Brown RA and Searl TD (1979) In: Altgelt KH and Gouw TH (eds) *Chromatography in Petroleum Analysis*. Ch. 13. New York: Marcel Dekker. (An account of early work on offline GC-UV.)

Dressler M (1986) *Selective Gas Chromatography Detectors*. Amsterdam: Elsevier. (A literature survey of most of the selective detectors described up to about 1984. Mainly of historic interest.)

Eicman GA (1990) In: Clement RE (ed.) *Gas Chromatography, Biochemical, Biomedical and Clinical Applications*, Ch. 14. New York: Wiley Interscience. (An account of the GC of organometallic compounds.)

Hill HH and McMinn DG (eds) (1992) *Detectors for Capillary Chromatography*. New York: Wiley Interscience. (An excellent book with chapters on the ELCD (by Hall), the NPD (by Patterson) and GC-FTIR (by Gurka) in particular.)

Gas Chromatography–Infrared Spectrometry

P. R. Griffiths, University of Idaho, Moscow, ID, USA

Knowing the identity of each component in a mixture is necessary for many analytical-scale separations, and simply measuring retention data for this purpose is often too ambiguous for the identification of molecules eluting from a capillary gas chromatography (GC) column, which has the capability of resolving several hundred components. Prior knowledge about the chemical structure of the components and spiking of the mixture with one or more reference standards may aid the identification process; however, a less ambiguous identification can be accomplished by interfacing the chromatograph to a sensitive, rapid-scanning spectrometer to obtain unique signatures of each component. This instrument should allow each component to be detected in real time without any loss in chromatographic resolution. Mass spectrometry (MS) is the most commonly applied technique for this purpose, but it has certain limitations, in particular for distinguishing between structural isomers, such as *ortho*-, *meta*- and *para*-xylene, whose electron-impact and chemical-ionization mass spectra are identical. For such molecules a technique complementary to MS is desired. Fourier transform infrared (FT-IR) spectrometry, which yields unique spectra for most structural isomers, has frequently been used as an alternative technique for this purpose.

Light-Pipe-Based GC-IR Instruments

Measurement of the Spectrum

The coupling of gas chromatographs and FT-IR spectrometers (GC-IR) has been accomplished by three approaches. In the first, and by far the simplest, the GC column is connected directly to a heated flow-through cell. For capillary GC, this cell is usually fabricated from a 10-cm length of heated glass tubing with an internal diameter of $\sim$1 mm. The inside bore of this tube is coated with a thick enough film of gold to be highly reflective to infrared (IR) radiation. IR-transparent windows (for example made of potassium bromide) are attached to both ends of the tube. IR radiation entering one window is multiply reflected down the gold-coated interior bore before emerging from the other window, giving rise to the name *light–pipe* for this device. The effluent from the GC column is passed into one end of the tube and out of the other via heated fused-silica transfer lines. The entire unit is held at a temperature between 250 and 300°C to preclude the condensation of semi-volatile materials.

Infrared radiation from an incandescent source, such as an SiC Globar, is collimated and passed through a rapid-scanning interferometer so that each wavelength in the spectrum is modulated at a different frequency. The beam of radiation is then focused onto the first window of the light-pipe and the infrared beam emerging from the second window is refocused onto a sensitive detector (typically a liquid-nitrogen-cooled mercury cadmium telluride (MCT) photoconductive detector). A typical system is illustrated schematically in **Figure 1**. The signal measured in this way is known as an *interferogram* and the Fourier transform of the interferogram yields a single-beam spectrum. By calculating the ratio of a single-beam spectrum measured when a component is present in the light-pipe to one measured when only the helium carrier gas is present, the transmittance spectrum, $T(\nu)$, of the component is obtained. The transmittance spectrum is usually immediately converted to an absorbance spectrum, $A(\nu)$, by the standard Beer's law operation, $A(\nu) = -\log_{10} T(\nu)$, as the relative intensities of bands in absorbance spectra are independent of the concentration of the analyte, thereby allowing spectral library searching to be

