The Invention, Development and Triumph of the Flame Ionization Detector

Leslie S. Ettre, Department of Chemical Engineering, Yale University, New Haven, Connecticut, USA.

Today, there is practically no gas chromatograph without a flame ionization detector. Besides the use of partition as the basis of separation and the open-tubular columns, it can be considered as the third most important invention in gas chromatography (GC). Most GC users take the flame ionization detector for granted, and very few are aware of its origin and the background behind its invention. This article deals with this subject: the reasons that led to its invention, the development of the flame ionization detector, and its rapid triumph in becoming the universal detector in GC.

In classic column chromatography the separated compounds could be observed as coloured rings on the column, and in paper- and thin-layer chromatography, the separated spots can be visualized relatively easily. However, the situation is different in gas chromatography (GC): Here, some methods have to be found to detect the separated compounds eluting from the column. A.T. James and A.J.P. Martin, in their first investigations on gas–liquid partition chromatography (GLPC) carried out at the laboratories of the British National Institute for Medical Research in London, used titration because their samples consisted of fatty acids[1,2] and amines.[3,4] However, naturally, titration could not be used for neutral compounds and the automated titration unit developed by Martin was too complicated for widespread use.

GC utilizing adsorption columns had already been carried out before James and Martin by Stig Claesson at the University of Uppsala, Sweden[5]; Fritz Prior and Erika Cremer at the University of Innsbruck, Austria[6,7]; and C.S.G. Phillips at Oxford University in the United Kingdom.[8] In those investigations, and also in other measurements involving gas mixtures, thermal conductivity detectors were utilized. Thus, it was logical for N.H. Ray of the British ICI laboratories — who visited Martin's laboratory in 1950, when GLPC was still in the development stage, to learn about the new technique — to adapt this detector to the gas chromatograph he built in 1950–1951 and used for the analysis of impurities in ethylene.[9,10]

When, in 1955–1956, the first commercial gas chromatographs were introduced in the United States, they all used thermal conductivity detectors.[11] These detectors were rugged, reliable and easy to use. However, they had two limitations. The first particularly restricted their use: for best performance helium was needed as the carrier gas, but at that time (in the second half of the 1950s) helium was practically unavailable outside America, and even if one could get it, its price was often prohibitive. The second limitation was the relatively poor sensitivity of the thermal conductivity detector, even when using helium, which was insufficient to analyse low sample concentrations. For these reasons early gas chromatographs built in the United Kingdom utilized other detectors that did not need helium. Thus, the instruments of Griffin and George utilized the gas density balance developed by Martin in 1954[12,13], while the GC system of Shandon Scientific Co. incorporated the so-called hydrogen flame detector of R.P.W. Scott.[14,15] In the hydrogen flame detector, the carrier gas contained hydrogen, which was burned at column end, and the temperature of the flame was continuously monitored. Without sample, the carrier gas produced a constant signal; however, when an organic vapour eluted from the column, the temperature of the flame increased, resulting in a response proportional to the amount of the eluting compound. For a short time, there was great hope with these detectors; however, they were difficult to use, without much improvement in the analytical results. A number of other detectors were also investigated, but none of those reached beyond the breadboard stage and are completely forgotten today.

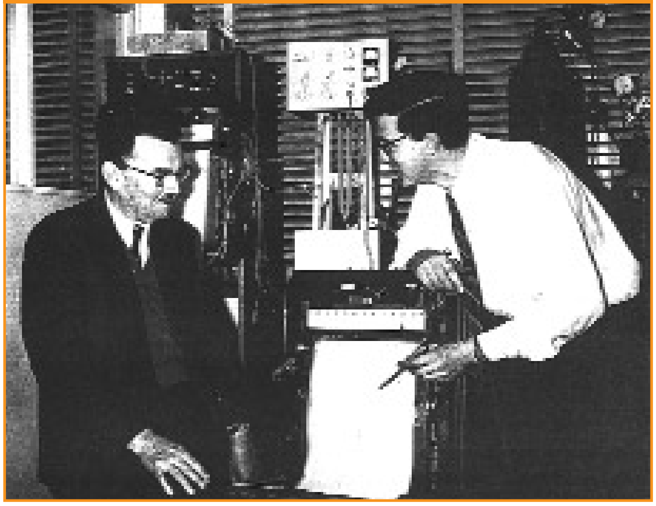


Figure 1: I.G. McWilliam (right) and R.A. Dewar, circa 1958. A self-constructed gas chromatograph can be seen in the background.

Then, in 1958, suddenly two ionization detectors were introduced that completely changed the situation: the argon ionization detector and the flame ionization detector.

