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EFFLUENT PLUME IMAGING

Final Report

Contract No. DAAD05-72-C-0360

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U. S. ARMY LAND WARFARE LABORATORY

Aberdeen Proving Ground, Maryland 21005

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ABSTRACT

The object of this study was to produce real time images from ambient temperature gases through their black or gray body radiation. The study comprised first, a feasibility analysis followed by laboratory measurements to investigate emission bands of various gases. Ammonia was the chief subject during this program phase, and emission from strong bands around 10 microns produced measurable signals from the room temperature samples. The spectral width of these bands was of the order of .05 microns.

The crucial stage of the laboratory experiments produced real time images of blackbody radiation from methane. This was accomplished by placing a narrow band interference filter in front of a cooled infrared (3-5 microns) vidicon. Infrared optics imaged one end of a two inch diameter gas cell through the filter onto the vidicon retina. Methane could be inserted or removed from the cell.

Video tapes recorded a typical cycle which began with an infrared image of the cell without gas. As methane filled the cell, the previously dark end glowed with radiation from the strong methane bands in the 4-5 micron band. Gradually as methane was cleared from the cell, the end became dark again. Such a cycle was repeated many times and recorded.

These experimental results verified theoretical predictions that gases can be detected, identified and imaged by passive techniques.

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EFFLUENT PLUME PROGRAM (PHASE II)

The experimental program phase achieved its laboratory objective by producing a real time image of a specific gas. An infrared vidicon supplied with an ultra narrow spectral filter and a lens produced an image of methane (CH_4) by detecting ambient temperature blackbody emissions from the 3.3 to 3.54μ CH_4 absorption band. A monitor displayed the image which was also recorded on video tape. The following paragraphs describe these results in detail.

1. PHYSICAL PRINCIPLES

A brief explanation as to how and why a gas at ambient temperature emits thermal (blackbody) radiation will help elucidate the technical discussions in the following paragraphs.

a. Kirchoff's Law

Kirchoff's law governs radiation from a substance in thermal equilibrium. Figure 1 illustrates Kirchoff's law for an ideal nonreflecting material (closely approximated by a gas). Energy, E_0 impinges on the medium and experiences absorption, allowing a net amount, $(1-a)E_0$, to pass through. The substance also radiates at the expense of its own internal energy.

Figure 1 indicates the equation required for energy balance; namely, $E_0 = (1-a) E_0 + E$. This equation results from the simple fact that, under thermal equilibrium, the incident power equals the emerging power. Rearrangement of the terms produces Kirchoff's law: $E = aE_0$. Thus, the energy radiated by the substance in thermal equilibrium equals the energy absorbed from the incident beam; this is Kirchoff's law.

When E_0 represents blackbody radiation, a measures the blackbody emittance. Evidently, under thermal equilibrium and in the absence of excitation sources, a material can radiate no more energy than a blackbody at the same temperature, and it can radiate this amount only if it completely absorbs the incident radiation. The quantity $\epsilon_\lambda(T)$ denotes thermal emission from a substance, where $\beta_\lambda(T)$ is the blackbody radiation formula, depending on wavelength, λ , and absolute temperature, T , and ϵ_λ is the "Radiant Emissivity" of the material. Kirchoff's law, therefore, states the very important fact that ϵ_λ ; that is, the radiant emissivity of a material equals its absorptivity. This fact enables great simplifications in radiation computations.

