NOTICE: When government or other drawings, specifications or other data are used for any purpose other than in connection with a definitely related government procurement operation, the U. S. Government thereby incurs no responsibility, nor any obligation whatsoever; and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use or sell any patented invention that may in any way be related thereto.

RESEARCH REPORT NO: RR 61-9

SPECTRAL RADIOMETRY AND TWO-PATH PYROMETRY OF ROCKET EXHAUST JETS

By

Frederick S. Simmons and Arthur G. DeBell

RESEARCH REPORT

$3.60

1 May 1961

ROCKETDYNE
A DIVISION OF NORTH AMERICAN AVIATION, INC.
6633 CANOGA AVENUE, CANOGA PARK, CALIFORNIA

ROCKETDYNE
A DIVISION OF NORTH AMERICAN AVIATION INC

SPECTRAL RADIOMETRY AND TWO-PATH PYROMETRY OF ROCKET EXHAUST JETS

Prepared by:

Frederick S. Simmons
and
Arthur G. DeBell

Approved by:

R. J. Thompson, Jr.
Director
Research

Research Report 61-9
1 May 1961

FOREWORD

This report was presented to the Fourth Symposium on Temperature, Its Measurement and Control in Science and Industry, Columbus, Ohio, March 29, 1961.

ABSTRACT

The fundamental relations governing radiative transfer are briefly reviewed, and the methods of relating the observed spectral radiance of a gaseous source to its intrinsic properties are outlined. The inhomogeneous character of rocket exhaust jets is illustrated. Descriptions are given of several unique instruments for making quantitative spectroscopic measurements of exhaust radiation: a "Telespectrograph," for measuring spectral radiance in the ultraviolet and visible; an "Infrared Spectral and Total Teleradiometer" for similar measurements in the infrared; a "Photographic Pyrometer" and a "Two-Path Spectral Radiometer" for two-path measurements of gas temperature and spectral emissivity. Typical results obtained with the various instruments are presented and discussed.

CONTENTS

ILLUSTRATIONS

INTRODUCTION

Knowledge of the temperature and radiative properties of the exhaust jets from modern rocket engines is useful for many purposes, ranging from the study of combustion processes to long-range detection of ballistic missiles. Such information, in practice, can only come from direct measurements of the spectral radiance of the exhaust products. However, there are a number of specific problems encountered in making quantitative spectroscopic measurements in conjunction with rocket engine operations. It is the purpose of this paper to discuss these problems, to describe several of the unique spectroscopic instruments developed at Rocketdyne for making such measurements, and to present and interpret some typical results obtained with these instruments.

REVIEW OF BASIC PRINCIPLES

The methods of relating the spectral radiance of a homogeneous, thermally equilibrated gaseous source to its temperature are well known and have been discussed in detail by Penner (Ref. 1), Broida (Ref. 2), and others. Nevertheless, since the degree to which measurements of spectral radiance possess meaning depends so greatly on their proper interpretation in light of the particular experimental conditions, a brief review of the basic relations might be appropriate at this point. The notation to be used will essentially follow the recommendations of Bell (Ref. 3).

The fundamental equation of radiative transfer, expressed in integral form in terms of the spectral radiance: the radiant power per unit area of the source per unit wavelength interval into unit solid angle, observed along a particular line of sight is (Ref. 4)

$$N_\lambda = \int_0^L j(\lambda)\ \rho(s)\ \exp\left[-\int_0^s k(\lambda)\ \rho(s)\ ds\right]\ ds \tag{1}$$

where N_λ is the spectral radiance in direction s, $j(\lambda)$ and $k(\lambda)$ the spectral emission and absorption coefficients, $\rho(s)$ the concentration of emitters, and L the geometrical depth of the emitting region. The emission coefficient for a gaseous source in local thermodynamic equilibrium is given by Kirchhoff's law:

$$j(\lambda) = k(\lambda)\ N^o_\lambda(T) \tag{2}$$

where $N^o_\lambda(T)$ is the appropriate blackbody radiance for the local temperature, $T(s)$.

For a region of uniform temperature and emitter concentration: $T(s)$ = const. and $\rho(s)$ = const., Eq. 1 and 2 reduce to the Beer-Lambert relation:

$$N_\lambda = N^o_\lambda(T)\quad \left\{1 - \exp\left[-k(\lambda)\ \rho L\right]\right\} \tag{3}$$

where the quantity in the bracket is recognized as the spectral emissivity*. Obviously, the use of an emissivity to characterize the emissive ability of a radiating gaseous region is restricted to the case where the temperature and concentration are invariant along the line of sight through the region. It will be subsequently shown that in a rocket exhaust jet, this condition is not generally met.

*Worthing's recommendation (Ref. 5) that "emittance" be used as a nondimensional expression of the emissive power of a body or system, and "emissivity" be restricted to describing an intrinsic property of a particular substance, has considerable merit and some current support. However, "emittance" is also in use as a dimensional expression of radiant emission. To avoid confusion and in keeping with general usage, "emissivity" will be retained in the present report.

Actually, the spectral radiance, as expressed in Eq. 1 and 3, is not a measurable quantity. The indications of a spectral radiometer can be related only to the average radiant power within a finite bandwidth, whether defined by a slit opening or by the transmission of a filter. The indicated radiance, $N(\lambda)$, can be expressed as

$$N(\lambda) = \int_{\delta\lambda} N_{\lambda} \, d\lambda \tag{4}$$

where $\delta\lambda$ is the effective instrumental bandwidth which can be so defined to account for the detector response, optical transmission, and if necessary, the slit function.

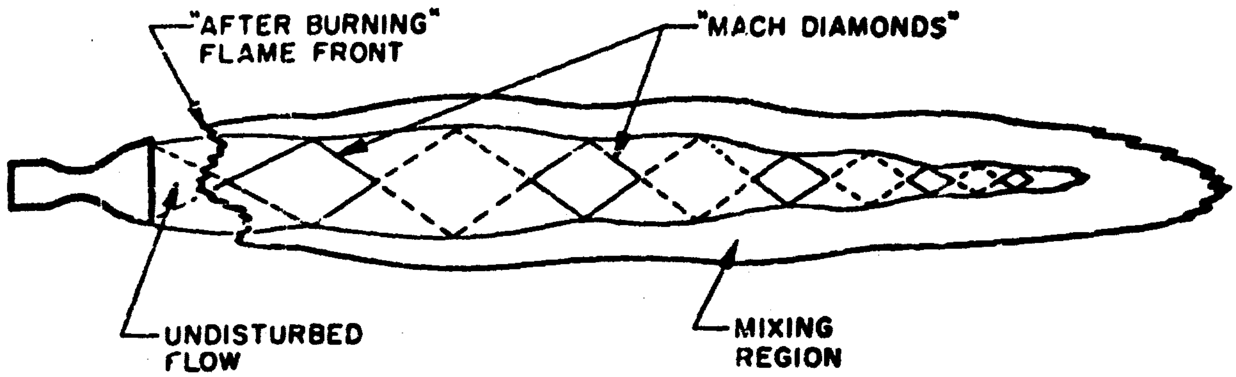
The utility of Eq. 1 through 4, in relating the indications of a spectroscopic instrument to the temperature and emitter concentration of a gaseous source, is largely dependent on the character of the spectral absorption coefficient $k(\lambda)$. Gases radiate selectively as a consequence of transitions in energy levels of vibrational, rotational, and electronic states; the absorption coefficient is a function of the transition probability, and for moderate pressures and path-lengths varies rapidly in wavelength intervals frequently too small to be resolved by the instrument in use. In this case, the "curve of growth," the observed variation of indicated radiance with the concentration of radiating gas and the path-length, will depart from Beer's law. As the pressure and path-length in the gas are increased, the individual lines in a band will broaden and eventually overlap to produce radiation continuous in appearance over appreciable wavelength intervals. Solids and liquids, of course, radiate continuously over extremely wide ranges in wavelength. A case of particular interest in rocketry is the radiation from a cloud of solids; e.g., soot or metallic oxides, suspended in the gas stream. For particles of sizes on the order of a wavelength, the emission and absorption of radiation again become selective, but with the absorption coefficient varying rather slowly with wavelength. For particles of simple geometry and known properties, electromagnetic theory may be used to calculate absorption coefficients as a function of particle size and wavelength (Ref. 6). Alternately, empirical relations of the form

$$k(\lambda) \propto \lambda^{-n} \tag{5}$$

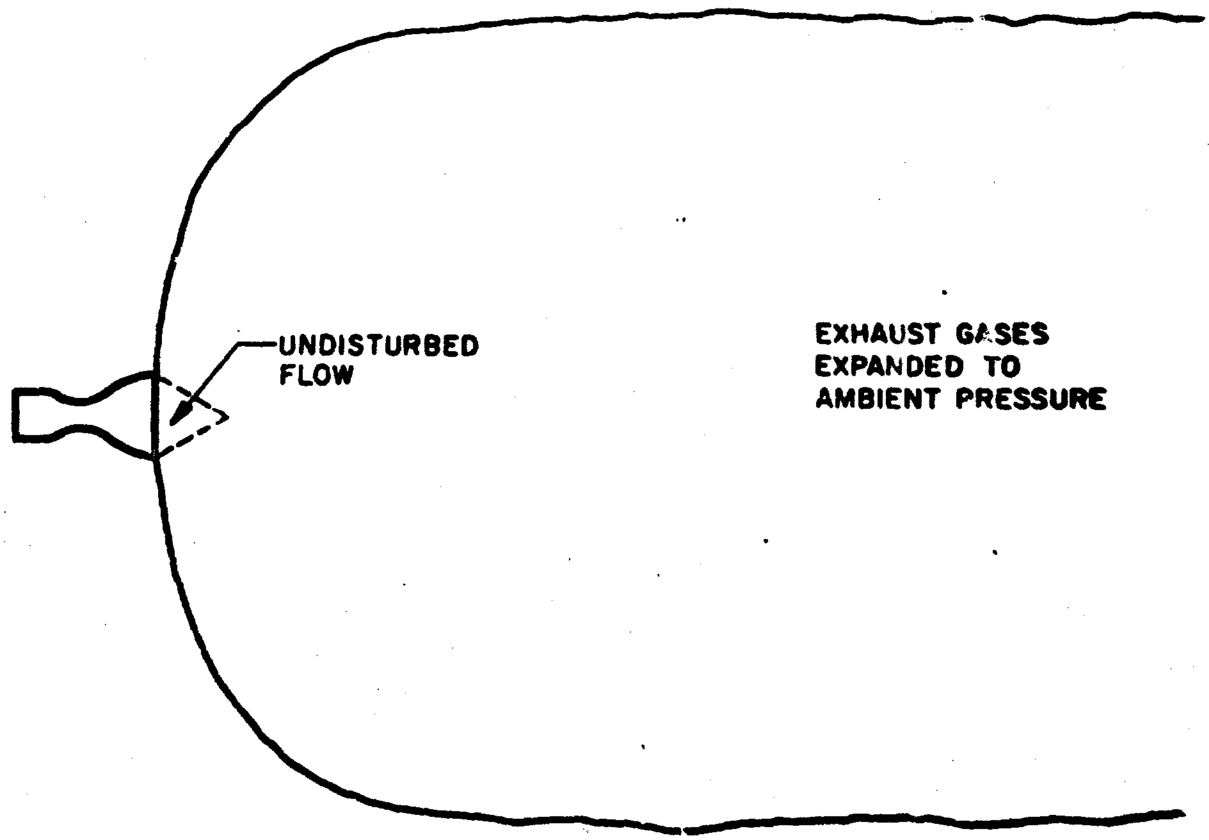
have been found to be useful over limited ranges of wavelength (Ref.7).