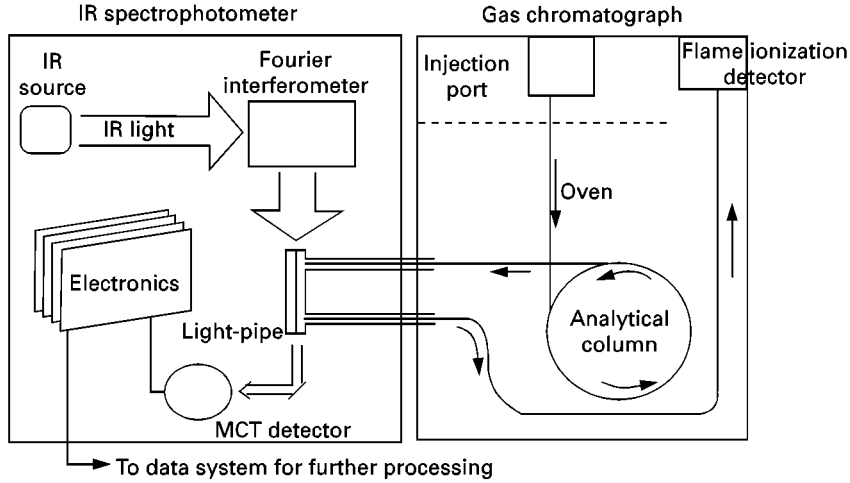

Figure 1 Schematic of typical light-pipe-based GC-FTIR interface (based on Hewlett Packard IRD).

performed. For light-pipe-based GC-IR systems, it is rarely necessary to measure spectra at high resolution, as the spectral bands are quite broad. Since most bands in the spectra of molecules in the vapour phase have a width of at least 10-cm^{-1}, the typical resolution at which GC-IR spectra are measured is 8 cm^{-1}.

When operated at their highest scan speeds, FT-IR spectrometers can measure between 5 and 20 interferograms per second that would yield spectra of this resolution. During a chromatographic analysis, interferograms are measured continuously. Thus for a 30-min-long chromatogram, it would be possible to measure tens of thousands of interferograms, giving rise to an amount of data that could exceed 100/MB and hence could exceed the capacity of the disk on a typical personal computer (PC). Fortunately, most GC peaks have a full-width at half-height (FWHH) of several seconds. Thus it is common practice to average blocks of interferograms for a period of time that is slightly less than the FWHH of the narrowest peak in the chromatogram (usually 1–2 s). The single-beam spectrum is then computed from this signal-averaged interferogram and ratioed against an appropriate background spectrum; finally, the resulting transmittance spectrum is converted to a linear absorbance format. On many fast PCs this entire sequence of operations is performed while the next block of interferograms is being acquired.

Reconstruction of Chromatograms

The end result of this process is that over 1000 absorbance spectra, corresponding to the contents of the light-pipe measured at approximately 1-s intervals throughout the entire chromatogram, are stored at the end of the run. Many of these spectra contain no useful information as they were measured when no component was present in the light-pipe; thus the next step in a GC-IR analysis is to determine which of the stored spectra contain useful information. To achieve this, a chromatogram must be reconstructed from the spectroscopic data. This is usually achieved in two ways, the first of which is known as the *Gram–Schmidt* (GS) vector orthogonalization method. Here, short, information-rich regions of the interferograms are treated as vectors and the vector distance between this part of each interferogram measured during the chromatographic run and several interferograms that were acquired when nothing except the helium carrier gas was flowing through the light-pipe (known as the basis set) is calculated. When an analyte elutes from the column, the magnitude of the vector difference is approximately proportional to the quantity of this material in the light-pipe. Because only a short region of the interferogram is examined. calculation of the GS 'signal' can be achieved in a few milliseconds. Furthermore, since all compounds besides monatomic and homonuclear diatomic molecules have at least one band in their IR spectrum, GS chromatograms are very nonselective. Some compounds yield much stronger IR spectra than others, however. For example, the spectra of most nonpolar compounds are rather weak, whereas the spectra of very polar compounds are usually much stronger. As an example, the detection limits for GS chromatograms of polycyclic aromatic hydrocarbons (which have very low absorptivities over most of their IR spectra) are about 20 times greater than the corresponding values for the barbiturates (which are very polar and have several strong IR absorption bands in their spectra).