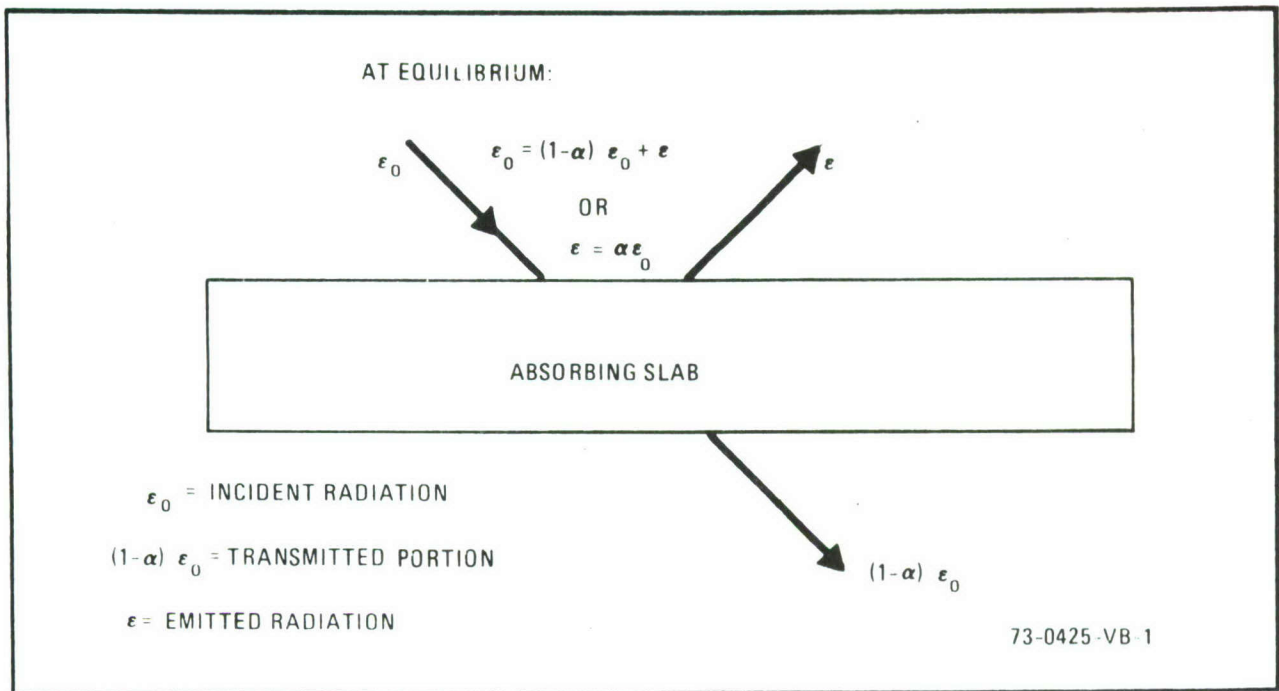


Figure 1. Illustration of Kirchhoff's Law in the Case of Zero Reflectance

2. THERMAL RADIATION FROM A GAS

By Kirchoff's law strong gas absorption bands exhibit blackbody emission. Weak absorption bands display weak emission. For example, figure 2 shows nighttime blackbody sky emission in the 8-13 μ atmospheric window. Note the 292.5°K blackbody envelope which defines the upper radiation limit. On either side of the window where absorption is almost complete, the sky radiates as a blackbody. Within the window the high spikes in an otherwise transparent atmosphere come from strong absorption lines. A typical spike carries the label, O₃.

a. Laboratory Demonstration of Gaseous Thermal Emission

Using appropriate monochromators and filters centered in strong ammonia absorption bands the Effluent Plume program detected room temperature blackbody thermal gaseous radiation from ammonia and imaged an effluent methane plume. The sample gases have strong absorption/emission lines in atmospheric windows, hence should be detectable over field ranges.

Figure 3 shows the laboratory equipment. Mounted on the optical bench are from left to right: the blackbody source, the gas cell, and a tube containing an iris diaphragm and a slot for the chopper. A Perkin-Elmer monochromator, model 210 rests on the small table. Above the behind the monochromator are from left to right: the display scope, an amplifier, a power supply, and a lock-in amplifier. Figures 4, 5, and 6 include traces made using the laboratory setup.

b. Ammonia Emission

Figure 4 shows two traces. The lower trace resulted from spectrally scanning from 6 μ to 12 μ a cold (-196°K) background. A beaker filled with liquid nitrogen at the position of the blackbody of figure 3 was the background. The cell contained no gas. The second trace resulted when ammonia entered the gas cell at approximately atmospheric pressure. The ammonia temperature is approximately 292°K.

Note the especially strong emission bands at 10.31 μ and 10.51 μ . These correspond, of course, to the ammonia absorption bands shown in figure 5. Here the upper trace represents blackbody (\approx 155°K) emission through the cell containing only laboratory air. The two lower traces resulted after filling the absorption cell with ammonia.

c. Methane Image

The image of methane, obtained with an infrared vidicon and displayed on the television monitor, achieved the laboratory objective of the Effluent Plume Program. The event was recorded on video tape which included the sequence from empty cell to gas filled cell to empty cell, thus demonstrating clearly the thermal emission even at ambient temperatures, of gas absorption lines. For permanent access, a 16-mm film recorded the video tape data. Figure 7 is a schematic of the setup. Figures 8, 9, and 10 are pictures derived from the film.