EXHAUST JET CHARACTERISTICS

In order to properly interpret measurements of spectral radiance from a rocket exhaust jet, account must be taken of the complex aerodynamic structure of the jet and the consequent heterogeneity of the radiation field. It may therefore be useful to also review briefly some of the physical characteristics of such jets. An idealized representation of an exhaust jet is shown in Fig. 1A. The completely reacted products of combustion enter the converging-diverging nozzle and expand to a supersonic velocity and a low pressure dependent primarily on the cross-sectional area. A perfectly designed nozzle will discharge the exhaust in a homogeneous parallel stream with a static pressure corresponding to that at the "design altitude"; within certain bounds, a mismatch in the exit pressure will result in an alternation of expansion and compression, the standing waves associated with which form the characteristic "Mach diamonds", a manifestation of large gradients in temperature and density across the jet. A further source of heterogeneity is chemical reaction occurring in the mixing region; optimum performance of a rocket engine is frequently found at propellant mixture ratios that



A. EXHAUST PLUME NEAR DESIGN ALTITUDE



B. EXHAUST PLUME AT HIGH ALTITUDE

Figure 1. Physical Characteristics of Rocket Exhaust Jets

produce large amounts of combustible gases in the exhaust which then react with the surrounding air. This "afterburning" often creates temperatures considerably greater than those in the interior of the jet.

Clearly, the region of the exhaust jet close to the nozzle exit is least affected by these interactions with the ambient atmosphere. This region is of most interest when radiation measurements are related to engine performance; it is also very important in studies of jet radiation at very high altitudes. In the latter case, the exhaust plume, in expanding to the ambient pressure, is of much lower temperature, different structure, and greater size, as illustrated in Fig. 1B. However, at the nozzle exit, a conical region, defined by the locus of the vector sum of the exhaust velocity and the local acoustic velocity normal to the axis, remains essentially invariant with altitude. Sea level measurements of the spectral radiance of this undisturbed region of flow can therefore be useful in estimating high-altitude emission.

Although the nozzle exit region of the jet is usually free from the externally induced heterogeneity, account must still be taken of gradients in the interior. Source flow may be assumed in conical nozzles, in which case the isotherms form spherical surfaces; the gradient intercepted by a normal at the nozzle exit can easily be estimated. However, a contoured or "bell" nozzle, which is generally much shorter (and hence lighter) than one designed for perfectly uniform flow, may introduce substantial gradients in temperature, density, and velocity in the exhaust which are much more difficult to determine.

In some instances, a further complication arises from the fact that the radiation measurement also represents a time integration. The average value of the radiance from even a homogeneous field varying uniformly in time; e.g., a longitudinal oscillation in the flow field, would not in general correspond to an average temperature; transverse oscillations in spinning modes, the more frequently encountered condition, create additional heterogeneity in the instantaneous radiation field.

SPECTRAL RADIOMETRY

From the preceding discussions, it is clear that radiometric instruments for studies of rocket exhaust radiation must be capable of resolving spatially as well as spectrally, i.e., the spectral radiance is the only measurable quantity amenable to interpretation in terms of intrinsic properties of the exhaust products. Accordingly, all of the instruments to be described could be characterized as spectral radiometers, which term herein implies a capability for measurement of spectral radiance. However, the names selected were considered to be more appropriate for describing their particular application. Four such instruments were designed, constructed, and put into operation for various studies of rocket exhaust emission at the Rocketdyne Propulsion Field Laboratory.

Telespectrograph

Essentially, this instrument consists of a 1.5-meter photographic grating monochromator and a set of telescopic entrance optics in an arrangement shown schematically in Fig. 2. The radiation from the remote flame is collected by the objective, an off-axis parabola, and brought to a focus to produce a real image in a plane intersected by the "preslit," a small, aluminized stripe on an otherwise clear piece of glass. The light incident upon the stripe is reflected and re-imaged on the slit of the monochromator by means of a quartz lens; the visible portion of the remainder of the image passes through the glass and a field lens and is

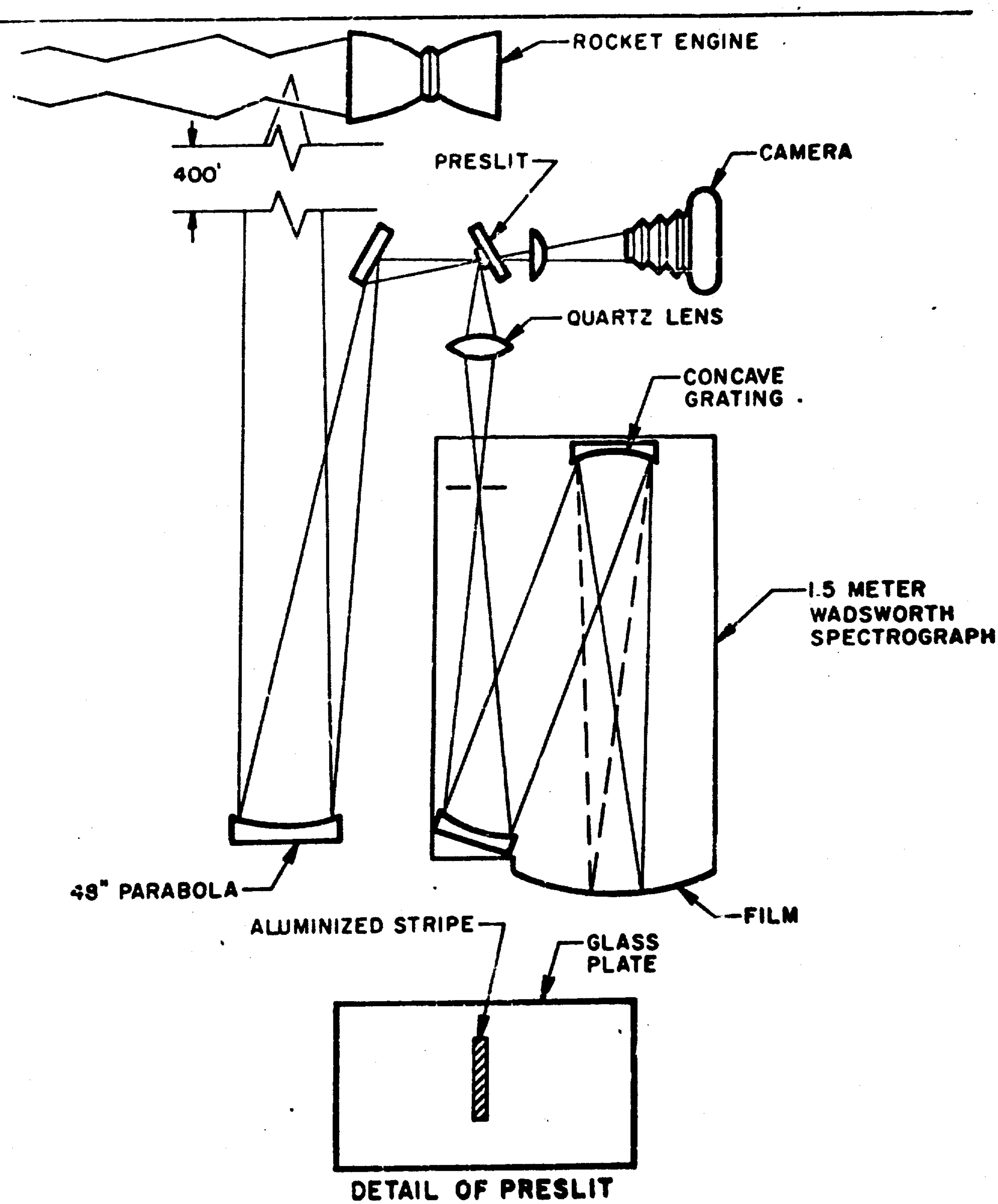
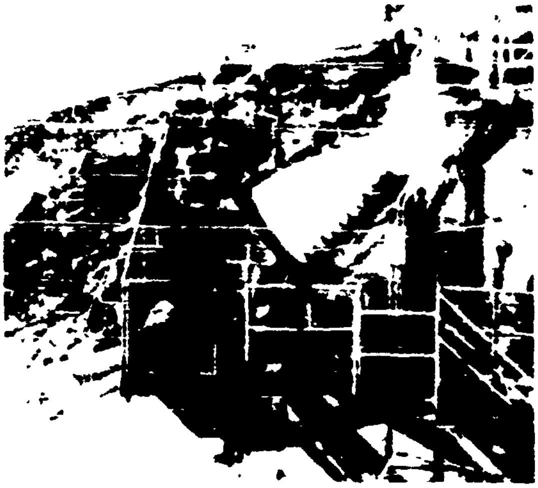


Figure 2. Telespectrograph-Optical Circuit

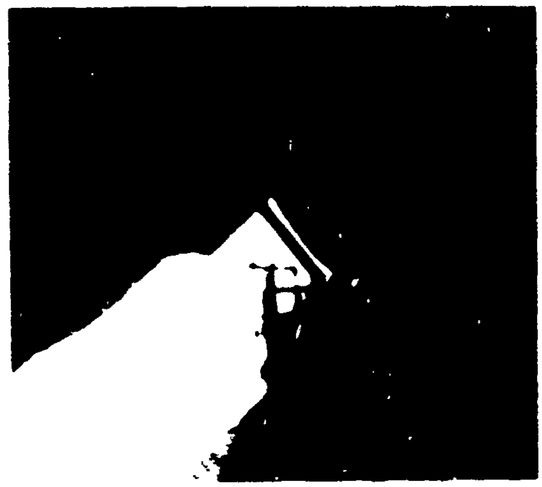
collected by a camera. In this manner, a fiducial photograph of the flame is produced; the shadow of the "preslit" positively locates the field of view within the flame under scrutiny. Typical fiducial photographs are shown in Fig. 3.

