

This installment of "Milestones in Chromatography" presents a brief overview of the evolution of capillary columns since their invention in 1957 by M.J.E. Golay. Leslie Ettre outlines the transition from metal tubes to glass and finally to fused-silica tubing and discusses improvements in stationary-phase technology. He also mentions some trends for further improvement of capillary column gas chromatography.

Leslie S. Ettre
Milestones in Chromatography
Editor

Evolution of Capillary Columns for Gas Chromatography

When I was a student at the Technical University in Budapest, Hungary, 60 years ago, we students had oral examinations in every course at the end of each semester. They were very formal and solemn affairs in the professor's office; nobody else was present, and students could never predict the questions asked. Our major subject in the first year was general and inorganic chemistry — a kind of chemistry 101 — and Prof. L. Putnoky required that we learn to think in reaction equations. He was not interested in detail of the actual processes; these were handled in detail in the second-year chemical technology course. He had a big blackboard in his office, and when he asked, "How do you prepare X?" indicating a certain substance, the student had to write the proper equations on the board. (I still remember that there were five ways to prepare sodium thiosulfate.)

I had a very bright classmate, and there was a story going around about his examination. He had no problem answering all the questions and wrote correctly one reaction equation after another on the blackboard. Finally, as the last question, Prof. Putnoky asked him, "How do you prepare sulfur?" For a second, my friend was speechless, because we had not learned any reaction equation for sulfur preparation. Finally, he stammered, "But sir, one doesn't have to prepare sulfur!" "Why?" interrupted Prof. Putnoky. "Because it exists," was my friend's answer.

Why do I tell this old story here? Because the present-day situation with capillary columns resembles it. Today, capillary columns *exist*; users don't have to worry how they are made. They simply open a supply house catalog, check the application they are interested in, and order the proper column by its code name and part number. Most times, users don't even know what the stationary phase is; it is unnecessary to consider the proper column dimensions or the film thickness of the phase, because the

producer already took care to optimize these parameters, which are automatically specified by the part number. Therefore, present-day chromatographers generally have very little knowledge of the long and tedious work of the pioneers that eventually led to the present state of the art in capillary chromatography.

The purpose of this "Milestones in Chromatography" report is to help readers learn more about capillary gas chromatography (GC). I shall go briefly through the evolution of capillary GC, explain the key problems the pioneers faced, and point out their individual achievements. I shall deal with the evolution of column technology only, because the evolution of the instrumentation (gas chromatographs) in which these columns are used is beyond the scope of this present discussion.

Invention

To start, I have to go back more than 40 years to the heyday of GC. The first American gas chromatographs were introduced in the spring of 1955 by Burrell Corp. (Pittsburgh, Pennsylvania) and Perkin-Elmer (Norwalk, Connecticut). About that time, Marcel J.E. Golay (Figure 1) joined Perkin-Elmer as a consultant after a 25-year distinguished career at the U.S. Signal Corps Engineering Laboratories in Fort Mon-

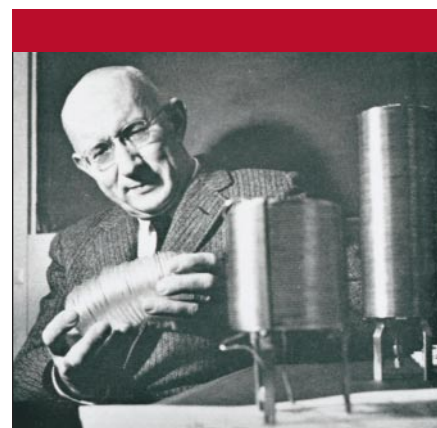


Figure 1: M.J.E. Golay, circa 1960.

mouth, New Jersey. He was originally trained as an electrical engineer and mathematician at the Federal Technical University of Zurich, Switzerland, which at that time was the world's most prestigious technical school. He received his Ph.D. in nuclear physics from the University of Chicago. Golay had a very broad range of interests and had worked in a number of fields. His connection with Perkin-Elmer was mainly due to his involvement in the development of an IR detector, originally conceived as an aircraft detecting device, and of a multiple-slit IR spectrometer.

When Golay joined Perkin-Elmer, everybody was excited by the versatility and the incredible separation power of GC; inevitably, he also became involved in various discussions of the new technique, which was a totally unknown field to him. He became intrigued by the mathematics of the separation process, and, being an electrical engineer by training and experience, he tried to interpret it with help of the

Telegrapher's Equation used to describe the process in transmission lines. He presented this unique comparison at the GC symposium organized in conjunction with the Spring 1956 National Meeting of the American Chemical Society (1).

In subsequent months Golay continued to investigate — at first theoretically — the separation process occurring in the packed chromatographic column. To simplify the system, he constructed in his mind a model, consisting of a bundle of capillary tubes, each corresponding to a passage through the column packing. These ideal capillaries would be unrestricted by the geometry of the packing or the randomness of the passages through it, which are beyond control. Therefore, the capillaries should behave close to the theoretical possibilities. Golay's considerations were outlined in a number of internal reports, of which the one dated 5 September 1956 was the most important (2). In this report, he suggested some experiments with a capillary

tube 0.5–1 mm in diameter and wetted with a suitable stationary phase, which corresponded to one of these passages.

These experiments were performed in the fall of 1956. A serious handicap was represented by the large volumes of the existing thermal-conductivity detectors and of the injection block. Therefore, Golay designed a micro thermal-conductivity detector and used it for his investigations. The results were indeed striking: Figure 2 presents Golay's first chromatograms obtained on a 12 ft \times 0.055 in. column and shows the analysis of a Phillips 37 hydrocarbon mixture and of a mixture of isomeric pentanes. (In the 1950s various Phillips mixtures were available as standard samples. They contained volatile and semi-volatile hydrocarbons, usually in small bombs. According to my best knowledge, these mixtures are not available anymore.)

