

AD-A095 349

ADA 095 349

TECHNICAL
LIBRARY

AD

TECHNICAL REPORT ARBRL-TR-02280

MEASUREMENT OF THE LINE REVERSAL
TEMPERATURE OF OH IN CH₄/N₂O FLAMES

William R. Anderson

January 1981



US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

Approved for public release; distribution unlimited.

Destroy this report when it is no longer needed.
Do not return it to the originator.

Secondary distribution of this report by originating
or sponsoring activity is prohibited.

Additional copies of this report may be obtained
from the National Technical Information Service,
U.S. Department of Commerce, Springfield, Virginia
22151.

The findings in this report are not to be construed as
an official Department of the Army position, unless
so designated by other authorized documents.

*The use of trade names or manufacturers' names in this report
does not constitute indorsement of any commercial product.*

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER TECHNICAL REPORT ARBRL-TR-02280	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) MEASUREMENT OF THE LINE REVERSAL TEMPERATURE OF OH IN CH ₄ /N ₂ O FLAMES	5. TYPE OF REPORT & PERIOD COVERED Technical Report	
	6. PERFORMING ORG. REPORT NUMBER	
7. AUTHOR(s) William R. Anderson	8. CONTRACT OR GRANT NUMBER(s)	
9. PERFORMING ORGANIZATION NAME AND ADDRESS U.S. Army Armament Research & Development Command U.S. Army Ballistic Research Laboratory ATTN: DRDAR-BLI Aberdeen Proving Ground, MD 21005	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 1L161102AH43	
11. CONTROLLING OFFICE NAME AND ADDRESS U.S. Army Armament Research & Development Command U.S. Army Ballistic Research Laboratory ATTN: DRDAR-BLI Aberdeen Proving Ground, MD 21005	12. REPORT DATE JANUARY 1981	
	13. NUMBER OF PAGES 24	
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report) Unclassified	
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE	
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release, distribution unlimited		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Band reversal Line reversal Flame temperature OH radical <i>Flames Seeding</i>		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) (clt) The reversal technique is universally accepted by the combustion community as an accurate method for flame-temperature measurements. This technique has generally involved the use of Na seeded in flames. However, for many burner types seeding is difficult. This work describes band-reversal measurements using OH, which occurs naturally in all flames containing oxygen and hydrogen. The theory is discussed as well as use of the technique in the burnt gas region of CH ₄ /N ₂ O flames. The experimental results are compared with laser-excited (continued on next page)		

DD FORM 1 JAN 73 1473

EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

20. ABSTRACT (cont'd)

fluorescence temperature measurements also performed in this laboratory. Excellent agreement was achieved.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

TABLE OF CONTENTS

	Page
I. INTRODUCTION	5
II. THEORY	5
III. EXPERIMENTAL	8
IV. DISCUSSION	15
V. ACKNOWLEDGEMENTS	17
REFERENCES	18
DISTRIBUTION LIST	19

I. INTRODUCTION

Temperature measurement is of vital interest in studies of flames. It is necessary for determination of number densities of species in flames from spectroscopic data. It is also useful for comparison with the results of detailed modeling calculations. One of the better accepted spectroscopic techniques for the measurement of flame temperature is the reversal method,¹ which has generally been applied using the sodium D lines. The technique is then termed line reversal. For certain burner types, however, Na seeding is difficult or impossible. In these cases it is wise to look for a transition involving one of the flame species. This paper describes application of reversal to the (0,0) R bandhead of the OH $A^2\Sigma^+ \rightarrow X^2\Pi$ system. The technique is best termed band reversal.

Reversal techniques do not provide the spatial resolution of laser based techniques, and measurements therefore cannot be made in the flame front by reversal. Such measurements, however, can be easily performed in the burnt gas region where the temperature gradients are not large. The results can be used for comparative purposes with those of the laser based methods.

This paper is written as an introduction to line reversal to point out some subtleties in what is conceptually a very simple experiment. First the theory behind the technique is discussed, then the experimental apparatus is discussed and, finally, results of reversal measurements are presented and compared with laser excited fluorescence measurements.

II. THEORY

Consider a gas inclosed by a blackbody in equilibrium at temperature T . Suppose that only radiative heat transfer is possible between the walls of the blackbody and the gas. The spectral intensity in the frequency range ν to $\nu + d\nu$ is isotropic and is given by²

¹A. G. Gaydon and H. G. Wolfhard, *Flames: Their Structure, Radiation and Temperature*, (Chapman and Hall, LTD., London, 1970).

²Y. B. Zel'dovich and Y. P. Raizer, *Physics of Shock Waves and High Temperature Hydrodynamic Phenomena*, (Academic, New York, 1966, Vol. 1, Chapter 2; S. S. Penner, *Quantitative Spectroscopy and Gas Emissivities*, (Addison-Wesley, Inc., Reading, Mass., 1959); L. D. Landau and E. M. Lifshitz, *Statistical Physics* (Addison-Wesley, Inc., Reading, Mass, 1958).

$$I_{\nu} d\nu = \frac{2h\nu^3}{c^2} \frac{1}{\exp(h\nu/kT)-1} d\nu \quad (1)$$

where h is Planck's constant, c the speed of light and k Boltzmann's constant. Since some confusion might easily result, it is worthwhile to discuss the physical meaning of I_{ν} and its relation to other observables in radiation theory. The quantity I_{ν} is the amount of radiant energy in the spectral interval $d\nu$ passing a unit area in space in unit time. The propagation vectors of I_{ν} are restricted to lie within a solid angle $d\Omega$ about the normal to the unit surface area. Typical units for I_{ν} are therefore erg/cm² sec Hz ster. Two other radiant energy observables are typically discussed. They are the spectral energy density, ρ_{ν} , and the intensity of parallel radiation, $I_{\nu p}$. The energy density is essentially $h\nu$ times the number of photons in the range $d\nu$ present in a unit volume at a given instant in time (for purposes of the present study, all observables are assumed to be time independent). The intensity of parallel radiation is defined for parallel radiation, as, for example, from lasers, and is the amount of radiant energy in the spectral interval $d\nu$ passing a unit area perpendicular to the direction of propagation in unit time. For isotropic radiation, $\rho_{\nu} = (4\pi/c)I_{\nu}$. For parallel radiation, $\rho_{\nu} = (1/c)I_{\nu p}$. Typical units for ρ_{ν} are thus erg/cm³Hz and for $I_{\nu p}$ are erg/cm² Hz sec. Care must be taken to avoid error by a factor 4π if intensity is used, especially in calculations of absorption or emission rates.