The output of this instrument is a spectrum on a photographic emulsion; it has a range of 2200 to 7800Å with a resolution of 0.3Å. Normal operation consists of recording a spectrum during an engine operation and calibrating immediately thereafter. The wavelength scale is determined by recording the spectrum of a mercury lamp on an adjacent portion of the film. An absolute intensity calibration is obtained by similarly recording several spectra from a standard source (in this case a tungsten ribbon lamp) set at temperatures spanning those of interest in the flame. Reduction of the data starts with analysis using a microdensitometer to produce a set of curves of photographic density vs wavelength for the standard lamp and the flame. Knowledge of the brightness temperature of the lamp at one wavelength (measured with an optical pyrometer), and the variation in spectral emissivity of the tungsten filament with temperature and wavelength, then permits point-by-point calculation of the absolute intensity of the light from the flame.

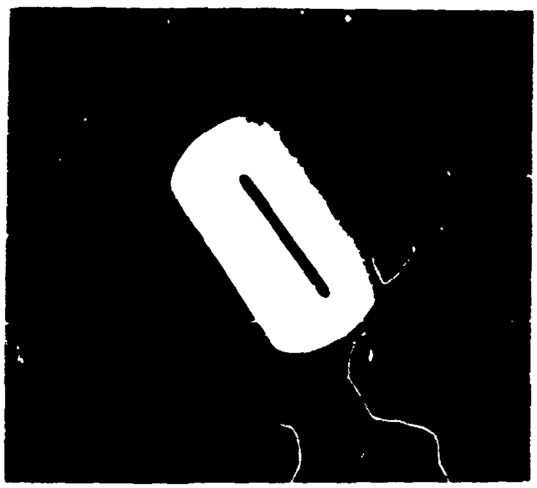
This instrument, like those to be described on the following pages, was designed so that radiation from both the flame and the calibrating source fill the limiting aperture of the system and the monochromator slit which defines the field of view. Since the area of the slit projected on the source will vary directly as the square of the range, the inverse-square loss is exactly compensated, and the indications of the instrument are independent of the range in regard to geometrical effects. However, atmospheric absorption and scattering are fuuctions of range and cannot, in general, be neglected. The final output of the instrument is therefore



A. BEFORE RUN



B. DURING RUN



C. DURING CALIBRATION

Figure 3. Fiducial Photographs

expressed in terms of an apparent spectral radiance of the source as observed at the instrument location. Typical data will be shown and discussed later.

Photographic Pyrometer

This instrument produces a photographic record of a spatial distribution in apparent spectral radiance at a low spectral resolution; its construction and use have been described in detail elsewhere (Ref. 8 and 9).

The optical arrangement is shown schematically in Fig. 4. The field of view of the camera includes both the rocket exhaust flame at some distance, and a set of tungsten ribbon lamps located in the instrument chassis. The lamps are set at brightness temperatures spanning those of interest in the flame; calibration is obtained using an optical pyrometer in place of the camera. The collimating lenses are adjusted so that the lamp filaments and the rocket flame are simultaneously brought into focus; field stops in front of the lamps define the portions of the filaments in use. Therefore, a single exposure simultaneously produces images of the flame and the calibrating lamps. Filters and films may be chosen to isolate relatively narrow bands as desired from 0.3 to 1.1μ; simultaneous operation at three distinct wavelength intervals was accomplished for a special purpose by use of a direct color-separation camera (Ref. 10).

Data reduction is similar to that previously described. For each film record the photographic densities are determined using a microdensitometer. A graph of density vs the corresponding reciprocal brightness temperature (which can be shown to be equivalent to the familiar density vs log exposure characterization of the film response) thus constitutes an individual calibration for each record. Control of exposure and

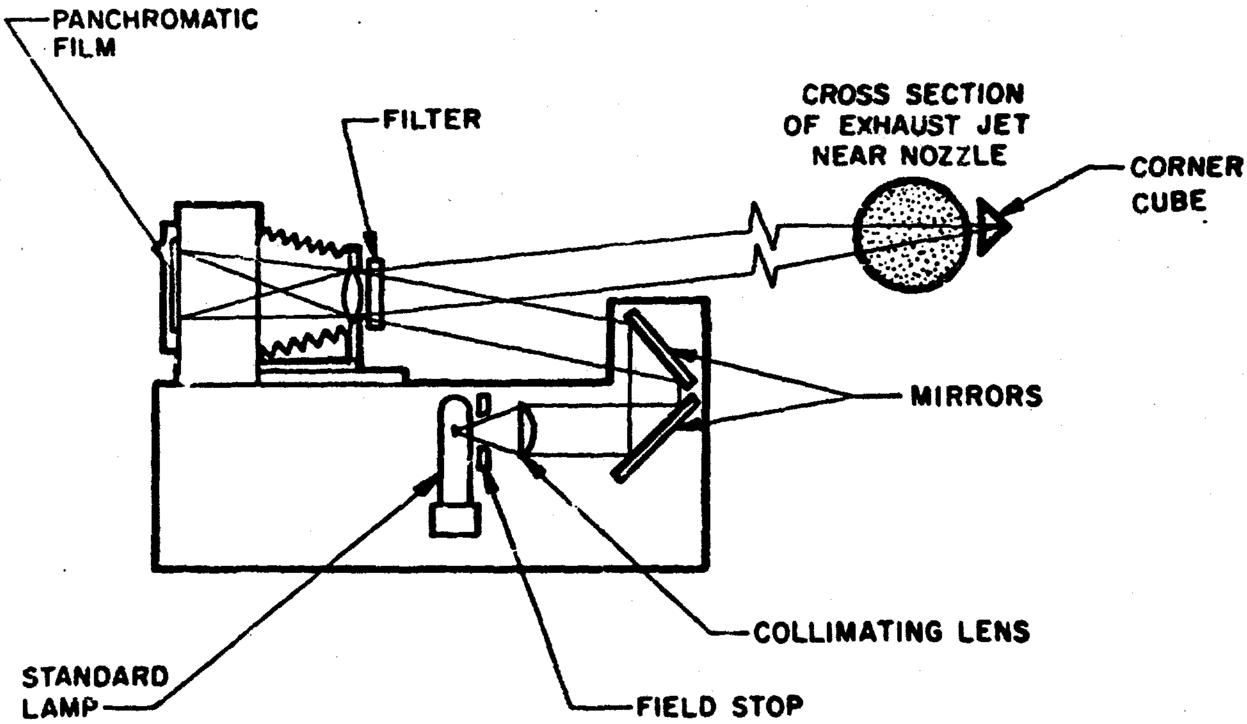


Figure 4. Photographic Pyrometer-Optical Circuit

development is necessary only to the degree required to produce photographic densities on the linear region of the film response. The local density within the film image of the exhaust flame can then be directly related to a brightness temperature which is, of course, an alternate expression of the spectral radiance. A complete analysis can so be made to produce a two-dimensional distribution in brightness temperature over the entire projected area of the exhaust jet. The advantages of photographic pyrometry for such purposes are quite obvious; the equipment is simple, inexpensive, remotely operable, insensitive to spurious signals generated by the high acoustic levels present, and capable of producing quantitative data on a permanent record which is at the same time photometric and fiducial. Spectral radiances obtained with this instrument in simultaneous observations with the telespectrograph were in very close agreement.

A somewhat distinct application of the photographic pyrometer lies in its use in a two-path arrangement whereby the actual gas temperature and the spectral emissivity of rocket exhaust products are simultaneously determined. Extensive use of the instrument in this manner has been made in studies of the expansion of liquid oxygen/kerosene combustion products in a rocket nozzle (Ref. 11). The nozzle and chamber geometry were such to produce a quite uniform and homogeneous exhaust at the nozzle exit; independent spectroscopic measurements verified the continuity of the emission over the bandpass of the instrument. A corner-cube reflector (in this case a glass prism) behind the flame effectively doubled the apparent depth of the flame, and two values of spectral radiance could thereby be simultaneously determiued. The nozzle exit temperature, T_e, could then be calculated using the relation

$$T_e^{-1} = T_{br}^{-1} + (\lambda/c_2) \quad \left\{1 - \left[R(\lambda)\right]^{-1} \left[(N'_\lambda/N_\lambda) - 1\right]\right\} \qquad (6)$$

where T_{br} is the single-path brightness temperature at the nozzle exit, $R(\lambda)$ the corner-cube reflectance, and N'_{λ}/N_{λ} the ratio of double-path and single-path radiance.

Figure 5 is a reproduction of a typical film record; Fig. 6 is an enlarged view of the nozzle exit region showing the brighter image of the corner cube. Data for a typical series of motor runs at various propellant mixture ratios are shown in Fig. 7 in comparison with the theoretical curves, the terms "frozen" and "shifting" referring to zero and infinite rates in the recombination of dissociated products during the expansion in the nozzle. An apparent difference is noted in the data obtained with a regeneratively cooled chamber compared with that obtained when the chamber was modified for water cooling. This modification was made to permit operation over a wider range of mixture ratio; in the process the length of the chamber was increased, and hence a greater heat loss was incurred before the products entered the nozzle. In both cases, the fact that the experimental data exceeded both theoretical values at very low mixture ratios was attributed to the failure of one or more of the idealizing assumptions taken in the thermochemical calculations. The scatter in the data are typical, and are presumed to be primarily due to intermittent inhomogeneities in the exhaust, which occur at random and appear as flashes in an otherwise more uniform flow.

