1. Introduction

In 1960 as a young technician I was fortunate to be offered a position with an instrument manufacturing company and was given the choice of working 'in pH' or 'in chromatography'.

The choice wasn't too difficult. I didn't know anything about chromatography and –log (hydrogen ion concentration) had no appeal whatsoever. So chromatography it was and I have never regretted the choice.

Like myself in those early days, you may be starting to use gas chromatography for the first time or you may have a little 'hands-on' experience but no real understanding of the theory and practice of the technique. Whichever is the case, the objective of this text is to provide you with a practical appreciation of gas chromatography using the *ACOL: Chromatography Separations* text to provide the theoretical background to the technique. As with any analytical technique there is no substitute for 'hands-on' experience. In gas chromatography the manipulative technique must be learned and practised and the results of experimental changes rigorously studied and understood.

The term chromatography covers those separation techniques in which the separation of compounds is based upon the partition, or distribution, of the analytes between two phases in a dynamic system. In gas chromatography (GC) we have a gaseous mobile phase and a liquid or solid stationary phase.

Where a mobile phase is a liquid, then we are dealing with liquid chromatography (LC)

II Complete the following table:

Nature of mobile phase	Nature of stationary phase	Name
Gas	Liquid	Gas–liquid chromatography
Gas	?	Gas–solid chromatography
Liquid	Liquid	?
Liquid	Solid	? solid chromatography

The answers are 'Solid', 'Liquid–liquid chromatography' and 'Liquid–'

The first publication describing gas chromatography was by Martin and James in *Biochem. J.*, **50,** 679 (1952), with the first commercial instruments being manufactured by Griffin and George, Pye, Perkin-Elmer, Wilkins, Hewlett-Packard and others.

Thus gas chromatography as we know it today developed in the late 1950s and early 1960s mainly as a packed column technique although development of capillary columns progressed at the same time. It was not until much later that capillary column gas chromatography became firmly established when fused silica column technology overcame the fragility and variable performance of glass capillary columns.

The introduction of chemically bonded fused silica capillary columns in the 1980s rejuvenated gas chromatography and considerably extended its useful range.

Much of the theory of chromatography was developed in the early years and there was intense rivalry between the leading workers to provide the most convincing arguments.

It was an exciting time for those of us involved.

Nomenclature, definitions and the fundamental parameters of chromatography are to be found in *ACOL: Chromatographic Separations* together with a categorisation of gas, liquid and planar chromatographic systems.

❙❙ What is the main feature which distinguishes gas chromatography and liquid chromatography from planar chromatography?

Gas and liquid chromatography are both carried out in columns while planar chromatography or thin layer chromatography (TLC) is carried out on plastic, metal or glass sheets coated with silica.

❙❙ What advantages might planar chromatography, i.e. TLC, have over gas and liquid chromatography?

If you answered 'cost' you would be correct, TLC is cheap, but that was not the answer we were looking for. In gas and liquid chromatography we inject samples into the column but we can never be absolutely certain that all the components are eluted from the column into the detector. In TLC it is possible, by use of visualisation methods, to 'see' all the components on the plate. Nothing need remain undetected.

In this volume we shall be considering gas chromatography, i.e. the system in which the analytes are partitioned between a stationary phase and a gaseous mobile phase. By definition therefore, the compounds to be analysed must be sufficiently volatile for them to be present in the gas phase in the experimental conditions, in order that they may be transported through the column. Fortunately there is generally little association between the vaporised solute molecules and those of the carrier gas which simplifies the chromatographic process.

As we shall discuss later, analyte volatility is one of the major limiting factors in the application of the technique. The basic principle of gas chromatography is that the greater the affinity of the compound for the stationary phase, the more the compound will be retained by the column and the longer it will be before it is eluted and detected.

It is perhaps simplest to remember that all solute molecules spend the same amount of time in the gas phase. The difference in retention times, i.e. how long it takes to elute the compound from the column, depends upon its retention by the stationary phase.

In later sections we shall discuss the nature of the stationary phase, how columns are prepared and how separations may be optimised.

Thus, the heart of the gas chromatograph is the column in which the separation of the components takes place, and to this must be added the source and control of the carrier gas flow through the column, a means of sample introduction and a means of detection of the components as they elute from the end of the column. Since temperature will influence the volatility of the analytes, the column is placed in a thermostatically controlled oven. Detectors and some injectors are also heated. A basic chromatograph is represented diagramatically in Fig. 1a.