The steradiancy² of an emitting surface is defined as the amount of radiant energy in unit frequency interval emitted per unit time from a unit area of the surface into unit solid angle. The intensity at a surface parallel to the emitter surface and placed along the normal to the emitter, but a great distance away, is equal to the steradiancy normal to the emitter. Therefore, for a blackbody emitter surface, the steradiancy normal to the surface is also given by Eq. 1.*

Let us now consider the gas at equilibrium with the blackbody inclosure. Suppose a transition between lower level 1 and upper level 2 of energy $h\nu$ is possible for the gas. The ratio of the number densities in the two states is then given by the familiar Boltzmann law:

$$N_2/N_1 = (g_2/g_1)\exp(-h\nu/kT) \quad (2)$$

* The steradiancy at an angle θ to the normal of the emitter surface drops by the factor $\cos \theta$ (see Ref. 1 and 2). One must take care to use only radiation from a small solid angle normal to the surface of calibrated emitters to avoid error.

where N_1 is number density and g_1 the level degeneracy. Radiative transfer occurs via three processes: absorption from the ground state, stimulated emission from the excited state and spontaneous emission from the excited state. The rate of absorption is given by $B_{12} I_\nu N_1$, stimulated emission by $B_{21} I_\nu N_2$ and spontaneous emission by $A_{21} N_2$, where A_{21} , B_{12} and B_{21} are the Einstein coefficients expressed in terms of spectral intensity.^{2,3} At equilibrium, the rate of absorption is equal to that of emission, assuming nonradiative energy transfer is negligible, and then

$$B_{12} I_\nu N_1 = B_{21} I_\nu N_2 + A_{21} N_2 \quad (3)$$

By substituting Eq. 2 into 3 and solving for I_ν (after rearrangement to the form of Eq. 1), one finds²

$$B_{21} = c^2 A_{21} / 2h\nu^3 \quad (4a)$$

and

$$B_{12} = (g_2/g_1) B_{21} \quad (4b)$$

Eqs. 4a and b were originally derived by Einstein as described above.* Rearranging Eq. 3 one finds

$$(B_{12} N_1 - B_{21} N_2) I_\nu = A_{21} N_2 \quad (5)$$

What happens if the blackbody and gas are not in equilibrium? Suppose the blackbody temperature, T_b , is lower than the gas temperature, T_g . Since I_ν is smaller at the lower temperature, the spontaneous emission is larger than the net absorption. There will thus be a net emission at ν . Similarly, if $T_g < T_b$, there will be a net absorption at ν . If $T_g = T_b$, there is no absorption or emission.

³A. C. G. Mitchell and M. W. Zemansky, Resonance Radiation and Excited Atoms, (Cambridge University Press, 1934) p. 92-5.

* Einstein's original derivation of the relation was in terms of energy density, ρ_ν . One must be extremely careful in rate calculations that the observable one is using (ρ_ν , I_ν or $I_{\nu p}$) is appropriate for the dimensions of B_{12} . An error by a hidden factor of 4 π can easily result otherwise.

A blackbody as described above is impractical for experimental work. If one places a blackbody emitter and a detector subtending the same solid angle, $d\Omega$, on either side of a gas confined to the volume V , as shown in Figure 1, one may analyze the situation for practical experiments. Since the spontaneous emission is isotropic, the rate of spontaneous emission into the detector is $A_2 I_1 N_2 V d\Omega / 4\pi$. The stimulated terms in Eq. 5 are affected by an equivalent factor since the solid angles for source and detector are equivalent. Thus, an experiment can be run without integrating over 4π ster.* The solid angle of the detector must be the limiting aperture, not the emitter. Otherwise, the emission of some of the flame gases, with no background irradiation, will enter the detector, causing erroneous measurements.

Let us now consider the most common emission source used in reversal work, the tungsten ribbon lamp. Such a lamp contains a strip of tungsten which is heated by a constant current source. Light emitted from the filament may pass through a pyrex window. However, this work necessitated use of a lamp with a fused silica window to pass ultraviolet radiation. The emissivity of tungsten is not unity so that Eq. 1 does not apply. Instead, the steradiancy is multiplied by an emissivity factor, E . Converting to unit wavelength interval $d\lambda$, since the lamp used in this work was calibrated in such units, and remembering $|d\nu| = cd\lambda/\lambda^2$, one finds the intensity normal to the surface is