Infrared Spectral and Total Teleradiometer

An infrared spectral and total teleradiometer, hereafter referred to as the IRSATT, was designed to produce absolute measurements of the apparent infrared spectral radiance of rocket exhaust jets from a remote station. This instrument has also been described in detail elsewhere (Ref. 12). Basically, it consists of a prism monochromator equipped with photoconductive detectors, and a set of telescopic entrance optics that feature

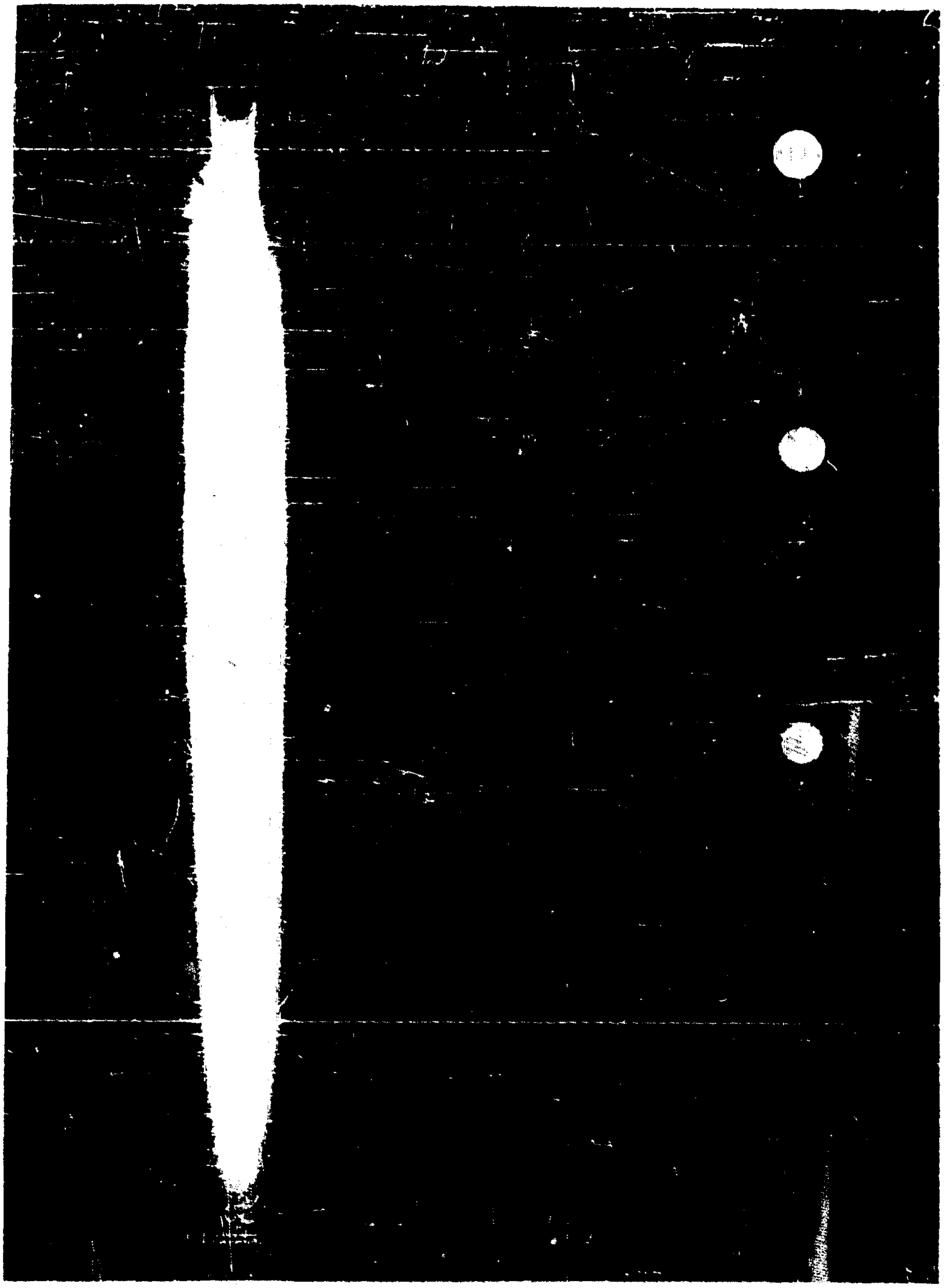


Figure 5. Reproduction of Typical Film Record

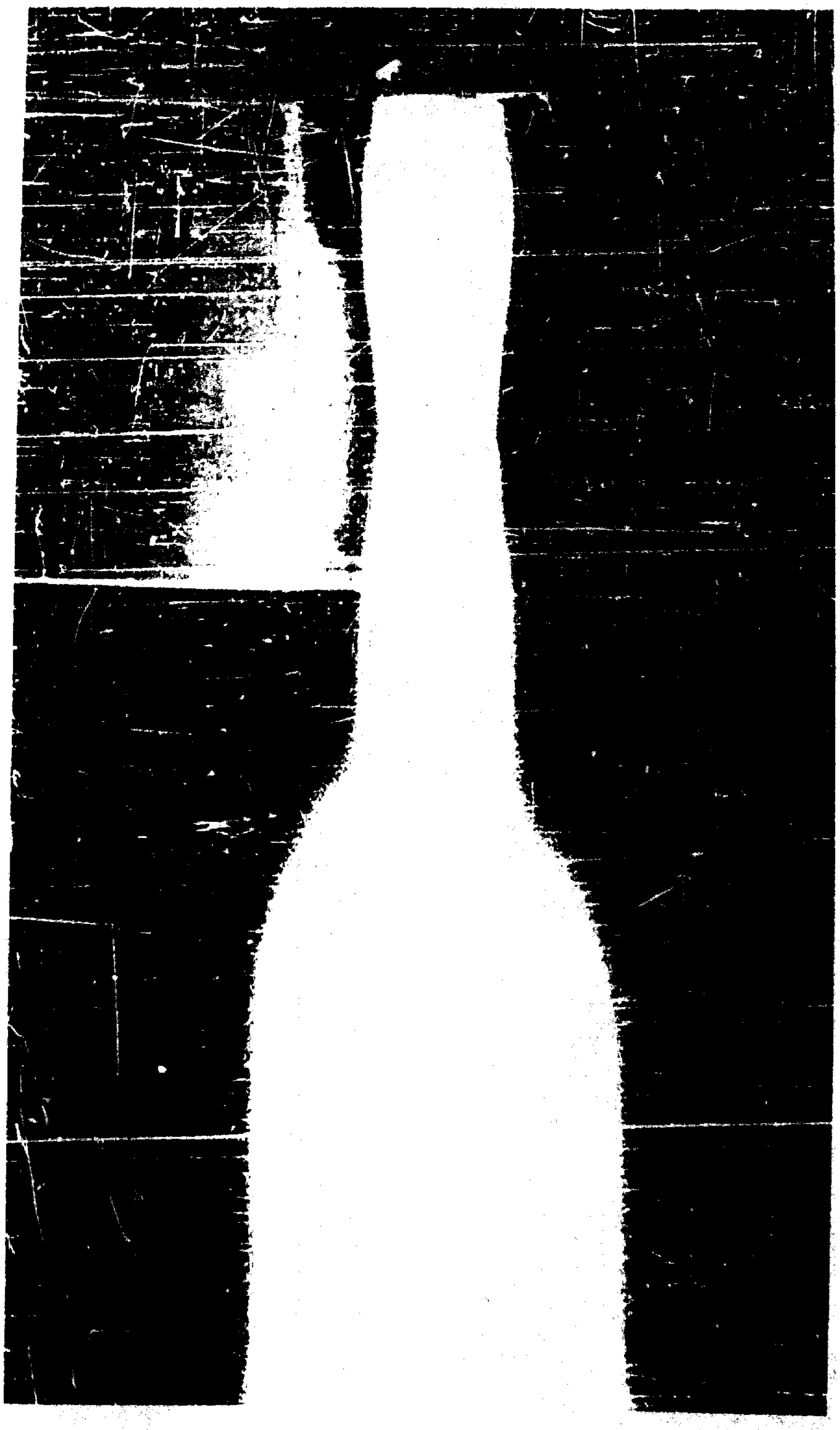


Figure 6. Enlarged View of Nozzle Exit Region

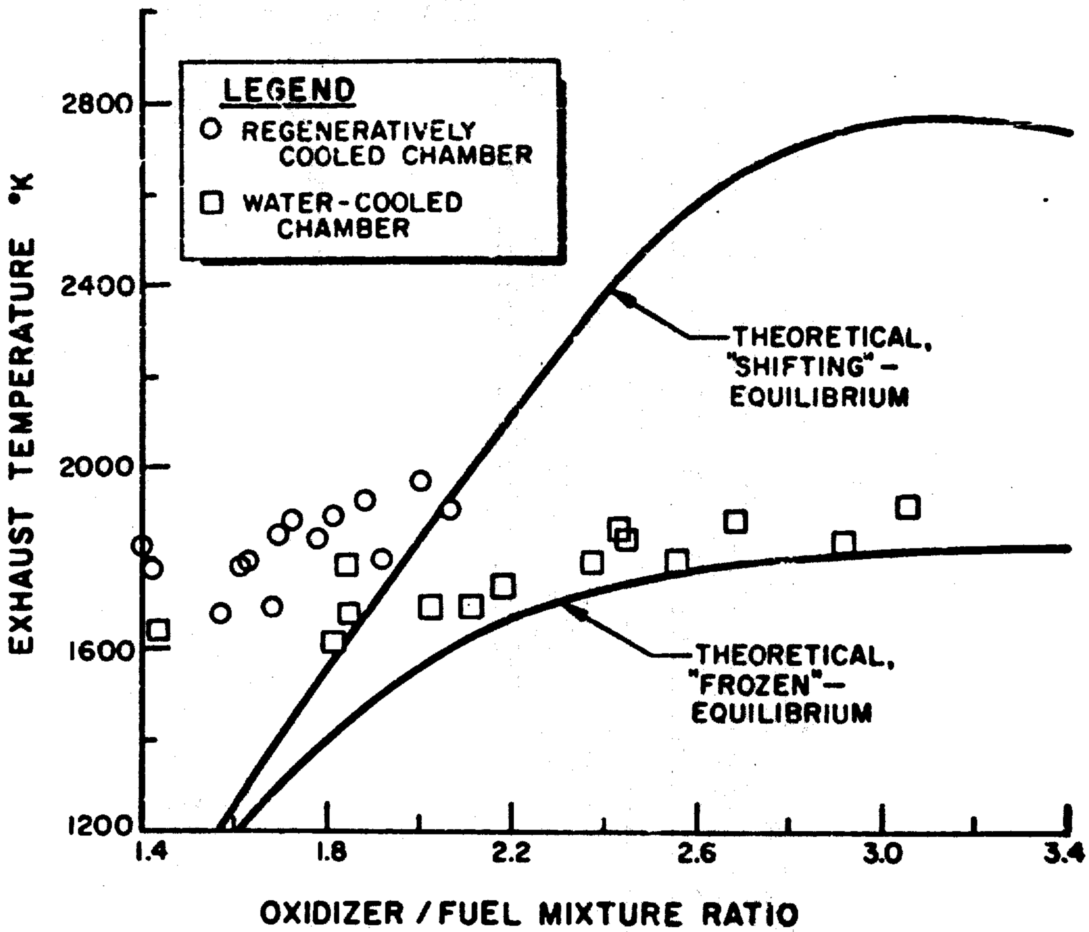


Figure 7. Nozzle Exit Temperatures Obtained at Various Mixture Ratios; Chamber Pressure = 24 atm; Expansion Ratio = 5.7; Nozzle Exit Diameter = 10 cm

