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ANALYSES OF SMOKE WEEK I FOR HC, WP, AND FOREIGN WP. (U)  
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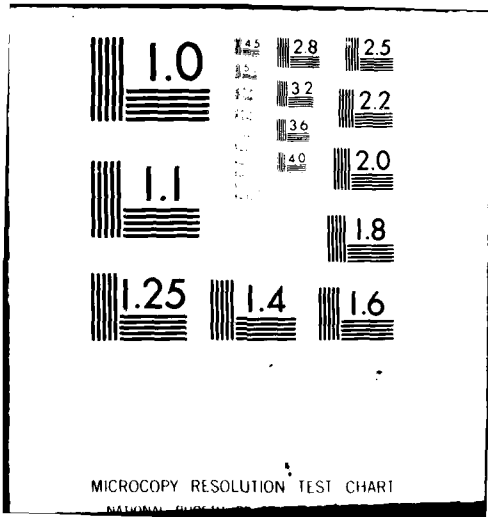
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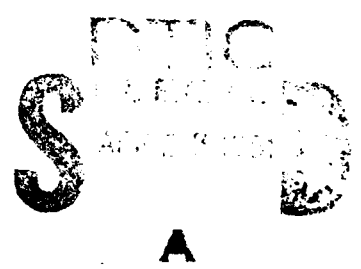
MARCH 1981

By

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Under Contract No. DAAD07-79-C-0008

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US Army Electronics Research and Development Command  
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1. REPORT NUMBER ASL-CR-81-0008-1 ✓	2. GOVT ACCESSION NO. AD-A098	3. RECIPIENT'S CATALOG NUMBER 590
4. TITLE (and Subtitle) ANALYSES OF SMOKE WEEK I FOR HC, WP, AND FOREIGN WP		5. TYPE OF REPORT & PERIOD COVERED R&D Technical Report
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Jack D. Drummond		8. CONTRACT OR GRANT NUMBER(s) DAAD07-79-C-0008 ✓
9. PERFORMING ORGANIZATION NAME AND ADDRESS Physical Science Laboratory New Mexico State University Las Cruces, New Mexico 88003		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS DA Task 1L162111AH71F2
11. CONTROLLING OFFICE NAME AND ADDRESS US Army Electronics Research and Development Command Adelphi, MD 20783		12. REPORT DATE March 1981
		13. NUMBER OF PAGES 22
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) Atmospheric Sciences Laboratory White Sands Missile Range, NM 88002		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 Contract Monitor: Frank V. Hansen		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Smoke munitions                      Electromagnetic spectrum Extinction coefficients              Visible light White phosphorus                      Infrared wavelengths Zinc chloride		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Using single and combined trials for data from Smoke Week I for HC, WP, and foreign WP, regression analyses were performed in order to determine extinction coefficients (and errors) at visible and infrared wavelengths. A frequency squared dependence for the extinction coefficient of HC is found. Results are presented in a series of tables and graphs.		

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## INTRODUCTION

Inventory Smoke Munitions Test (Smoke Week I) was held at Dugway Proving Grounds during November 1977. The objectives of the test as reported in reference a were:

- 1) to obtain smoke characteristics of inventory smoke munitions,
- 2) to obtain data required by JTCG/ME smoke obscuration model for evaluation of existing inventory munitions,
- 3) to obtain attenuation characteristics of inventory smoke munitions, and
- 4) to obtain data on the effects of screening smokes on the optical properties of existing and developmental electro-optical systems.

The smoke types selected for analysis from Smoke Week I are HC (hexachloroethane, zinc oxide, aluminum mixture), WP (white phosphorus), and FWP (foreign white phosphorus). Two trials each of HC and WP were conducted, while each FWP was tested once. A summary of the test trials appears in Table 1.

An aerosol photometer was used to measure the concentration loading (CL) or column density of the smoke, while various transmissometers measured transmission through each smoke at visual ( $0.4 - 0.7 \mu\text{m}$ ), near IR ( $1.060 \pm 0.008 \mu\text{m}$ ), mid-IR ( $3.443 \pm 0.079 \mu\text{m}$ ), and far IR ( $9.750 \pm 2.121 \mu\text{m}$ ) wavelengths.

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## METHOD

Data, in the form of time and CL, and time and transmittance for four wavelengths, was transferred from seven-track tapes to cassette data tapes for use with an HP9830 desk top calculator and an HP9876 plotter. This facilitated virtually no-cost data analysis. Measurements of CL and transmittance were taken at one to two second intervals, but were not synchronized to each other. Therefore, the CL values were linearly interpolated to the time of the recorded transmittance measurement. As each point (CL versus transmittance) was plotted, a normal equation coefficient matrix was formed, which allowed a regression analysis to be performed on not only each trial, but by adding the individual normal matrices, on combined trials as well.

In addition to each entire trial, analysis was made of the data in one to two minute blocks. In this way, an apparently anomalous series of points (due to saturation below a certain transmission level, for instance) could be avoided, or analyzed separately, if desired. Ultimately, a subjective determination of the best (the "cleanest" typical or representative) one or two minute interval was selected for inclusion in the final analysis.