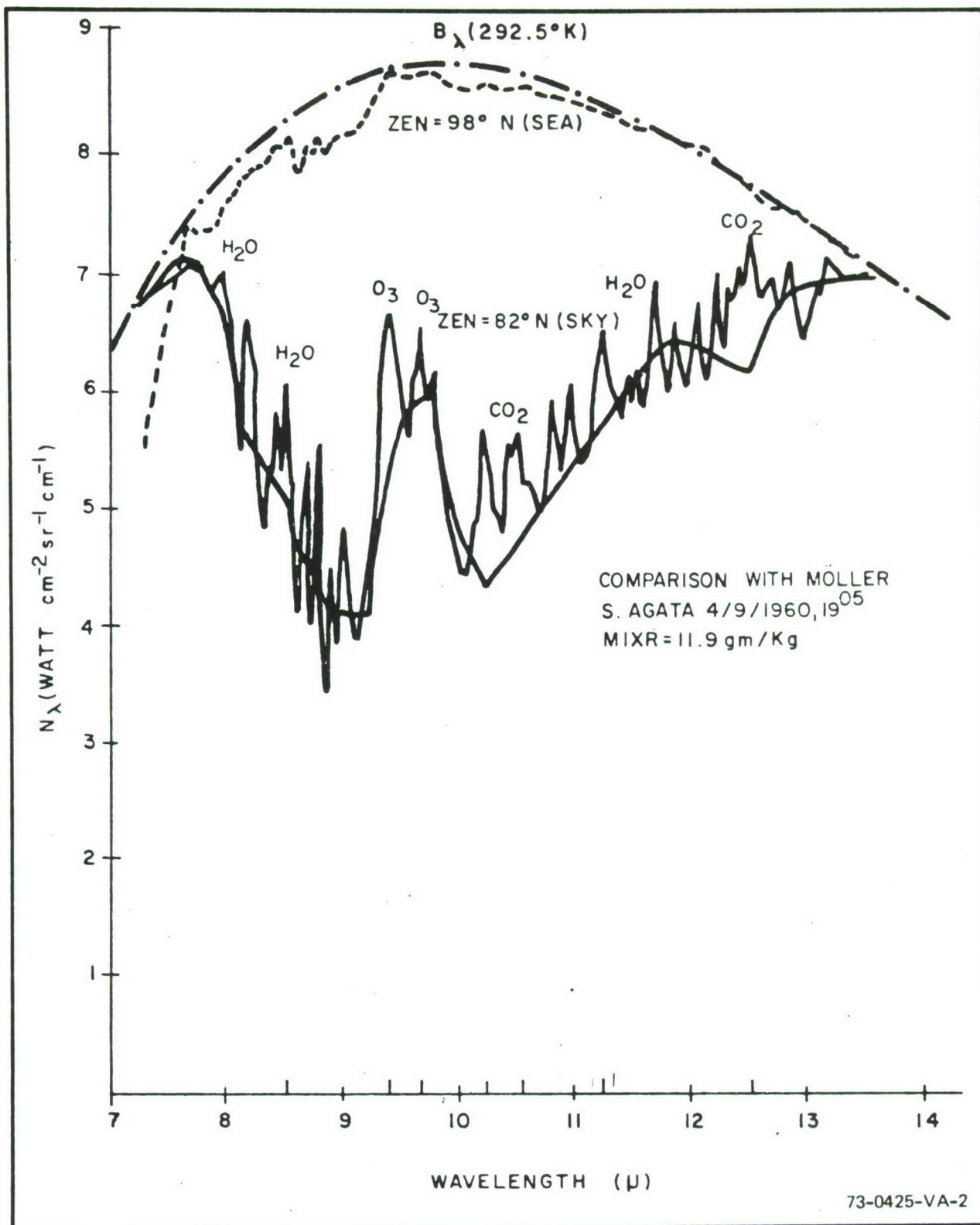


Figure 2. Sky Thermal Emission in the 8- to 10- Micrometer Spectral Window

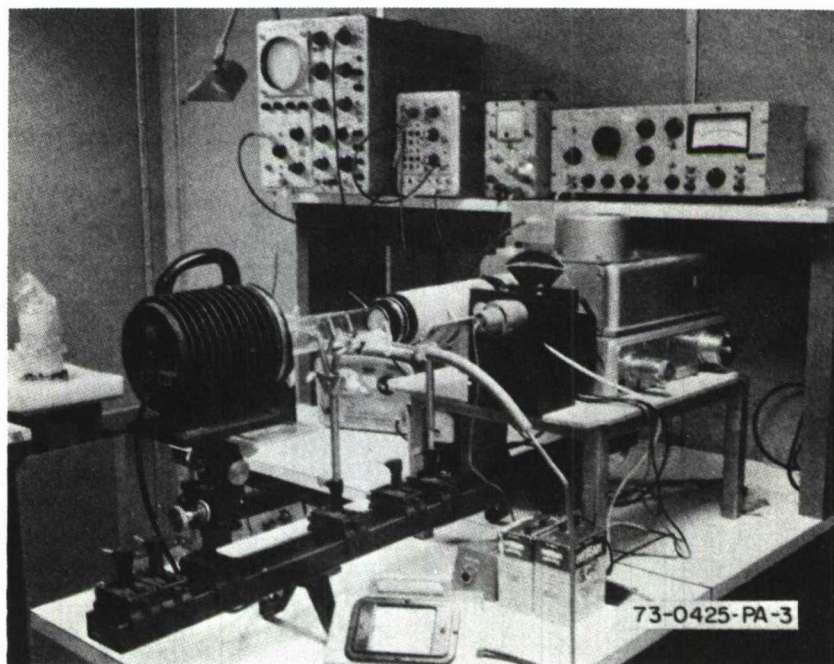


