

Flame detection/study/monitoring with lithium tantalate
pyroelectric detectors

by David Cima

Introduction:

Of nature's many phenomena, the flame is by no means the simplest. The typical hydrocarbon flame is a mixture of molecules--some being created and some being destroyed. It's an aerodynamic event with regions of laminar and/or turbulent flow. To say that a flame is "generally exothermic" is the supreme understatement. A flame is truly energized matter.

And since the energy of the flame is not contained as in controlled fusion, the direction of the energy is outward to equilibrium. The energy is moving by conduction, convection, and radiation. Wishing to keep my distance from the flame, I'll ignore conduction and convection and focus on radiation. The making and breaking of molecular bonds requires that atoms be energized to the extent that electrons jump orbits--and thus emit photons, in the visible and ultraviolet region of the spectrum.

Combustion is rarely complete, and minute agglomerates of solid carbon are formed, heated to a glowing red or even white heat. These particles have a very high emissivity and behave as miniature black bodies radiating a planckian spectral distribution of photons, many of which are in the infrared.

One very useful phenomena in the hydrocarbon flame is very strong infrared emission at 4.3 micrometers--a consequence of the almost violent molecular agitation of carbon dioxide.

Normally, at ambient temperatures, 4.3 micrometers is an absorption band for carbon dioxide. In fact, the carbon dioxide in the atmosphere is enough to absorb the 4.3 micrometer energy from the sun.

In what may appear to be a tangent from the topic of "flames," let me note that we live in a sea of electromagnetic waves: radio, visible light, earth-temperature infrared distributions, a few gamma rays, etc. But there's not much 4.3 micrometer radiation in our environment. The filament of an incandescent bulb, glowing white hot is certainly emitting 4.3 infrared. Nevertheless, the filament is in a glass envelope--and most glasses have little or no transmission at 4.3 micrometers.

So if we wish to detect/study/monitor any phenomena, we usually do best by restricting our view to some aspect that is peculiar to that phenomena. Thus my emphasis on the 4.3 micrometer emission of a hydrocarbon flame.

The "peculiar aspect" must be practically instrumentable to be useful. And, fortunately, such a device is at hand.

The device is a lithium tantalate pyroelectric detector. The lithium tantalate is a single-crystal material, like quartz or diamond. So it doesn't age. Technically, lithium tantalate is a noncentrosymmetrical crystal. And there is one axis along which a temperature change will produce not only a lattice stress, but also an electric dipole moment--generation of charge. By properly cutting the crystal into a wafer and electroding the surfaces, the charge can be collected and used as a signal. Since the insulation resistance is above 10 teraohms, the electrodes make the crystal sandwich a capacitor. Thus the detector can be viewed as an "active capacitor." A high megohm resistor is put across the plates of the capacitor so the generated charge becomes a voltage potential. One terminal of the resistor is presented to the gate of a field effect transistor and the other terminal to ground. Placing from +5 to +15 volts on the drain of the transistor and a resistor from the source to ground completes a source-follower circuit and the device now has a low impedance(usable) output.

Alternately, one side of the crystal/capacitor can be presented to the negative input of a transimpedance amplifier and the other side of the crystal to ground. A high megohm resistor connected to the input and output of the amplifier becomes the gain-controlling feedback loop and the device functions as a very high-gain current to voltage converter.

Eltec Instruments makes both types of devices described above and variations as well--all in a standard TO-5 transistor housing.

The pyroelectric detector is a "thermal" detector. Thus photons are absorbed by the electrode and crystal as heat--and the heat stresses the lattice to produce the charge. The crystal doesn't care what kind of photons it absorbs. The photons can be ultraviolet, visible, near infrared, and far infrared to 1,000 micrometers in wavelength. So to make it a dedicated flame detector, a narrow bandpass interference optical filter/window is placed over the crystal. The window, as you would expect by now, has its transmission centered at 4.3 micrometers.

The pyroelectric detector is an AC device. It has to see a change to respond. No change, no output.