In the next 16 months, Golay carried out a very intensive theoretical study, in addition to some experimental work. He presented an interim report at the GC symposium organized by the Instrument Society of America and held in August 1957 in East Lansing, Michigan (3). He also discussed the new concept and theory with a number of scientists outside Perkin-Elmer, most notably with A.J.P. Martin, the inventor of gas-liquid partition chromatography, and A.I.M. Keulemans, who at that time was one of the most widely known scientists in this field. His final report with the full theory of open-tubular capillary columns — which is still valid today, 42 years later — was presented at the next international GC symposium held in Amsterdam, The Netherlands, in May 1958 (4).

The successive steps of Golay's work from invention to the establishment of the full theory and illustration of the superior performance of capillary columns represent one of the most logical systematic scientific developments in the long history of chromatography. It is a fascinating story, and one well documented in the literature (5).

Realization

Golay's presentation at the Amsterdam symposium with its 93 equations was impressive enough in itself. In the original form published in the preprints of the lectures, it probably would have had little impact, because it sounded too theoretical. However, in his actual presentation he showed two chromatograms obtained just a couple of days earlier by Richard D. Condon, his young associate at Perkin-Elmer, and these chromatograms showed the sepa-

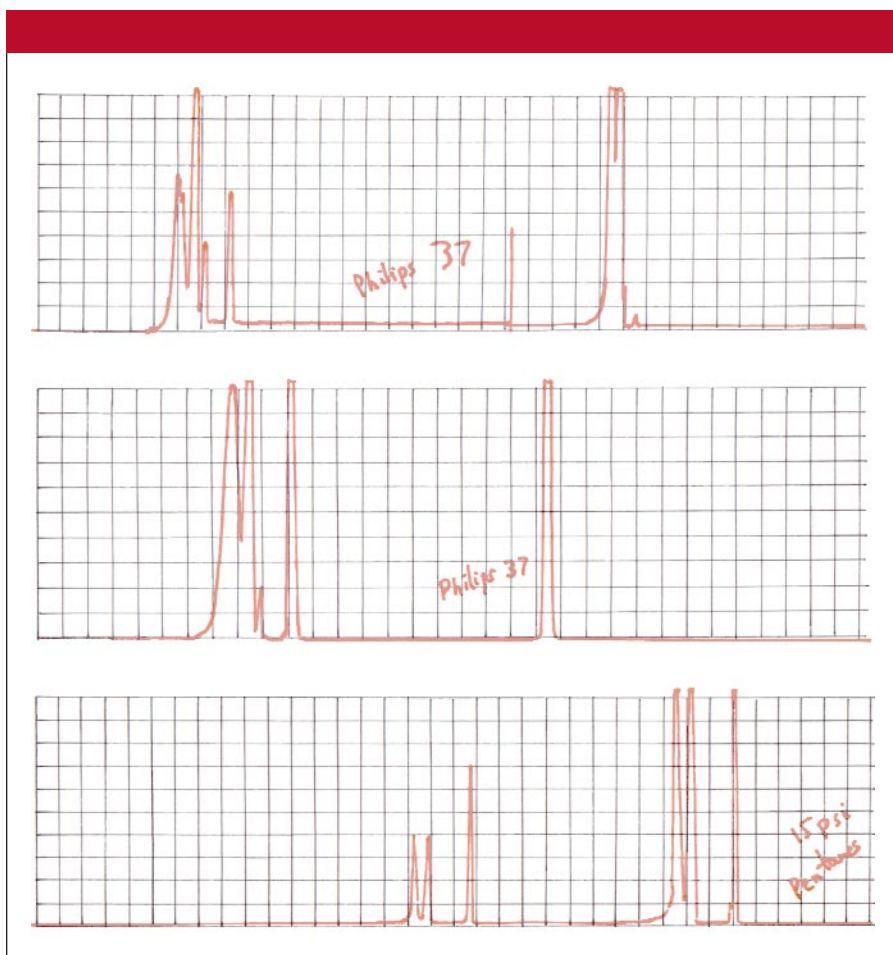


Figure 2: Copies of Golay's first chromatograms on capillary columns showing the analysis of a Phillips 37 mixture and isomeric pentanes. Column: 12 ft (366 cm) \times 0.055 in. (1.37 mm), coated with Carbowax 1540 poly(ethylene glycol); detection: Sanborn high-speed recording galvanometer and a specially built micro thermal-conductivity detector. The chromatograms were obtained at room temperature.

ration of C₈ hydrocarbons and the xylene isomers on a 150 ft × 0.010 in. stainless steel column coated with diisodecyl phthalate. Thirty years later, Dennis H. Desty, the organizer of the symposium and who in the subsequent years had a major role in the general use of capillary columns, still remembered the excitement caused by these chromatograms, demonstrating the exceptional separation power of capillary columns, until then impossible to achieve (6):

I well remember the gasp of astonishment from the audience at this fantastic performance that was to change the whole technology of gas chromatography over the next decade. We were all enraptured by the elegant simplicity of Marcel's concept and I could not wait to dash off to my laboratory to start experiments with the wonderful new tool.

As mentioned earlier, Golay had to build a special micro thermal-conductivity detector for his investigations because the existing detectors had a much-too-large volume and not enough sensitivity for the small sample sizes and low carrier-gas flow rates needed. Fortunately, at the same Amsterdam symposium, I.G. McWilliam and R.A. Dewar described in detail the flame ionization detector (7), and within a short time, James E. Lovelock modified his argon-ionization detector and made it suitable for capillary column work (8). Thus, all the necessary basic ingredients soon were available for the practical use of capillary columns.

Most likely, the first person who used a capillary column–flame ionization detection system was Desty at British Petroleum Co. Ltd. (Sunbury-on-Thames, United Kingdom). According to his personal recollections (9), he and his group put together a crude setup practically days after returning from Amsterdam: It consisted of a breadboard model of the flame ionization detector; a 250-ft long stainless steel tube coated with squalane, using the dynamic coating technique described by G. Dijkstra and J. De Goey at the Amsterdam symposium (10); and a split injection system. Within a few weeks his group, comprising B.H.F. Whyman, A. Goldup, and W.T. Swanton, constructed a complete apparatus for operation at temperatures as high as 250 °C and explored the separation of a wide variety of samples using columns made of stainless steel and copper tubes. Desty first reported about this system at a symposium held 9–11 October 1958 in

Leipzig, Germany (then East Germany) (11), and later made a detailed presentation at the meeting of the British Gas Chromatography Discussion Group held on 10 April 1959 in London (12).