Figure 3. Gaseous Thermal Emission Demonstration Setup

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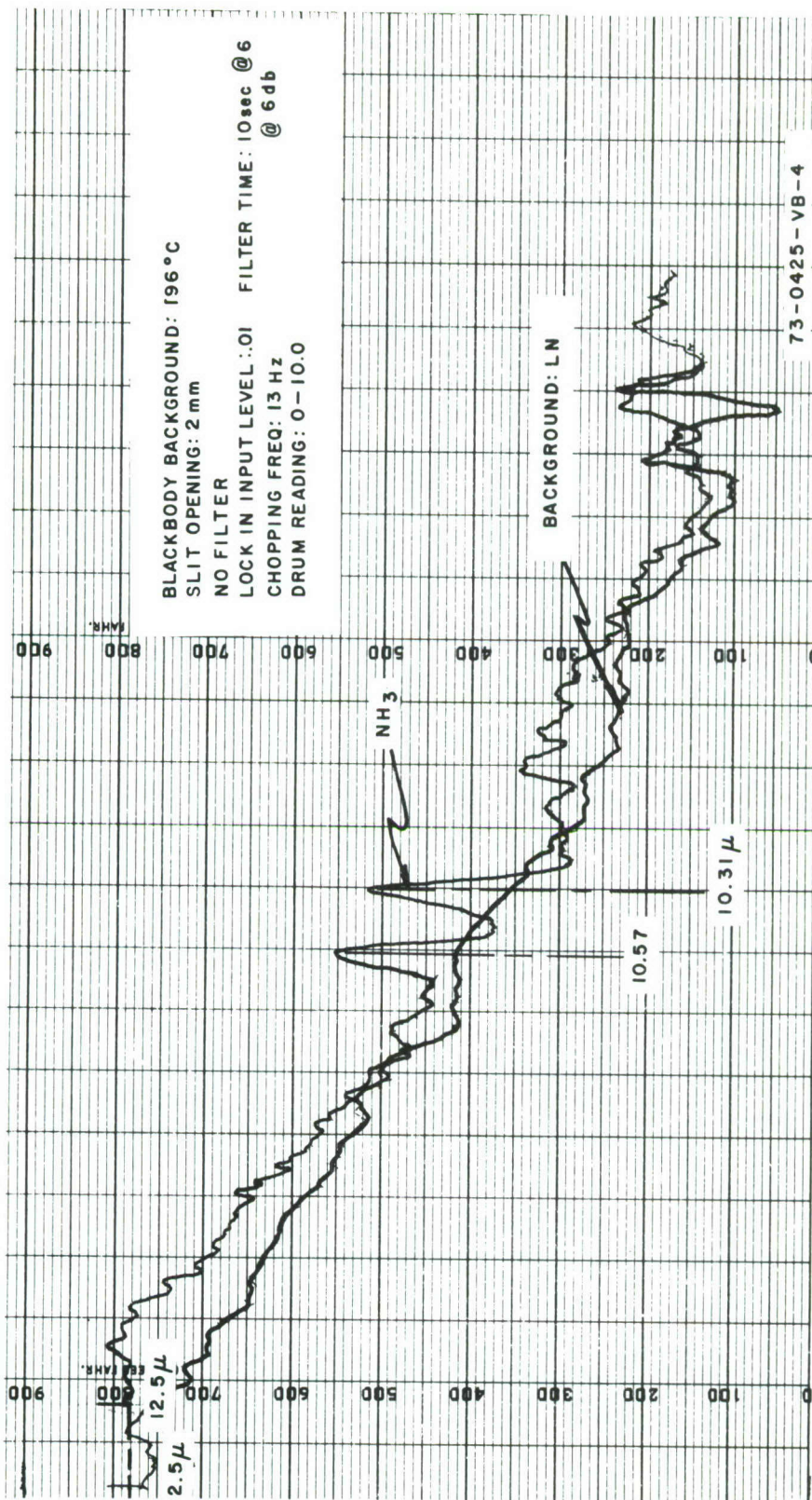