## ANALYSIS

There are two points of view regarding the relationship between CL and transmittance and, therefore, the analysis of the data. Physically, transmittance (T) is a function of the concentration loading (CL), i.e.,  $T = f(CL)$ . However, to the artillery commander, who wants to know the CL necessary to achieve a certain transmittance level, CL is considered the dependent variable, i.e.,  $CL = f(T)$ . Mathematically, of course, either approach is valid, but the least squares analysis leads to slightly different answers in each case. Results from regressing both CL on T and T on CL are included in this report for the sake of completeness.

Let an incident beam of light,  $I_0$ , transit a path length of  $ds(m)$ , through a medium of density  $\rho(\text{gm}/\text{m}^3)$ , with a mass extinction coefficient  $k(\text{m}^2/\text{gm})$ , the sum of absorption and scattering processes. The attenuation of the beam is

$$dI = kI\rho ds,$$

from which it follows that

$$\frac{dI}{I} = k\rho ds$$

or

$$d(\ln I) = k\rho ds.$$

Integrating,

$$\ln I - \ln I_0 = k\rho s,$$

where  $\ln I_0$  is the constant of integration. Thus

$$\ln \frac{I}{I_0} = k\rho s$$

is the fitting equation for the linear least squares analysis, with  $\frac{I}{I_0}$  defined as the transmittance (in fraction of incident beam transmitted), and  $\rho s(\text{gm}/\text{m}^2)$  defined as the concentration loading, also referred to as cross wind integrated concentration (CWIC) or column density. Thus

$$\ln T = kCL$$

or

$$T = e^{kCL}$$

For the case where CL is considered the dependent variable, the fitting equation is

$$CL = k' \ln T.$$

If the correlation between CL and  $\ln T$  were perfect,  $k'$  would equal  $\frac{1}{k}$ . Since it is not, both  $k'$  and  $k$  are shown in Tables 2-4.

In addition to  $k'$  and  $k$ , Tables 2-4 present the standard errors ( $e$ ) of  $k'$  and  $k$ , and the standard error of estimate ( $Se$ ) of the dependent variable on the independent variable for each trial and for combined ensembles of the same smoke type. The traditional definition of  $Se$  and  $e$  are

$$Se = \left[ \frac{\sum_{i=1}^N (y_i - ax_i)^2}{N-1} \right]^{1/2}$$

and

$$e = \sum_{i=1}^N \left[ (x_i - \bar{x})^2 \right]^{-1/2} \cdot Se,$$

respectively, where  $y_i - ax_i$  are the residuals and  $N$  is the total number of points.

For FWP it may be inappropriate to compute ensemble averages since the smoke types may be slightly different for each FWP. Combining each of the HC and the WP trials, however, should be valid because presumably they are the same smoke types.

In order to test the hypothesis that each of the two trials for a given smoke type is drawn from the same statistical population, a two-sample  $t$  test for  $k$  and  $k'$ , and a two-tail  $F$  test on the  $e$ 's, were performed. In all cases, the

tests indicate overwhelmingly that the two trials are not taken from the same population. This is interpreted to mean that either the smoke types used are not exactly the same (e.g., trial 2-33 and 2-4 did not involve the same HC), or that other variables (e.g., temperature, humidity, sun angle, etc.) in the experimental process were not constant from one trial to the other. Additional results from subsequent inventory smoke tests may shed light on the reason for the discrepancies between the k's and k's. As it stands, the potential user of this information is left with the option of choosing a single trial or the ensemble as representative of the smoke characteristics. Detailed data surrounding each trial can be found in reference a.

## DISCUSSION

Figure 1 shows transmittance as a function of CL for the HC and WP smoke types at each of four wavelengths. For each smoke and wavelength, two lines are drawn representing  $k$  and  $1/k'$ , respectively. It can be seen that at visual and near IR wavelengths HC is not as opaque as WP (or FWP), but at longer wavelengths the reverse is true.

Figures 2, 3, 4, and 5 depict, for each wavelength, the individual trial's  $k$  and  $1/k'$  (dashed lines), the combined  $k$  and  $1/k'$  (middle solid lines), and the standard error of estimate for this combined  $k$  and  $1/k'$  (outside parallel solid lines) for HC, WP, and FWP. Note that one of the three trials of FWP (DPI-005-4) appears anomalous compared to the other two. Since this particular trial contributes fewer points to the ensemble, however, the combined result is weighted towards the other two similar trials.

Figures 6 and 7 illustrate the frequency ( $\nu$ ) dependence of combined  $k$  and  $1/k'$ , respectively. A relationship with a correlation coefficient of  $>0.99$  is revealed for HC. The extinction coefficients are related to  $\nu$  for HC by

$$k(\text{HC}) = -1.28 \times 10^{-29} \nu^2$$

and

$$1/k'(\text{HC}) = -1.44 \times 10^{-29} \nu^2$$

The WP and FWP smoke types show a reversal in the trend of  $k$  and  $1/k'$  for far IR; also noticeable in Figure 1, the WP smoke types are less opaque at far IR wavelengths than they are at mid-IR. Because of this, no attempt was made to find a simple relationship between  $k$  ( $1/k'$ ) and  $\nu$ . The  $\nu^2$  dependence of  $k$  ( $1/k'$ ) for HC is at this time unexplained and rather surprising. It is known that Rayleigh scattering follows a  $\nu^4$  dependence and absorption follows a  $\nu^1$  dependence, but only a unique combination of particle size distributions and scattering and absorption properties would result in the extinction coefficient being proportional to  $\nu^2$ . In fact, the most surprising aspect of the result is that the extinction coefficient depends on an integer power of the frequency for any combination of size distribution and extinction properties.