two beam-splitting devices: a "preslit" similar to that used in the telespectrograph to define the field of view within a real image of the rocket exhaust flame; and a reflecting chopper, positioned close to the slit of the monochromator, to permit the distinguishing of temporal from spectral variations in the observed radiance. (The optical arrangement is essentially the same as that of the two-path spectral radiometer, which is to be discussed in more detail presently.)

The IRSATT was designed specifically for rocket exhaust radiation measurements; accordingly, the resolution and range of scanning rates were chosen as best compromises for that application. The spectral range of the instrument depends on the detector and prism combination; at 2 microns, the resolution is 0.005 microns and the scanning rate is variable from 0.003 to 3.0 microns/second. It was constructed to accommodate a variety of detectors.

Representative data obtained with this instrument, using a lead sulfide detector, are shown in Fig. 8, along with data obtained with the telespectrograph. These data represent the apparent spectral radiance of the exhaust jet from a medium-size, pressure-fed rocket thrust chamber using liquid oxygen and kerosene as propellants. The dominant feature of the spectrum is a continuum, presumably due to solid carbon borne by the gases. Superimposed on this continuous radiation are the molecular emission bands of water and carbon dioxide, the centers of which are missing by virtue of the atmospheric absorption between the flame and the instrument. Absolute intensity calibration was accomplished in a manner similar to the calibration of the telespectrograph by use of a blackbody source and a pair of auxiliary mirrors. The repeatability was such that spectra, obtained at different times from engines operating under essentially identical conditions, were virtually indistinguishable except for variations in the atmospheric absorption with changes in the ambient humidity.

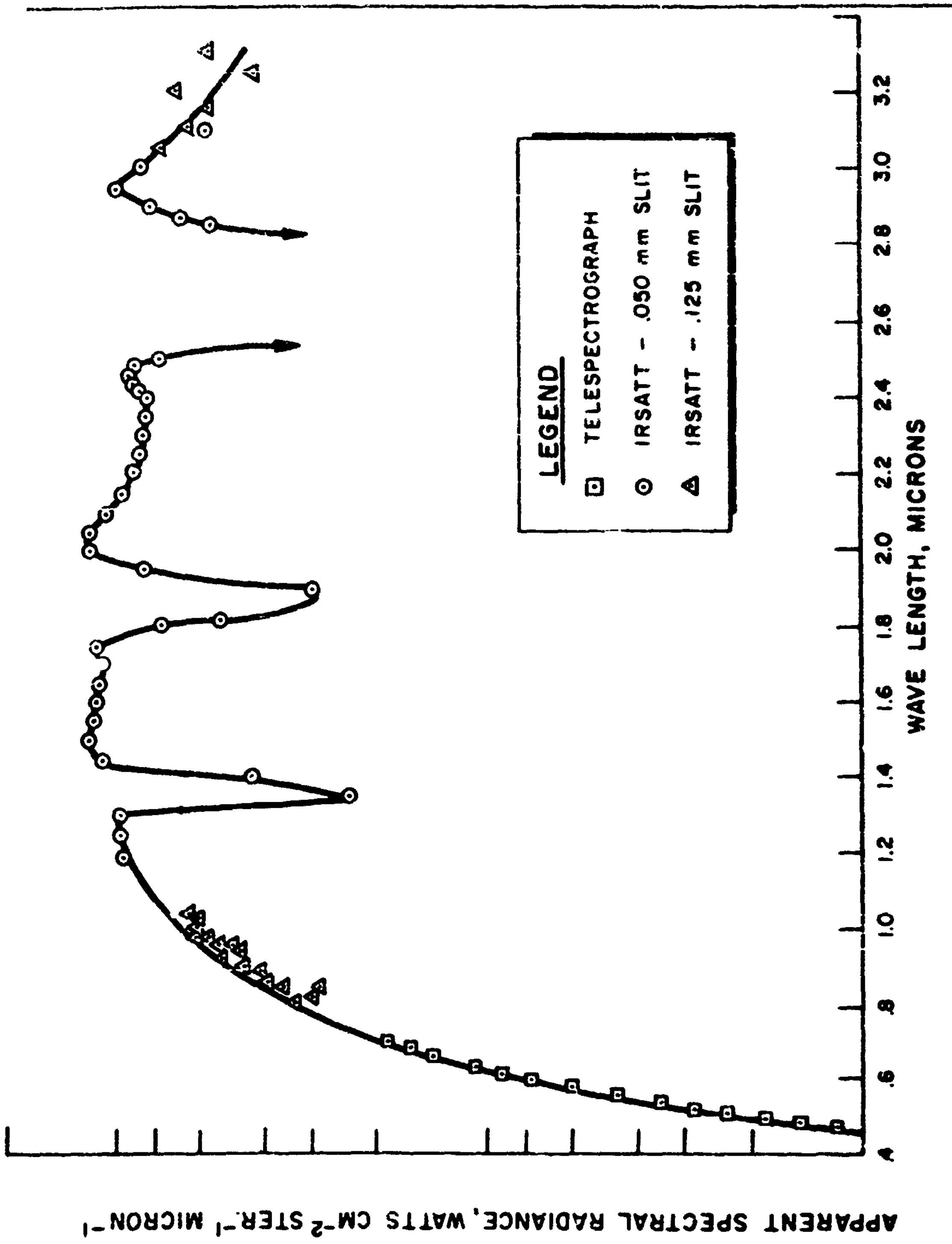


Figure 8. Apparent Spectral Radiance of a Luminous Rocket Exhaust Jet

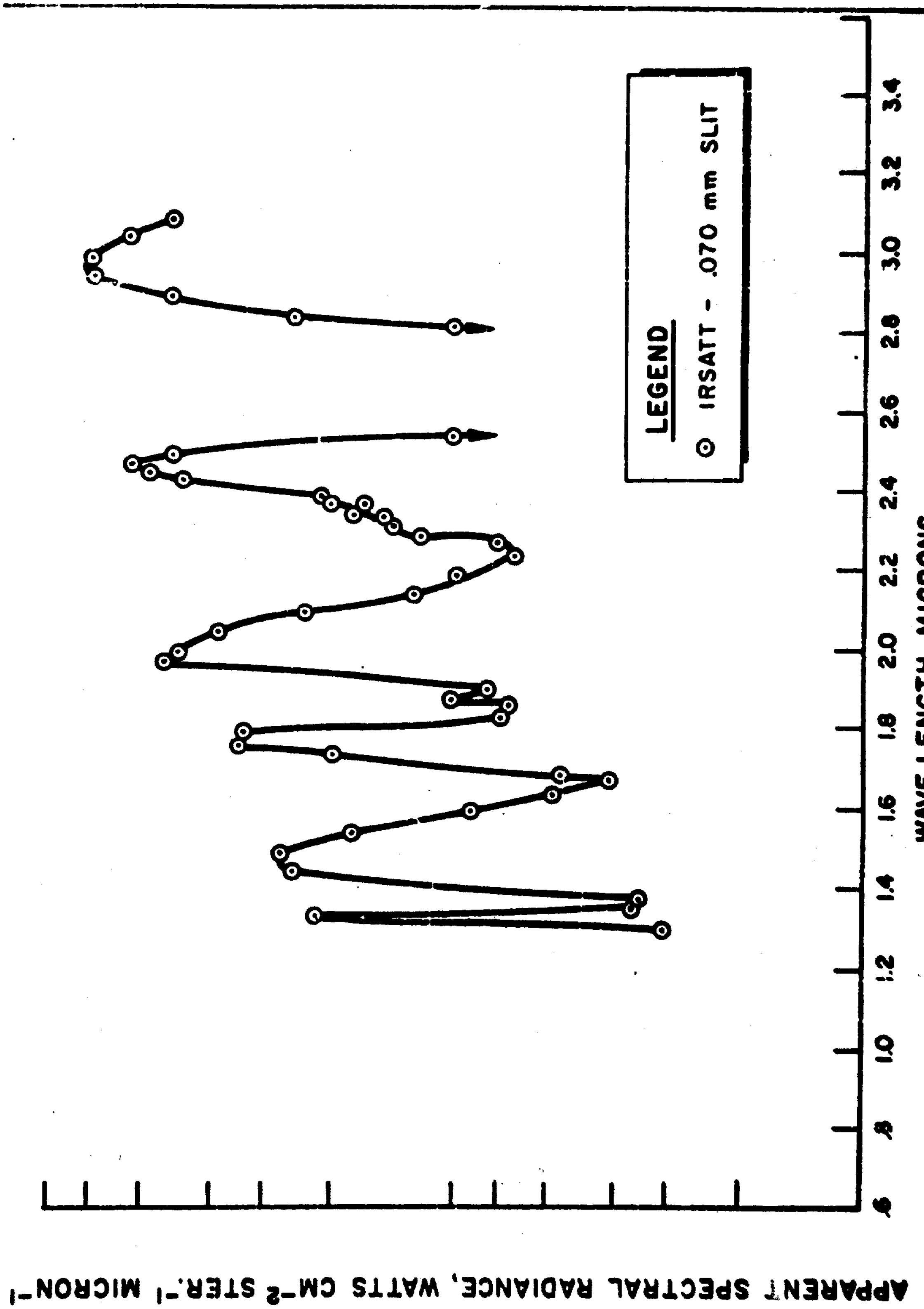


Figure 9. Apparent Spectral Radiance of a Non-Luminous Rocket Exhaust Jet

Comparable measurements of the apparent spectral radiance of a soot-free exhaust jet in which water was the major constituent are shown in Fig. 9. The spectrum consists of the wings of the emission bands from the hot molecules, and therefore represents radiation primarily from transitions among levels above the ground state, the corresponding transitions in absorption by the cool water in the surrounding atmosphere being highly improbable.

