PERSPECTIVES IN INORGANIC MICRO AND TRACE ANALYSIS

R. Belcher

Department of Chemistry, University of Birmingham, P.O. Box 363,
Birmingham, 15, England

Abstract - Although some isolated small-scale procedures may have been
described in previous times, it was not until the 18th century that methods
were described that could be truly termed micro inorganic analysis. These
were generally based on tests requiring the use of the microscope. In the
latter half of the 19th century, "Chemical Microscopy" as it came to be
called was applied extensively and several famous names are connected with
this development. The acknowledged pioneer of inorganic microanalysis was
Friedrich Emich. Shortly before and during the 2nd World War great
developments in instrumental methods took place and this had its effect on
the practice of inorganic microanalysis. As instrumental methods have
developed, the segregation of the scales of operation has disappeared, for
the methods are interchangeable regardless of the amount of sample taken.
Accordingly, it is difficult to refer to the future progress of inorganic
microchemistry. However, unless some unusual equipment is made available
the only foreseeable progress lies in the refinement of the various
techniques that are used on the micro and (sub-micro) scales. Fortunately,
many of the newer techniques such as atomic absorption, MECA spectroscopy,
candoluminescence spectroscopy, readily lend themselves to the analysis of
micro samples and it is probably in the application of techniques such as
these that the future of inorganic microanalysis lies.

It is not an easy matter to establish when microchemical methods were first used.
Analytical methods were established in civilised communities as far back as history records
and it is not inconceivable that some tests were applied on a very small scale; for example,
some of the early chemists analysed drops of solution, but they did not regard this scale
of operation as a different technique. The first truly microchemical method that most of us
know is Pliny's test for iron sulphate, as an adulterant in copper sulphate, described in the
first century A.D. This was also the first known spot-test, for papyrus soaked in extract
of nut-galls was used as the reagent. It is also said to be the first application of a
chelate compound in analysis. It is surprising that similar simple tests of this kind were
not developed; if they were I have been unable to find any examples.

Undoubtedly, the discovery of the microscope encouraged the development of small-scale
methods of testing. It is believed that Robert Hooke in 1677 was the first to use the
microscope for chemical identification (1). He collected, on a sheet of white paper, the
sparks from striking flint on steel. These particles were then examined under the microscope
and Hooke showed that they were very small particles of flint and of iron, although the
latter preponderated.

TABLE 1. Notable contributors to the development of chemical microscopy
in the second half of the 19th century

Helvigg	1865	Sorby	1869	Streng	1883
Harting	1866	Boricky	1877	Haushofer	1885
Wormley	1867	Goldschmidt	1883	Behrens	1894

In the following century (1751) Marggraf examined the reactions of platinum under the microscope and was the first to use flame tests to distinguish potassium and sodium (2). Somewhat later Lowitz (3) differentiated sodium and potassium chloroplatinates under the microscope. During this same period he recorded the crystal forms and other properties of various compounds under the microscope as a basis for their identification.

Several decades were to pass after this period before any similar outstanding work was reported. During the latter half of the 19th century chemical microscopy developed simultaneously in several countries and was applied in many fields of analysis. The names of these various investigators are shown in Table 1.

They were to be followed in the present century by teachers and investigators such as Kley, Schoorl, van Nieuwenberg, Chamot and Mason, and later by A. and L. Kofler and Maria Kuhnert-Brandstätter who extended the applications.

It was not to be expected that methods of quantitative microanalysis would be developed during these times, because suitable balances were not then available. Thus only qualitative methods were developed and the bulk of these were based on the methods of chemical microscopy. However, there were some exceptions: some form of spot-testing on paper and on glass slides was referred to by D.B. Reid (4) at a meeting of the British Association in 1835. These methods were used in Reid's courses at the University of Aberdeen. I have never been able to find details of Reid's system of analysis, although these should be available.

Amongst sensitive tests that were developed was Marsh's test (1836) for arsenic, which was the forerunner of many other tests based on the generation of arsine and later to be made quantitative. It is interesting to note that Marsh recognized that antimony behaved likewise and he developed a differentiating test. It may be mentioned that the reaction mechanism of the latest method of arsenic determination, based on arsine evolution – the silver dithiocarbamate method – is the subject of some controversy. Another sensitive test was the Griess test for nitrite which still remains as one of the most sensitive tests known. There are many variations of this test and the history of it has been described very recently (5). As a final example of sensitive methods of detection, Bayley's separations on filter-paper deserve mention (2). He detected copper and cadmium on filter-paper by a procedure very similar to spot-tests as used today.

Thomas Andrews, of Queen's University, Belfast, detected nanogram amounts of sodium in one drop of solution by the depolarizing action of sodium hexachloroplatinate. Andrews also proved the composition of "electrolytic" gas by the use of micro-methods (1855). He collected the gases in thermometer tubing and measured the relative amounts (4). Possibly this was the very first <u>quantitative</u> micro-method to be described.

In 1880, Robert Mauselius analysed 67 mg of Kainosit from Nordmarken (6). He determined silica, yttrium oxide, iron, calcium, magnesium, alkali metals and water. This was a semi-micro amount of sample, rather than a micro-sample, but it was the smallest mass of material that had been analysed quantitatively up to that time.