If we are dealing with an "unfriendly" flame, as might break out in a chemical plant, the detector is looking at an area with no flame(no 4.3 micrometer radiation) and then, an instant later, at a flame. There's a change in 4.3 micrometer radiation(from none to lots) and there's a healthy change in the detector output to trigger an alarm or automatic foam generating equipment. If only a smoke detector had been relied upon, everyone would have been killed and the plant destroyed by the time the smoke was sufficient to trigger the device.

I may have given the impression that there is no other possible source of 4.3 micrometer radiation than a hydrocarbon flame. A very hot object, as Planck has shown, emits 4.3 infrared.

But an uninsulated steam pipe in the field of view will emit either a constant stream of 4.3 infrared(no change, no output), or a change in 4.3(as the pipe heats up or cools down) at a rate well below the thermal time constant of the detector(again, no change).

But say the detector is in a steel mill and hot beams are moved past the detector by rail. The detector will indeed respond!

Now I go back to the physical flame. The flame exhibits a phenomena known as "flicker." The flicker is a bulk phenomena exhibiting an alternate increase-decrease in radiated energy at the rate of about from 5 to 15 Hz. If I now add a narrow bandpass electrical filter prior to the alarm comparator, I now get an alarm only if the "source" is emitting 4.3 infrared and only within my electrical passband(perhaps taking more than one sample for good measure).

The electrical filtering and sampling may give me a response time of 1 second. If that's too slow, there is another approach.

The other approach is to use two detectors. One detector has a 4.3 micrometer window and the other detector has a reference window. Some use 3.8 micrometers as a reference and some use 5 micrometers as a reference. Now, if a hot object passes in front of both detectors they will give similar(but not identical) output magnitudes. But if there is a hydrocarbon fire, the detector with 4.3 infrared window will give a substantially greater output. And the alarm will be sounded!

Thus the usefulness of the pyroelectric detector as a sensor in a fire alarm.

If you are dealing with a "friendly" flame, as in a boiler, you always have the flicker output. No output, no flame. Shut off the gas to the boiler.

The detector can also be used to study flames. Namely, does the flicker frequency relate to efficient operation of a flame? Does the behavior of the flame in other regions of the spectrum relate to efficiency or some other parameter(the detector can be fitted with any optical bandpass window--with a linear response throughout the spectrum).

Additionally, the radiation to the detector can be modulated(chopped) giving a drift-free AC signal proportional to the input radiation(as from the hot carbon particles referred to earlier) to actually monitor the temperature of the flame(with an appropriate window).

In summary, lithium tantalate pyroelectric detectors are yet another tool in mankind's ancient quest to tame, use and understand fire.

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FLAME DETECTION AND THE EMISSION/ABSORPTION BANDS
OF CARBON DIOXIDE

by David Cima, Eltec Instruments

The selection of the wavelength band for an optical filter for flame detection is more involved than the simple choice of the analytical absorption region of carbon dioxide. The 4.3 band of high absorption goes from 4.19 to 4.45 micrometers (Infrared Handbook). And a hydrocarbon flame will produce strong emission within that band.

However, the 300 PPM of CO₂ in our atmosphere is of sufficient concentration so as to provide almost total absorption within relatively short distances between about 4.2 micrometers and somewhat beyond 4.3 micrometers. Recent work by Chris Prozzo of Janos Technology shows the effects of this absorption at a distance of 70 feet.

Nevertheless, the combined action of temperature and pressure within a flame extend the emission region to beyond 4.6 micrometers. Thus subtracting from the flame spectra the absorption from atmospheric carbon dioxide, we find both maximum emission and transmission in the region of 4.4 micrometers.

Sunlight interference? Working within the atmospheric absorption band, around 4.3 micrometers, all of the relevant energy from the sun is eliminated in its long path through our atmosphere. Thus false alarms from sunglints are minimized. Yet, the spectral irradiance (maximum) from the sun in the band from, say, 4.4 to 5.4 micrometers is only about 0.16 milliwatts/sq cm. Thus the potential difficulties posed by solar interference must be weighed against the benefits of greatly increased transmission at 4.4 micrometers and beyond.