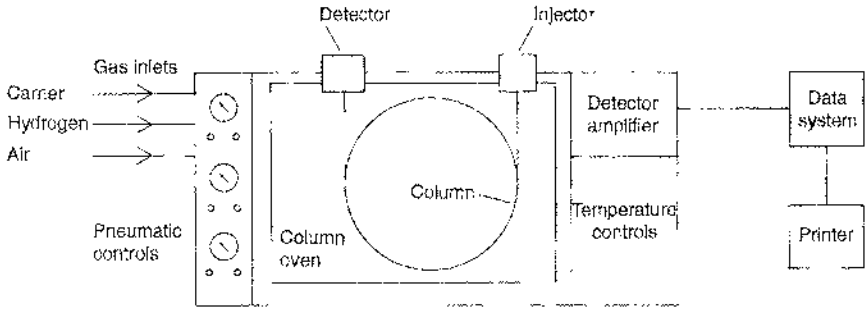

Fig. 1a. *Schematic representation of a basic gas chromatograph*

Since the earliest days of gas chromatography there has been much interest in both the quantitative and qualitative aspects of the technique. It was natural that having been able to separate mixtures of compounds, the questions, 'How much?' and 'What are they?' should soon be asked.

Initially, detectors were very primitive and in many cases the mechanisms of detection were unclear. Some detectors had their origins in gas analysis and their internal geometry was far from ideal for their application in the dynamic, small-volume gas chromatographic environment where concentrations of analyte in the gaseous medium were low and where fast response was essential if the eluting peaks were to be faithfully monitored.

The earliest detectors were based on thermal conductivity, to be followed later by the flame thermocouple, the first flame detector, argon ionisation detector and then the flame ionisation detector.

Others followed, but without question the flame ionisation detector, (FID), has been the workhorse in GC. Detectors will be discussed in Part 6.

How might the structure and elemental composition of the compound influence its response in the detector and how would this affect quantitative analysis? Could peak heights be used as a measure of 'how much' or was it necessary to use peak areas? Would compounds respond linearly with mass injected? Would compounds of similar structure have similar responses? These were some of the questions, sometimes very difficult questions, facing the early gas chromatographers.

Thus, although in truth, quantitative analysis with the early GC system was poor due to non-linear response detectors and rather primitive data systems, things improved as new equipment was developed.

To answer the 'what' question the direct combination of gas chromatography with mass spectrometry (MS) in the early 1960s was a major step forward in compound identification, particularly in the case of complex mixtures. Today GC–MS and GC–infrared (IR) are routine, having been simplified by the technological developments which have taken place.

Π What do you consider to have been the major problem to be overcome in combining gas chromatography with mass spectrometry?

Mass spectrometers work under high vacuum, typically 1×10^{-6} to 1×10^{-8} torr whereas the outlet from the gas chromatographic column is at atmospheric pressure. Interfaces had to be designed to handle these pressure differences, and in the case of packed column gas chromatography where gas volume flow rates were typically 30–50 ml/min, capable of removing the bulk of the carrier gas preferentially, thus increasing the concentration of analyte entering the source in the mass spectrometer.

Those becoming involved for the first time in gas chromatography might conclude that gas chromatography started as a packed-column

technique and then in the 1980s when capillary columns were invented, everyone 'went for it' and threw away their packed columns.

Indeed packed-column gas chromatography, as we know it, did become established first in the late 1950s to early 1960s but in fact as early as 1958, Marcel Golay proposed the use of capillary columns.

Development of the capillary column took time but early in the 1960s quite spectacular separations were being obtained for complex hydrocarbon mixtures. Commercial exploitation was hindered for some years by patent problems and, in effect, it was the development of the robust fused silica columns in the 1980s which brought about the resurgence in the application of this technology.

It is appropriate in this book to split the text into sections which deal specifically with aspects of packed and capillary systems.

Although we shall consider the two types of column systems in detail in later sections it is perhaps appropriate to define packed and capillary at this stage.

A packed gas chromatographic column consists of a suitable tube containing an inert solid which has been coated with a relatively involatile liquid phase. The solid acts as a support for this liquid phase, called the stationary phase. A gas, normally inert, i.e. the carrier gas, is passed through the packed bed and differences in the partition coefficients of the individual components in the mixture between the gaseous and stationary phases causes a separation of a mixture of solutes placed at the beginning of the column. The resolving power of packed columns, measured in theoretical plates, may be in the order of a few thousand plates for a column 1 metre long.

In capillary column chromatography, the scale of the chromatographic system is reduced, the column is a narrow capillary, 0.1–0.5 mm internal diameter, 10 m–60 m in length, the solid support is dispensed with and the stationary phase is coated directly onto the column wall.

The chromatographic process remains the same, partition of the solutes between the gas and stationary phase and retention based upon affinity for the stationary phase. Capillary columns frequently

generate 50 000–100 000 or even more theoretical plates although it is prudent to bear in mind that resolution is not always simply a matter of theoretical plates. Let me give you an example.