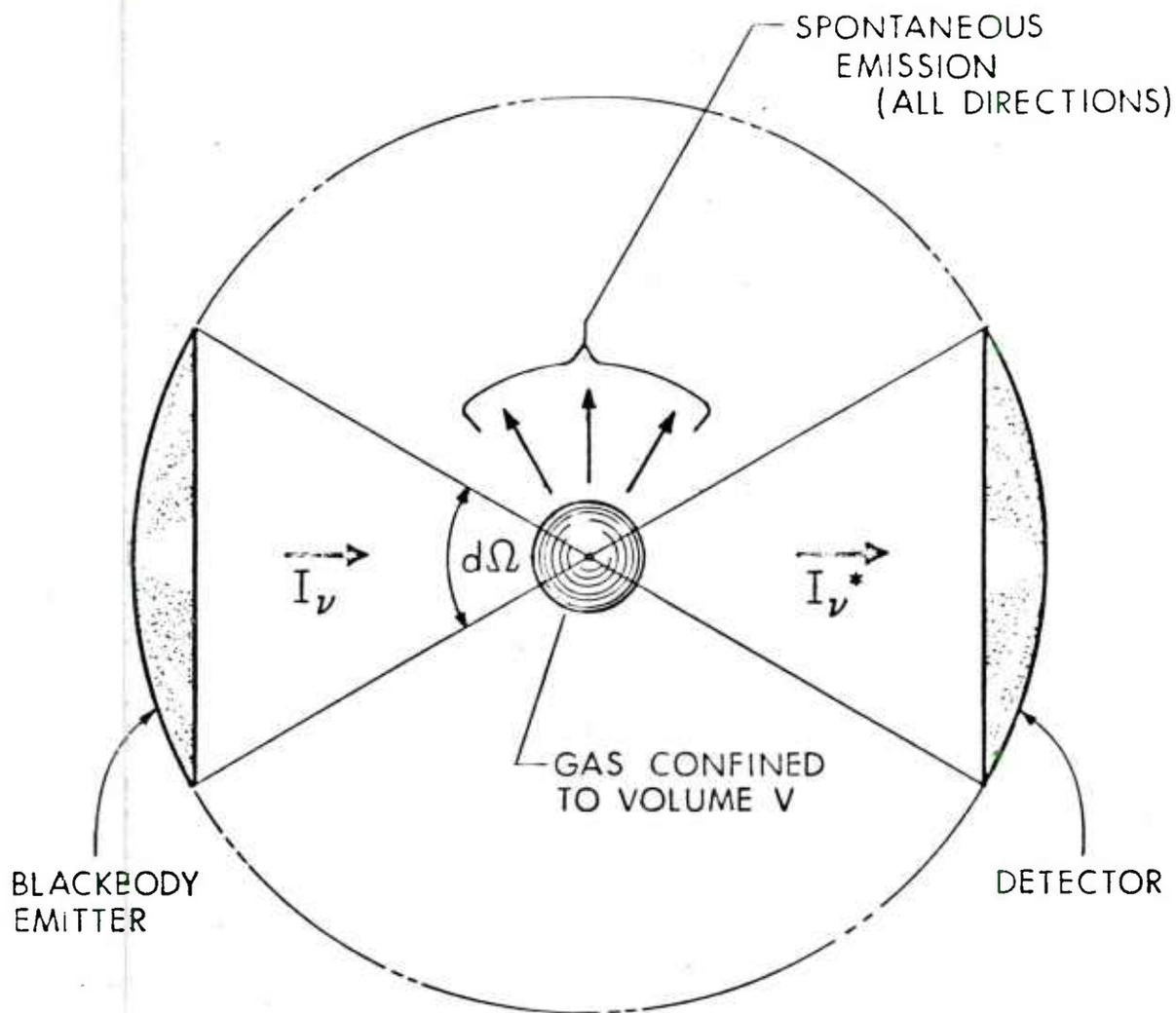
$$I_\lambda d\lambda = \frac{2hc^2 E(\lambda, T)}{\lambda^5} \frac{1}{\exp(hc/\lambda kT) - 1} d\lambda \quad (6)$$

where T is the temperature of the filament. Tables of emissivity for tungsten may be found in ref. 1, if needed. However, the method described in this work requires usage of Eq. 6 only for a hypothetical blackbody emitter which has $E = 1$.

III. EXPERIMENTAL

A diagram of the apparatus used in this work is shown in Figure 2. The standard lamp is a tungsten ribbon lamp with a fused silica exit window which is calibrated for steradiancy normal to the surface vs.

*In this design, the spontaneous emission loss is not compensated by a surrounding blackbody inclosure. Collisional excitation and quenching usually dominate the energy partitioning. However at sufficiently low pressures, as discussed in ref. 1, the radiative losses may appreciably lower the temperature of the electronic modes. This phenomenon can result in measured reversal temperatures which are quite low compared to the translational temperature.



$$I_\nu^* = I_\nu - \text{ABSORPTION} + \text{STIMULATED EMISSION} + \text{SPONTANEOUS EMISSION OCCURRING IN } d\Omega$$

Figure 1. Gedanken reversal experiment for an emitter-detector combination of solid angle $d\Omega$. In a real experiment, the gas in volume V is replaced by a flame and the emitter by a lens. The blackbody emitter could equally well be represented by a point blackbody emitter at the center of the sphere.

REVERSAL APPARATUS

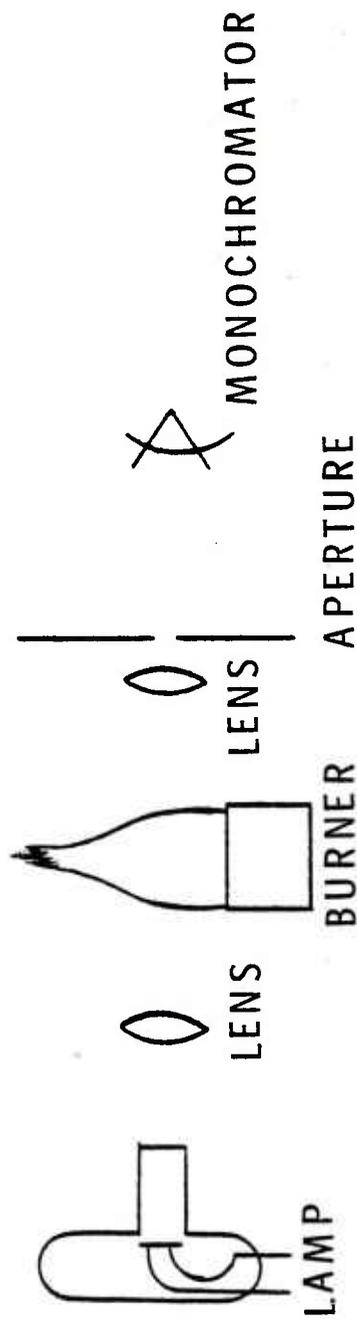


Figure 2. Diagram of Reversal Apparatus. The lamp is a tungsten ribbon lamp with a fused silica window. The lenses are also made of fused silica. The aperture is adjustable. The apparatus is set up for 1:1 imaging of the tungsten filament at the center of the flame and at the monochromator slits.