TABLE 1. Summary of Smoke Week I Test Trials

Trial Identification	Date	Smoke Type	Caliber of Munition	Type of Munition	Number of Munitions	Fire Time (MST)	Remarks
DPI-002-33	15 Nov 77	HC	105 mm	M84A1 Canister	9 18*	1201:00	
DPI-002-4	19 Nov 77	HC	105 mm	M84A1 Canister	36*	1258:00	
DPI-002-24	19 Nov 77	WP	155 mm	M110E2	12	1026:00	
DPI-002-34	19 Nov 77	WP	155 mm	M110E2	6	1149:00	
DPI-005-4	18 Nov 77	FWP	82 mm	Foreign	11	1448:00	Cloud lifted off ground; no information for visual wavelength
DPI-005-12	18 Nov 77	FWP	122 mm	Foreign	6	1542:00	
DPI-005-16	18 Nov 77	FWP	130 mm	Foreign	6	1733:00	Trial conducted at night

\* Number of submunitions or canisters

TABLE 2. Analysis of HC for  $CL = k' \ln T$  and  $\ln T = kCL$

Trial Identification	No. of Points	$k' \pm e$	Se	$k \pm e$	Se
Visual					
DPI-002-33	67	$-0.216 \pm 0.005$	0.090	$-4.446 \pm 0.110$	0.409
DPI-002-4	75	$-0.291 \pm 0.017$	0.148	$-2.727 \pm 0.161$	0.452
Combined	142	$-0.232 \pm 0.007$	0.133	$-3.826 \pm 0.116$	0.539
Near IR					
DPI-002-33	182	$-0.895 \pm 0.012$	0.419	$-1.081 \pm 0.015$	0.461
DPI-002-4	126	$-1.158 \pm 0.028$	0.447	$-0.804 \pm 0.020$	0.373
Combined	308	$-0.941 \pm 0.013$	0.481	$-1.007 \pm 0.014$	0.498
Mid-IR					
DPI-002-33	181	$-6.820 \pm 0.154$	0.725	$-0.134 \pm 0.003$	0.102
DPI-002-4	199	$-9.080 \pm 0.179$	1.515	$-0.102 \pm 0.002$	0.161
Combined	380	$-8.547 \pm 0.133$	1.300	$-0.107 \pm 0.002$	0.145
Far IR					
DPI-002-33	194	$-19.116 \pm 0.534$	0.874	$-0.045 \pm 0.001$	0.043
DPI-002-4	181	$-26.184 \pm 0.532$	1.568	$-0.036 \pm 0.001$	0.058
Combined	375	$-25.516 \pm 0.404$	1.361	$-0.037 \pm 0.001$	0.053

TABLE 3. Analysis of WP for  $CL = k' \ln T$  and  $\ln T = kCL$

Trial Identification	No. of Points	$k' \pm e$	Se	$k \pm e$	Se
Visual					
DPI-002-24	116	$-0.372 \pm 0.013$	0.249	$-2.341 \pm 0.084$	0.625
DPI-002-34	113	$-0.553 \pm 0.011$	0.289	$-1.732 \pm 0.034$	0.511
Combined	229	$-0.493 \pm 0.010$	0.325	$-1.854 \pm 0.038$	0.630
Near IR					
DPI-002-24	180	$-1.005 \pm 0.014$	0.361	$-0.963 \pm 0.013$	0.353
DPI-002-34	128	$-1.354 \pm 0.021$	0.299	$-0.717 \pm 0.011$	0.217
Combined	308	$-1.082 \pm 0.014$	0.418	$-0.880 \pm 0.011$	0.377
Mid-IR					
DPI-002-24	268	$-5.032 \pm 0.057$	1.367	$-0.192 \pm 0.001$	0.267
DPI-002-34	224	$-5.904 \pm 0.097$	1.589	$-0.160 \pm 0.003$	0.261
Combined	492	$-5.311 \pm 0.054$	1.564	$-0.179 \pm 0.002$	0.287
Far IR					
DPI-002-24	269	$-4.721 \pm 0.050$	1.293	$-0.206 \pm 0.002$	0.270
DPI-002-34	221	$-5.231 \pm 0.084$	1.552	$-0.181 \pm 0.003$	0.289
Combined	490	$-4.893 \pm 0.046$	1.456	$-0.196 \pm 0.002$	0.291