The argon ionization detector was invented by J.E. Lovelock, then associated with the British National Institute for Medical Research. The detector used argon as the carrier gas. The argon molecules were ionized by radiation from a radioactive source and excited to their metastable state. Upon collision with an organic molecule, the energy of these metastable atoms is transferred, creating ions, provided the organic molecule's ionization potential is less than the excitation potential of the argon atoms. The result is an increased current through the detector cell.[16–18] This detector was almost immediately commercialized by W.G. Pye and Co., who introduced the argon chromatograph at the International GC Symposium held in May 1958 in Amsterdam, The Netherlands.[19] The argon ionization detector had a high sensitivity and opened GC to the field of biochemistry. However, within a few years it was superseded by the flame ionization detector, which did not need a radioactive source and had better linearity. At the same time, a modification of the argon ionization detector, the so-called electron-capture detector, developed again by Lovelock, revolutionized environmental analysis.[20] The development of the argon ionization detector and electron-capture detector is discussed in detail in an interesting autobiography by Lovelock, which was published recently.[21]

The second ionization detector, developed almost simultaneously with the argon ionization detector, is the flame ionization detector. Due to its high sensitivity, predictable response, and extended linear range, within a few years it became the most widely used GC detector, included in almost every gas chromatograph. Its development and rapid acceptance is the subject of this report.

Invention

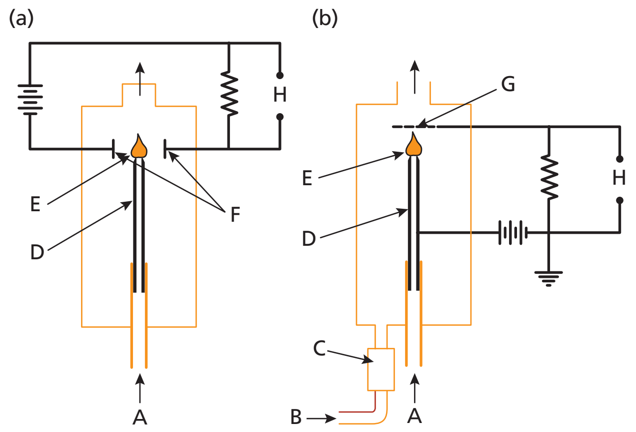
The flame ionization detector was developed in 1957 in two locations: the Central Research Laboratories of Imperial Chemical Industries of Australia and New Zealand (ICIANZ) by I.G. McWilliam and R.A. Dewar, and at the Department of Physical Chemistry, University of Pretoria in South Africa by J. Harley, W. Nel and V. Pretorius. Neither group knew about the activities of the other. They worked almost simultaneously, but the ICIANZ group had a slight edge and pursued its work to completion, whereas the Pretoria group did not follow up its original work.

Work in Australia: The laboratories of ICI in Australia and the United Kingdom had fairly close contact with each other, and associates of ICIANZ frequently visited the United Kingdom laboratories. In 1955, during such a visit, R.A. Dewar (1908–1981), associate research manager of ICIANZ, became familiar with the results of Ray[10] and, upon returning to Australia, initiated work on GC. However, being aware of the limitations of the thermal-conductivity detector, his aim was not just to copy Ray's system, but to improve it. At that time Ian Gordon McWilliam (born 1933), a fresh graduate of Melbourne University, joined ICIANZ and was assigned to this project (Figure 1). Twenty-five years later, he discussed in detail their work and results in two retrospective articles,[22,23] and thus, we have a firsthand account of this exciting story.

McWilliam and Dewar tried to improve the thermal conductivity detector and investigated various modifications, but without any real advances. Meanwhile, they also learned about Scott's hydrogen flame detector[14], so they built one and investigated it. However, they soon realized its fundamental problem: The continuously burning hydrogen (part of the carrier gas) results in a high background, while the burning of small concentrations of sample components causes only small temperature changes. (It is like establishing the weight of a captain by weighing the ship with and without him.) Therefore, they decided to modify the system by measuring the ion current in the flame and not its temperature.

These investigations started in early 1957. A 23-gauge hypodermic needle (~0.34 mm i.d.) was used as the jet, two metal electrodes were placed on opposite sides of the flame, and the ion current produced by placing a battery in series with the electrodes was measured. Originally, air for combustion was simply obtained from the surrounding atmosphere; however, it was found that this contained a large amount of dust particles

Figure 2: Early flame ionization detector designs of McWilliam and Dewar. (a) First design with parallel-plate electrodes; (b) flame ionization detector with the jet as one of the electrodes and filtered air.[23]



A = column effluent and hydrogen, B = air, C = filter, D = metal jet, E = flame, F = electrodes, G = wire gauze collector electrode, H = recorder.

that burned in the flame, creating a noisy background. Therefore, the design was modified by introducing filtered air into the detector housing. Changes were also made in the electrical system, among them using the metal jet as one electrode and a wire gauze as the collector electrode (Figure 2). A further modification was to use two flame ionization detectors, one at the end of the analytical column and the second at the end of a reference column, and measuring the difference between the outputs of the two detectors. In this way, background current disturbance could be offset.

By the summer of 1957 the prototypes of the flame ionization detector (Figure 3) showed excellent performance, high sensitivity and good linearity. At this time McWilliam and Dewar prepared a short paper describing the principles of the flame ionization detector (both in the single- and dual-jet form) for submission to the journal *Nature*, whose editorial offices are in London, and ICIANZ also filed a patent application (see later).