Fig. 1b and Fig. 1c show chromatograms of a simple mixture of fatty acid esters. In the case of Fig. 1b, a 2 m packed column has been used and baseline separation achieved. Fig. 1c shows the same mixture analysed on a capillary column but, although very sharp peaks are

Fig. 1b. *Gas chromatogram of a methyl ester mixture, using a 2 m packed column*

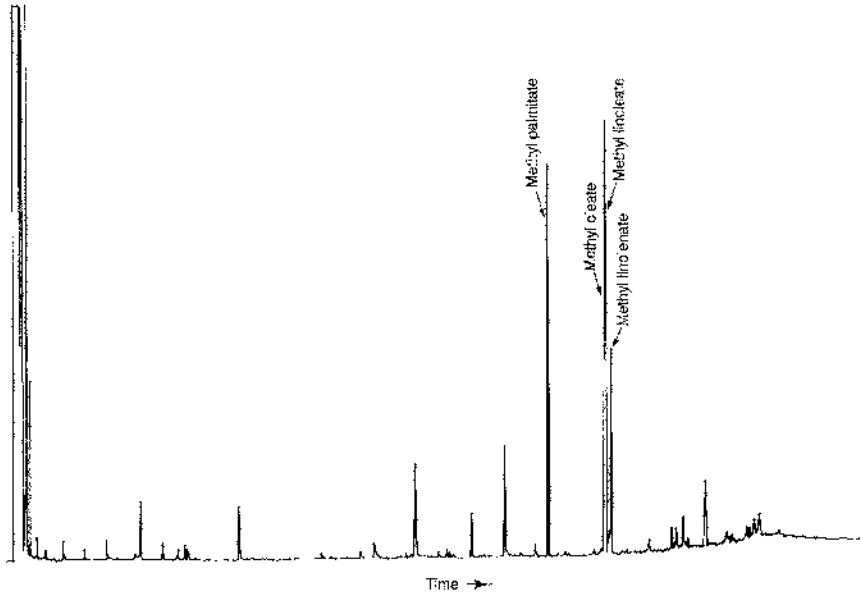

Fig. 1c. *Gas chromatogram of a methyl ester mixture, using a 25 m capillary column*

observed, indicating much greater column efficiency, two components are not resolved. Clearly there is more to separation than just efficiency.

Π Why do you think separation has been achieved on the packed column and not on the capillary?

The packed column contains a more polar stationary phase which produces a greater affinity difference between the closely eluting peak pair compounds than does the capillary column, thus promoting better separation.

The technology of the gas chromatograph reflects the need to optimise the advantages of the different column system, thus whereas injection systems for packed columns are relatively simple, more sophisticated injection devices are required to place the small quantity of sample required by a capillary column into the column, without compromising the potential high separation efficiency of the system.

Modern capillary columns in which the stationary phase is chemically bonded to the silica column wall have extended the temperature range of gas chromatography, effectively expanding the scope of the technique and making possible the analysis of compounds previously considered the preserve of high performance liquid chromatography (HPLC). In addition, polar stationary phases can also be chemically bonded onto the column wall providing an additional degree of selectivity to enhance the resolving power of the large number of theoretical plates.

The advantages of capillary columns are really two-fold. The much greater number of potential theoretical plates means greater resolution of components in complex mixtures. Many organic chemists rue the advent of the capillary column! Chromatographic peaks are much narrower on capillary chromatograms, cf. Figs 1b and 1c, and this enhances sensitivity to detection of low-level components. The combined effect of these two advantages is a higher degree of precision in quantitative analysis.

SAQ 1a List the differences between packed and capillary columns.

SAQ 1a

Without doubt, capillary column gas chromatography requires a much greater degree of operator skill, it is not just a simple case of changing from one column type to another. The skills must be learned by 'hands-on' experience, not just by reading the instructions supplied with the column or by reading this book, no matter how good these may be! Always remember the scale in which you are working and focus your attention to detail accordingly.

Gas chromatography is still a developing technology, particularly in the areas of new stationary phases and in its combination in multi-dimensional chromatographic and spectroscopic systems.

Above all enjoy your chromatography. For me, gas chromatography is still an exciting technique offering new opportunities for solving problems.

Learning Objectives of Part 1

After studying the material in Part 1, you should be able to:

- define gas chromatography and delineate its boundaries;

- discuss the basic principle of gas chromatographic separation;
- describe the structure of a basic gas chromatograph;
- discuss the fundamental difference between packed column and capillary column gas chromatography;
- discuss the relative merits of the two alternative methods;
- realise the potential of gas chromatography for both qualitative and quantitative analysis.