TABLE 4. Analysis of FWP for  $CL = k' \ln T$  and  $\ln T = kCL$

Trial Identification	No. of Points	$k' \pm e$	Se	$k \pm e$	Se
Visual					
DPI-005-4		(no data available for visual wavelengths)			
DPI-005-12	176	$-0.410 \pm 0.010$	0.229	$-2.202 \pm 0.055$	0.531
DPI-005-16	235	$-0.359 \pm 0.006$	0.111	$-2.622 \pm 0.043$	0.299
Combined	411	$-0.389 \pm 0.006$	0.175	$-2.357 \pm 0.036$	0.430
Near IR					
DPI-005-4	87	$-1.200 \pm 0.019$	0.182	$-0.815 \pm 0.013$	0.150
DPI-005-12	256	$-1.208 \pm 0.023$	0.531	$-0.756 \pm 0.015$	0.420
DPI-005-16	205	$-1.049 \pm 0.010$	0.217	$-0.935 \pm 0.009$	0.205
Combined	548	$-1.141 \pm 0.013$	0.407	$-0.822 \pm 0.009$	0.345
Mid-IR					
DPI-005-4	109	$-1.792 \pm 0.062$	0.416	$-0.495 \pm 0.017$	0.218
DPI-005-12	254	$-4.421 \pm 0.075$	0.550	$-0.211 \pm 0.004$	0.120
DPI-005-16	240	$-4.548 \pm 0.057$	0.872	$-0.212 \pm 0.003$	0.188
Combined	603	$-4.153 \pm 0.053$	0.973	$-0.219 \pm 0.003$	0.224
Far IR					
DPI-005-4	151	$-2.091 \pm 0.054$	0.316	$-0.435 \pm 0.011$	0.144
DPI-005-12	254	$-3.798 \pm 0.059$	0.505	$-0.248 \pm 0.004$	0.129
DPI-005-16	241	$-4.288 \pm 0.047$	0.799	$-0.227 \pm 0.003$	0.184
Combined	646	$-4.005 \pm 0.039$	0.772	$-0.235 \pm 0.002$	0.187

## REFERENCES

- a. Letter, DRCPM-SMK-T, Project Manager Smoke, January 26, 1978, Subject: Transmittal of Test Data for Inventory Smoke Munition Test (Smoke Week No.1).