At Perkin-Elmer, prototypes of the flame ionization detector also were constructed soon after the Amsterdam symposium. When I joined the company in the fall of 1958, Dick Condon was already obtaining one excellent chromatogram after another on a working prototype of a gas chromatograph with open-tubular columns and a flame ionization detector. This instrument was introduced at the Pittsburgh Conference in March 1959, and Condon made a major presentation describing this system and illustrating the wide-range applications of capillary columns at the conference (13). Parallel to but independently of this work, Albert Zlatkis of the University of Houston (Houston, Texas) (14) and S.D. Lipsky of Yale University Medical School (New Haven, Connecticut) (15,16), both with the help of J. Lovelock, explored the use of capillary columns and reported their results in the first months of 1959.

The evolution of capillary columns from this beginning to the present universal use went through a number of steps. Readers interested in details can find information in the literature (see references 17–21). In this “Milestones in Chromatography” column, I want to deal with only a few key developments that finally made capillary columns everyday tools.

Columns Made of Metal

The very first capillary column investigated by Golay was actually an uncoated 10 m × 3 mm PTFE tube; however, he soon switched to glass and then to stainless steel tubes of two internal diameters — 0.010 in. (0.25 mm) and 0.020 in. (0.51 mm). These tubes could be easily obtained; as mentioned by Golay during the discussion of his Amsterdam paper, “you buy them by weight.” Capillary columns made of stainless steel (and, to a lesser extent, of copper) have been in general use for well over a decade. It is true that these columns had definite limitations because of the relative unevenness of the inside tube surface, necessitating a relatively thick stationary-phase film coating, and because of the activity of the metal surface. In spite of these limitations, properly coated metal capillary columns — with both nonpolar and polar phases — have been successfully used for the analysis of a wide variety of samples. Thus, statements speaking about

the “terrible state of affairs” with the metal columns and complaining about their short life (22) are gross exaggerations. The two chromatograms shown in Figures 3 and 4 (both obtained in 1963) should answer the first criticism. With respect to lifetime of the columns, Halász stated during a discussion at the 1961 Lansing Symposium, “With a copper column coated with squalane, we worked for about 7 months, 8 to 10, sometimes for 24 hours daily” (23).

An interesting problem with the metal tubing was that as a result of the manufacturing process, the tubing had a residual liquid coating on its inside surface, which could actually be relatively significant. In 1963, Porcaro indicated the presence of such a film consisting mostly of polyisobutylene (24), and its thickness could be computed to be as much as 0.32 μm. Because of this coating, the metal tubing had to be cleaned before it could be coated with the stationary phase. This cleaning procedure may have been fairly elaborate; O.L. Hollis, for example, recommended successive washing with five solvents before coating (25). It is possible that some of the complaints about the poor performance of self-made metal capillary columns may be traced to improper or nonexistent cleaning of the tubing.

The early stainless steel columns (see Figure 1) were made of thick-wall tubing (approximately 1.6 mm) and were heavy and bulky. However, by 1962, improved stainless steel tubing with a thin wall (0.12–0.15 mm) became available. This tubing was much more flexible and had a better, more inert, and smooth inner surface.

With regard to the coating technique, practically everybody adapted the dynamic procedure originally described by G. Dijkstra and J. De Goey (10). In this procedure, a plug of the stationary-phase solution was slowly forced through the tubing with the aid of a dry inert gas, wetting the inside wall of the tube with the solution. Subsequently the solvent was evaporated by blowing dry gas through the column for a few hours. This technique has been discussed in detail in the literature (26,27), and, if carried out skillfully, it resulted in columns with good performance and long life. A major advantage of the dynamic method is that it requires no complicated setup; however, its shortcoming is that the thickness of the coated film depends on the coating conditions, and it cannot be readily established but only guessed. In

spite of this limitation, the technique had been in general use for well more than a decade and was replaced only slowly in the 1970s by the static coating technique, as described in 1968 by J. Bouche and M. Verzele (28). In this version of the static coating technique, the tube was filled with the stationary-phase solution and one end of the tubing was closed, then the solvent slowly was evaporated through the open end under reduced pressure at a temperature below the solvent's boiling point. The major advantage of this technique is that

the thickness of the coated film can be readily established from the concentration of the coating solution (21).

In 1961, Warren Averill (29) proposed the addition of a small amount (approximately 1–2%) of a surface-active agent to the stationary phase to reduce the activity of the inner tube surface. A typical such additive is Atpet 80, which chemically is sorbitan monooleate.