The other commonly used algorithm by which chromatograms are constructed from the IR data involves calculating the integrated absorbance in one

or more specified spectral regions. These regions are usually chosen to correspond to the characteristic absorption frequencies of functional groups present in the class(es) of molecules of interest. The chromatograms generated by this approach have been called by a variety of names including Chemigrams™, functional group (FG) chromatograms and selective wavelength (SW) chromatograms. FG chromatograms are, of course, far more selective than GS chromatograms, but are rarely completely selective as many molecules have weak overtone and combination bands over much of the fingerprint region of the spectrum. For compounds with functional groups giving rise to intense absorption bands, such as the C=O stretching mode of carbonyl compounds, the limits of detection of FG chromatograms may be less than those of the corresponding GS chromatograms, but the two algorithms often have comparable sensitivity. A useful way to detect the presence of a particular functional group is to compare the relative heights of peaks in the GS and FG chromatograms. If the ratio of the peak heights in the FG and GS chromatograms is large, the presence of that functional group in that component is indicated: if the ratio is small, there is a much smaller probability that the analyte contains that functional group.

Spectral Searching

Once the chromatography has been completed, the spectra of those components of interest can be displayed. (In fact, several GC-IR software packages allow the spectra to be displayed while data acquisition is still in progress.) Each component generating a peak in the GS chromatogram with a signal-to-noise ratio greater than about 10 can usually be identified by comparing its spectrum to a library of vapour-phase reference spectra. The unknown and reference spectra are first scaled so that the most intense band in each spectrum has the same absorbance (usually 1.0). By treating the spectra as vectors, the Euclidean distance between the unknown and each reference spectrum is calculated. This distance is usually called the *hit quality index* (HQI); the smaller the HQI, the better is the spectral match. The highest probability for the identity of the unknown is that of the compound in the reference library yielding the smallest HQI. Some software scales the Euclidean distance and then subtracts it from, say, 1000 to give the HQI; in this case, of course, the larger the HQI, the better the spectral match. However unequivocal identifications cannot be made on this basis alone, for several reasons. The reference spectrum of the authentic analyte may not be present in the spectral library. If the spectrum of the unknown is noisy, the value of the HQI may be determined more by noise than by the true absorption spectrum. The reference spectrum may have been measured with the sample at a different temperature from the light-pipe, measured at a slightly different resolution, or computed with a different apodization function. Finally, some members of homologous series can have very similar spectra, so it is not uncommon for compounds of the same type (e.g. methacrylate esters) to give similar HQI values.

It is always recommended that the user should make a side-by-side comparison of the GC-IR spectrum and the reference spectra of the top few 'hits' to get a good idea of the probability that the structure of the top hit, or by one of the other close hits, or whether there is enough similarity between the GC-IR spectrum and all of the closely matching reference spectra that unequivocal identification is impossible. In this case, the simultaneous application of MS may be necessary to yield an unequivocal identification.

Limits of Detection and Identification

The limit of detection (LOD) for an acceptable GC-IR response for most compounds is between about 1 and 20 ng (injected) per component, the actual value depending on the chemical nature of the analyte. The LOD is often defined with respect to the strongest band in the spectrum. Most bands in the IR spectra of nonpolar compounds are fairly weak and so these compounds tend to have the highest LODs, but even these compounds usually have at least one band in the spectrum with a high absorptivity. Examples include the C–H stretching bands of alkanes and the aromatic C–H out-of-plane deformation bands of polycyclic aromatic hydrocarbons. Detection limits also depend on the width of the GC peak; the wider the peak, the more dilute the analyte and the higher the LOD.