Meanwhile, McWilliam left Australia for a two-year stay at the ICI laboratory in Manchester, United Kingdom. To speed up the handling of the manuscript, he personally delivered it on 18 September 1957 to the editorial offices of *Nature* in London, instead of mailing it from Australia. In the United Kingdom, the first meeting in which he participated was the informal discussion organized by the British Gas Chromatography Discussion Group at Cambridge University on 4 October 1957, and there, McWilliam briefly described the newly developed flame ionization detector. His presentation, which was the first public disclosure of the detector, aroused considerable interest.

The manuscript presented to *Nature* underwent the usual editorial process and was accepted tentatively with the condition that the somewhat lengthy description of the electrical circuit be replaced by a diagram. However, then the comedy of errors started. The administrators of the journal ignored the fact that McWilliam gave them his address in the United Kingdom, and sent this letter dated 6 November 1957 to Australia by sea mail, which, of course, took many weeks to arrive there. ICIANZ returned the letter to McWilliam, who immediately carried out the required modification; however, due to this delay, he could submit the final manuscript to the editorial offices of *Nature* only at the beginning of January 1958.

Figure 3: Photograph of the first flame ionization detector made by McWilliam and Dewar in 1957. (Courtesy of Orica Australia Pty. Ltd. (the successor of ICIANZ).)

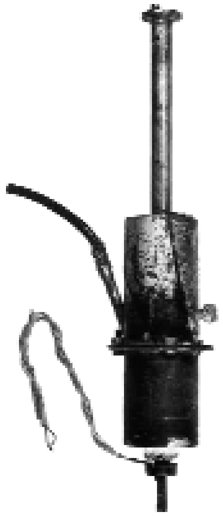
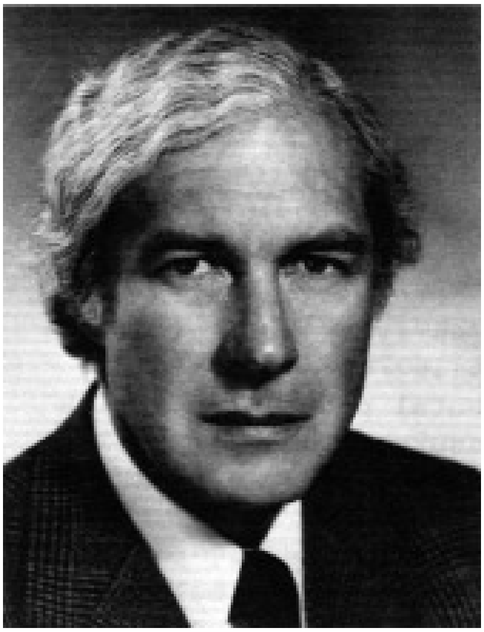


Figure 4: Victor Pretorius.



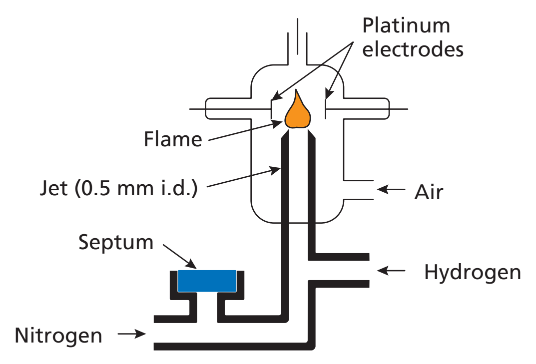
A few days later McWilliam was shocked to read in the 18 January issue of the journal a short paper titled “Flame Ionization Detector for Gas Chromatography” (the same title as his manuscript!) by Harley, Nel and Pretorius of the University of Pretoria in South Africa.[24] Upon his enquiries, the editorial office of *Nature* apologized. Apparently, the two papers were handled by different editors and because there was no editorial comment on the South African paper, it was published earlier. The situation was even worse because *Nature* does not give the date when a manuscript was submitted and thus, for the reader, the Pretorius paper had priority. Finally, the McWilliam–Dewar paper was published two months later, in the 15 March 1958 issue of the journal.[25]

Work in South Africa: Let us now turn our interest to the University of Pretoria in South Africa, where at that time Victor Pretorius (Figure 4) had just started his independent academic career.

Victor Pretorius (1928–1989) was a descendant of Andries Pretorius, one of the leaders of the Boer pioneers in the first part of the nineteenth century, after whom the city of Pretoria was named. A brilliant student at the University of Pretoria, Victor was awarded a Rhodes Scholarship to Oxford University in 1952, where he fully utilized his potential, obtaining a Ph.D. under the Nobel Laureate Sir Cyril Hinshelwood. At Oxford, Pretorius’ research subject was the investigation of the products formed during the gas-phase polymerization of olefins. Pretorius heard about the work of Ray at ICI and, after a visit to his laboratory, he also built a gas chromatograph with a thermal-conductivity detector.