Electric lights? Fluorescent lamps are efficient sources of visible radiation and do not provide interference at 4.3 micrometers. Incandescent lamps have a white-hot filament which does indeed produce energy in the 4.3 micrometer band. However, the glass envelope of the bulb does not transmit at 4.3, so lamps turning on or off will not trip properly designed flame alarms. Note: Incandescent bulbs with thin quartz envelopes will transmit some 4.3 micrometer radiation. This fact can be used to advantage if a system self-test feature is desired. But use and placement of such a bulb must be carefully considered lest the device pose an explosion hazard. A final observation on incandescent bulbs is simply the realization that if the bulb is kept energized the long wave energy produced by the filament cannot escape through the envelope and will be absorbed--raising the temperature of the envelope and thus emitting 4.3 micrometer radiation. However, this

will be a steady-state emission which will not be detected by a pyroelectric detector.

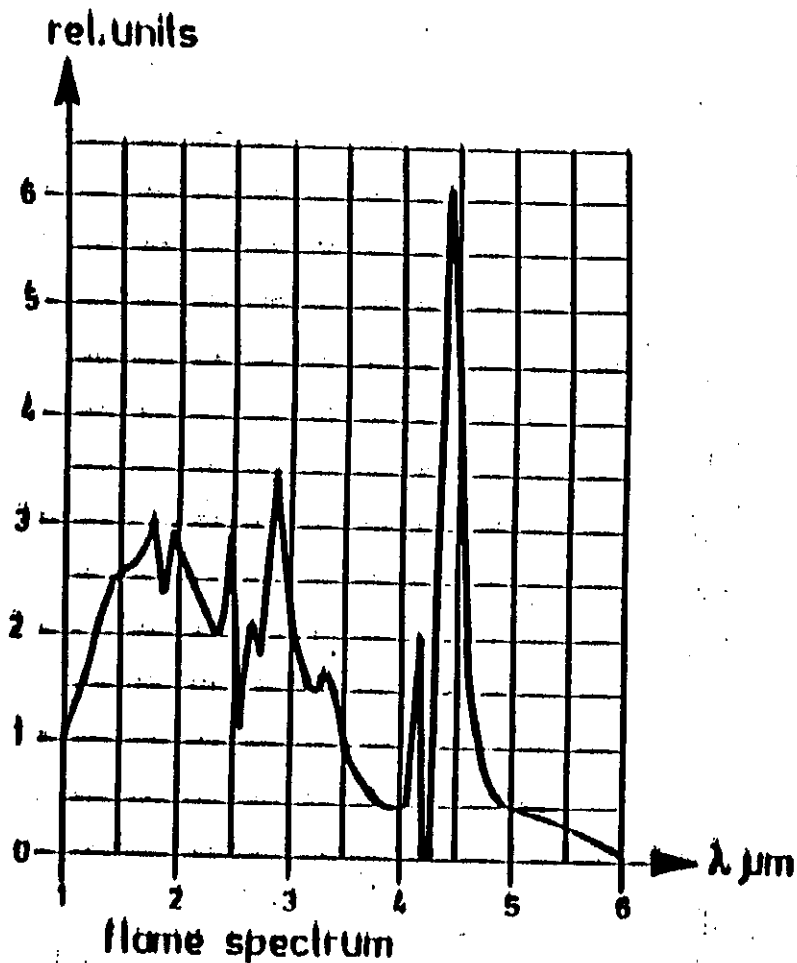
Carbon monoxide. Hydrocarbon flames are rarely perfectly stoichiometric and thus produce carbon monoxide as well as carbon dioxide. Unfriendly flames are diffuse (as opposed to a premixed bunsen burner) and produce significant quantities of carbon monoxide radiating about 4.65 micrometers. The flame alarm designer has the choice of using a bandpass for carbon dioxide only, or expanding the bandpass so as to capture the radiation from hot carbon monoxide as well.