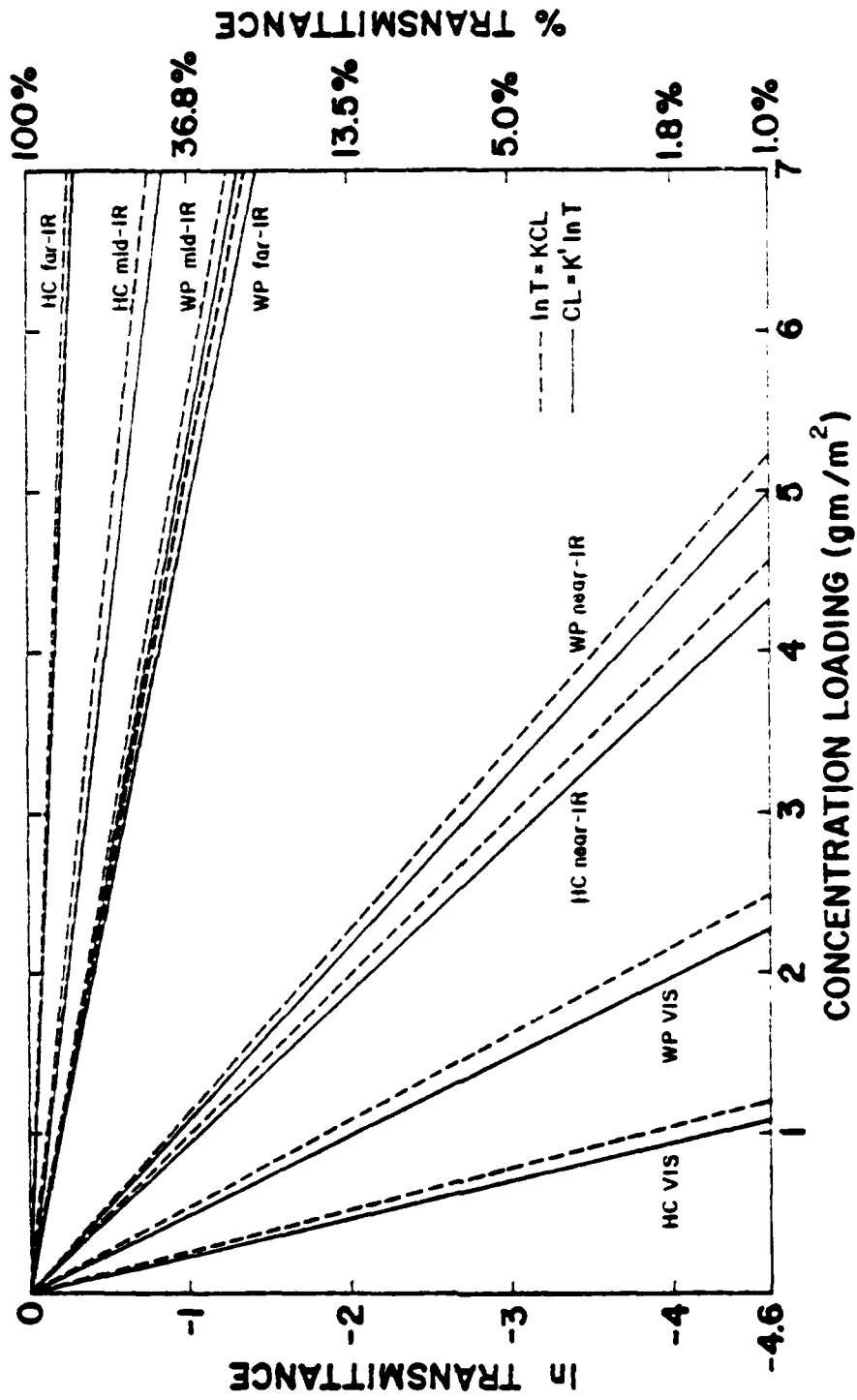


FIGURE 1. Transmittance vs. CL for combined trials of HC and WP

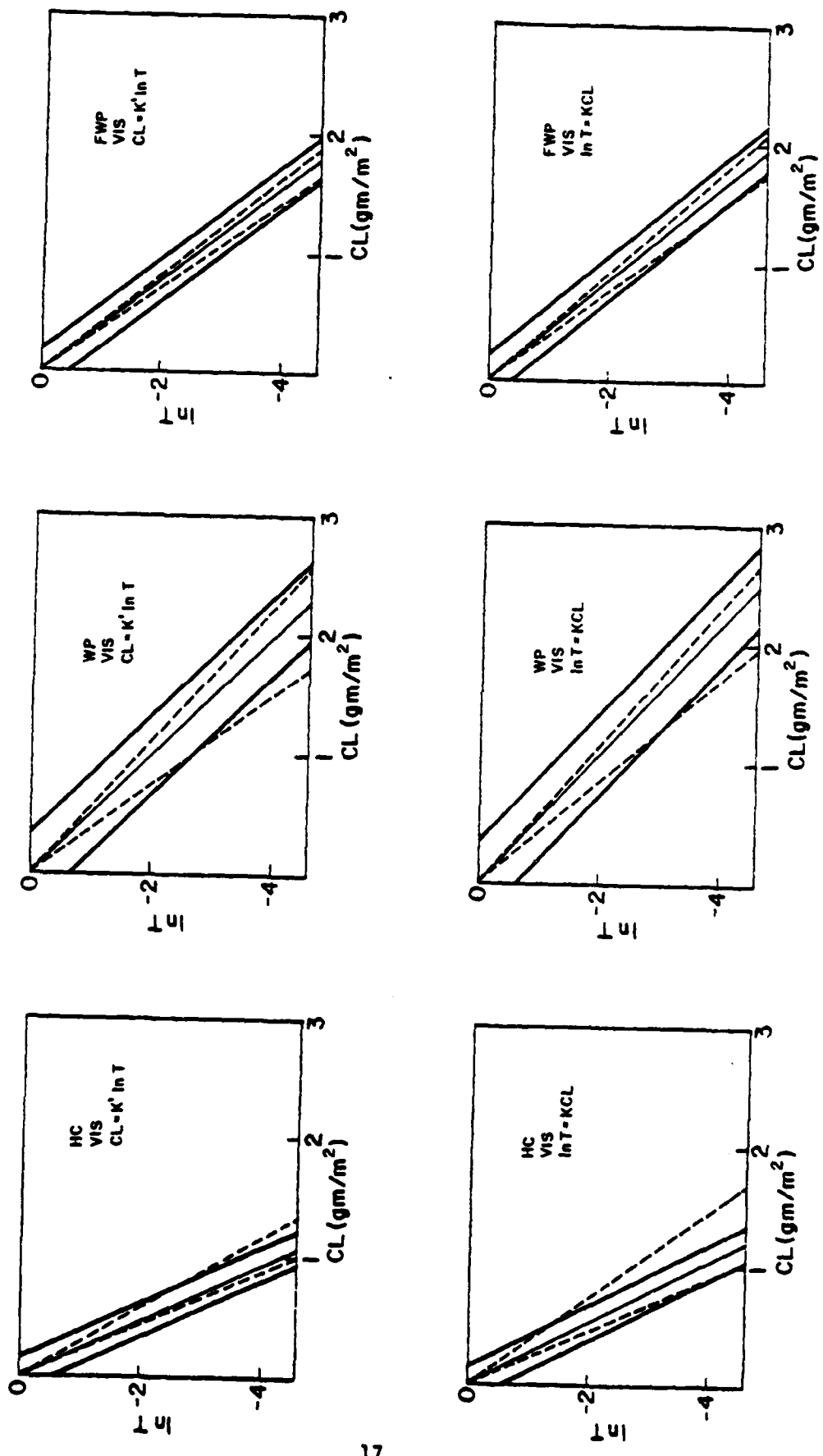


FIGURE 2. ln T vs CL, Visual Wavelengths

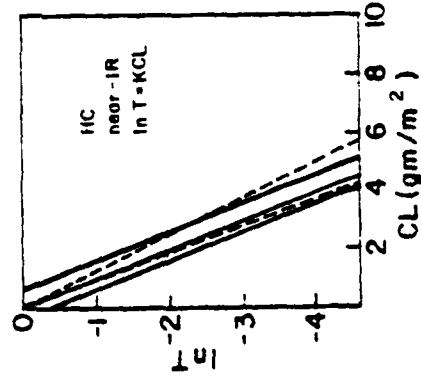