Upon returning to South Africa at the end of 1954 and rejoining the University of Pretoria, Pretorius continued these investigations. However — just as the ICIANZ group in Australia — he was not satisfied with the sensitivity of the thermal-conductivity detector (particularly since helium was

Figure 5: The original all-glass flame ionization detector constructed by Pretorius in early 1957. In its initial testing, no column was used: The sample was directly injected into the nitrogen stream.[27] The platinum electrodes were located 5 mm apart and 2 mm above the jet.



unavailable in South Africa), so he tried other ways of detection, among them a self-built glow-discharge detector.[26] In early 1957, at the request of a colleague, he also built a hydrogen flame detector based on Scott's work.[14] As narrated by Pretorius[27], while testing this detector, he remembered reading somewhere that the electrical resistance of a flame changes with the composition of the gases being combusted. He constructed a simple, all-glass detector to test this possibility (Figure 5). (In this respect, it is interesting to note that McWilliam, in his 1958 presentation in Amsterdam,[28] specifically advised against using a glass jet, because traces of alkaline ions would provide an abnormally high background.) The electrical circuit of the newly built flame ionization detector was put together by J. Harley, a technical assistant at the university, and the first tests showed the high sensitivity of the new detector. After some additional investigations (in a GC system with a column), Pretorius submitted a short paper to *Nature* with Pretorius, Harley and W. Nel, an assistant of Pretorius, listed as co-authors. As mentioned earlier, the paper was published in the 18 January 1958 issue of the journal,[24] two months before the communication of McWilliam and Dewar.[25]

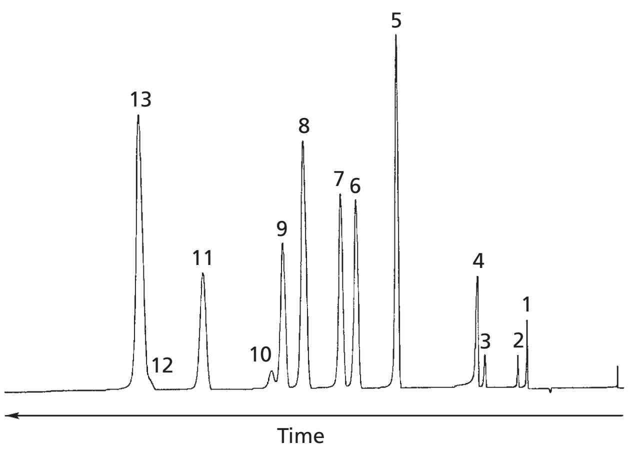
Further Developments

Pretorius did not follow up his initial work on the flame ionization detector; however, the ICIANZ group carried out detailed investigations on detector characteristics, optimum conditions, and the nature of its response. At the Second International GC Symposium held in Amsterdam in May 1958, McWilliam presented a detailed report on those results.[28] He also stated in his lecture that the flame ionization detector is essentially a carbon counter because its response is proportional to the number of carbon atoms in the compound's molecule. This observation was very important because it facilitated the prediction of detector response.

In Amsterdam a very extensive discussion followed McWilliam's presentation, particularly on the possibility of using the flame ionization detector in conjunction with capillary columns (also introduced at the symposium) where sample sizes and column flow-rates are much smaller than with packed columns. Soon after the symposium, extensive research was started at a number of places, particularly in conjunction with capillary columns. Probably the first group involved in such investigations and constructing a gas chromatograph incorporating a capillary column and a flame ionization detector was D.H. Desty's at British Petroleum. Desty first reported publicly about the system and the obtained results at a GC symposium held in the fall of 1958 in Leipzig, East Germany[29], followed a few months later by a lecture at an informal symposium of the British GC Discussion Group in London on 10 April 1959.[30] At that time McWilliam also carried out investigations on the use of the flame ionization detector with glass capillary columns (Figure 6).

As mentioned earlier, McWilliam had given a brief informal description of the new detector at a meeting on 4 October 1957, in London, six months before the publication of their paper in *Nature*. Scientists from the Koninklijke/Shell Laboratories in Amsterdam participated at this meeting and, apparently, immediately picked up the new idea. Thus, at the 1958 Amsterdam Symposium, Hendrik Boer of Shell could report on some of the company's results during the discussion of McWilliam's paper. [28] Meanwhile, one of the Shell scientists, A.I.M. Keulemans, became professor and head of the Laboratory of Instrumental Analysis at the new University of Technology at Eindhoven, The Netherlands. One of his first graduate students was Leo Ongkiehong, a chemist at the Koninklijke/Shell laboratory, who had been involved in these preliminary investigations on the flame ionization detector and, thus, this subject was selected for his PhD thesis. At that time, the laboratories of the new university were not yet ready, so Ongkiehong actually carried out his thesis work at the Koninklijke/Shell laboratories and completed it toward the end of 1959.[31] The thesis represented probably the most detailed investigations on this detector. A summary of Ongkiehong's results was presented at the Third International GC Symposium, held in June 1960 in Edinburgh.[32] We at PerkinElmer already received in 1959 a preliminary copy of Ongkiehong's thesis from Professor Keulemans and, thus, my colleague R.D. Condon was able to further expand these investigations, reporting on additional data at Edinburgh.[33] At the same

Figure 6: A chromatogram obtained by McWilliam in 1959, using a glass capillary column with a flame ionization detector.