Flame flicker. Both laminar and turbulent flames exhibit periodic oscillations referred to as flicker. This flicker occurs in the frequency range of from about 7 to 19 Hz. This phenomenon is, in effect, a self-modulation of a significant portion of the emissive power of the flame. In many flame detection systems the output of the pyroelectric detector is fed through an electronic filter network such that the output of the detector is not regarded as a flame unless the character of the signal corresponds to a flicker modulation. Thus there is a double-discrimination prior to initiation of a flame alarm: 1) optical radiation between 4.x to 4.y micrometers and 2) flicker modulation between a given bandwidth.

Explosions. Explosion detection often requires response within 1 to 10 milliseconds, for which pyroelectric detectors are well qualified. However, the alarm designer must first determine: Even if timely response is obtained, can suppression mechanisms be initiated quickly enough to contain damage or preserve life? If so, as in certain chemical plant locations and in military tank interiors, then circuitry beyond flicker detection must also be employed as well as detectors optimized for fast response. Possible or probable signal magnitudes and frequency content of explosive induced signals should be available to the designer. Also, since pyroelectric detectors are also piezoelectric devices to some extent, provision should be made to null or disregard mechanical shock-produced signals.

Fiber Optics. Both arsenic trisulfide and sapphire fibers are commercially available and have high transmission in both the carbon dioxide and monoxide emission wavelengths.

Window (optical filter) selection. From all that has been said, the flame alarm designer has available the following Eltec windows: A. For broadband detection of emissions from both hot carbon dioxide and carbon monoxide, Eltec -23 (on sapphire substrate) and Eltec -12 (on silicon substrate) with transmission from 4.17 to 4.79 micrometers; B. For hot carbon dioxide emission, Eltec -79 (on silicon) with transmission from 4.29 to 4.61 micrometers; C. For narrower band, straddling the absorption/emission CO₂ region, from 4.26 to 4.44 micrometers, Eltec -30 (on sapphire) and Eltec -112 (on silicon): (Note, these windows are also excellent for carbon dioxide concentration monitors where the energy source is only inches from the detector); and D. For narrow band detection within the CO₂ absorption (atmospheric) band, Eltec -43 from 4.25 to 4.35 micrometers.