The amount of a given component that must be injected into the chromatograph to yield an identifiable spectrum, often known as the minimum identifiable quantity (MIQ), depends not on the *strongest* band, but on the signal-to-noise ratio of the *most characteristic bands* in the spectrum. For an analyte with a spectrum that is very different from any other spectra in the reference database, the MIQ may be only slightly higher than the LOD. On the other hand, there are often only very subtle differences between the spectra of members of this class of compounds. If the analyte is a member of a homologous series and several reference spectra of members of this series are contained in the library, the signal-to-noise ratio of the spectrum must be high, and hence the MIQ will be much greater than the LOD if the analyte is to be correctly identified.

If a minor peak is present in a chromatogram measured with a conventional GC detector such as a flame ionization detector (FID), but is not observable in the GS or FG chromatogram, it may be possible simply to inject a greater volume of the sample into the chromatograph. Even if the major components overload GC column in this case, the minor components will not. However, sometimes the major peaks will broaden to the point that they start to overlap a neighbouring minor peak. In this case, it may become necessary to subtract the spectrum of the major peak (linear in absorbance) from the spectrum measured in the region of the minor peak, to identify the minor component. This procedure is needed because of the relatively low sensitivity of light-pipe-based GC-IR instruments. Two other approaches that have led to increased sensitivity for GC-IR measurements are described here.

Matrix-Isolation GC-IR

In the first approach, argon is mixed with the helium mobile phase, either as a minor ($\sim 1\%$) component in the carrier gas or by addition at the end of the GC column. The column effluent is then sprayed from a heated fused-silica transfer line onto a rotating gold-plated disk that is maintained at a temperature of less than 15 K. Helium does not condense at this temperature but argon does. By locating the end of the transfer line an appropriate distance from the cooled disk, argon is deposited as a track approximately 300 μm in width. Any component emerging from the transfer line at the same time is trapped in the argon matrix. After the separation has been completed, the disk is rotated to a position where the focused beam from an FT-IR spectrometer is transmitted through the track of argon, reflects from the gold-coated disk, passes again through the argon and then is collected and focused on to an MCT detector, as shown in **Figure 2**. In principle, if the concentration of any analyte in the argon matrix is low enough, each analyte in the argon matrix is low enough, each analyte molecule will be isolated from similar molecules by the argon matrix. Despite the fact that the concentration is usually a little too high for true matrix isolation to be achieved in GC-IR measurements, this technique none the less is known as *matrix-isolation GC-IR*. By rotating the disk slowly, a series of spectra can be measured that is analogous to the series of spectra that is measured in real-time during a light-pipe-based GC-IR run and either GS or FG chromatograms can be constructed from these data. Each component may be identified by spectral library searching, but a special library of spectra of matrix-isolated standards is required.

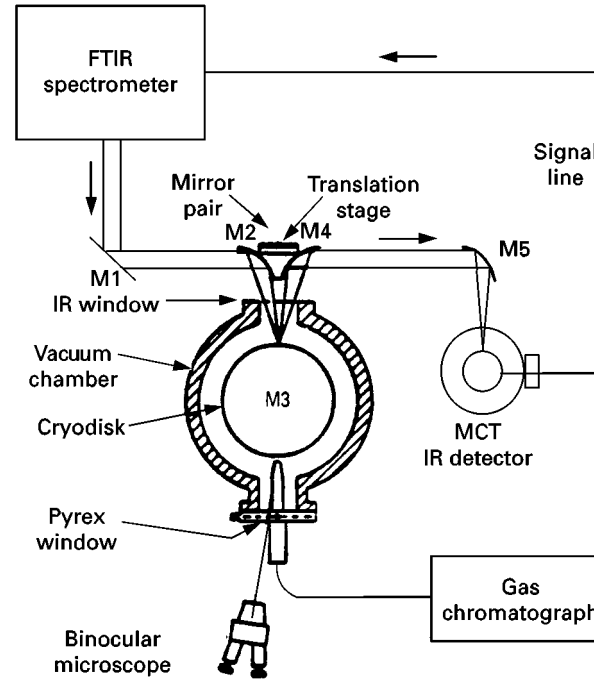

Figure 2 Schematic diagram of matrix-isolation GC-FTIR interface (based on Mattson Instruments Cryolect).