Peaks: 1 = acetone, 2 = methyl acetate, 3 = ethyl acetate, 4 = carbon disulfide, 5 = benzene, 6 = cyclohexane, 7 = cyclohexene, 8 = isooctane, 9 = n-heptane, 10 = isobutyl acetate, 11 = methyl cyclohexane, 12 = n-butyl acetate, 13 = toluene.

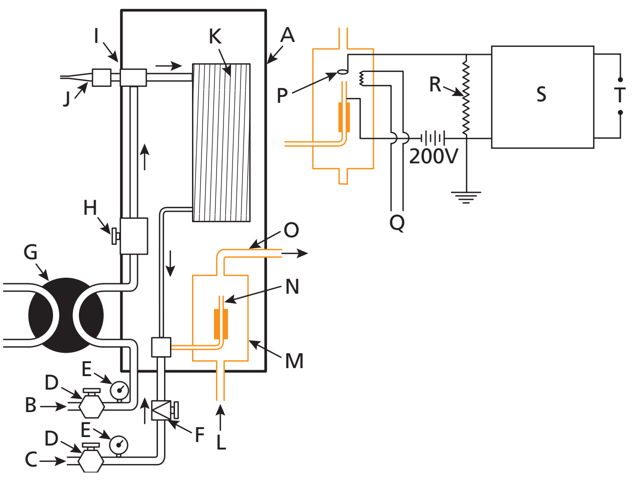
meeting, D.H. Desty also reported on their investigations on the performance of the flame ionization detector.[34] I should also mention here the basic paper of J.C. Sternberg, presented one year later, at the International GC Symposium organized by the Instrument Society of America and held in East Lansing, Michigan.[35] These papers — together with the seminal paper of McWilliam and Dewar[28] as well as two additional papers by them, reporting on further investigations[36,37] — provided the theoretical and practical basis for the rapid and widespread application of the flame ionization detector.

Instrumentation

The possibility of using the flame ionization detector in conjunction with capillary columns was already discussed at the Amsterdam Symposium. In fact, the flame ionization detector was the ideal detector for such applications because it had high sensitivity and zero dead volume, important for the small sample sizes and low flow-rates used with capillary columns. To the best of my knowledge, the first instrument company that investigated the possibility of incorporating the flame ionization detector into a commercial gas chromatograph was PerkinElmer. These investigations started almost immediately after Amsterdam, and when I joined the company's GC group on 6 October 1958, there was already a prototype detector designed by R.D. Condon. It eventually became part of the model 154-C gas chromatograph introduced at the Tenth Pittsburgh Conference in March 1959. This was the first commercial instrument incorporating a flame ionization detector; it was described at the conference in a paper by Condon, together with illustrations of its use with capillary columns (Figure 7).[38]

In the next few years the flame ionization detector became the most commonly used GC detector and was incorporated into almost every gas chromatograph manufactured by scores of instrument companies. The flame ionization detector was particularly important for the growth of Wilkens Instrument and Research Co., the predecessor of the present Varian chromatography division. The phenomenal growth of this company in the early 1960s could be mainly attributed to the introduction of its model 600 gas chromatograph in the spring of 1961 (Figure 8). This was a simple instrument, easy to use, that incorporated a flame ionization detector. It was commonly called the Aerograph Hy-Fi, and as the story goes, the name was concocted by Adele Dimick (the wife of Keene Dimick, the founder of the company) from the initials of hydrogen flame ionization.[39,40]

Figure 7: Schematic diagram of the PerkinElmer model 154-C gas chromatograph with a flame ionization detector, for use with capillary columns, introduced in March 1959.[38]



A = GC oven, B = carrier gas, C = hydrogen, D = pressure regulator, E = pressure gauge, F = restriction valve, G = gas sampling valve, H = flash vaporizer for liquid samples, I = split point, J = variable needle restrictor (split vent), K = capillary column, L = filtered air inlet, M = flame ionization detector housing, N = jet, O = detector vent ("chimney"), P = collector electrode, Q = igniter, R = high impedance resistor, S = amplifier, T = recorder.

Originally, the ICIANZ group developed two types of the flame ionization detector, the first with a single and the second with a dual jet. The latter configuration aimed to offset background current disturbance. Soon, however, it was found that this is not necessary because the same effect can also be obtained by a proper electrical circuit. Thus, most of the commercial instruments utilized only a single flame. In some instruments two flame ionization detectors were installed, but for a different purpose: for use in the dual column–baseline compensation technique developed in 1961 by Emery and Koerner[41,42] to compensate the baseline drift in programmed-temperature operation due to the increasing bleeding of the liquid stationary phase with temperature. These systems essentially consisted of two separate flame ionization detectors, with two separate electrical circuits, and the baseline drift measured from the reference column was subtracted automatically from the output of the flame ionization detector connected to the outlet of the analytical column. At that time a special instrument was also developed for this purpose: the model 800 gas chromatograph introduced by PerkinElmer at the 1962 Pittsburgh Conference. In this instrument the two jets fed one amplifier, providing a single output.[43,44] In the last

Figure 8: The Aerograph model 600 Hy-Fi gas chromatograph, introduced around the time of the 1961 Pittsburgh Conference by Wilkens Instrument and Research Co. The upper part of the flame ionization detector can be seen on the top of the instrument.