Figure 4. NH₃ Emission

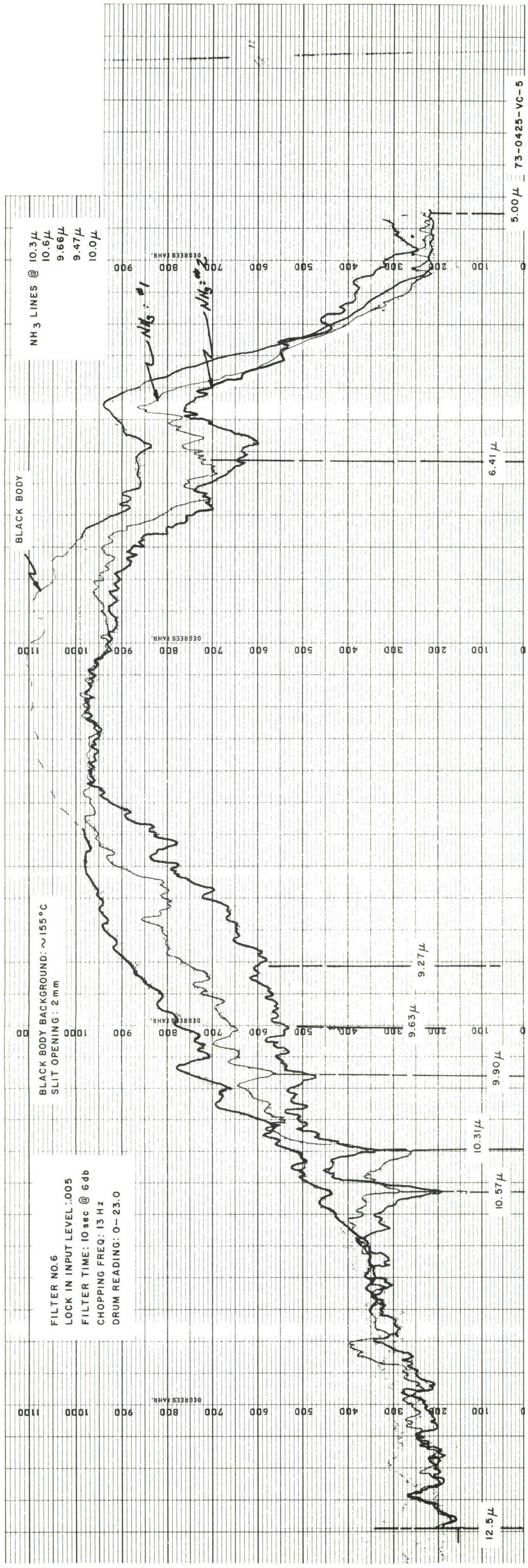


Figure 5. NH₃ Absorption Bands

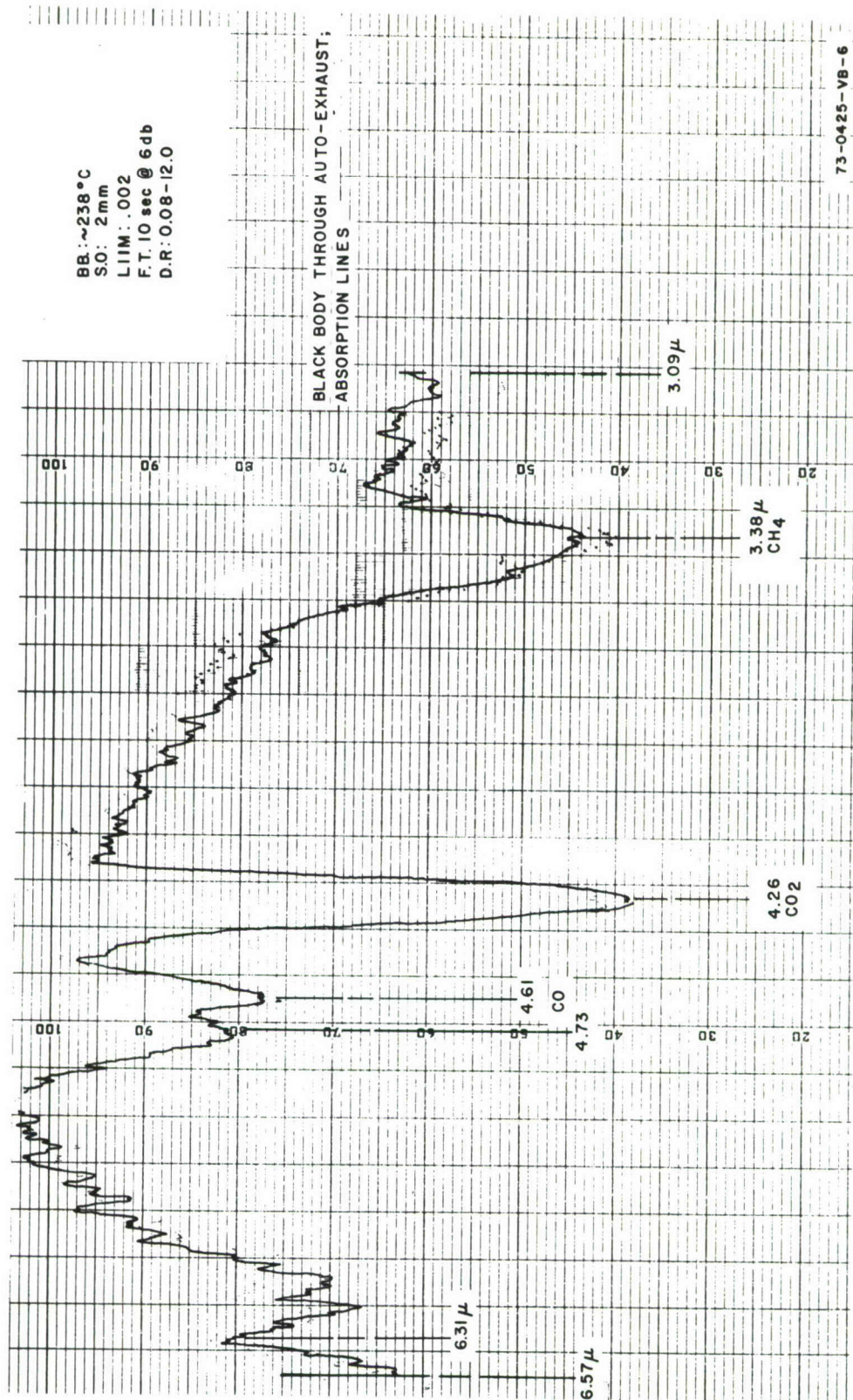


Figure 6. Spectra of Auto Exhaust

Figure 8, taken before methane entered the cell, is an infrared image of the gas cell, holders, laboratory wall, and a hand. The narrow spectral region indicated by the filter transmission curve in figure 11 almost exactly coincides with the strong methane absorption band centered around 3.38μ (figure 6). Seen in figure 8 is a dark circle in the middle of the cell which results from viewing through the cell to the cold background (s sponge dipped in liquid nitrogen). Note that the ends of the cell do not radiate because they are transparent at 3.4μ (again Kirchoff's law). The cell walls, on the other hand, radiate almost as perfect blackbodies because glass absorbs in this spectral region.

Figure 9 shows the cell with methane. The previously transparent cell is now opaque to the 3.4μ radiation due to absorption by methane in the cell. Again, by Kirchoff's law the methane absorption bands exhibit blackbody emission. Thus, the cell window appears very bright as it transmits the methane radiation. The gas temperature probably did not exceed 65°F , the approximate room temperature.

Figure 10 is the scene after methane leaves the cell. The background reappears through the cell ends which in the absence of gas are again dark. The absorber having left the cell, blackbody emission is no longer possible.