The advantages of matrix isolation are based on the following considerations. First, the width of the track is about 300 μm, compared with 1 mm for the diameter of a light-pipe. Thus the sample is more concentrated over the cross-sectional area of the IR beam and a given amount of sample will yield a spectrum with more intense absorption bands. Second, because each component is trapped on the disk, it is common practice when minor components are to be identified by matrix isolation GC-IR to signal-average interferograms for several minutes with the disk stationary, enabling a significant increase in sensitivity to be achieved over real-time measurements. A final advantage that has been claimed for matrix-isolation GC-IR measurements is the increase in the absorptivity at the peak of each band in the spectrum because of the decrease in bandwidth that occurs on matrix isolation (the band area remaining approximately constant). This is true for small molecules, but large molecules disrupt the crystal structure of the argon to such an extent that a certain amount of molecular motion is possible. As a result, the widths of many bands in the spectra of large asymmetric molecules prepared in this way are surprisingly similar to widths of corresponding bands in the spectra of the corresponding molecules prepared as KBr disks.

The exception to this behaviour is observed in the spectra of compounds that contain O–H or N–H groups. In the crystalline form of such compounds,

the O–H and N–H groups are strongly intermolecularly hydrogen bonded. As a consequence, the O–H and N–H stretching bands in their KBr-disk spectra are exceptionally broad, often having a width of several hundred wavenumbers. When these molecules are isolated in an argon matrix, however, no intermolecular hydrogen bonding takes place, and the O–H and N–H stretching bands appear as very narrow spectral features. Thus, when the spectra of matrix-isolated species such as alcohols, phenols or amines are measured at high resolution, excellent specificity is often gained by matrix-isolation GC-IR.

The major problem with this approach to GC-IR (which can to a certain extent be shared with vapour-phase measurements) is the lack of extensive libraries of appropriate reference spectra. This disadvantage has largely been overcome by the final type of GC-IR interface, which is described next.

Direct-Deposition GC-IR

In the remaining approach to GC-IR, the effluent from the column is directed at a slowly moving, cooled window mounted on a computer-controlled *x–y* stage. Zinc selenide cooled to the temperature of liquid nitrogen is the most commonly used substrate. Each eluting component is deposited on the window as a very narrow spot. In the commercially available form of this interface, shown in **Figure 3**, the typical width of each spot is about 100 μm. The stage moves so that each deposited component passes through the beam focus of an IR microspectrometer shortly after deposition. As for light-pipe-based GC-IR systems, spectra are measured continuously throughout the chromatographic run and GS and/or FG chromatograms can be output in real time. This *direct deposition* approach for GC-IR has two important advantages over light-pipe or matrix isolation GC-IR systems – it yields higher sensitivity and the measured spectra are very similar to reference spectra of standards prepared as KBr disks. Let us first recognize the reason for the increased sensitivity of direct deposition GC-IR measurements.

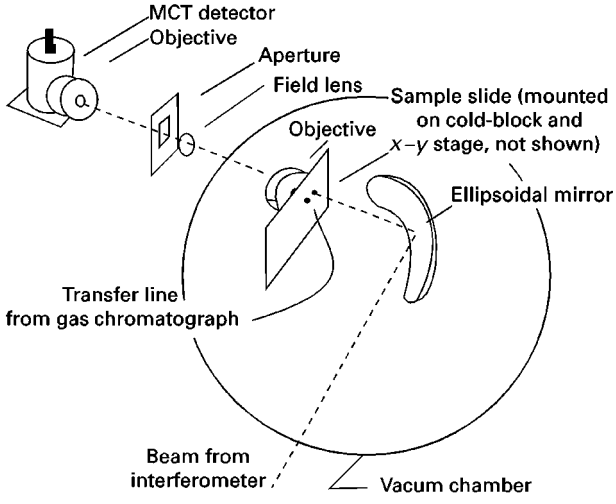

Figure 3 Schematic diagram of direct deposition GC-FTIR interface (based on Bio-Rad/Digilab Tracer).