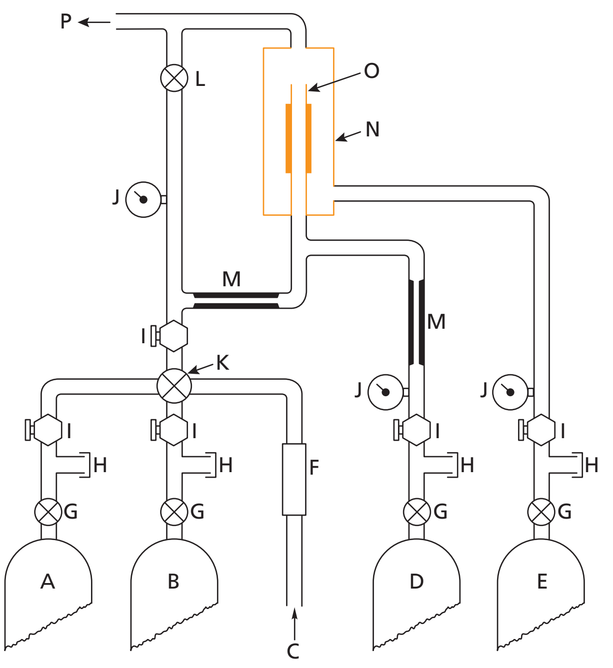
two decades the use of systems with two flame ionization detectors lost its importance: Present-day stationary phases have very little bleeding, and if still needed, correction of baseline drift can be carried out by computers.

The introduction of the flame ionization detector coincided with the growing interest in air pollution research and control. Because of this, an easy and accurate way to measure the total organic content of the atmosphere and automobile exhaust was much sought after. Because the flame ionization detector was essentially a carbon counter, it was proposed almost immediately after its introduction that it should be adapted for this purpose. Such portable instruments — the so-called hydrocarbon analysers (Figure 9) — were developed in 1959 almost simultaneously by a number of companies such as American Cyanamide Co.[45], Perkin-Elmer[46,47] and Beckman.[48] In these instruments no column was used, and the sample gas (e.g., atmospheric air or automobile exhaust) was pumped at a constant flow-rate through the detector in lieu of the carrier gas. The detector's response was proportional to the total concentration of organics present in the sample gas.

Patents

In the story of the flame ionization detector, the patent situation is particularly important. On 4 July 1957, ICIANZ filed a patent application in Australia, in McWilliam's name.[49] The patent was issued on 21 October 1959. Subsequently, applications were filed in a number of countries, among them, naturally, the United States. Meanwhile, Harley, the former associate of Pretorius, already applied for a US patent. After Harley left the University of Pretoria, he joined the South African Iron and Steel Corp., where there was an active patent department that encouraged employees to file patent applications at no cost to the employee. Harley used this opportunity, particularly because Pretorius expressed his disinterest in a patent application.[27] Thus, there were some complications with the American ICI application. Although there was a clear priority of the Australian application, based on their notebook recordings and patent filing in Australia, ICI decided not to get into a legal fight; rather the company made an agreement with Harley, providing him a regular yearly payment. This agreement cleared the way for the issuance of the U.S. patent.[50] Subsequently, ICI granted 37 licenses to instrument companies and their income from these licenses was substantial. As mentioned by McWilliam[23], at one stage the US royalties alone paid for the whole cost of the ICI office in New York City!

Figure 9: Flow schematic of the PerkinElmer model 213 hydrocarbon analyser, introduced in the spring of 1960.[46,47] The gases for the portable instrument were supplied from built-in lecture-size gas cylinders (A, B, D, E); however, it was also possible to connect the instrument to outside gas sources via panel fittings (H).



A = zero gas, B = test gas, C = sample gas inlet, D = hydrogen, E = air, F = filter, G = valves, H = alternate gas inlets, I = pressure regulators, J = pressure gauges, K = selector valve, L = toggle valve, M = restrictor, N = flame ionization detector housing, O = detector jet, P = vent.

One country was inadvertently forgotten by ICI when filing the patent applications: Japan. This was obviously a serious oversight, and ICI tried to correct the situation as soon as the error was recognized, but without success.[22] Thus, the Japanese instrument companies could produce gas chromatographs without requiring any license for the flame ionization detector.

Personalities

I cannot finish the story of the flame ionization detector without saying a few words about the continuing activities of the principal players.

In 1960 Victor Pretorius became professor of physical chemistry and director of the Chromatography Research Unit at the University of Pretoria. Then, in 1973, he expanded the unit and created the Institute for Chromatography, which he led until his untimely death on 28 December 1989, at the age of 61.[51] He became one of the most original thinkers in chromatography, always full of ideas, mostly ahead of his time. However, his major handicap was that he was working thousands of miles away from other chromatography groups and, particularly in the first decade, with very limited means. It was like being out nowhere, on an island, where a ship arrives only once every six months. From 1965 on, he was finally able to establish contact with fellow chromatographers at the various international symposia held in the United States and Europe, but even so, he was not in the mainstream of chromatographic development. Because of this situation, most of his ideas remained unfinished: After trying an idea and illustrating its feasibility by a few experiments, he moved to another subject, with the hope that somebody else would eventually pick up his results. The best example for the fate of his ideas is his pioneering work on the concept of using electroosmosis to generate flow of the mobile phase in liquid chromatography. He first proposed this approach in 1974, at the Ninth International Symposium on Advances in Chromatography in Houston, Texas, however, without any follow-up.[52] His ideas finally became a reality only in the last decade of the twentieth century.