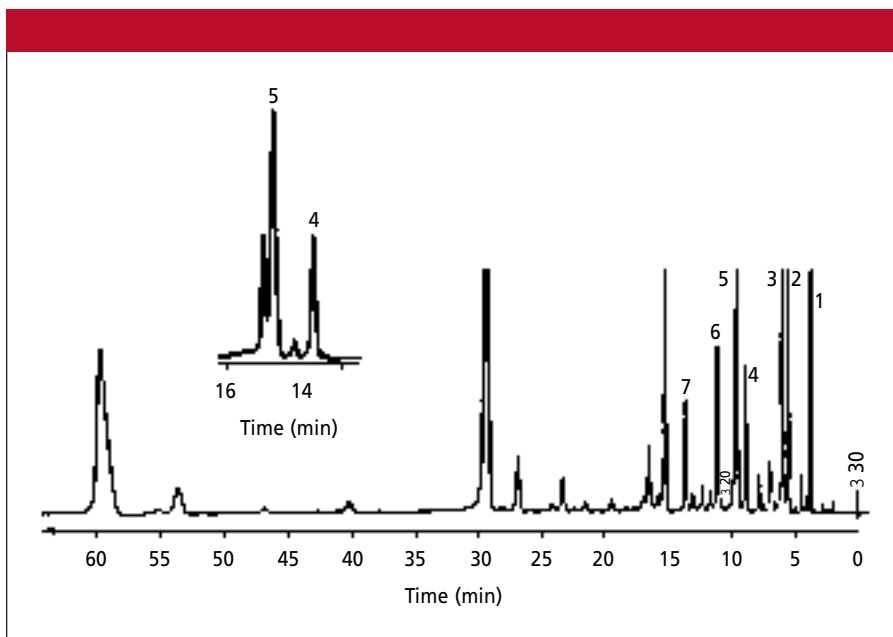


Figure 3: Analysis of a fatty acid methyl ester mixture obtained from menhaden oil. Column: 150 ft (45.7 m) \times 0.010 in. (0.25 mm) capillary, coated with butanediol succinate; carrier gas: nitrogen for the full chromatogram (40-psig inlet pressure) and helium for the inset chromatogram (24-psig inlet pressure); column temperature: 185 °C; split injection; flame ionization detector. Peaks: methyl esters of 1 = myristic acid, 2 = palmitic acid, 3 = palmitoleic acid, 4 = stearic acid, 5 = oleic acid, 6 = linoleic acid, 7 = linolenic acid. (F.J. Kabot, Perkin-Elmer, 1963).

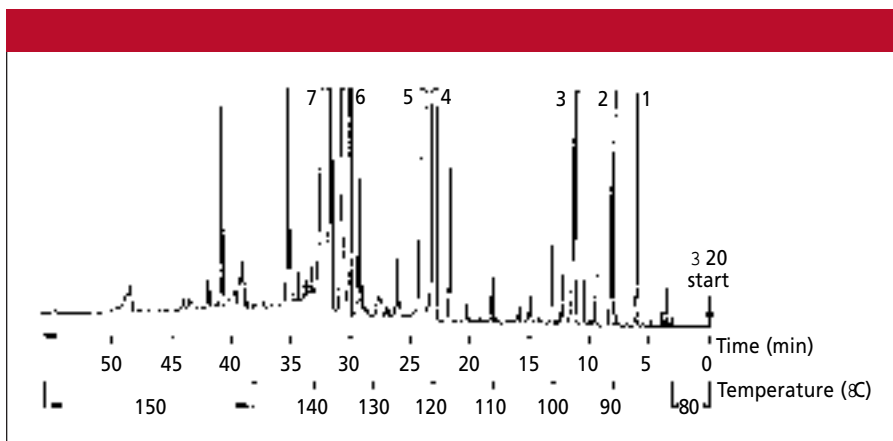


Figure 4: Analysis of a peppermint oil sample from Yakima Valley, Washington. Column: 150 ft (45.7 m) \times 0.010 in. (0.25 mm) capillary, coated with Ucon Oil 50 HB 200 poly(propylene glycol); carrier gas: helium with 20 psig inlet pressure; column temperature: programmed, at 2 °C/min; injection: split injection; flame ionization detector. Peaks: 1 = α -pinene, 2 = β -pinene, 3 = eucalyptol, 4 = menthone, 5 = menthofuran, 6 = menthyl acetate, 7 = menthol. (E.W. Cieplinski and W. Averill, Perkin-Elmer, 1963).

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The polar hydroxy groups at one end of the molecule are permanently adsorbed by the tube wall, deactivating its active sites. At the same time, the long hydrocarbon chain remains free, resulting in a velvet-like structure that spans the interface between the tube wall and the coated stationary-phase film. As F. Farré-Rius and coauthors (30) pointed out, another effect of these types of additives may be that they reduce surface tension and thus facilitate the spreading of the stationary phase.

The application of such additives was particularly advantageous in the case of nonpolar phases. At Perkin-Elmer, my co-workers and I routinely used them in the preparation of the stainless steel capillary columns. With polar phases, the wall effect was less pronounced because the polar groups of the phase also act similarly.

Readers may wonder why I deal in such detail with the intricacies of capillary column preparation in the early period of its development. After all, today no chromatographers prepare their columns; they purchase them from the major supply houses, which provide clear specifications and guaranteed performance. However, the situation was quite different in the first 10–15 years of capillary GC development; at that time, column supply houses simply did not exist. Out of necessity, instrument companies also produced columns but only as a secondary function of their activities. In this period, most chromatographers prepared their own capillary columns; thus, understanding the difficulties they encountered is important for a retrospective of the evolution of GC.

Columns Made of Plastic Tubing

In spite of the convenience of metal (most often, stainless steel) columns, it was obvious from the beginning that a more inert tube material would be necessary. Plastic tubing was proposed by R.P.W. Scott (31), but it had obvious disadvantages, such as temperature limitations, poor coatability, and short life caused by plasticizer migration. Thus, except for some early work (32), plastic columns never gained ground.

The Era of Glass Capillary Columns

An obvious choice for tube material would have been glass, and this possibility was explored by Golay in his early work. In fact, in the publicity photograph taken circa 1960 (Figure 1), he was holding a glass capillary tube in his hands. At that time, a number of chromatographers tried

to prepare capillary columns made of glass. However, this task was not as simple as it sounds.

Usually the era of glass is considered to have started with the development of an ingenious device to prepare glass capillary tubes by Desty and his co-workers (33) in 1960; a similar device in France was also described at that time by A. Kreyenbuhl (34). In 1960–1961, Desty and his associates published a number of papers in which they used glass capillary columns, the most famous being the analysis of a Ponca crude petroleum sample on a 263 m \times 0.14 mm column in 3.5 h (35). Then, in the second part of the 1960s Desty's machine became commercially available from Hupe & Busch (Karlsruhe, Germany) and a few years later also from Shimadzu (Kyoto, Japan). With these machines, capillary tubes of various lengths and diameters could be prepared using both soda-lime and borosilicate (Pyrex) glass tubes. The capillary tubes produced in these machines had thick walls, and their final form was that of rigid coils. Typical dimensions were a 13–15 cm coil diameter, a 0.23–0.27 mm column internal diameter, and a 0.20–0.25 mm wall thickness (36).