As we saw in the previous section, the smaller the cross-sectional area of the sample, the greater the absorbance of all bands in the spectrum. Because the sample is contained in a 100-μm diameter spot rather than a 1-mm diameter light-pipe, its cross-sectional area is 100 times less, so that bands will be about 100 times more intense. To attain the optimal sensitivity, the diameter of the IR beam should be approximately equal to the width of the spot, i.e. about 100 μm, and a detector of the same size should also be used. Several other optical factors should be included in the comparison, but in general it is found that the signal-to-noise ratio of GC-IR spectra measured online using the direct deposition technique is about 50 times greater than the corresponding measurement made using a light-pipe system. The sensitivity advantage of direct-deposition GC-IR systems can be further increased by post-run signal averaging in a manner analogous to the matrix-isolation GC-IR system described previously. If each real-time spectrum is measured over 1-s blocks, post-run averaging for just 1 min will yield an improvement in sensitivity of almost a factor of eight.

As noted previously, the MIQ or direct-deposition GC-IR measurements varies with the polarity of the analyte. The LOD for real-time measurements of several analytes by this technique is about 50 pg. When very polar analytes are injected, this number can be further reduced. For example, the LOD for several barbiturates is found to be about 13 pg. Spectra of these barbiturates in the high-wavenumber region measured by a light-pipe-based GC-IR instrument (Hewlett Packard IRD) and a direct-deposition system (Bio-Rad/Digilab Tracer) are shown in **Figure 4**. Differences between the vapour-phase and condensed-phase spectra of molecules that can exhibit strong intermolecular hydrogen bonding are readily apparent in this figure. For example, the sharp bands absorbing near 3430 cm^{-1} in the vapour-phase spectra are due to the N–H stretching vibrations of isolated (non-hydrogen-bonded) molecules. In the corresponding condensed-phase spectra measured by direct deposition GC-IR, the N–H stretching modes of the intermolecularly hydrogen-bonded barbiturates are seen as broad bands near 3220 and 3110 cm^{-1}. Similar differences between vapour-phase and condensed-phase spectra of barbiturates are also seen in the spectral region between 2000 and 1000 cm^{-1} (see