wavelength at a constant current of 35 amp (Eppley Laboratory, Inc.). A similar working lamp is used for most measurements and later calibrated against the standard lamp. Light from the lamp is 1:1 imaged into the flame by a quartz lens. Thus, the intensity at the flame is equal to the lamp steradiancy (neglecting lens losses). The lamp radiation and flame emission are 1:1 imaged on the slits of a monochromator. An aperture stop limits the acceptance angle of the monochromator so that it views equal solid angles of the flame and background radiation. The aperture must be small enough to restrict the background emission to that portion which is nearly normal to the filament.

Care must be taken to avoid chromatic aberration of the lenses. Variation in the index of refraction with wavelength causes the focal length of the lenses used to change for 12.70 cm in the visible to 12.07 cm at 3070Å, as calculated using the lensmakers equation. Ignorance of this change can introduce a 100-200 K systematic error into the results.

As previously stated, the flames used in this work were CH₄/N₂O flames. The flames were produced by a water-cooled, sintered bronze flat-flame type burner of 6.4 cm diameter. Capillary flow regulators provided supply gases to the burner. The absolute flow rates were accurate to within 1%.⁴

A 0.3-m Heath monochromator was used in this work. A 100-micron slitwidth was used yielding a bandpass of $\sim 3\text{\AA}$ FWHM. Output from the monochromator was detected by an EMI 9558QA photomultiplier (PMT). Current from the PMT was monitored by a picoammeter. Hard copy of the picoammeter output was obtained on a strip-chart recorder.

The transmission of the first lens after the lamp was determined in the following manner. The PMT response was determined with the apparatus set up as shown in Figure 2 with the flame off. Then the lens and burner were removed. The lamp was moved to the point where the tungsten filament was above the center of the original burner position, i.e., at the original imaging point. The ratio of PMT responses yields the transmission. Of course, the lamp supply current, slitwidth and wavelength observed must be held constant.

In a typical temperature run, the monochromator was scanned from about 3050 to 3080 Å across the R₁ and R₂ bandheads of the OH (0,0) vibrational band. Figure 3 shows a scan of the flame emission with the lamp turned off. The R₁ and R₂ bandheads appear as a splitting on the peak between 3060 and 3075 Å. The sharp rise at 3060 Å and the splitting of the peak were found to be very useful in temperature runs with low signal to noise ratio. For a given flame, the lamp current is changed and the monochromator is scanned each time until the reversal point is

⁴M. A. Dewilde, "Capillary Flowmeters for Accurate Stable Flows of Gases". BRL Technical Report ARBRL-TR-02230, March 80. (AD #A083874)