Apart from these isolated examples, the microchemistry of the last century was almost exclusively qualitative analysis based on micro-crystalloscopic methods.

It is generally recognized that Friedrich Emich was the pioneer of quantitative inorganic analysis. Emich began his studies in the last decade of the 19th century; he studied first micro-crystalloscopic methods and other qualitative methods, but later developed general methods of separation. In 1909 he and his co-worker Donau described methods for the determination and separation of several cations, using 10 mg or less of sample; the Nernst-Donau torsion balance was used for weighing. The Emich-Donau methods were not to become widely used. It has been suggested that the reason may have been due to the shortcomings of their balance; it required great skill and patience for its operation. These objections disappeared when the Kuhlmann assay balance was modified by Pregl and became the first micro-balance.

It is well known that after the turn of the century microchemistry in all its aspects was developed mainly in Austria. It should also be mentioned that Donau, who was one of Emich's earliest co-workers, was the first to apply candoluminescence spectroscopy for analytical purposes. Although this fact is mentioned briefly by Feigl in the preface to his book, the possibilities of this technique remained unnoticed until quite recent times.

In the 1920s Feigl, working in the University of Vienna, began to develop his well known spot-tests. These soon proved a rival to the micro-crystalloscopic tests because they were generally more sensitive and the simplest of equipment was suitable. The success of these methods has tended to obscure the more important contributions that Feigl made. The new reagents he developed and the new reactions he discovered later proved the basis for many spectrophotometric procedures. His study of masking reactions (a term that he himself coined) facilitated the later development of compleximetric titrations. Feigl's spot-tests

became widely used and are still probably the most convenient and simple means for ad hoc testing. As an example of the general application the rhodizonic acid test for lead is used widely in forensic analysis, when it shows whether the suspect has fired a gun.

It may be mentioned that Robert Boyle was probably the first to establish sensitivity of a reagent. He showed that Pliny's reagent was sensitive to 1 part of iron in 6000. This system of expressing sensitivity is still used. Unfortunately, it still remains to find a simple system of grading selectivity.

In general, high selectivity has been considered as the most desirable property of an organic reagent, but there are instances where low selectivity can be used advantageously. One of the first notable examples of this was by R.L. Mitchell (7) in 1946. In order to determine trace metals in soils, he concentrated them by precipitation from the aqueous solution by a mixed reagent consisting of 8-hydroxyquinoline, thionalide and tannic acid. All the heavy metals were precipitated and were then determined by the emission spectrograph. Ammonium pyrrolidinedithiocarbamate is used in compleximetric titrations to remove heavy metals so that the titration of calcium and magnesium is facilitated. It is also used to extract and concentrate heavy metals for final determination by atomic-absorption spectroscopy (8). This method is often used in the analysis of sea-waters.

As a final example of this type of reagent (there are many more), the β-diketones may be mentioned. They can be used to extract heavy metals as their chelate compounds and the extracts can be analysed by gas-liquid chromatography (9).

In a considerably less spectacular manner instrumental analysis was quietly developing in the period after the 1st World War. Such techniques as emission spectroscopy and potentiometric titration were used routinely. In this same period polarography was discovered. Other instrumental methods of analysis were receiving attention, particularly spectrophotometry. Shortly before and during the 2nd World War, there were great developments in instrumental methods which had their effect on the practice of inorganic microanalysis. For example, because of the development of accurate spectrophotometers, it was possible to determine many ions accurately by spectrophotometric measurement; the need for separations was avoided because of the use of highly selective reagents. Consequently, much of the elegant earlier equipment became obsolete. Nevertheless, the availability of such equipment should never be overlooked, because special cases may arise where its application can solve many problems.

It was perhaps shortly before the 2nd World War that the confusion arose between trace methods of analysis and inorganic microanalysis. They are really quite separate techniques, but it is still possible to find the terms confused. The situation was not helped when the Analytical Division of IUPAC changed the name of its Microchemical Commission so that it incorporated trace analysis. I consider that inorganic microanalysis is concerned with the analysis of very small samples and the determinations are almost always associated with percentage amounts. On the other hand, trace analysis deals with parts per million and less, and the amounts of sample are generally in the macro-range. It is only the amount being determined that is a micro amount, but, as it is a trace amount, the required accuracy is much less than that demanded in authentic microanalysis. It is not surprising that this confusion arose, because some of the new instrumental methods were suitable for application in both fields and I believe it was this fact that led to the confusion.

One of the problems that is associated with development and refinement of instrumentation is that the more sophisticated it becomes, the more specialized attention it needs and the chemist becomes entirely dependent on the whims of the visiting engineer. The earlier chemists had to produce even their own analytical reagents as well as equipment. Chemists have become progressively more dependent on the manufacturer and supplier. Although a certain amount of dependence is inevitable, complete dependence should be avoided as far as possible.