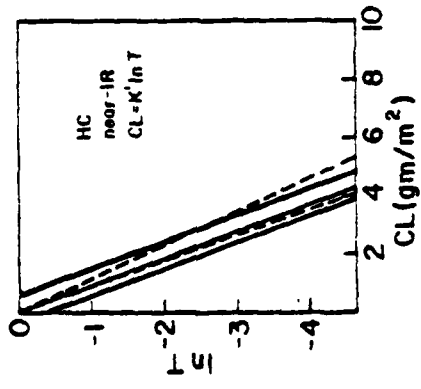
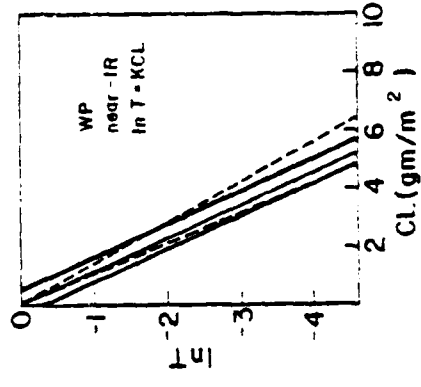
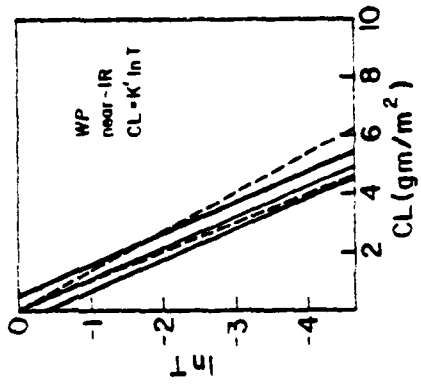
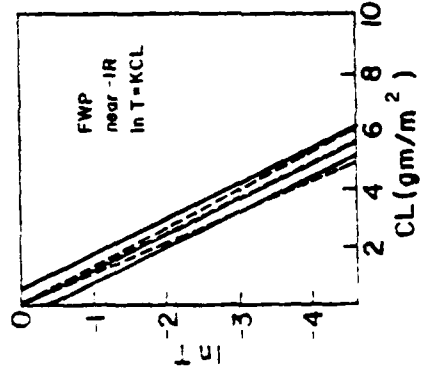
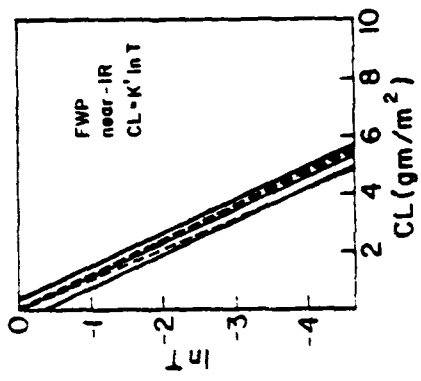