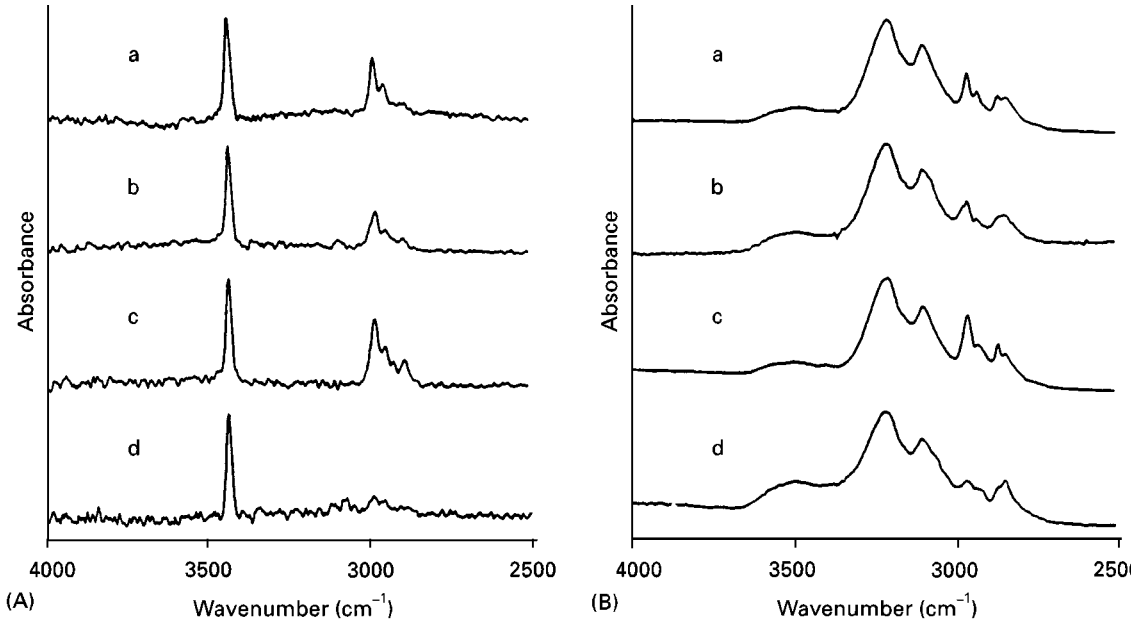

Figure 4 (A) Flow-cell and (B) direct-deposition GC-FTIR spectra of (a) barbital, (b) aprobarbital, (c) butabarbital and (d) phenobarbital from 4000 to 2500 cm^{-1}; 12.5 ng and 375 pg of each component were injected for the light-pipe and direct-deposition spectra, respectively.

Figure 5). The difference between the sensitivity of the light-pipe and direct-deposition GC-IR measurements can be seen by comparing the noise levels of the spectra shown in Figure 4 and recognizing that it required 30 times more of each barbiturate to be injected for the spectra measured using a light-pipe than for those measured using direct deposition.

On deposition, the molecules of a given analyte form randomly oriented crystallites on the zinc selenide window. These crystallites are similar to the crystallites that are formed on grinding of solid samples during the preparation of KBr disks or mineral-oil mulls. Not surprisingly, therefore, the spectra of compounds obtained by direct-deposition GC-IR are

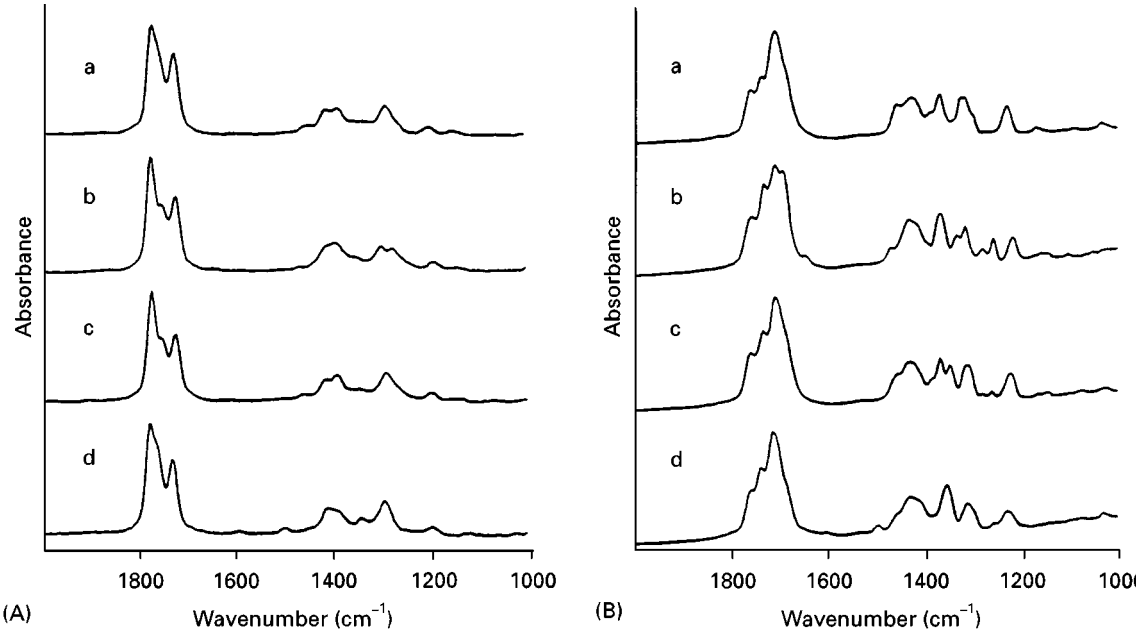

Figure 5 Low-wavenumber region of the spectra shown in Figure 4.