Naturally, glass capillary columns were fragile. In the hands of skilled operators, however, very little damage was done. Thus, one may ask, why did glass tubing replace metal only in the early 1970s, more than 10 years after the description of the glass-drawing machine?

The problem arose from the poor coatability and short life of glass capillary columns prepared in this period. The situation was well characterized by Halász in his earlier quoted remark at the 1961 Lansing symposium (23). Although emphasizing the long life and good performance of metal columns, he continued by saying that

with glass capillary columns . . . coated with squalane, we were unable to work longer than two or three days. On glass columns coated with squalane, you can see with your eyes after two days that your film is not in one place.

Although squalane was a bad example — it was found that even with the best column pretreatment and coating technique, the forming of a stable squalane film on glass was very difficult — this statement illustrates the state of the art in the first part of the 1960s. It took years until researchers understood the reasons for

this problem: it was due to the strong cohesive forces of liquids on the glass surface. These forces are characterized by the surface tension, which in turn can be characterized by the contact angle of a drop on the solid surface; that is, the higher the contact angle, the poorer the spreading of the liquid. The extent of this phenomenon was first investigated in 1962 by Farré-Rius and co-workers (30), who measured the contact angles of liquid phases on various potential column tube materials. Because of this problem, the inside surface of the glass tube needed to be treated in some way before coating to increase its wettability.

The breakthrough came in 1965–1968 with the work of K. Grob (37,38), who described a way to deposit a carbon layer, and M. Novotný and K. Tesařík (39,40), who etched the internal surface of the tube with dry hydrochloric or hydrofluoric acid. In the following decade, researchers developed scores of different ways for treating the inside surface of the glass capillary tube. This treatment was needed not only to improve the coatability but also to make the tube more inert. People often do not realize that glass is not inert; metal or other ions in its composition could be detrimental and had to be eliminated. A particular problem was boron, which is present in fairly high concentration (13% as B₂O₃) in borosilicate glass (41).

It would be practically impossible to even mention the many methods developed to improve glass capillary tubing. Interested readers should look at the detailed review of Novotný and Zlatkis (42) — which deals with the early period — the excellent monograph of W.G. Jennings (43), and a few selected books and review articles (44–49) that, in turn, provide scores of additional references.

The decade of the 1970s was an exciting period in the evolution of capillary columns. These columns really started to become everyday tools, and chromatographers even created a special acronym to describe their field, calling it (GC)² for glass capillary gas chromatography. These columns were made in different lengths and diameters and coated with a wide variety of stationary phases and in a wide range of film thicknesses. Figure 5 shows one of the most impressive chromatograms, which was obtained on a column with a coated film thickness of less than 0.1 μ m, and it demonstrates the analysis of amino acid derivatives from a ribonuclease hydrolyzate (50).

The increased importance of glass capillary columns was also demonstrated by the organization of the International Symposia on Glass Capillary Columns in 1975. In the first decade, these symposia were held in Hindelang, Bavaria, and from then on in Riva del Garda, Italy, and periodically in the United States and Japan. Today the scope of these annual symposia is enlarged to encompass the whole field of capillary column chromatography. During this period, supply houses specializing in the manufacturing of glass (and after 1980, fused silica) capillary columns started to supply them to chromatographers. However, at the end of the decade, the situation suddenly changed, almost from one day to the next, by the introduction of capillary columns made of flexible fused-silica tubing.

Fused-Silica Columns

Back in 1960, when the glass-drawing machine was developed by Desty's group, its use to make capillary columns from

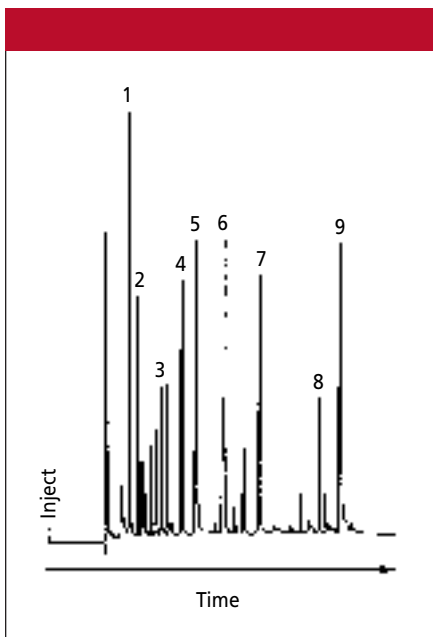


Figure 5: Analysis of the amino acids in ribonuclease hydrolyzate, in the form of the *n*-propyl, *N*-acetyl derivatives. Column: 50 m \times 0.27 mm glass capillary, coated with a 1:1 mixture of Carbowax 20M and Silar CP; film thickness: less than 0.1 μ m; carrier gas: helium with a flow rate of 0.75 mL/min; column temperature: programmed at 8 $^{\circ}$ C/min from 110 to 190 $^{\circ}$ C and then ballasted to 250 $^{\circ}$ C; split injection; thermionic detector, sensitive for nitrogen-containing compounds. Peaks: 1 = alanine, 2 = valine, 3 = norleucine (internal standard), 4 = threonine, 5 = serine, 6 = aspartic acid, 7 = glutamic acid, 8 = tyrosine, 9 = lysine. The retention time of the last peak is less than 30 min. Reprinted with permission from Preston Publications (50).

quartz was also mentioned (51). However, at that time no further work was done along this line, because the burner would need to be modified to facilitate the needed much-higher temperatures for such use. Later, Desty went back to this possibility and built a modified capillary drawing machine for this application. In a paper presented at the 1975 Hindelang symposium, he briefly described this modified capillary drawing machine and showed a photograph of it (52) but had no data on actual column manufacturing. It should be noted that the system developed by Desty would have produced rigid, thick-walled quartz (fused-silica) columns, and his major problem at that time was to find suitable platinum tubes that could be heated to the necessary 1250–1350 $^{\circ}$ C temperatures for the formation of the coiled capillary tubes.