Two-Path Spectral Radiometer

This instrument is essentially a smaller model of the IRSATT and was designed specifically for close-range measurements on smaller rocket engines in a two-path arrangement.

The optical arrangement is shown schematically in Fig. 10. Radiation from the flame is reflected by two diagonal flats into a Newtonian telescope which creates an image of the flame in a plane intersected by the "preslit." The light reflected by the "preslit" is re-imaged on the slit of the monochromator. A reflecting chopper interrupts the beam, half of which enters the monochromator, and is dispersed in a double pass through the prism; the reflected half is directed onto a thermistor bolometer, the function of which is to monitor the gross radiation from the flame while the dispersed light is being scanned. In this way temporal variations may be distinguished from spectral variations during the scan; "hot flashes" would appear as spikes on both record, true spectral information only on the output of the detector in the monochromator. As with the previously described instruments, a small camera produces a fiducial photograph with the shadow of the "preslit" defining a field of view within the flame.

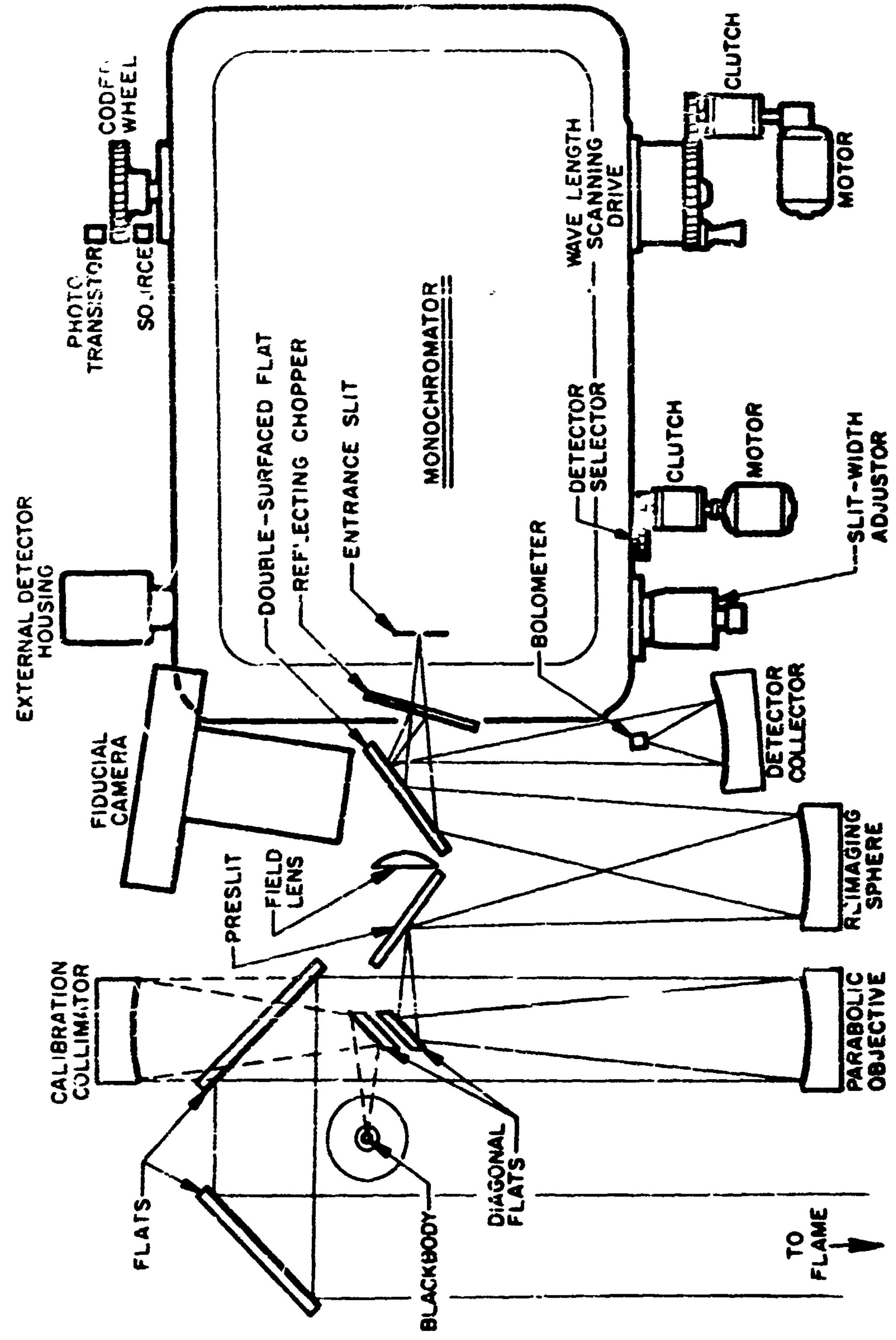


Figure 10. Two-Path Spectral Radiometer - Optical Circuit

An absolute intensity calibration is obtained by removing the second diagonal flat in the optical path for the flame radiation. This permits the radiation from a blackbody source to enter the optical system with precisely the same number of reflections, thus obviating any need for reflectance corrections. The blackbody radiator, designed specifically for this purpose, is capable of continuous operation at temperatures up to 2000 K, and is therefore able to span those normally encountered in rocket exhaust flames. The aperture of the blackbody is a 1 x 5 mm rectangle, the image of which fills the "preslit" and hence the entrance slit of the monochromator also.

Motor drives are provided for remote operation of the wavelength scanning drive and the internal-external detector change mechanism. A coded wheel on the wavelength drive shaft interrupts light on a small phototransistor, the recorded output of which establishes the wavelength during scanning. The output of the two spectral and the total detectors are a-c amplified, synchronously rectified, and recorded on a direct-writing oscillograph; parallel channels with adjustable electronic gain provide increased dynamic range. An uncooled lead-sulfide cell and a photomultiplier tube, as internal and external detectors, provide an effective wavelength range of 0.4 to 3.0 microns.

The doubling of apparent depth of the exhaust flame was achieved, in the same manner previously described for the photographic pyrometer, by sighting on a corner-cube reflector which was positioned behind the flame and periodically obscured with a rotating shutter. This reflector was constructed of first-surfaced aluminized quartz flats contacted together, and had a clear aperture of 2 inches; the face of the shutter was corrugated with narrow grooves and finished with a matte black paint to reduce its reflectance. The experimental arrangement is shown in Fig. 11.

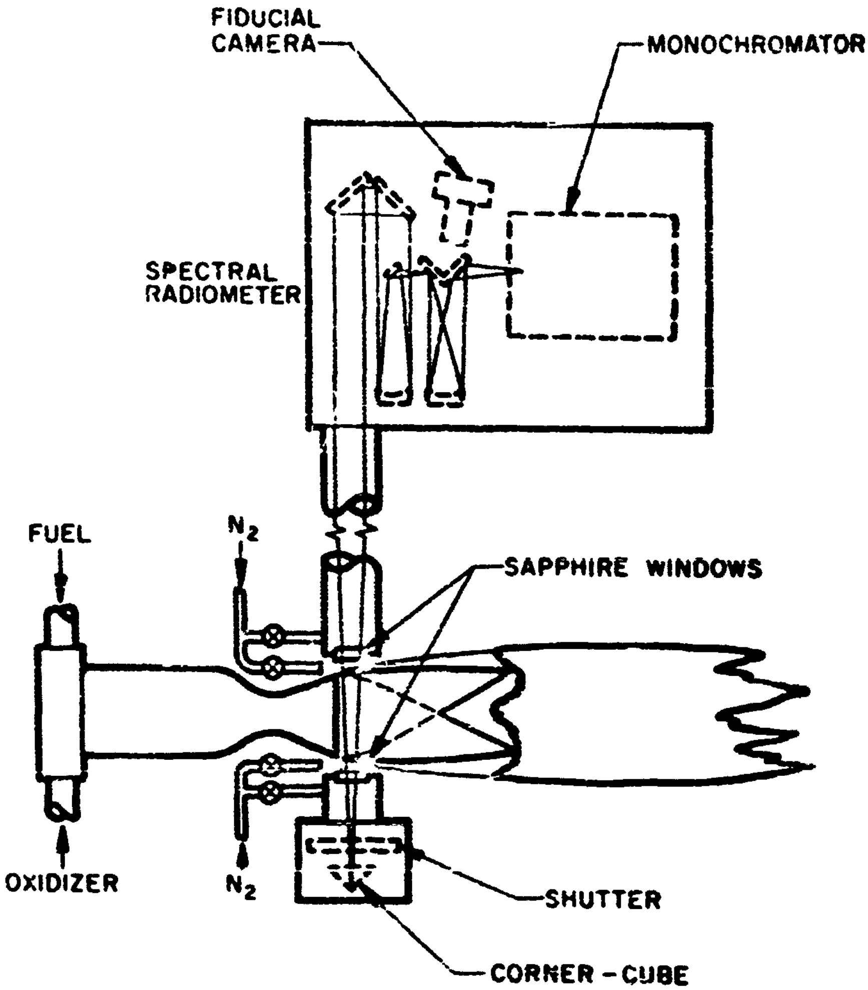


Figure 11. Experimental Arrangement for Two-Path Measurements Through A Non-Absorbing Atmosphere

The duct through which the instrument is sighted affords control of the atmosphere in the optical path. For absorption-free measurements, sapphire windows are installed at the duct ends adjacent to the flame, and the entire optical path, including that within the radiometer itself, is flushed with dry nitrogen.