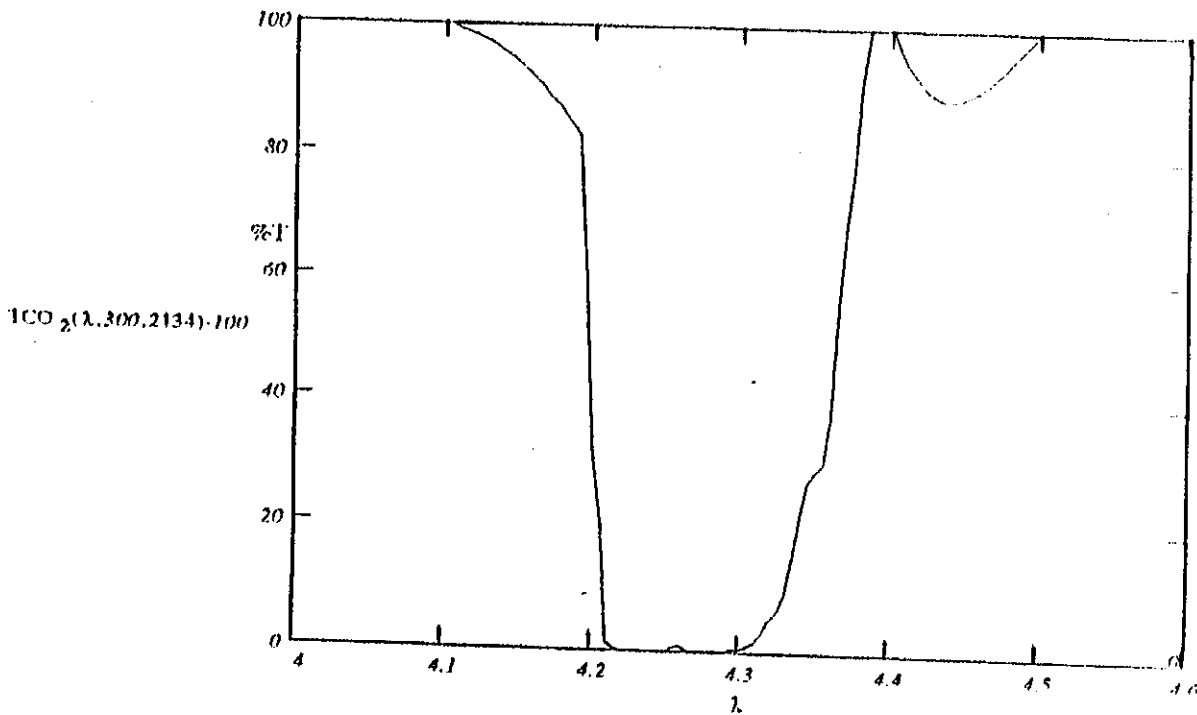
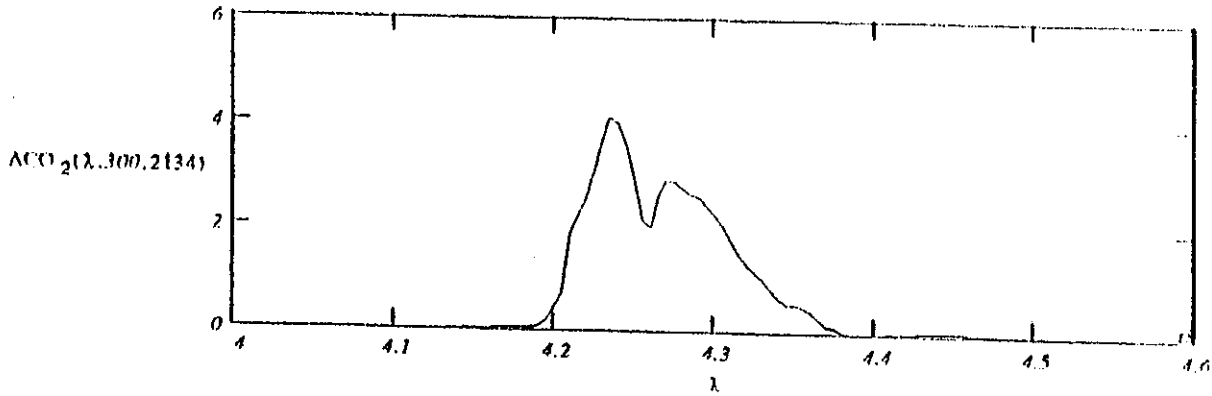
(from "Infrared technology applied to security systems,
 by J. Muggli and P. Wagli, Cerberus Ltd., Maennedorf,
 Switzerland)

Absorbance and Transmission of 300ppm CO₂ in 2134cm path

NOTE: Absorbance is linear with pathlength. %T is not.

Absorbance units

$\lambda = 4.0, 4.005, 4.6$



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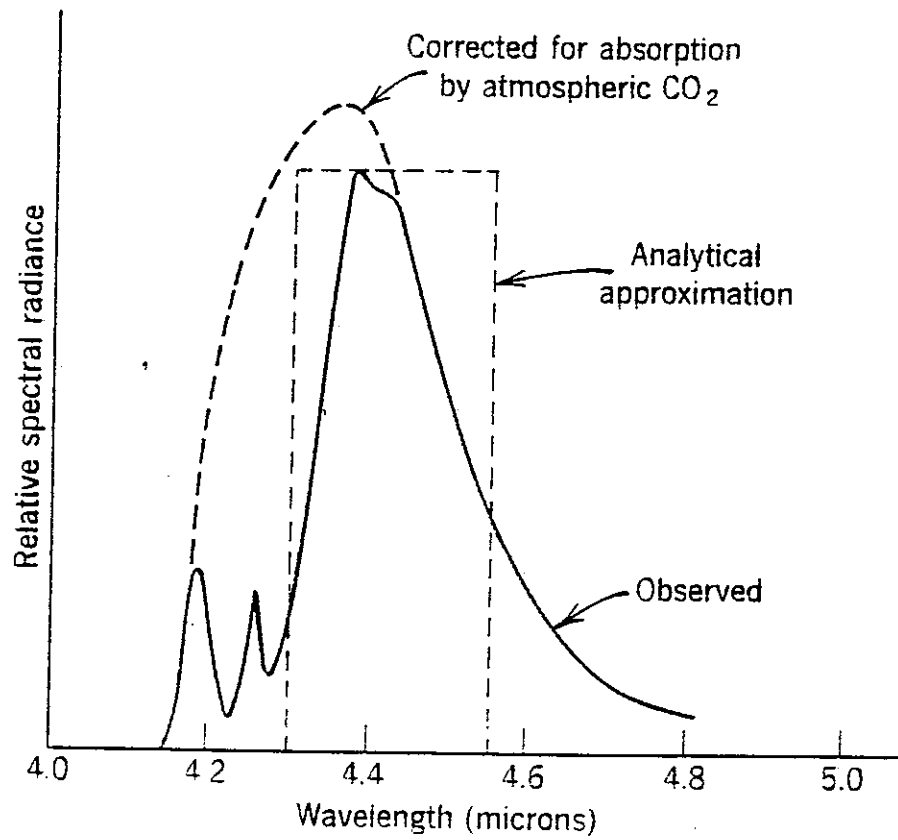