It is interesting to note that in the mid-1970s Grob also was considering the use of quartz as column tube material. He recognized that quartz is more inert than glass; however, he believed that his methods developed to modify the inner surface of glass capillaries were satisfactory and saw no need to change to a new tubing material (53).

Because of this lack of previous work, the paper by R.D. Dandeneau and E.H. Zerenner (54) presented at the Third Hindelang Symposium (29 April–3 May 1979) was a complete surprise to the participants. They described the production and use of *thin-walled, flexible* fused-silica columns. Their tubing was an adaptation of the production of fiber optics already manufactured at Hewlett-Packard's Palo Alto, California, facilities. They also realized that cracks could develop in the thin walls of the tubing and eventually lead to breakage. To prevent cracks and breaks, they coated the outside of the tubing immediately after drawing, at first with silicone rubber but later changed to polyimide (55; also see R.D. Dandeneau as quoted in reference 22).

There is no question that the introduction of fused-silica columns changed not only capillary GC but the whole field of separation techniques. Within a few months, column supply houses started to sell fused-silica capillary columns to users, and very soon these fused-silica columns made glass columns obsolete. I remember an advertisement from this period by J&W Scientific (Folsom, California) — one of the major suppliers of capillary columns — in which a glass capillary column was

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placed around the neck of a toy dinosaur, indicating that both were fossils . . . Soon after the introduction of fused-silica columns, Jennings (56) gave a good comparison of the characteristics of glass and fused-silica capillary columns in a short monograph.

Above I used the words *quartz* and *fused silica* interchangeably. In practice, however, the first term is always used for the natural material, and the latter refers to the synthetic product prepared from silicon tetrachloride. The difference between the two is in the amount of impurities present; natural quartz may contain trace amounts of metals at a total concentration of approximately 50–60 ppm, and the total amount of metallic impurities in the synthetic fused silica is in the order of 0.08–0.5 ppm (57).

Following the presentation of Dandeneau and Zerenner, other scientists also investigated the various questions associated with fused-silica capillary columns. In this respect, I would like to particularly emphasize the activities of S.R. Lipsky (57,58). A few years later he also pioneered the development of columns that could be used at temperatures as high as 400–450 °C and that had a bonded stationary phase and a very thin aluminum outer coating instead of polyimide (59,60).

Today, fused-silica capillary columns are used universally in GC. They are manufactured by a number of companies that provide columns with specified parameters and performance and that also illustrate their application fields. These supply houses also provide columns that are tailor-made for special applications. From the users' point of view, this service represents a significant advance because they no longer have to worry about selecting the proper phase, column parameters, and column preparation. Columns are ordered by code name, and manufacturers have already taken care to optimize the column parameters that are automatically specified by the part number. In many cases, users don't even know the chemical composition of the stationary phase; even the analytical conditions for a certain application may be indicated by column suppliers. Naturally, this service helps users; on the other hand, its obvious disadvantage is that chromatographers performing analyses no longer are involved in the intricacies of columns.

Many unresolved problems still need further studies and improvements. A good example is the recent investigation of J.E.

Cahill and D.H. Tracy (61), who showed that helium (used as the carrier gas) at elevated temperatures will permeate through the wall of thin-walled, fused-silica capillary tubing, even with the normal outer polyimide coating, and will cause peak broadening and changes in the gas holdup time. This effect may be particularly pronounced when programming the column to high temperatures.

Immobilized and Bonded Stationary Phases

I cannot finish the discussion of the evolution and continuous improvements of capillary GC without mentioning one additional subject: improvements in stationary phases.

During the first two decades of the evolution of GC, most of the stationary phases used in the columns were taken from the shelf, and chemicals readily available in the laboratory were used. Except for a few, these were fairly low-boiling point, low molecular weight compounds that had significant vapor pressures even at moderate temperatures. This fact restricted the temperature range of GC, and experience has shown that the upper temperature limit of capillary columns was actually lower than that of packed columns. In fact, even by the middle of the 1970s, one could rarely find a capillary chromatogram in which the column was heated to temperatures higher than 200 °C.

In the 1970s the situation changed drastically with the introduction of silicone (polysiloxane) phases, which were custom-made for GC and particularly for capillary column use. These phases were high molecular weight polymers with molecular weights in the thousands or tens of thousands range, with a few even exceeding 100,000. In contrast, squalane, one of the most common phases of the 1960s, has a molecular weight of 423, and the average molecular weight of Carbowax 1540 poly(ethylene glycol) — another popular phase of the period — is 1540. These new phases can be coated well from their solution on the inner surface of the glass (and also fused-silica) tubing; they provide excellent chemical and thermal stability with low bleeding, permitting the extension of the column upper temperature limit. Blomberg (62,63) and Haken (64) gave good summaries of the characteristics of the new silicone phases.

An obvious requirement in capillary column preparation is that the stationary

phase should be soluble; after all, the inner tube wall is coated by using a solution of the phase. This condition represents a limitation on the molecular weight of the substance to be used as the stationary phase because, in general, the higher the molecular weight, the more difficult it is to dissolve the substance. Therefore, chromatographers had to find ways to overcome this limitation. This was accomplished by an additional step: a secondary polymerization in the column, which resulted in a coated stationary-phase film with very high molecular weight. The products of this process are called *immobilized phases*. Additionally, a chemical bond may also be formed between the stationary-phase molecules and the surface silanol groups on the inside surface of the fused-silica tubing; in this way, the so-called *bonded phases* are created.

Immobilization is a result of cross-linking the primary polymer molecules, which is initiated by a variety of free radical initiators, such as organic peroxides or azo compounds, or by gamma irradiation. To achieve chemical bonding, stationary-phase molecules that are terminated by hydroxy groups are coated onto the inner wall of the column tubing; subsequently, the column is temperature programmed to an elevated temperature at which condensation reactions occur between the surface silanols of the fused-silica surface and the terminal OH groups of the phase molecules.