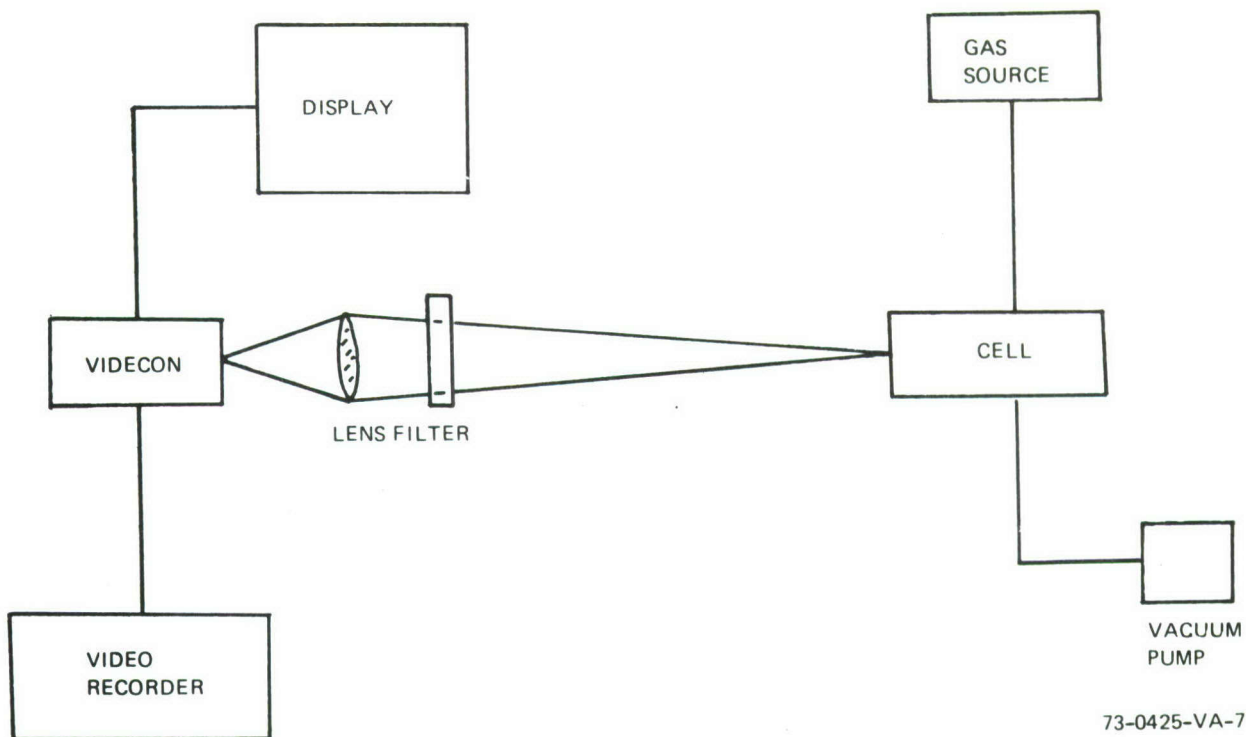


Figure 7. Schematic of Experimental Arrangement for Imaging Radiant Gases



Figure 8. End View of Cell Before CH_4 Admission

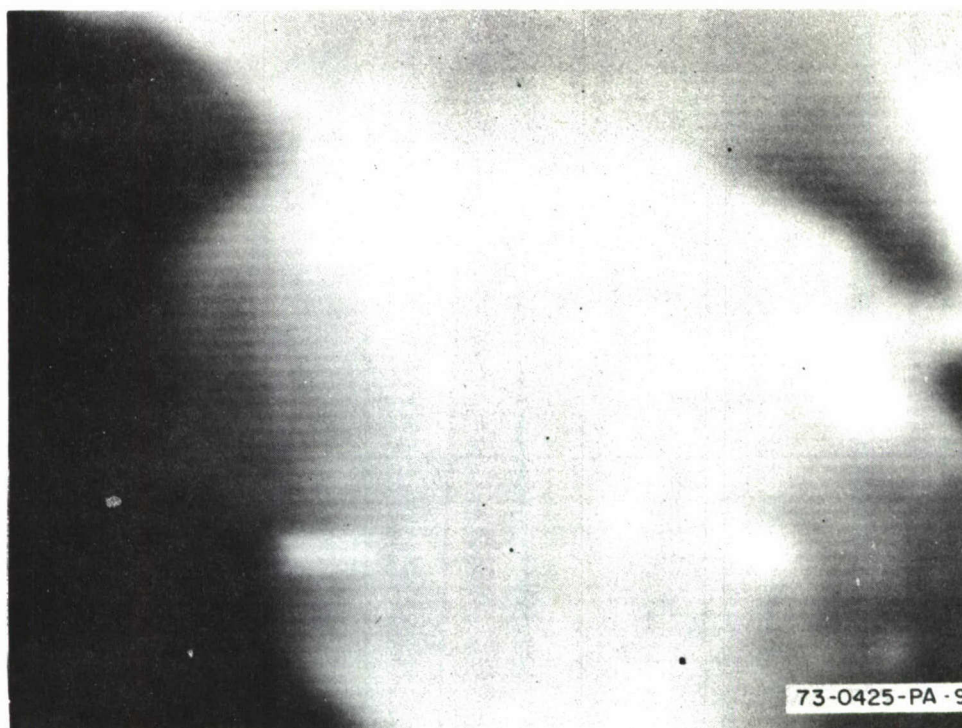


Figure 9. End View of Cell With CH₄



Figure 10. End View of Cell After CH₄ Evacuation

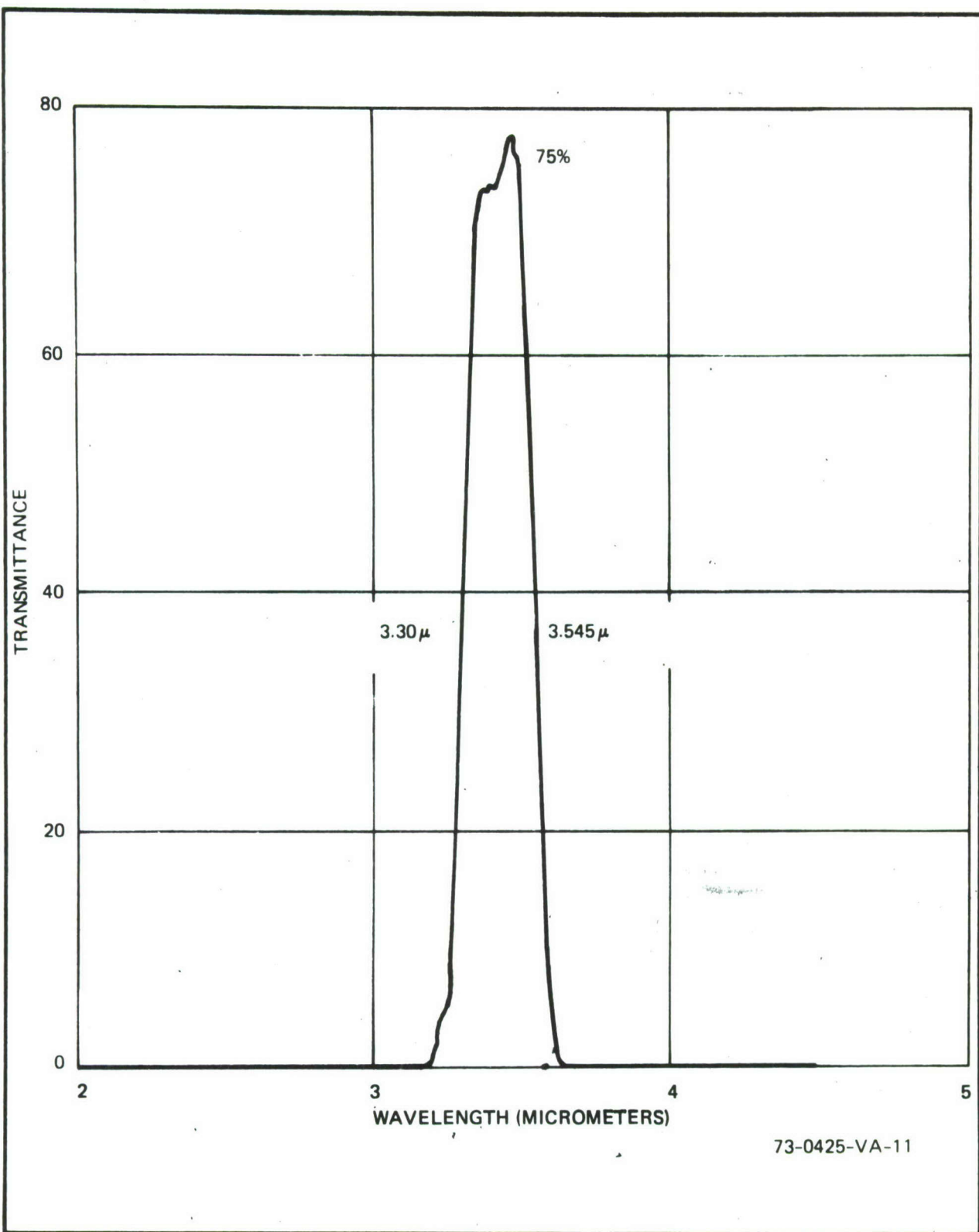


Figure 11. Filter Transmission Curve

3. CONCLUSIONS

The above paragraphs described the successful laboratory demonstration of a real-time image of a specific gas by sensing its ambient thermal radiation. Questions now remaining pertain to detection limits. In particular, the continued experimental phase of the Effluent Plume program must include field trials to study the effect of atmospheric and terrestrial backgrounds in order to determine feasible operating ranges. This will require investigation into contrast enhancement techniques, optimum filtering, and correlation techniques to enhance signal-to-noise ratios. Ultimately, a detection limit occurs when the processing time needed to remove noise and enhance contrast exceeds criteria for real-time imaging.

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