      DO 130 JJ=1,3
      CALL FADER(JJ,TEMP,A,VOLTC(JJ),DWA,DWT)
      SUM1= SUM1 + (SIG(JJ) - VOLTC(JJ))**2
130  SUM2 = SUM2 + (SIG(JJ) - ANEAN)**2
      SEE = SQRT(SUM1)
      SD = SQRT(SUM2/2.)
      RATIO = 1. - (SEE/SD)**2
70  CORCON= SQRT(RATIO)
      DISPLAY * *
      DISPLAY* OBSERVED      CALCULATED*
      DISPLAY* VOLTAGE      VOLTAGE*
      DISPLAY*-----*
      DO 210 K=1,3
      PRINT 220, SIG(K), VOLTC(K)
220  FORMAT(1X,E10.3,3X,E10.3)
210  CONTINUE
      DISPLAY* *
      PRINT 230,CORCON
230  FORMAT(1X,*CORRELATION COEFFICIENT =*F10.3)
      DISPLAY* *

```

Figure 6. (continued)

```

      DISPLAY* *
      GO TO 30
400 STOP
      END
      SUBROUTINE FADER(N,TEMP,A,VOLT,DWA,DWT)
C      THIS SUBROUTINE CALCULATES THE INTEGRAL OF THE
C      PRODUCT OF THE BLACKBODY FUNCTION TIMES THE FILTER
C      TRANSMISSIONS AND ALSO THE INTEGRAL OF THE PRODUCT
C      OF THE DERIVATIVE OF THE BLACKBODY FUNCTION WITH
C      RESPECT TO TEMPERATURE TIMES THE FILTER
C      TRANSMISSION.
      COMMON/CAL/CALIB
      COMMON/SLIT/XLAMBDA,S,NPTS,STEP
      COMMON/CONST/CON1,CON2
      DIMENSION XLAMBDA(3,14),S(3,14),CALIB(3),VOLTC(3)
      BEFF=0.0
      BWT=0.0
      DO 60 J=1,NPTS
51  EXPON=CON2/(XLAMBDA(N,J)*TEMP)
      BWAVE = CON1/(XLAMBDA(N,J)**5*(EXP(CON2/(XLAMBDA(N,J)*TEMP))-1.))
      BEFF1=BWAVE*S(N,J)
      PAREN = EXP(EXPON) -1.
      BDERIV=CON1*CON2*EXP(EXPON)/(XLAMBDA(N,J)**6*TEMP**2*PAREN**2)
      BWT1 = BDERIV*S(N,J)
      IF((J.EQ.1).OR.(J.EQ.NPTS)) GO TO 30
      GO TO 40
30  BEFF1 =BEFF1/2.
      BWT1 = BWT1/2.
40  BEFF = BEFF + BEFF1*2.E-7
      BWT = BWT + BWT1*2.E-7
60  CONTINUE
      VOLT = CALIB(N)*A*BEFF
      DWA = VOLT/A
      DWT=CALIB(N)*A*BWT
61  RETURN
      END
      SUBROUTINE TEST(SIG,A,TEMP,VOLTC)
C      THIS SUBROUTINE CALCULATES THE TEMPERATURE
C      AND AREA USING A BINARY FIT PROCESS.
      DIMENSION SIG(3), VOLTC(3)
      TEMP = 2500.
      STEP=750.
40  SUM1 = 0.0
      SUM2 = 0.0
      SUM3 = 0.0
      SUM4 = 0.0
      DO 10 N = 1,3
      AA = 1.
45  CALL FADER(N,TEMP,AA,VOLT,DWA,DWT)
      VOLTC(N)=VOLT
      SUM1 = SUM1 + SIG(N)*VOLT

```

Figure 6. (continued)

```

SUM2 = SUM2 + VOLT**2
SUM3 = SUM3 + SIG(N)*DWT
SUM4 = SUM4 + DWT*VOLT
10 CONTINUE
ALPH1 = SUM1/SUM2
ALPH2 = SUM3/SUM4
15 EPS = ALPH1 - ALPH2
IF(EPS.LE.0.) GO TO 20
TEMP = TEMP - STEP
STEP = STEP/2.
IF(STEP.LE.1.) GO TO 50
GO TO 40
20 TEMP = TEMP + STEP
STEP = STEP/2.
IF (STEP.LE.1.) GO TO,50
GO TO 40
50 A=ALPH1
RETURN
END

```

[LOG,0

Figure 7. Original Pyrometer Configuration

Figure 8. Original Pyrometer Configuration With Channels Changed