FIGURE 3. lnT vs CL, Near Infrared

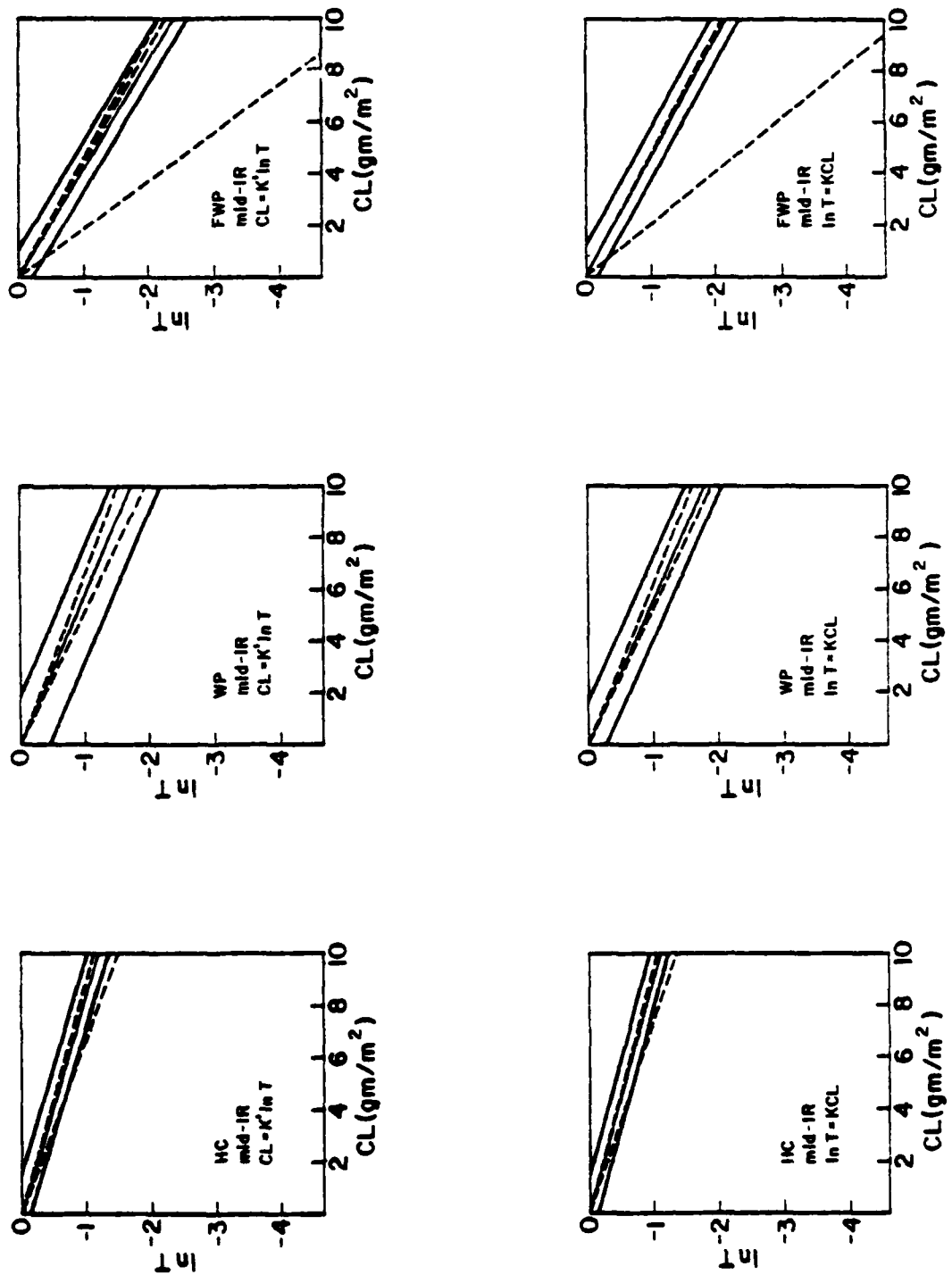


FIGURE 4.  $\ln T$  vs  $CL$ , Mid Infrared

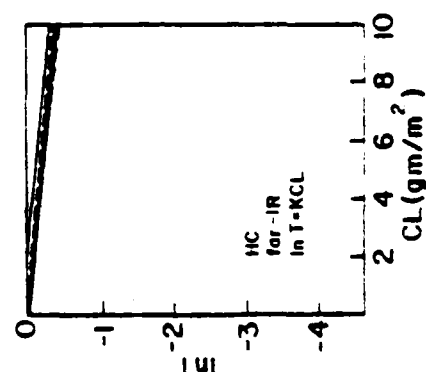
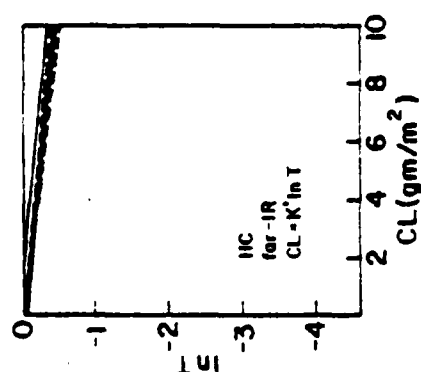
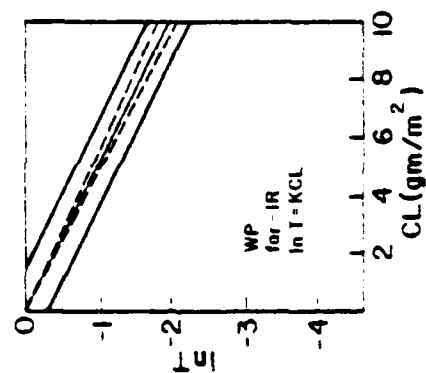
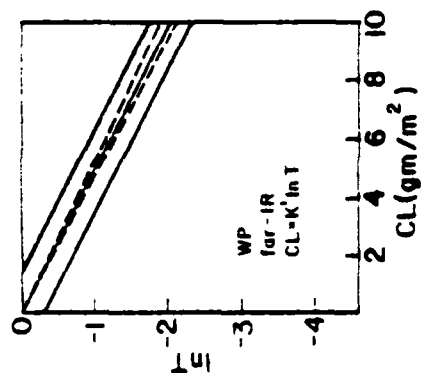
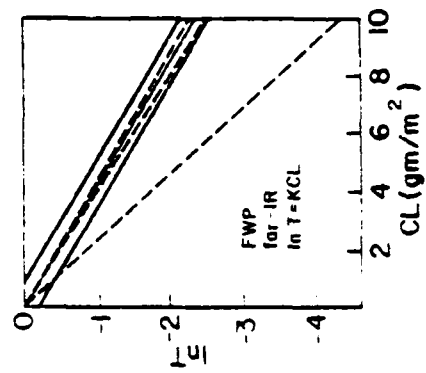
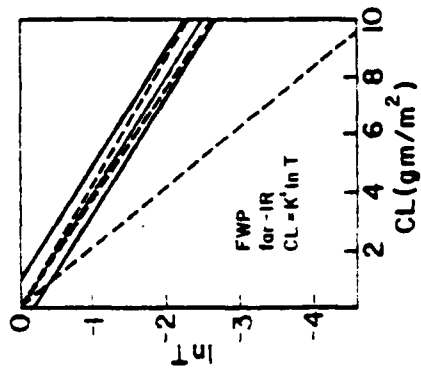