In addition to providing capillary columns that can be safely used at higher temperatures, immobilization and chemical bonding of the stationary phase result in two additional advantages. This type of phase can tolerate the injection of large volumes of a solvent without dissolution in it. In addition, it is possible to prepare stable capillary columns with a wide range of film thickness, even with a very thick film. Without this treatment, these columns would soon lose most of their original coating through bleeding.

The basic work on immobilization and cross-linking was performed between 1976 and 1986 by a number of groups, including those headed by C. Madani in France, L. Blomberg in Sweden, K. Grob in Switzerland, P. Sandra in Belgium, G. Schomburg in Germany, V. Pretorius in South Africa, and S.R. Lipsky and M.L. Lee in the United States. A very good summary of the questions associated with this revolution in column technology (as paraphrased by K. Grob [65]) was provided by

E.F. Barry, who also provided the pertinent references (66). From the mid-1980s on, these techniques became part of routine column manufacturing technology.

Future Developments

Today fused-silica, open-tubular, capillary columns are used almost universally in GC. A number of supply houses offer a wide variety of columns with reliable performance. However, this availability does not mean that the evolution of capillary columns is finished. Continuous development work is carried out by the supply houses, instrument companies, and a number of research groups. Instrument companies further improve the systems in which the columns are used for separation; the supply houses optimize their columns for new applications and further improve their stability; and various research groups work mainly in two areas. The first usually is characterized by one word: *miniaturization*. There is a definite trend to drastically reduce the size of the instruments and the dimensions of the columns, not only to use less space in the laboratory, but also to further the second aim: *to increase the speed of separation*. This goal implies the use of short capillary columns with small diame-

ters, use of hydrogen as the carrier gas, very fast temperature programs, and instrumental systems that can cope with the resulting very sharp peaks that have widths of less than 1 s.

Another interesting new development is in the selection of the column tube material. Reading the literature extolling the importance of fused silica would lead chromatographers to believe that it is the ultimate column tube material. However, this is not necessarily so, at least not in every application. Recent developments in surface treatment technology make it possible to coat the inside of stainless steel tubing with a robust layer of silicon, which is then oxidized to form a silica surface that accepts deactivation and bonded stationary-phase deposition. These columns flex without disturbing the inner surface layer, and their physical strength, robustness, and thermal stability are superior to those of fused-silica columns. Thus, in certain applications (for example, portable instruments or high-temperature operation in which the outer coating of the fused-silica tubing is no longer stable) such tubing may be preferable.

Capillary GC is a living science; every day brings something new and exciting to

benefit chromatographers who are using the technique in their daily work for the analysis of the widest variety of samples.

References

- (1) M.J.E. Golay, *Anal. Chem.* **29**, 928–932 (1957).
- (2) M.J.E. Golay, "Discussion of the Results With Three Experimental Gas-Liquid Chromatographic Columns," Engineering Report No. 523, Perkin-Elmer Corp. (Norwalk, Connecticut, 5 September 1956).
- (3) M.J.E. Golay, in *Gas Chromatography (1957 Lansing Symposium)*, V.J. Coates, H.J. Noebels, and I.S. Fagerson, Eds. (Academic Press, New York, 1958), pp. 1–13.
- (4) M.J.E. Golay, in *Gas Chromatography (1958 Amsterdam Symposium)*, D.H. Desty, Ed. (Butterworths, London, 1958), pp. 36–55.
- (5) L.S. Ettre, *J. High Resolut. Chromatogr.* **10**, 221–230 (1987).
- (6) D.H. Desty, *Chromatographia* **23**, 319 (1987).
- (7) I.G. McWilliam and R.A. Dewar, in *Gas Chromatography 1958 (Amsterdam Symposium)*, D.H. Desty, Ed. (Butterworths, London, 1958), pp. 142–152.
- (8) J.E. Lovelock, *Nature (London)* **182**, 1663–1664 (1958).
- (9) D.H. Desty, in *75 Years of Chromatography — A Historical Dialogue*, L.S. Ettre and A. Zlatkis, Eds. (Elsevier, Amsterdam, 1979), pp. 31–42.
- (10) G. Dijkstra and J. De Goey, in *Gas Chromatography 1958 (Amsterdam Symposium)*, D.H. Desty, Ed. (Butterworths, London, 1958), pp. 56–68.