Figure 3.7 The 4.4 μ emission band of carbon dioxide (adapted from Plyler[57]).

(from Infrared Systems Engineering)

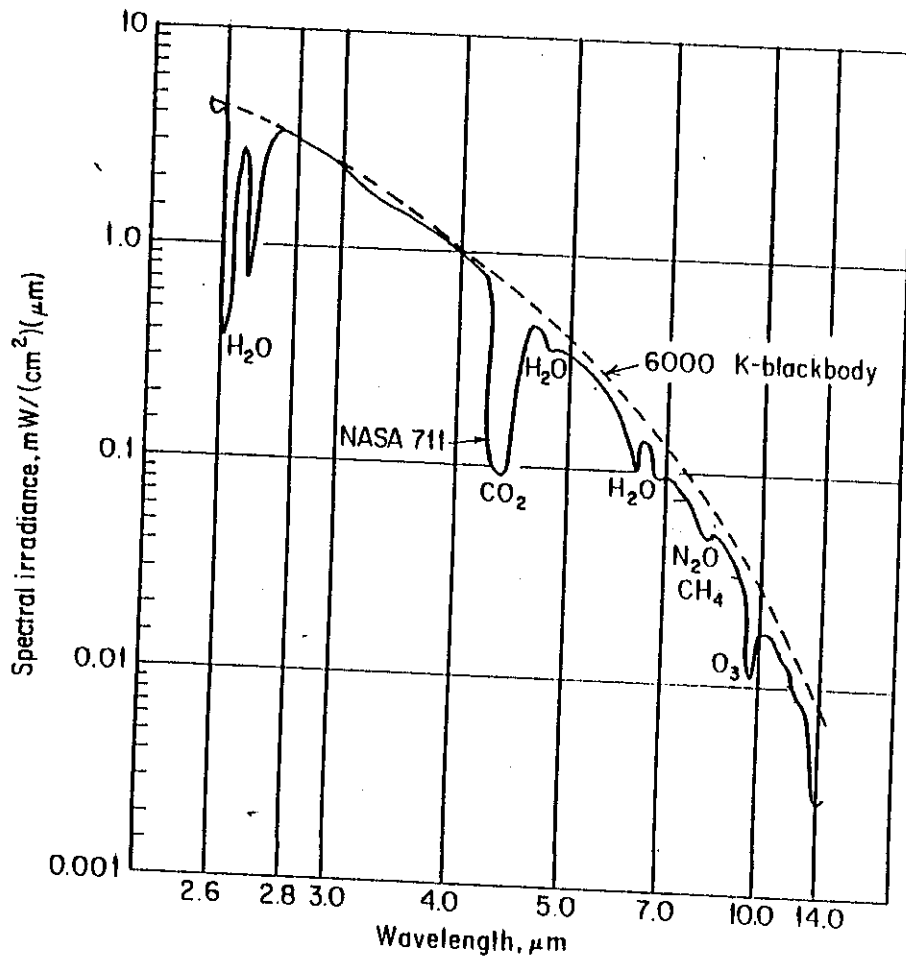


Fig. 53 Solar spectrum at 1.13 air mass from the I-4 interferometer. [Thekaekara et al. (1969).]