FIGURE 5.  $\ln T$  vs  $CL$ , Far Infrared

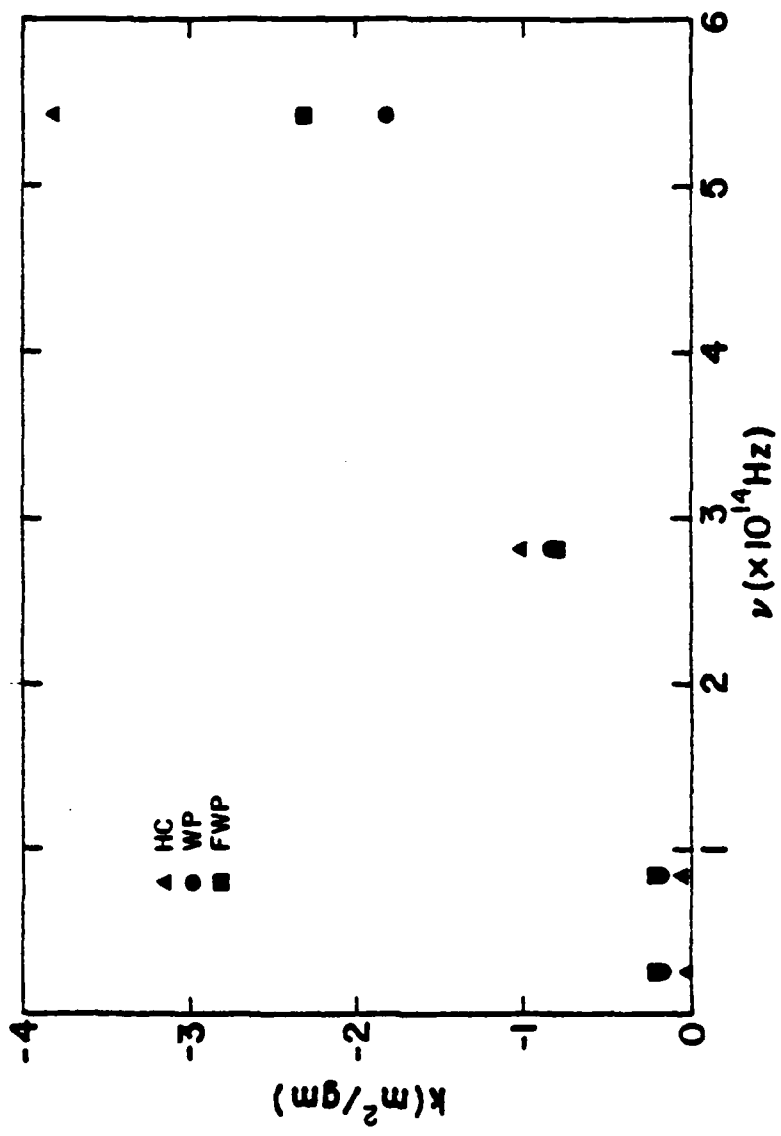


FIGURE 6. Extinction Coefficient ( $k$ ) vs frequency ( $\nu$ )

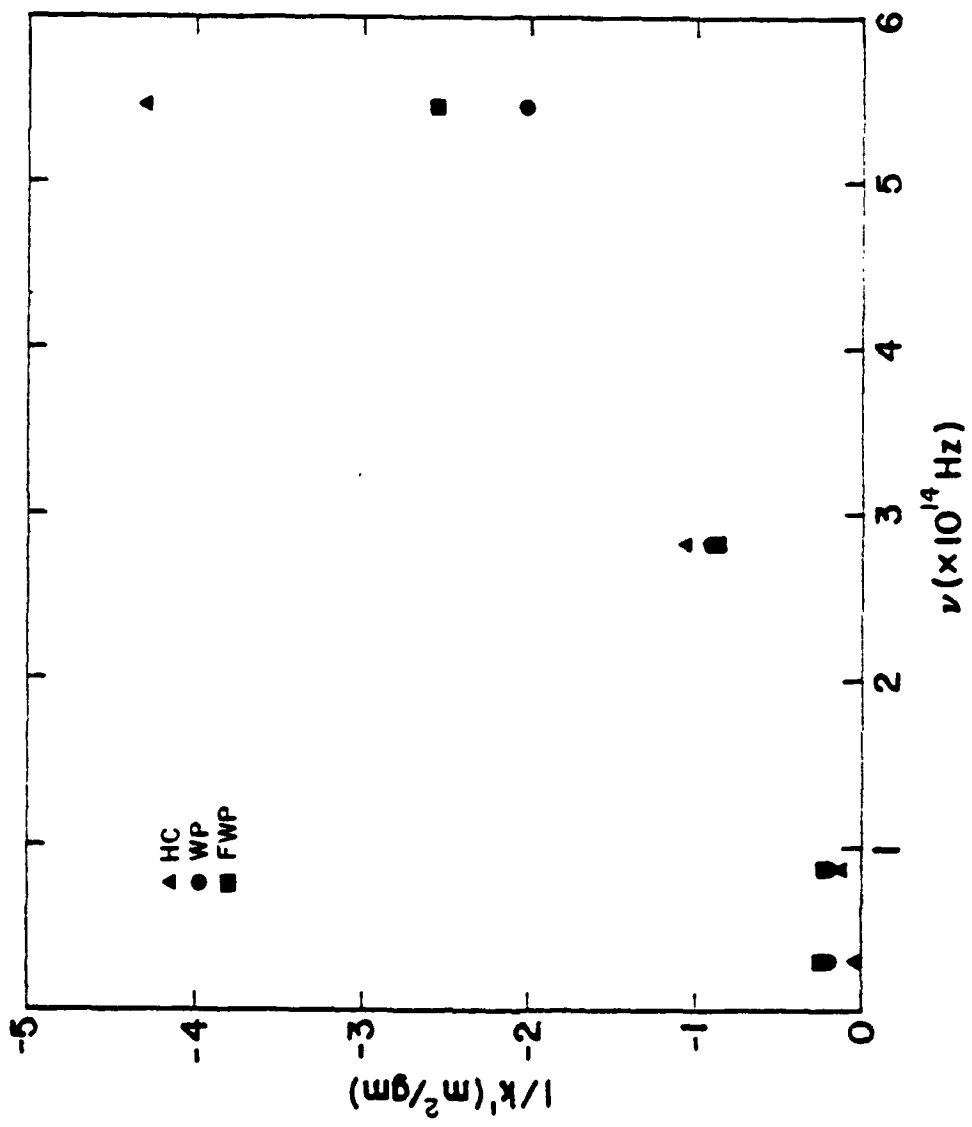


FIGURE 7. Extinction Coefficient ( $1/k'$ ) vs frequency ( $\nu$ )

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