In this two-path arrangement, from the two values obtained for the apparent spectral radiance, the spectral emissivity and absorption coefficient may be determined. Typical results of a specific study to determine the emissivity of the carbon soot in oxygen-hydrocarbon combustion products are shown in Fig. 12, in comparison with values predicted from electromagnetic theory. The experimental data shown were obtained during a single run of the motor at a particular chamber pressure and mixture ratio. Spectral emissivities measured during a number of runs showed similar distributions slightly displaced, as would be expected for different amounts of soot; the concentration has been found to vary in a somewhat random fashion, but on the average is greater at higher pressures and lower mixture ratios.

SOURCES OF ERROR

The ultimate attainable precision of the measurements of apparent spectral radiance of rocket exhausts as reported herein would depend upon the accuracy of the optical pyrometer used to calibrate the standard lamps and blackbody sources built into the various instruments. In practice the precision depended more upon such factors as the readability of records, detector drifts or optical misalignments in the instruments between calibration and operation, the detector responsivity, and the slope of the blackbody function. For the case where atmospheric absorption and scattering can be shown to be negligible, this precision in the measurement of the apparent spectral radiance is easily determined and can be

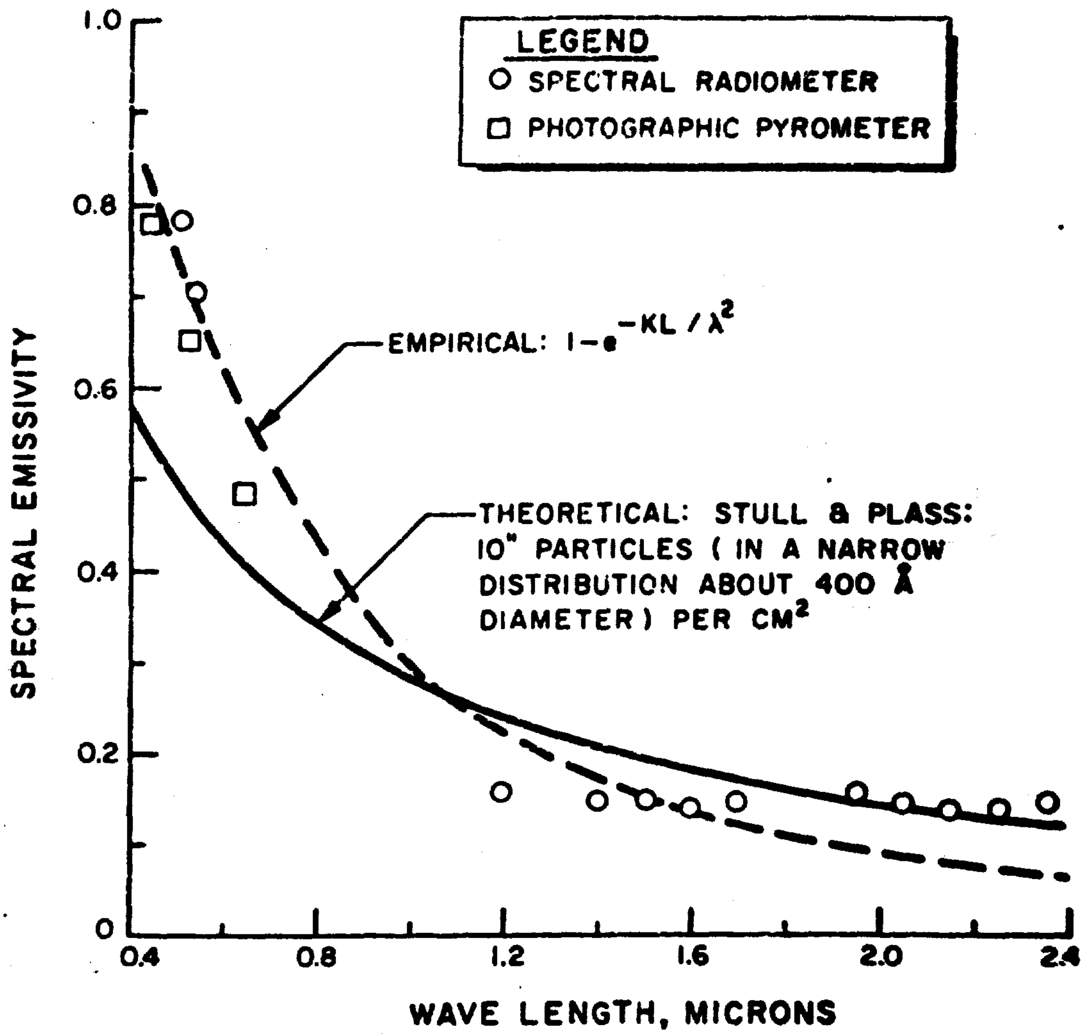


Figure 12. Typical Values for the Spectral Emissivity of Carbon Soot in Oxygen/Kerosene Exhaust: Chamber Pressure = 24 atm; Mixture Ratio = 2.3; Nozzle Exit Diameter = 10 cm

taken directly to be the absolute accuracy in a measurement of the actual spectral radiance of the exhaust, provided, of course, the radiation originates along the line of sight within the flame. Obviously, error would be introduced by radiation from background sources seen through the exhaust, or scattered into the optical path by condensed material dispersed in the exhaust gases. In the latter regard, an interesting possibility is that radiation from the much hotter and denser gases in the chamber may be scattered by the exhaust. In this case, the scattered component of the apparent radiance observed in the plane of the nozzle exit would be plane-polarized in the direction normal to the line of sight and the axis of the jet. It has been shown that scattering contributes negligibly to the observed emission from small flames (Ref. 13); its contribution to the emission from the larger and optically more dense rocket exhaust has not been determined.

When measurements of spectral radiance are to be related to a thermodynamic temperature of the gas stream, no statement of the absolute accuracy of a temperature measurement can be made; the reliability of the deduced temperatures depends strictly on the validity of the assumptions involved in the deduction. Perhaps the most frequent source of error in this regard is an incorrect assumption of a homogeneous radiation field; the effects of "self-absorption" due to macroscopic gradients along the line of sight have been discussed previously. However, nonequilibrium on the microscopic scale can also introduce large errors, and it becomes necessary to consider the source of the radiation being measured. For many of the presently reported measurements, the emission was from a relatively low concentration of solid carbonaceous material borne by the gases. Evaluation of such errors in this case reduces to a determination of any difference in temperature between the two phases at the plane of the measurement. Calculations (Ref. 14) have shown that spherical particles of carbon smaller than 1000Å should not significantly lag the gas temperature during the expansion in the nozzle. In order to determine particle sizes, samples of soot collected from the combustion chamber and the exhaust jet of the motor used in the two-path experiments were examined by electron microscopy**. Figure 13 is a micrograph of soot deposited on a quartz disc momentarily immersed in the exhaust jet. The particles are seen as approximately spherical in shape and range in diameter from 200 to 400Å. Similar micrographs of samples collected on a window in the combustion chamber during operations at various mixture ratios showed particles of 300 to 700Å diameter.

For emission from atomic or molecular transitions, the criterion for local thermodynamic equilibrium is that the radiative lifetime of the emitting species be longer than the time required to attain energy equilibration by collisions with other components of the gas. Since radiative lifetimes for vibration-rotation transitions are relatively long compared to those for electronic transitions, nonequilibrium radiation is more likely to be observed as ultraviolet or visible emission; also it is more likely to be produced by a low-pressure gas which is absorbing large quantities of energy from a local chemical reaction or from an extraneous source. A thorough analysis of the energy transfer and emissive processes for a rocket engine would have to include these and other characteristic times associated with the flow of combustion products through the chamber, the nozzle, and the standing waves in the exhaust jet. Such an analysis is beyond the scope of the present report; again, however, such complicating effects would be minimal at the nozzle exit region of the exhaust.

**Performed by Sloan Research Industries, Inc., Santa Barbara, Calif.

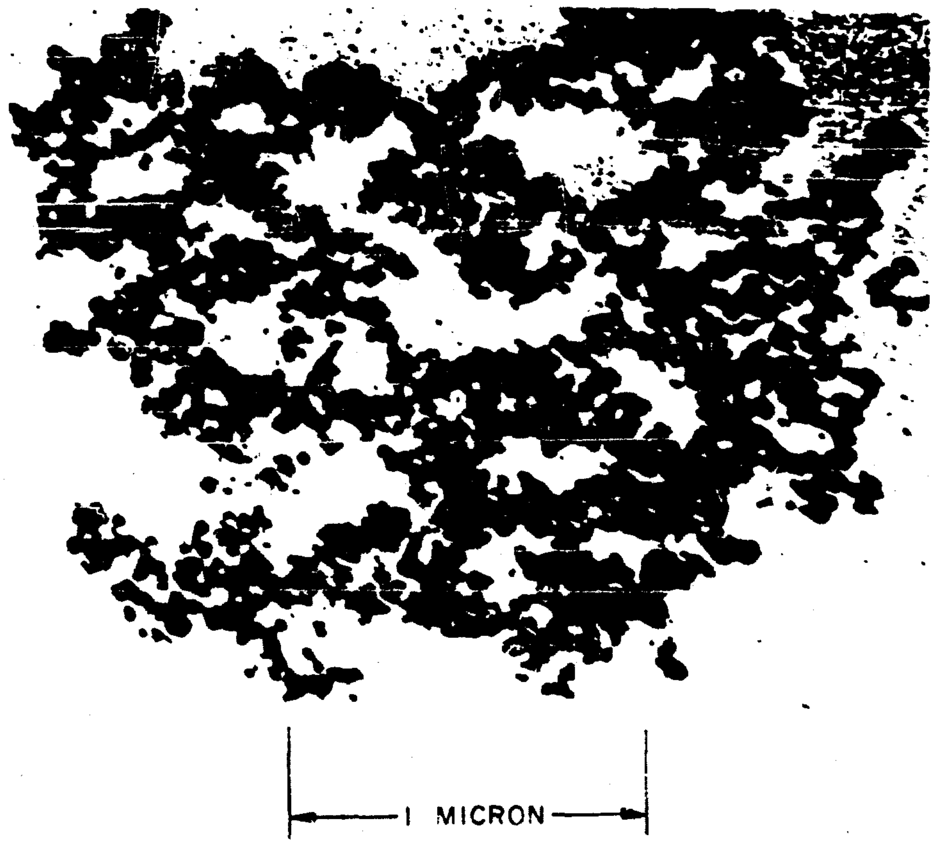


Figure 13. Micrograph of Carbon Soot from Exhaust Jet

SIGNATURE PAGE

APPROVED BY:

R. S. Levine
Chief
Physical Processes Section

F. S. Simmons
Principal Scientist
Physics and Measurements Unit

J. E. Witherspoon
Group Scientist
Physics and Mathematics Group

A. G. DeBell
Project Scientist
Physics and Measurements Unit

ACKNOWLEDGMENT

The work reported herein was supported in part by the Geophysics Research Directorate of the Air Force Cambridge Research Laboratories, under the sponsorship of The Advanced Research Projects Agency.