Ian McWilliam remained with ICIANZ until 1968 when he joined Monash University on a Shell Research Fellowship. Two years later he moved to the Department of Applied Chemistry at Swinburne College (now Institute) of Technology. During his three decades at that university, he has been involved in a number of research projects, mainly related to investigations of various aspects of ionization in a flame. Thus, he remained faithful to his first love for the rest of his professional career.

Triumph

In a review article on GC detectors[53] E.R. Adlard, one of the GC pioneers, characterized the flame ionization detector in the following way:

"The flame ionization detector was first described…at a crucial moment in the development of gas chromatography, when a high sensitivity, low dead volume detector was required… The ease of construction of the flame ionization detector and its relative insensitivity to variation in operating parameters ensured an instant success."

G.R. Primavesi, another GC pioneer, called it "an almost incredible analytical tool",[54] and I could continue with quotations praising the importance of the flame ionization detector in the evolution of GC. Indeed, the flame ionization detector was the right detector, introduced at the right time, at the moment when the meteoric rise of the use of gas chromatography started, when the technique used up to that time only by a limited number of laboratories suddenly became everybody's tool.

Today there is practically no gas chromatograph without a flame ionization detector. In the first 15 years of its existence, more than 60 000 detectors have been manufactured under license from ICI.[55] Today, the number of detectors used in the world can be counted in the hundreds of thousands. Thus, there is probably no other analytical instrument that has made as great a contribution to the daily investigations in research and industry, biochemistry and clinical chemistry, and environmental protection, as the little device conceived in 1957. Its triumph is the continuous proof of the foresight of its inventors.

Acknowledgements

I would like to express my gratitude to I.G. McWilliam for providing copies of the photographs for Figures 1 and 6 and to Peter Dawes (SGE International Pty Ltd, Ringwood, Victoria, Australia) for his help.