OH A \rightarrow X EMISSION IN CH₄/N₂O FLAME

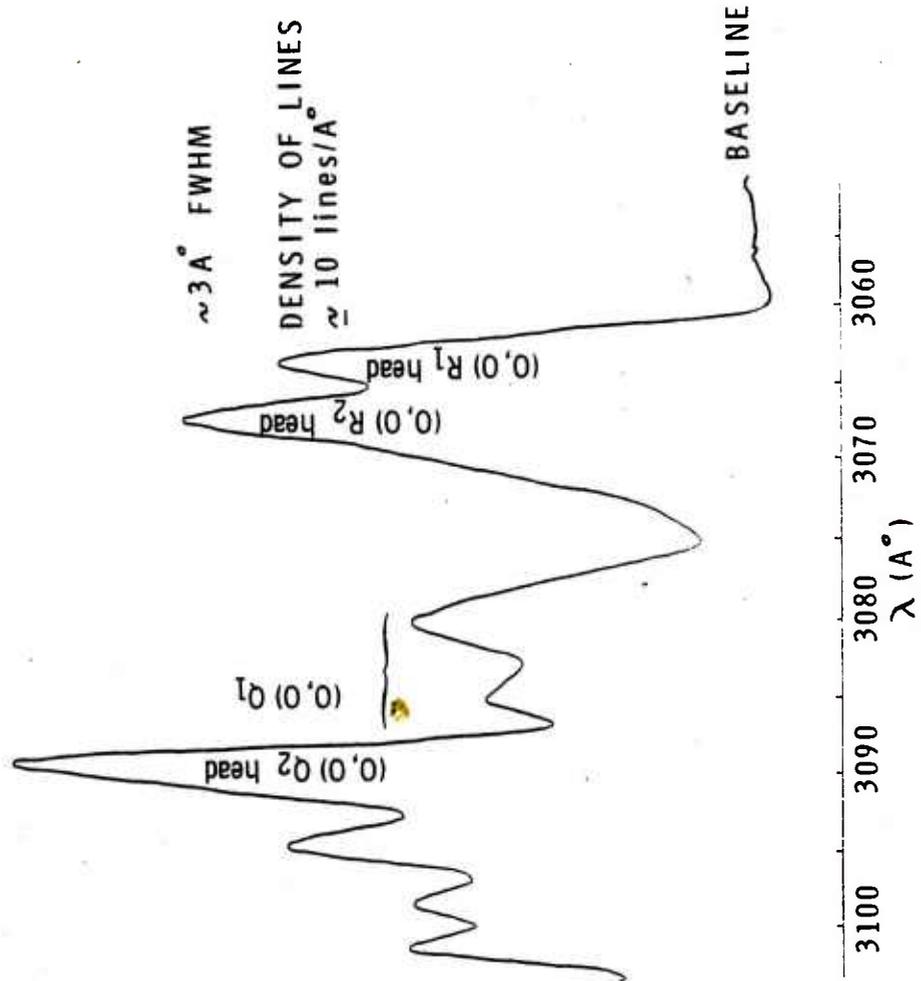


Figure 3. OH Emission Scan in CH₄/N₂O Flame

obtained. A typical set of scans is shown in Figure 4. The graybody curve of the lamp is shown in Figure 4a with the flame off. With the flame on, the OH spectrum shows up, in Figure 4b, as an emission. The splitting of the R₁ and R₂ bandheads may be discerned on the scan. The peak positions are pointed out by arrows on the scan. Though the exact temperatures are not known, the background temperature was lower than, but very close to, the flame temperature. Once the reversal point had been determined, the monochromator was scanned with the lamp current set + 0.5 and - 0.5 amps away from the reversal point to be sure that absorption and emission, respectively, could be discerned. The ± 0.5 amp current setting typically introduced ± 25K into the error limits.

The reversal temperature was determined in the following manner. The monochromator was set at 3070Å, the approximate center of the OH peak used. The PMT current was then determined for the working lamp at the reversal current and for the standard lamp at its calibration current (35 amps). The steradiancy, S, of the standard lamp was known from its calibration vs. wavelength. The intensity at the reversal point is thus

$$I(3070 \text{ \AA}) = (C_w/C_s)St \quad (7)$$

where C_w is the PMT current for the working lamp at the reversal point, C_s that for the standard lamp at its calibration current and t is the transmission of the lens. The temperature of the flame is then that at which a blackbody (not the tungsten filament!!!) produces the intensity of Eq. 7. This temperature is determined by inserting E = 1 in Eq. 6 and solving for T.

The absorption measured in this work was of the order of 5%. This low signal level made discerning the absorption peak from background noise very difficult. In retrospect, it would probably have been better to use a high resolution monochromator with bandwidth of order 0.05 Å, the approximate bandwidth of a single rotational line of OH in the flame, and use pulse counting techniques. The signal to noise ratio should be much higher and the reversal of individual lines could be examined.

No other species besides OH were used in this study. The primary reason for this restriction was the impracticality of seeding the porous sintered bronze burner with sodium salts or other materials commonly used in reversal work. A scan of emission from the burnt gas region of the CH₄/N₂O flames revealed the presence of minor emissions from NH (3360 - 70 Å) and CN (3880 Å) which probably were too small to yield useful results by this technique. (However, with a higher resolution monochromator they might be used). Strong H₂O bands were observed at 6930 and 7165 Å. The first has a sufficiently sharp bandhead that it might yield good results, but neither was tried in this study.

OH BAND REVERSAL

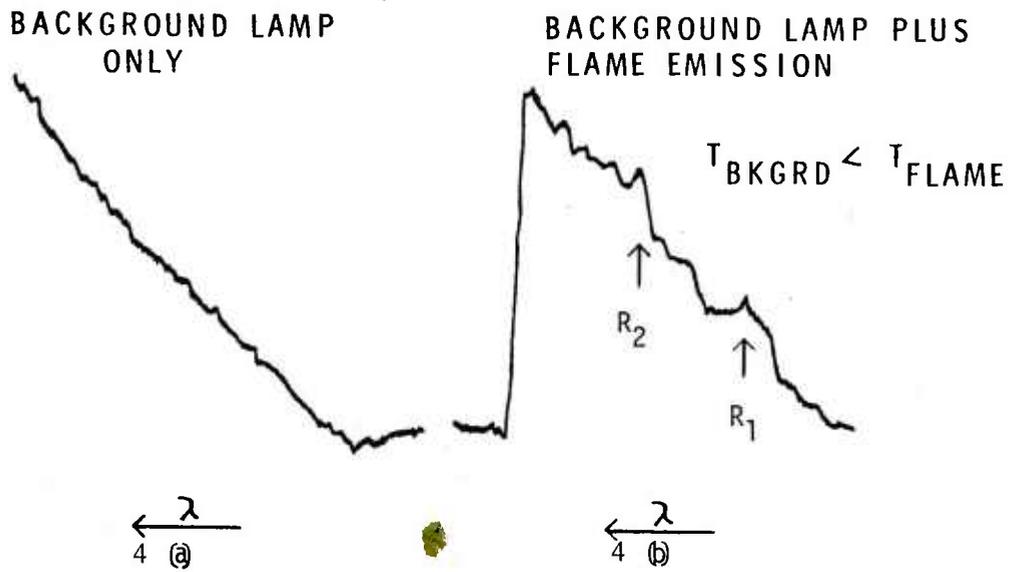


Figure 4. Scan of lamp plus OH Emission. The R_1 and R_2 bandheads of Figure 3 are pointed out in Figure 4b.

The OH reversal temperature was determined in the burnt gas region of stoichiometric, slightly lean and slightly rich CH₄/N₂O flames. The results are presented in the next section and compared with the results of laser-excited fluorescence measurements.

IV. DISCUSSION

The flame temperature was measured in the burnt gas region of several CH₄/N₂O flames by line reversal and at several heights by OH laser-excited fluorescence.⁵ The results are shown in Table 1. The fluorescence measurement at $\phi = 1.01$ is the average over four measurements at various heights above the burner, all in the burnt gas region, shown in Table 2. As can be seen, the temperature does not vary, within error limits, above the burner. This result is important since the reversal resolution was only good to about 1 cm in this study. For the fluorescence technique, the resolution was much better, the beam diameter being about 200 microns. The agreement between the results is most gratifying. Note also that the temperature probably peaks near an equivalence ratio of 1.0, as one would expect.

The OH band reversal measurement is essentially a determination of the electronic temperature of the OH in the flame. As such, in spite of the wide acceptance of reversal measurement by the combustion community, the technique is subject to errors as grievous as other less well accepted techniques. Even if great care is taken to avoid systematic errors, as discussed by Snelleman in ref. 6, the electronic temperature of the reversed species can differ from the translational temperature of the flame gases, resulting in error. The technique lacks good spatial resolution. It is a line of sight method which cannot be easily applied in flames with large horizontal temperature gradients. Yet, it is an inexpensive and relatively easily applied technique.