REFERENCES

1. S. S. Penner: Optical Methods for the Determination of Flame Temperature. Am. J. Physics 17, pp 422-429, 491-500 (1949).
2. H. P. Broida: Experimental Temperature Measurements in Flame and Hot Gases. Temperature, its Measurement and Control in Science and Industry. Vol. II, pp 265-286 (1955).
3. E. E. Bell: Radiometric Quantities, Symbols and Units. Proc.. IRE 47, 1432 (1959).
4. S. Chandrasekhar: Radiative Transfer. Dover Publications, Inc. (1960).
5. A. G. Worthing: Temperature Radiation Emissivities and Emittances. Temperature - Its Measurement and Control in Science and Industry. Vol. 1, p 1164 (1941).
6. V. N. Stull and G. N. Plass: Emissivity of Dispersed Carbon Particles. J. Opt. Soc. Am. 50, 121 (1960).
7. F. Rossler and H. Behrens: Bestimmung des Absorptions Koeffizienten von Russteilchen verschiedener Flammen. Optik 6, 145 (1950).
8. F. S. Simmons and A. G. DeBell: Photographic Technique for Measuring Temperatures in Luminous Rocket Exhaust Flames. J. Opt. Soc. Am. 48, 717 (1958).

9. F. S. Simmons and A. G. DeBell: Photographic Pyrometry of Rocket Exhaust Jets. Aircraft Eng. 31, 144 (1959).

10. F. S. Simmons and A. G. DeBell: Photographic Pyrometry with a Color-Separation Camera. J. Opt. Soc. Am. 49, 735 (1959).

11. F. S. Simmons: Expansion of Liquid-Oxygen RP-1 Combustion Products in a Rocket Nozzle. Am. Roc. Soc. J. 30, 193 (1960).

12. A. G. DeBell: Infrared Spectral and Total Teleradiometer. J. Opt. Soc. Am. 50, 1126 (1960).

13. H. G. Wolfhard and W. B. Parker: Temperature Measurements of Flames Containing Incandescent Particles. Proc. Phys. Soc. (London) 62, 523 (1949).

14. F. S. Simmons and F. G. Spadaro: Thermal Lag of Solid Carbon in Rocket Nozzle Flow. Combustion and Flame 4, 190 (1960).

ROCKETDYNE
A DIVISION OF NORTH AMERICAN AVIATION INC

STANDARD DISTRIBUTION

The purpose of the standard distribution is to provide adequate circulation avenues throughout the Rocketdyne Engineering Department. It is requested that this report be circulated by those listed within their organizations.

Engine Operations

C. Anselmo	596-166
A. T. Bruschi	596-173
D. M. Carpenter	596-160
J. J. Hary	596-165
R. F. Gompertz	596-164
D. S. Jolicoeur	596-164
R. D. Lumley	596-167
M. A. McClure	596-160

Engineering Operations

J. E. Kendall	596-302

Nuclionics Subdivision

R. H. Boden	584-370
R. B. Dillaway	584-370
S. V. Gunn	596-101
T. M. Littman	584-379
C. J. McDole	584-379

Research Department

Research Supervision	591 (35)

Advanced Design

J. O. Bates	589-335 CMA
P. D. Castenholz	596-148
V. R. Degner	589-335
D. W. Hege	589-330
L. L. Jirsa	589-334
R. S. Kraemer	589-335
R. J. Riddlesbarger	589-335
R. W. Rogers	589-335
A. J. Sobin	589-335
G. P. Sutton	597
E. A. Neu	589-338
R. C. Schwartz	589-330
I. E. Tuhy	589-336
J. G. Vehige	589-332

Liquid Propulsion Operations

W. J. Brennan	596-110
J. M. Cumming	596-101
M. C. Ek	596-125
H. W. Gilfillan	596-110
J. R. Hahn	596-120
I. M. Hirschfeld	596-121
D. K. Huzel	596-148
F. A. Jennings	596-123
J. J. MacGregor	596-125
J. P. Morris	596-125

Director of Research

M. Madoff	591-350

Solid Propulsion

R. R. Morin	595-201
D. O. Klute	595-280
D. M. Leitch	595-290

McGregor

J. F. Tormey	595
Albanese (2)	

ROCKETDYNE
A DIVISION OF NORTH AMERICAN AVIATION INC

Rockctdyne Representatives

W. Hines	Washington
G. Misko	Washington
M. Murray	Huntsville

Liquid Propulsion Operations

W. W. Mower	596-122
N. C. Reuel	596-140
K. N. Watts	596-141

Correspondence

Library	596-106 (3)
W.F. Herwig	596-152 CMA (3)
Central Files	588-832 (3)

Program Offices

J. J. Griffin	596-101
R. Healy	596-101
V. Just	596-101
R. E. Linse	596-158
E. B. Monteath	596-101
J. A. Schelke	596-101
D. J. Sanchini	596-101
E. Straub	596-101
W. N. Studhalter	596-101
O. T. Thorsen	596-101

Technical Reports

W. Kaysing	596-308
J. McCafferty	596-308
V. Schwartz	596-308

Supplementary

R. Raagas	589-336
C. Fingerhood	591-368
S. Logan, Jr.	589-331
J. Hines	589-331
R. Andres (2)	589-336
D.R.V. Golding	591-366
V. H. Monteil	591-368

Applications

W. J. Cecka	597
W. B. Mechling	597
D. E. Wright	597
W. R. Johnson	597
H. S. Stratton	597

ASTIA (10)

F. S. Simmons 591-351 (20)

UNCLASSIFIED

SPECTRAL RADIOMETRY AND TWO-PATH PYROMETRY OF ROCKET EXHAUST JETS

Research Report 61-9, 1 May 1961

1. Review of Basic Principles
2. Exhaust Jet Characteristics
3. Spectral Radiometry
4. Sources of Error

UNCLASSIFIED

SPECTRAL RADIOMETRY AND TWO-PATH PYROMETRY OF ROCKET EXHAUST JETS

Research Report 61-9, 1 May 1961

1. Review of Basic Principles
2. Exhaust Jet Characteristics
3. Spectral Radiometry
4. Sources of Error

UNCLASSIFIED

SPECTRAL RADIOMETRY AND TWO-PATH PYROMETRY OF ROCKET EXHAUST JETS

Research Report 61-9, 1 May 1961

1. Review of Basic Principles
2. Exhaust Jet Characteristics
3. Spectral Radiometry
4. Sources of Error

UNCLASSIFIED

SPECTRAL RADIOMETRY AND TWO-PATH PYROMETRY OF ROCKET EXHAUST JETS

Research Report 61-9, 1 May 1961

1. Review of Basic Principles
2. Exhaust Jet Characteristics
3. Spectral Radiometry
4. Sources of Error

UNCLASSIFIED ABSTRACT

The fundamental relations governing radiative transfer are briefly reviewed, and the methods of relating the observed spectral radiance of a gaseous source to its intrinsic properties are outlined. The inhomogeneous character of rocket exhaust jets is illustrated. Descriptions are given of several unique instruments for making quantitative spectroscopic measurements of exhaust radiation: a "Telespectrograph," for measuring spectral radiance in the ultraviolet and visible; an "Infrared Spectral and Total Teleradiometer" for similar measurements in the infrared; a "Photographic Pyrometer" and a "Two-Path Spectral Radiometer" for two-path measurements of gas temperature and spectral emissivity. Typical results obtained with the various instruments are presented and discussed.

UNCLASSIFIED ABSTRACT

The fundamental relations governing radiative transfer are briefly reviewed, and the methods of relating the observed spectral radiance of a gaseous source to its intrinsic properties are outlined. The inhomogeneous character of rocket exhaust jets is illustrated. Descriptions are given of several unique instruments for making quantitative spectroscopic measurements of exhaust radiation: a "Telespectrograph," for measuring spectral radiance in the ultraviolet and visible; an "Infrared Spectral and Total Teleradiometer" for similar measurements in the infrared; a "Photographic Pyrometer" and a "Two-Path Spectral Radiometer" for two-path measurements of gas temperature and spectral emissivity. Typical results obtained with the various instruments are presented and discussed.

UNCLASSIFIED ABSTRACT

The fundamental relations governing radiative transfer are briefly reviewed, and the methods of relating the observed spectral radiance of a gaseous source to its intrinsic properties are outlined. The inhomogeneous character of rocket exhaust jets is illustrated. Descriptions are given of several unique instruments for making quantitative spectroscopic measurements of exhaust radiation: a "Telespectrograph," for measuring spectral radiance in the ultraviolet and visible; an "Infrared Spectral and Total Teleradiometer" for similar measurements in the infrared; a "Photographic Pyrometer" and a "Two-Path Spectral Radiometer" for two-path measurements of gas temperature and spectral emissivity. Typical results obtained with the various instruments are presented and discussed.

UNCLASSIFIED ABSTRACT

The fundamental relations governing radiative transfer are briefly reviewed, and the methods of relating the observed spectral radiance of a gaseous source to its intrinsic properties are outlined. The inhomogeneous character of rocket exhaust jets is illustrated. Descriptions are given of several unique instruments for making quantitative spectroscopic measurements of exhaust radiation: a "Telespectrograph," for measuring spectral radiance in the ultraviolet and visible; an "Infrared Spectral and Total Teleradiometer" for similar measurements in the infrared; a "Photographic Pyrometer" and a "Two-Path Spectral Radiometer" for two-path measurements of gas temperature and spectral emissivity. Typical results obtained with the various instruments are presented and discussed.