very similar to the KBr-disk spectra of the corresponding compounds. Extensive libraries ($>150\,000$ entries) of reference spectra of standards prepared in this way are available commercially. The only compounds that cannot be readily identified in this manner are molecules with very strongly hydrogen-bonding groups or for analytes exhibiting polymorphism. For trace analytes containing O–H or N–H groups, the best results on library searching are usually found by examining only the spectral region below 2000 cm^{-1} and eliminating the region containing the strong, broad O–H and N–H stretching modes from the search.

Prognostication

Online IR spectrometry is proving to be an important way of identifying molecules eluting from a gas chromatograph. Light-pipe-based systems are the simplest, least expensive and most reliable, but often prove to have inadequate sensitivity for the identification of minor components. Of the two deposition-based techniques, the direct-deposition approach has LODs that rival those of benchtop GC-MS systems and has the great advantage of producing spectra that are directly comparable with KBr-disk reference spectra, of which there are over 150 000 available in digital form (i.e. suitable for computerized library searching). Thus one can forecast an increasing use of systems based on this principle in the future. It is also noteworthy that interfaces between FT-IR spectrometers and both supercritical-fluid and liquid chromatographs based on the same principle have been described.

See also: **II/Chromatography: Gas:** Detectors: General (Flame Ionization Detectors and Thermal Conductivity Detectors); Detectors: Mass Spectrometry; Detectors: Selective; Gas Chromatography-Ultraviolet.

Further Reading

Bourne S, Haefner AM, Norton KL and Griffiths PR (1990) Performance characteristics of a real-time direct deposition GC/FT-IR system. *Analytical Chemistry* 62: 2448–2452.

Griffiths PR and de Haseth JA (1986) *Fourier Transform Infrared Spectrometry*, ch. 18. New York: Wiley-Interscience.

Herres W (1987) *HRGC-FTIR*: *Capillary Gas Chromatography – Fourier Transform Infrared Spectroscopy*; *Theory and Application*. Heidelberg: Huethig.

Norton KL and Griffiths PR (1995) Comparison of direct deposition and flow-cell gas chromatography-Fourier transform infrared spectrometry of barbiturates. *Journal of Chromatography A* 703: 383–392.

Reedy GT, Ettinger DG, Schneider JF and Bourne S (1985) High resolution gas chromatography/matrix isolation infrared spectrometry. *Analytical Chemistry* 57: 1602–1609.

White R (1990) *Chromatography/Fourier Transform Infrared Spectroscopy and its Applications*. New York: Marcel Dekker.

Gas Chromatography–Mass Spectrometry

See **II / CHROMATOGRAPHY: GAS / Detectors: Mass Spectrometry**

Gas Chromatography–Ultraviolet

V. L. Lagesson and L. Lagesson-Andrasko,
GC–UV Center, Linköping, Sweden

During recent decades much interest has been focused on hyphenated analytical techniques. Gas chromatography (GC), liquid chromatography (LC), mass spectrometry (MS) and Fourier transform infrared (FTIR) spectrophotometry have been arranged online, usually in a series. For example a GC separation directly combined with IR or MS is established and widespread. The combination considerably increases the degree of selectivity and identification possibilities. This is also applicable for ultraviolet (UV) absorption spectrophotomery, but GC–UV has been largely overlooked. The interest concerning UV absorption spectrophotometry for analytical purposes has been directed towards the liquid phase for the vast majority of studies involving UV absorption because of its frequent use as a detector for high performance liquid chromatography (HPLC).

However, the first attempt to utilize UV absorption detection combined with GC was made by Kaye in