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- (11) D.H. Desty, in *Gas-Chromatographie 1958*, H.P. Angelé, Ed. (Akademie Verlag, Berlin, 1959), pp. 176–184.
- (12) D.H. Desty, A. Goldup, and B.H.F. Whyman, *J. Inst. Petrol.* **45**, 287–298 (1959).
- (13) R.D. Condon, *Anal. Chem.* **31**, 1717–1722 (1959).
- (14) A. Zlatkis and J.E. Lovelock, *Anal. Chem.* **31**, 620–621 (1959).
- (15) S.R. Lipsky, R.A. Landowne, and J.E. Lovelock, *Anal. Chem.* **31**, 852–856 (1959).
- (16) S.R. Lipsky, J.E. Lovelock, and R.A. Landowne, *J. Am. Chem. Soc.* **81**, 1010 (1959).
- (17) L.S. Ettre, in *Applications of Glass Capillary Gas Chromatography*, W.G. Jennings, Ed. (Marcel Dekker Inc., New York, 1981) pp. 1–47.
- (18) L.S. Ettre, *Chromatographia* **16**, 18–25 (1982).
- (19) L.S. Ettre, *Chromatographia* **17**, 117 (1983).
- (20) L.S. Ettre, *Anal. Chem.* **57**, 1419A–1438A (1985).
- (21) L.S. Ettre, *Chromatographia* **34**, 613–628 (1992).
- (22) R. Stevenson, *Am. Lab.* **30**(5), 30–34 (1998).
- (23) I. Halász, in *Gas Chromatography (1961 Lansing Symposium)*, N. Brenner, J.E. Callen, and M.D. Weiss, Eds. (Academic Press, New York, 1962), p. 560.
- (24) P.J. Porcaro, *J. Gas Chromatogr.* **1**(6), 17–19 (1963).
- (25) O.L. Hollis, *Anal. Chem.* **33**, 352–355 (1961).
- (26) R. Kaiser, *Chromatography in the Gas Phase, vol. II: Capillary Gas Chromatography* (Butterworths, London, 1963).
- (27) L.S. Ettre, *Open Tubular Columns in Gas Chromatography* (Plenum Press, New York, 1965).
- (28) J. Bouche and M. Verzele, *J. Gas Chromatogr.* **6**, 501–505 (1968).
- (29) W. Averill, in *Gas Chromatography (1961 Lansing Symposium)*, N. Brenner, J.E. Callen, and M.D. Weiss, Eds. (Academic Press, New York, 1962), pp. 1–6.
- (30) F. Farré-Rius, J. Henniker, and G. Guiochon, *Nature (London)* **196**, 63–64 (1962).
- (31) R.P.W. Scott, *Nature (London)* **183**, 1753–1754 (1959).
- (32) A. Zlatkis and H.P. Kaufman, *Nature (London)* **184**, 2010 (1959).
- (33) D.H. Desty, J.N. Haresnape, and B.H.F. Whyman, *Anal. Chem.* **32**, 302–304 (1960).
- (34) A. Kreyenbuhl, *Bull. Soc. Chim. France* **1960**, 2125–2127 (1960).
- (35) D.H. Desty, A. Goldup, and W.T. Swanton, in *Gas Chromatography (1961 Lansing Symposium)*, N. Brenner, J.E. Callen, and M.D. Weiss, Eds. (Academic Press, New York, 1962), pp. 105–135.
- (36) M.J. Hartigan and L.S. Ettre, *J. Chromatogr.* **119**, 187–206 (1976).
- (37) K. Grob, *Helv. Chim. Acta* **48**, 1362–1370 (1965).
- (38) K. Grob, *Helv. Chim. Acta* **51**, 718–737 (1968).
- (39) M. Novotný and K. Tesařík, *Chromatographia* **1**, 332–333 (1968).
- (40) K. Tesařík and M. Novotný, in *Gas-Chromatographie 1968 (Berlin Symposium)*, H.G. Struppe, Ed. (Akademie Verlag, Berlin, 1968), pp. 575–584.
- (41) M.L. Lee, F.J. Yang, and K.B. Bartle, *Open-tubular Column Gas Chromatography: Theory and Practice* (John Wiley & Sons, New York, 1984), p. 53.
- (42) M. Novotný and A. Zlatkis, *Chromatogr. Rev.* **14**, 1–44 (1971).
- (43) W.G. Jennings, *Gas Chromatography With Glass Capillary Columns* (Academic Press, New York, 2nd ed., 1980).
- (44) J. Merle d'Aubigne, C. Landault, and G. Guiochon, *Chromatographia* **4**, 309–326 (1971).
- (45) G. Schomburg, H. Husmann, and F. Wecke, *J. Chromatogr.* **99**, 63–79 (1974).
- (46) K. Grob, *J. High Resolut. Chromatogr.* **2**, 599–604 (1979).
- (47) G. Alexander, *Chromatographia* **13**, 651–660 (1980).
- (48) W.G. Jennings, Ed., *Applications of Glass Capillary Gas Chromatography* (Marcel Dekker Inc., New York, 1981).
- (49) K. Grob Jr., *Making and Manipulating Capillary Columns for Gas Chromatography* (Hüthig Verlag, Heidelberg, Germany, 1986).
- (50) R.F. Adams, F.L. Vandemark, and G.L. Schmidt, *J. Chromatogr. Sci.* **15**, 63–68 (1977).
- (51) D.H. Desty, J.N. Haresnape, and B.H.F. Whyman, British patent number 899,909, applied 9 April 1959, issued 27 June 1962.
- (52) D.H. Desty, *Chromatographia* **8**, 452–455 (1975).
- (53) K. Grob and G. Grob, *Wissenschaftl. Zeitschr. der Karl-Marx-Univ., Math.-Naturwiss. Reihe* **26**(4), 379–384 (1977).
- (54) R.D. Dandeneau and E.H. Zerenner, *J. High Resolut. Chromatogr.* **2**, 351–356 (1979).
- (55) R.D. Dandeneau and E.H. Zerenner, *LCGC* **8**(12), 908–912 (1990).
- (56) W.G. Jennings, *Comparison of Fused-Silica and Other Glass Columns in Gas Chromatography* (Hüthig Verlag, Heidelberg, Germany, 1981).
- (57) S.R. Lipsky, W.J. McMurray, M. Hernandez, J.E. Purcell, and K.A. Billeb, *J. Chromatogr. Sci.* **18**, 1–9 (1980).
- (58) S.R. Lipsky and W.J. McMurray, *J. Chromatogr.* **217**, 3–17 (1981).
- (59) S.R. Lipsky and M.L. Duffy, *J. High Resolut. Chromatogr.* **9**, 376–382 (1986).
- (60) S.R. Lipsky and M.L. Duffy, *J. High Resolut. Chromatogr.* **9**, 725–730 (1986).
- (61) J.E. Cahill and D.H. Tracy, *J. High Resolut. Chromatogr.* **21**, 531–538 (1998).
- (62) L. Blomberg, *J. High Resolut. Chromatogr.* **5**, 520–533 (1982).
- (63) L. Blomberg, *J. High Resolut. Chromatogr.* **7**, 282–284 (1984).
- (64) J.K. Haken, *J. Chromatogr.* **300**, 1–77 (1984).
- (65) K. Grob and G. Grob, *J. Chromatogr.* **347**, 351–356 (1985).
- (66) E.F. Barry, in *Modern Practice of Gas Chromatography*, R.L. Grob, Ed. (John Wiley & Sons, New York, 3rd ed., 1995), pp. 198–203.

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