The laser-excited fluorescence measurements were performed in the (1,1) vibrational band of the A $2\Sigma^+ \leftarrow X 2\Pi$ electronic transition.⁵ The temperature measured was the rotational temperature in the first excited vibrational state of the ground electronic state of OH. Measurements by this technique could also be subject to effects of nonequilibration with the translational temperature. However, one would intuitively expect the rotational levels in the ground electronic state to equilibrate much more quickly than electronic states due to the relative energy transfer rates involved. Thus, if a reaction produces electronically excited OH, the slow equilibration could be especially problematic leading to

⁵W. R. Anderson, "Laser Excited Fluorescence Measurement of OH Rotational Temperatures in a CH₄/N₂O Flame", Eastern Section Meeting, Combustion Institute, Atlanta, Georgia, Nov 1979, paper 3; L. J. Decker and W. R. Anderson, to be published.

⁶W. Snelleman, "Errors in the Method of Line-Reversal", *Combust. Flame* 11, 453 (1967).

TABLE 1. CH₄/N₂O TEMPERATURES IN THE BURNT GAS REGION.
THE TEMPERATURES WERE MEASURED AT SEVERAL EQUIVALENCE
RATIOS, $\phi = 4[\text{CH}_4]/[\text{N}_2\text{O}]$.

ϕ	<u>Line Reversal [K]</u>	<u>Laser-Excited Fluorescence [K]</u>
1.18	2129 ± 50	2113 ± 38
1.01	2194 ± 45	2199 ± 53*
0.55	2089 ± 70	not measured

* Average of the four measurements in Table 2. The temperature above the burner does not change in the burnt gas region so that this average is meaningful.

TABLE 2. CH₄/N₂O TEMPERATURE AS MEASURED BY LASER EXCITED
FLUORESCENCE. THE TEMPERATURE IS MEASURED AS A FUNCTION
OF HEIGHT ABOVE THE BURNER AT THE EQUIVALENCE
RATIO $\phi = 1.01$

<u>Height (cm)</u>	<u>Temperature (K)</u>
0.25 ± 0.05	2220 ± 48
0.50 ± 0.05	2186 ± 55
1.00 ± 0.05	2201 ± 76
2.50 ± 0.05	2189 ± 36

erroneously high temperature measurements. Equilibration in the burnt gas region of atmospheric pressure flames is not expected to be a serious problem as no reactions leading to electronically excited OH are expected to be important and rotational equilibration is rapid.* The agreement between the rotational and electronic temperatures substantiates these arguments.

The usefulness of the OH band reversal technique is demonstrated in this work. The technique provides a temperature measurement for comparison with results of less-well-accepted techniques. It is hoped that this paper will help others avoid some of the subtle errors encountered in this work.

V. ACKNOWLEDGMENTS

The author would like to thank Mr. Mark A. Dewilde for assistance setting up the burner and Dr. John A. Vanderhoff for help in taking some of the data and for a critical reading of the manuscript.

*In emission spectra of radicals in the primary reaction zones of flames, as discussed in ref 1, the radicals are sometimes extremely rotationally hot. Often, the rotational distribution will have two very distinct temperature regimes for the high vs low rotational levels. This phenomenon doubtless occurs due to production of rotationally hot molecules in an excited electronic state due to a chemical reaction. Preferential quenching of states at one end of the distribution probably leads to the observed dual temperature distributions. However, such effects are observed only in low pressure flames.

REFERENCES

1. A. G. Gaydon and H. G. Wolfhard, Flames: Their Structure, Radiation and Temperature, (Chapman and Hall, Ltd., London, 1970).
2. Y. B. Zel'dovich and Y. P. Raizer, Physics of Shock Waves and High Temperature Hydrodynamic Phenomena, (Academic, New York, (1966) Vol. 1, Chapter 2; S. S. Penner, Quantitative Spectroscopy and Gas Emissitivities, (Addison-Wesley, Inc., Reading, Mass., 1959); L. D. Landau and E. M. Lifshitz, Statistical Physics, (Addison-Wesley, Inc., Reading, Mass., 1958).
3. A. C. G. Mitchell and M. W. Zemansky, Resonance Radiation and Excited Atoms, (Cambridge University Press, 1934) p. 92-5.
4. M. A. Dewilde, "Capillary Flowmeters for Accurate, Stable Flows of Gases", BRL Technical Report ARBRL-TR-02230, March 1980. (AD #A083874)
5. W. R. Anderson, "Laser Excited Fluorescence Measurement of OH Rotational Temperatures in a CH₄/N₂O Flame", Eastern Sectional Meeting, Combustion Institute, Atlanta, Georgia, Nov 1979, Paper 3; L. J. Decker and W. R. Anderson, to be published.
6. W. Snelleman, "Errors in the Method of Line-Reversal", Combust. Flame **11**, 453 (1967).