References

1. A.T. James and A.J.P. Martin, (20 October 1950 Meeting of the Biochemical Society), *Biochem. J.*, **48**(1), vii (1951).
2. A.T. James and A.J.P. Martin, *Biochem. J.*, **50**, 679–690 (1952).
3. A.T. James, A.J.P. Martin and G.H. Smith, *Biochem. J.*, **52**, 238–242 (1952).
4. A.T. James, *Biochem. J.*, **52**, 242–247 (1952).
5. S. Claesson, *Arkiv Kem. Mineral. Geol.*, **23A**(1), 1–133 (1946).
6. F. Prior, *Application of the Chromatographic Method in the Gas Phase*, PhD thesis, University of Innsbruck, May 1947.
7. E. Cremer and F. Prior, *Z. Elektrochem.*, **55**, 66–70 (1951).
8. C.S.G. Phillips, *Disc. Faraday Soc.*, 7, 241–248 (1949).
9. N.H. Ray, in 75 Years of Chromatography — A Historical Dialogue, L.S. Ettre and A. Zlatkis, Eds. (Elsevier, Amsterdam, 1979), 345–350.
10. N.H. Ray, *J. Appl. Chem.*, **4**, 21–25, 82–85 (1954).
11. L.S. Ettre, *J. Chromatogr. Sci.*, **15**, 90–110 (1977).
12. A.T. James and A.J.P. Martin, *Brit. Med. Bull.*, **10**, 170–176 (1954).
13. A.J.P. Martin and A.T. James, *Biochem. J.*, **63**, 138–142 (1956).
14. R.P.W. Scott, *Nature*, (London) **176**, 793 (1955).
15. R. Müller, *Anal. Chem.*, **29**(3), 55A (1957).
16. J.E. Lovelock, *Nature*, (London) 181, 1460–1462 (1958).
17. J.E. Lovelock, *J. Chromatogr.*, **1**, 35–46 (1958).
18. J.E. Lovelock, *Nature*, (London), **182**, 1663–1664 (1958).
19. *Anal. Chem.*, **30**(11), 47A (1958).
20. J.E. Lovelock and S.R. Lipsky, *J. Am. Chem. Soc.*, **82**, 431–433 (1960).
21. J.E. Lovelock, Homage to Gaia: The Life of an Independent Scientist (Oxford University Press, Oxford, UK, 2000), 124–127, 181–190.
22. I.G. McWilliam, Proceedings of the International Conference on Detectors and Chromatography (Melbourne, 30 May–3 June 1983), A.J.C. Nicholson, Ed. (Australian Scientific Industry Assoc., Melbourne, Australia, 1983), 5–20.
23. I.G. McWilliam, *Chromatographia*, **17**, 241–243 (1983).
24. J. Harley, W. Nel and V. Pretorius, *Nature*, (London), **181**, 177–178 (1958).
25. I.G. McWilliam and R.A. Dewar, *Nature*, (London), **181**, 760 (1958).
26. J. Harley and V. Pretorius, *Nature*, (London), **178**, 1244 (1956).
27. V. Pretorius, in 75 Years of Chromatography — a Historical Dialogue, L.S. Ettre and A. Zlatkis, Eds. (Elsevier, Amsterdam, 1979), 333–338.
28. I.G. McWilliam and R.A. Dewar, in Gas Chromatography 1958 (Amsterdam Symposium), D.H. Desty, Ed. (Butterworths, London, 1958), 142–152.
29. D.H. Desty, in Gas Chromatographie 1958, H.P. Angelé, Ed. (Akademie Verlag, Berlin, 1959), 176–184.
30. D.H. Desty, A. Goldup and B.H.F. Whyman, *J. Inst. Petrol.*, **45**, 287–298 (1959).
31. L. Ongkiehong, The Hydrogen Flame Ionization Detector, PhD thesis, Institute of Technology, Eindhoven, 19 January 1960.
32. L. Ongkiehong, in Gas Chromatography 1960 (Edinburgh Symposium), R.P.W. Scott, Ed. (Butterworths, London, 1960), 7–15.
33. R.D. Condon, P.R. Scholly and W. Averill, in Gas Chromatography 1960 (Edinburgh Symposium), R.P.W. Scott, Ed. (Butterworths, London, 1960), 30–45.
34. D.H. Desty, C.J. Geach, and A. Goldup, in Gas Chromatography 1960 (Edinburgh Symposium), R.P.W. Scott, Ed. (Butterworths, London, UK, 1960), 46–64.
35. J.C. Sternberg, W.S. Gallaway and D.T.L. Jones, in Gas Chromatography (1961 Lansing Symposium), N. Brenner, J.E. Callen, and M.D. Weiss, Eds. (Academic Press, New York, 1962), 231–268.
36. I.G. McWilliam, *J. Chromatogr.*, **6**, 110–117 (1961).
37. R.A. Dewar, *J. Chromatogr.*, **6**, 312–323 (1961).
38. R.D. Condon (10th Pittsburgh Conference, Pittsburgh, Pennsylvania, 2–6 March 1959), Anal. Chem., **31**, 1717–1722 (1959).
39. L.S. Ettre, *J. Chromatogr. Sci.*, **15**, 90–110 (1977).
40. K.P. Dimick, LCGC, **8**, 782–786 (1990).
41. E.M. Emery and W.E. Koerner, *Anal. Chem.*, **33**, 523–527 (1961).
42. E.M. Emery and W.E. Koerner, *Anal. Chem.*, **34**, 1196–1198 (1962).
43. R.D. Condon, "Dual Column Chromatography Utilizing Ionization Detection," 13th Pittsburgh Conference, Pittsburgh, Pennsylvania, 5–9 March 1962.
44. L.S. Ettre, R.D. Condon, F.J. Kabot, and E.W. Cieplinski, *J. Chromatogr.*, **13**, 305–318 (1964).
45. A.J. Andreach and R. Feinland (11th Pittsburgh Conference, Pittsburgh, Pennsylvania, 29 February–4 March 1960), *Anal. Chem.*, **32**, 1021–1024 (1960).
46. H.N. Claudy and L.S. Ettre, Instrument-Automation Conference, Instrument Society of America, San Francisco, California, 9–12 May 1960 (ISA Preprint Number 20-SF-60).
47. L.S. Ettre, (53rd Annual Meeting of the Air Pollution Control Association, Cincinnati, Ohio, USA, 22–26 May 1960), *J. Air Pollution Control Assoc.*, 11, 34–43 (1961).
48. R.L. Chapman, (53rd Annual Meeting of the Air Pollution Control Association, Cincinnati, Ohio, USA, 22–26 May 1960), *J. Air Pollution Control Assoc.*, **10**, 463–464 (1960).
49. I.G. McWilliam (assigned to ICI of Australia and New Zealand Ltd.), Australian patent number 224,504 (applied for 4 July 1957; issued on 21 October 1959).
50. I.G. McWilliam (assigned to ICI of Australia and New Zealand Ltd.), U.S. patent number 3,039,856 (issued 19 June 1962).
51. D.H. Desty, *Chromatographia*, **29**, 203–204 (1990).
52. V. Pretorius, B.J. Hopkins and J.D. Shieke, *J. Chromatogr.*, **99**, 23–30 (1974).
53. E.R. Adlard, *Crit. Rev. Anal. Chem.*, **5**(1), 1–36 (1975).
54. G.R. Primavesi, in 75 Years of Chromatography — a Historical Dialogue, L.S. Ettre and A. Zlatkis, Eds. (Elsevier, Amsterdam, The Netherlands, 1979), 339–343.
55. Leaflet issued by the Central Research Laboratories of ICI Australia and New Zealand Ltd. on Open Day, 26 June 1986.

Leslie S. Ettre is a research afiiliate of the Chemical Engineering Department of Yale University and a member of the editorial advisory board of *LC•GC Europe*.