(from Handbook of Optics)

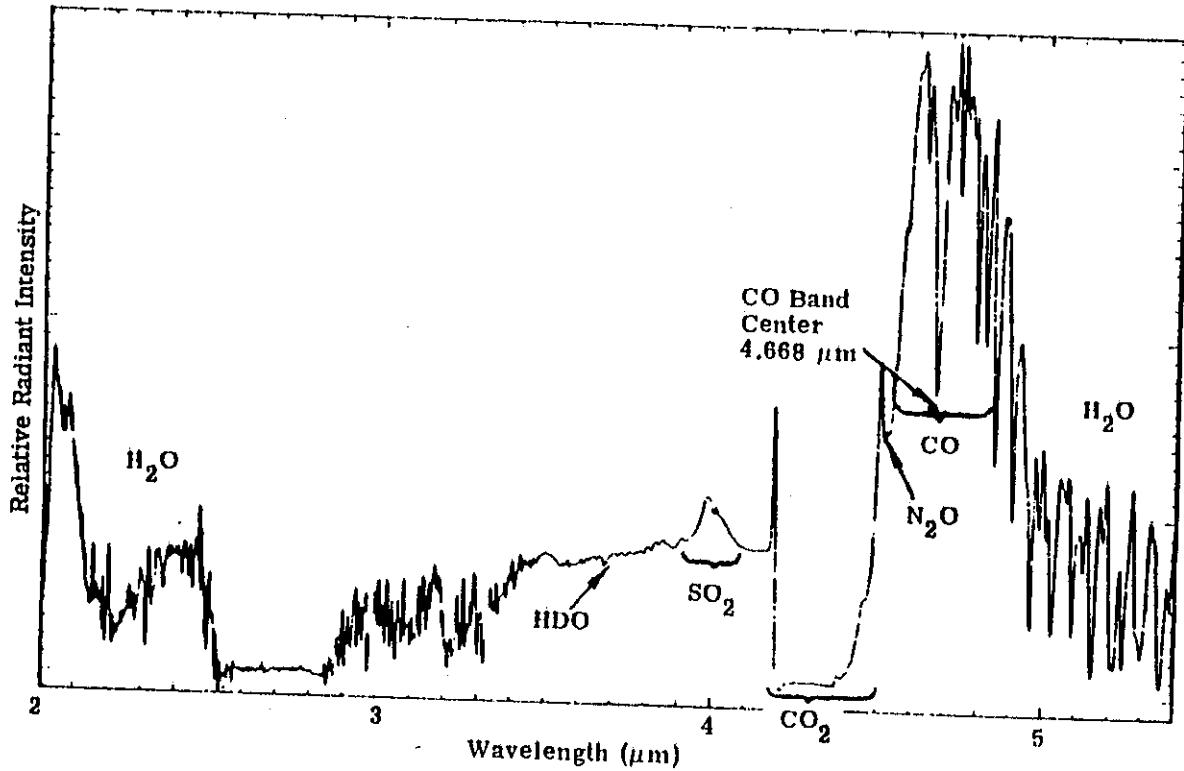


Fig. 2-67. Emission from a high temperature industrial smokestack [2-42].