DISTRIBUTION LIST

<u>No. of Copies</u>	<u>Organization</u>	<u>No. of Copies</u>	<u>Organization</u>
12	Commander Defense Technical Info Center ATTN: DDC-DDA Cameron Station Alexandria, VA 22314	1	Director US Army ARRADCOM Benet Weapons Lab ATTN: DRDAR-LCB-TL Watervliet, NY 12189
1	Director Defense Advanced Research Projects Agency ATTN: LTC C. Buck 1400 Wilson Boulevard Arlington, VA 22209	1	Commander US Army Watervliet Arsenal ATTN: Code SARWV-RD, R.Thierry Watervliet, NY 12189
2	Director Institute for Defense Analyses ATTN: H. Wolfhard R. T. Oliver 400 Army-Navy Drive Arlington, VA 22202	1	Commander US Army Aviation Research and Development Command ATTN: DRSVAV-E P. O. Box 209 St. Louis, MO 63166
1	Commander US Army Materiel Development and Readiness Command ATTN: DRCMDM-ST 5001 Eisenhower Avenue Alexandria, VA 22333	1	Director US Army Air Mobility Research and Development Laboratory Ames Research Center Moffett Field, CA 94035
2	Commander US Army Armament Research and Development Command ATTN: DRDAR-TSS Dover, NJ 07801	1	Commander US Army Communications Rsch and Development Command ATTN: DRDCO-PPA-SA Fort Monmouth, NJ 07703
4	Commander US Army Armament Research and Development Command ATTN: DRDAR-LCA, J. Lannon DRDAR-LC, T.Vladimiroff DRDAR-SCA, L. Stiefel DRDAR-LCE, R.F. Walker Dover, NJ 07801	1	Commander US Army Electronics Research and Development Command Technical Support Activity ATTN: DELSD-L Fort Monmouth, NJ 07703
1	Commander US Army Armament Materiel Readiness Command ATTN: DRSAR-LEP-L, Tech Lib Rock Island, IL 61299	1	Commander US Army Missile Command ATTN: DRSMI-YDL Redstone Arsenal, AL 35809

DISTRIBUTION LIST

<u>No. of Copies</u>	<u>Organization</u>	<u>No. of Copies</u>	<u>Organization</u>
1	Commander US Army Natick Research and Development Command ATTN: DRXRE, D. Sieling Natick, MA 01762	1	Commander Naval Sea Systems Command ATTN: J.W. Murrin, SEA-62R2 National Center Bldg. 2, Room 6E08 Washington, DC 20362
1	Commander US Army Tank Automotive Research & Development Cmd ATTN: DRDTA-UL Warren, MI 48090	1	Commander Naval Surface Weapons Center ATTN: Library Br., DX-21 Dahlgren, VA 22448
1	Commander US Army White Sands Missile Range ATTN: STEWS-VT White Sands, NM 88002	2	Commander Naval Surface Weapons Center ATTN: S.J. Jacobs/Code 240 Code 730 Silver Spring, MD 20910
1	Commander US Army Materials and Mechanics Research Center ATTN: DRXMR-ATL Watertown, MA 02172	1	Commander Naval Underwater Systems Ctr Energy Conversion Department ATTN: R.S. Lazar/Code 5B331 Newport, RI 02840
5	Commander US Army Research Office ATTN: Tech Lib D. Squire F. Schmiedeshaff R. Ghirardelli M. Ciftan P. O. Box 12211 Research Triangle Park NC 27706	2	Commander Naval Weapons Center ATTN: R. Derr C. Thelen China Lake, CA 93555
1	Director US Army TRADOC Systems Analysis Activity ATTN: ATAA-SL, Tech Lib White Sands Missile Range NM 88002	1	Commander Naval Research Laboratory ATTN: Code 6180 Washington, DC 20375
1	Director US Army TRADOC Systems Analysis Activity ATTN: ATAA-SL, Tech Lib White Sands Missile Range NM 88002	3	Superintendent Naval Postgraduate School ATTN: Tech Lib D. Netzer A. Fuhs Monterey, CA 93940
2	Office of Naval Research ATTN: Code 473 G. Neece 800 N. Quincy Street Arlington, VA 22217	2	Commander Naval Ordnance Station ATTN: Dr. Charles Dale Tech Lib Indian Head, MD 20640

DISTRIBUTION LIST

<u>No. of Copies</u>	<u>Organization</u>	<u>No. of Copies</u>	<u>Organization</u>
2	AFOSR ATTN: D. Ball L. Caveny Bolling AFB, DC 20332	1	Foster Miller Associates, Inc. ATTN: A. J. Erickson 135 Second Avenue Waltham, MA 02154
2	AFRPL (DYSC) ATTN: D. George J. N. Levine Edwards AFB, CA 93523	1	General Electric Company Armament Department ATTN: M. J. Bulman Lakeside Avenue Burlington, VT 05402
2	National Bureau of Standards ATTN: J. Hastie T. Kashiwagi Washington, DC 20234	1	General Electric Company Flight Propulsion Division ATTN: Tech Lib Cincinnati, OH 45215
1	Lockheed Palo Alto Rsch Labs ATTN: Tech Info Ctr 3521 Hanover Street Palo Alto, CA 94304	2	Hercules Incorporated Alleghany Ballistic Lab ATTN: R. Miller Tech Lib Cumberland, MD 21501
1	Aerojet Solid Propulsion Co. ATTN: P. Micheli Sacramento, CA 95813	1	Hercules Incorporated Bacchus Works ATTN: B. Isom Magna, UT 84044
1	ARO Incorporated ATTN: N. Dougherty Arnold AFS, TN 37389	1	IITRI ATTN: M. J. Klein 10 West 35th Street Chicago, IL 60615
1	Atlantic Research Corporation ATTN: M. K. King 5390 Cherokee Avenue Alexandria, VA 22314	1	Olin Corporation Badger Army Ammunition Plant ATTN: J. Ramnarace Baraboo, WI 53913
1	AVCO Corporation AVCO Everett Research Lab Div ATTN: D. Stickler 2385 Revere Beach Parkway Everett, MA 02149	2	Olin Corporation New Haven Plant ATTN: R. L. Cook D. W. Riefler 275 Winchester Avenue New Haven, CT 06504
2	Calspan Corporation ATTN: E. B. Fisher A. P. Trippe P. O. Box 400 Buffalo, NY 14221		