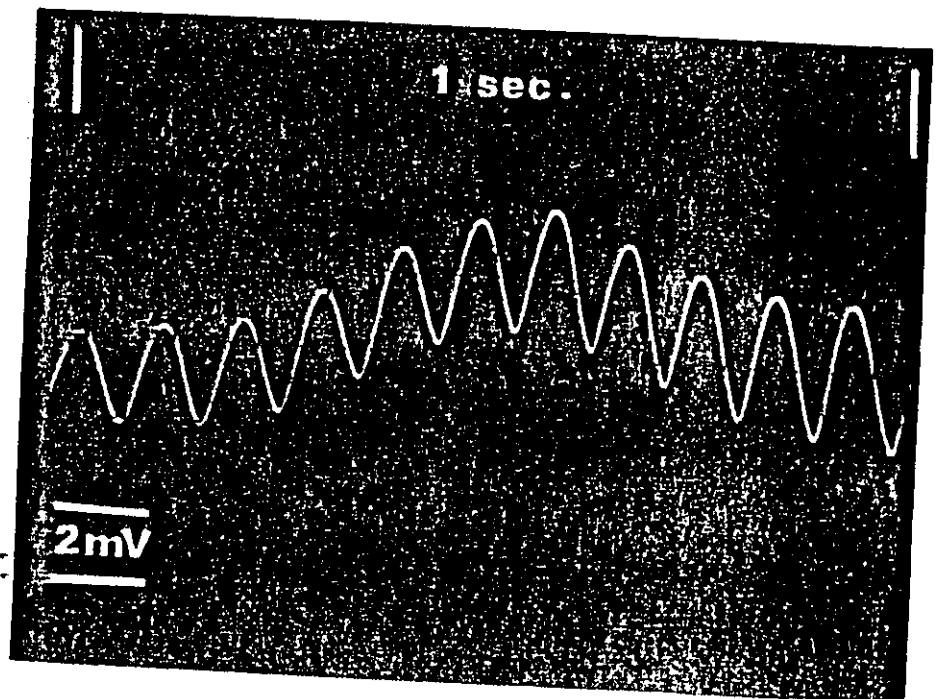
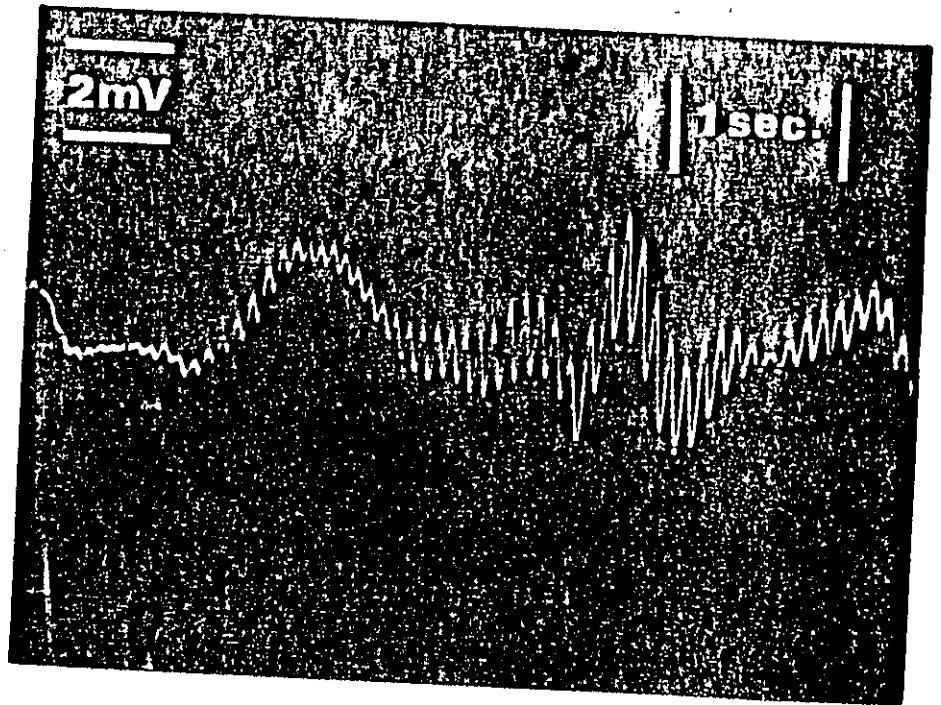
(from Infrared Handbook)

FLAME FLICKER DETECTION

Scope photo shows 11 Hz flame
flicker riding on flame dance.

Alcohol flame--10 inches from Eltec
Model 410-12 infrared detector.
Detector used without optics or
amplifier, directly into scope
(AC coupled).

(from testing at Eltec Instruments)



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