DISTRIBUTION LIST

<u>No. of Copies</u>	<u>Organization</u>	<u>No. of Copies</u>	<u>Organization</u>
1	Paul Gough Associates, Inc. ATTN: P. S. Gough P. O. Box 1614 Portsmouth, NH 05801	3	Thiokol Corporation Huntsville Division ATTN: D. Flanigan R. Glick Tech Lib Huntsville, AL 35807
1	Physics International Company 2700 Merced Street Leandro, CA 94577	2	Thiokol Corporation Wasatch Division ATTN: J. Peterson Tech Lib P. O. Box 524 Brigham City, UT 84302
1	Pulsepower Systems, Inc. ATTN: L.C. Elmore 815 American Street San Carlos, CA 94070	1	TRW Systems Group ATTN: H. Korman One Space Park Redondo Beach, CA 90278
3	Rockwell International Corp Rocketdyne Division ATTN: C. Obert J. E. Flanagan A. Axeworthy 6633 Canoga Avenue Canoga Park, CA 91304	2	United Technologies Chemical Systems Division ATTN: R. Brown Tech Lib P. O. Box 358 Sunnyvale, CA 94086
2	Rockwell International Corp. Rocketdyne Division ATTN: W. Haymes Tech Lib McGregor, TX 76657	1	Universal Propulsion Co. ATTN: H.J. McSpadden 1800 W. Deer Valley Rd. Phoenix, AZ 85027
1	Science Applications, Inc. ATTN: R. B. Edelman Combustion Dynamics & Propulsion Division 23146 Cumorah Crest Woodland Hills, CA 91364	11	Battelle Memorial Institute ATTN: Tech Lib R. Bartlett (10 cys) 505 King Avenue Columbus, OH 43201
1	Shock Hydrodynamics, Inc. ATTN: W. H. Anderson 4710-16 Vineland Avenue N. Hollywood, CA 91602	2	Brigham Young University Dept of Chemical Engineering ATTN: M. W. Beckstead Provo, UT 84601
1	Thiokol Corporation Elkton Division ATTN: E. Sutton Elkton, MD 21921		

DISTRIBUTION LIST

<u>No. of Copies</u>	<u>Organization</u>	<u>No. of Copies</u>	<u>Organization</u>
1	California Institute of Tech 204 Karmar Lab Mail Stop 301-46 ATTN: F.E.C. Culick 1201 E. California Street Pasadena, CA 91125	1	Pennsylvania State University Dept of Material Sciences ATTN: H. Palmer University Park, PA 16801
1	Case Western Reserve Univ Division Of Aerospace Sciences ATTN: J. Tien Cleveland, OH 44135	1	Princeton Combustion Research Laboratories ATTN: M. Summerfield 1041 U.S. Highway One North Princeton, NJ 08540
3	Georgia Institute of Tech School of Aerospace Eng. ATTN: B.T. Zinn E. Price W. C. Strahle Atlanta, GA 30332	2	Princeton University Forrestal Campus ATTN: I. Glassman Tech Lib P. O. Box 710 Princeton, NJ 08540
1	Institute of Gas Technology ATTN: D. Gidaspow 3424 S. State Street Chicago, IL 60616	2	Purdue University School of Mechanical Eng. ATTN: J. Osborn S.N.B. Murthy TSPC Chaffee Hall W. Lafayette, IN 47906
1	Johns Hopkins University/APL Chemical Propulsion Info Ag ATTN: T. Christian Johns Hopkins Road Laurel, MD 20810	1	Rutgers State University Dept of Mechanical and Aerospace Engineering ATTN: S. Temkin University Heights Campus New Brunswick, NJ 08903
1	Massachusetts Inst. of Tech Dept of Mech Engineering ATTN: T. Toong Cambridge, MA 02139	4	SRI International ATTN: Tech Lib D. Crosley J. Barker D. Golden 333 Ravenswood Avenue Menlo Park, CA 94025
1	Pennsylvania State University Applied Research Lab ATTN: G. M. Faeth P. O. Box 30 State College, PA 16801	1	Stevens Institute of Tech Davidson Library ATTN: R. McAlevy, III Hoboken, NJ 07030
1	Pennsylvania State University Dept of Mechanical Engineering ATTN: K. Kuo University Park, PA 16801		

DISTRIBUTION LIST

<u>No. of Copies</u>	<u>Organization</u>
1	University of California, San Diego Ames Department ATTN: F. Williams P. O. Box 109 La Jolla, CA 92037
1	University of Illinois Dept of Aeronautical Engineering ATTN: H. Krier Transportation Bldg. Rm 105 Urbana, IL 61801
1	University of Minnesota Dept of Mechanical Engineering ATTN: E. Fletcher Minneapolis, MN 55455
1	University of Southern California Department of Chemistry ATTN: S. Benson Los Angeles, CA 90007
1	University of Texas Department of Chemistry ATTN: W. Gardiner H. Schaefer Austin, TX 78712
2	University of Utah Dept. of Chemical Engineering ATTN: A. Baer G. Flandro Salt Lake City, UT 84112

Aberdeen Proving Ground

Dir, USAMSAA
ATTN: DRXSY-D
DRXSY-MP, H. Cohen
Cdr, USATECOM
ATTN: DRSTE-TO-F
Dir, USACSL, Bldg. E3516
ATTN: DRDAR-CLB-PA

USER EVALUATION OF REPORT

Please take a few minutes to answer the questions below; tear out this sheet, fold as indicated, staple or tape closed, and place in the mail. Your comments will provide us with information for improving future reports.

1. BRL Report Number _____

2. Does this report satisfy a need? (Comment on purpose, related project, or other area of interest for which report will be used.)

3. How, specifically, is the report being used? (Information source, design data or procedure, management procedure, source of ideas, etc.) _____

4. Has the information in this report led to any quantitative savings as far as man-hours/contract dollars saved, operating costs avoided, efficiencies achieved, etc.? If so, please elaborate.

5. General Comments (Indicate what you think should be changed to make this report and future reports of this type more responsive to your needs, more usable, improve readability, etc.) _____

6. If you would like to be contacted by the personnel who prepared this report to raise specific questions or discuss the topic, please fill in the following information.

Name: _____

Telephone Number: _____

Organization Address: _____