By the application of amplification reactions as a prelude to the use of an instrumental method, very great sensitivity can be achieved by using only conventional equipment (10). For example, phosphorus can be determined by extraction as the 12-molybdophosphate. After back-extraction the molybdenum is determined by atomic-absorption spectroscopy. The first amplification method was first described as long ago as 1855 (3).

Sometimes it is advantageous to combine the instrument and the reaction. For example, if a chloride solution is treated with phenyl mercuric nitrate, phenyl mercuric chloride is formed and can be extracted into an organic solvent. This can then be analysed by G.L.C. methods, for HgPhCl gives a characteristic peak. This provides one of the most sensitive methods known for the determination of chloride and neither partner of the marriage could achieve this alone. Spectrophotometric, polarographic and atomic-absorption methods can also be used to complete the determination.

Naturally, various attempts were made to lower the scale of operation and during the decade before the 2nd World War microgram methods of analysis were developed. This system of analysis was termed ultra-microanalysis. The late Professor Benedetti-Pichler was the leading pioneer in this area. These methods proved to be invaluable in studying the chemical reactions of the new elements produced during the Manhattan Project. They have since been applied in various other fields; the best description in English is to be found in the book by Alimarin and Petrikova (11).

Another interesting technique which was developed extensively before the 2nd World War and later, was micro-diffusion analysis. These methods, ably developed mainly by E.J. Conway, were used universally in clinical chemical laboratories, but have now been replaced by automated and direct spectrophotometric methods. These methods were simple in operation, elegant and remarkably accurate (12).

About the turn of the present century, although methods of qualitative inorganic analysis based on micro-crystalloscopic tests had been developed, attempts were made to develop micro-analytical methods based on one of the conventional schemes of qualitative analysis (there were many in existence even at that time). Some very successful methods were developed, using ingenious equipment and techniques. Many of us here have used these techniques in various teaching courses. Those students who had the privilege of learning these methods acquired great skill as experimentalists. Unfortunately, with the expansion in the size of teaching courses and the overall drop in the quality of the student, it became impossible to teach such methods. Consequently, semimicro methods were developed. These required only a little more manipulative skill than the test-tube methods that they replaced. Very little specialized equipment was necessary and the only expensive item was the centrifuge. H. Holness (13) was in the forefront in developing semimicro methods of qualitative analysis and it was he who was primarily responsible for the production of a cheap centrifuge.

The semimicro technique was not only more rapid than the macro technique, but was more economical in reagents and materials. It virtually superseded all forms of qualitative analysis used in the U.K. Unfortunately, most universities in the U.S.A. abandoned this technique many years ago and the U.K. later followed suit. This is unfortunate because, as I have said on many occasions (14) qualitative inorganic analysis is the best means for the student to become acquainted with chemical reactions and reagents. It is because this valuable teaching tool is no longer popular that we get statements such as "silver chloride is a green gas" (15) and exercises in some "advanced" examinations, where manganese dioxide and sodium chloride are put up in sample tubes and the candidate is asked to find out which is which. Twenty years ago any schoolboy could have answered the last question merely by inspection.

I have also mentioned on many other occasions (14) that one of the reasons that made qualitative analysis unpopular was that many of the tests that were recommended needed re-examination. It is a tragedy, now that all the unreliable tests and unreliable reactions have been eliminated, and highly efficient tests are available (16) that the technique is hardly used, at least in the U.K. I understand that some attempt at reaction chemistry is practised by adding reagents to known solutions. A duller way of learning chemical reactions cannot be imagined. However, I am quite sure that one day some enterprising young teacher will discover that these reactions can be classified into different groups and qualitative inorganic analysis will be rediscovered.

Surprisingly, not all the new developments in analytical techniques required increasingly sophisticated components. Two notable developments were the ring oven and catalytic methods. The ring oven is an ingenious method of refining spot-test procedures and even rendering them quantitative. The apparatus is well known and requires no description here (17). It is extremely valuable, of course, for qualitative purposes, but in more recent times it has been developed for quantitative work and has proved invaluable in trace analysis. So far it has resisted all the attempts of the "machinists" to render the apparatus more complicated.

Catalytic or kinetic reactions are not, of course, new. The first analytical method based on catalysis was the test for vanadium by means of its catalytic effect on the formation of aniline black, by Guyard in 1876 (2). Later Witz and Osmond (1885) attempted to apply the reaction quantitatively. The first reliable method was not developed until half a century later. This was the determination of iodide by its catalytic effect on the cerium(IV) and arsenite reaction by Kolthoff and Sandell (18). During the last decade or so, quantitative methods have been developed extensively (19). Enzymatic methods have also been developed (20). Although only simple equipment is used, the methods are amongst the most sensitive available. These catalytic reactions can also be utilized for other purposes, e.g. for detecting the end-point in titrimetry, and they can also be used in conjunction with ion-selective electrodes.

Because of the great development of instrumental methods in recent times the segregation of

these various techniques has tended to disappear, for the methods are interchangeable regardless of the amount of sample taken. Accordingly, it is difficult to predict the future progress of inorganic microchemistry. However, unless some unusual equipment or technique is made available, the only foreseeable progress lies in the refinement of the various techniques that are already used on the micro and sub-micro scales, e.g. spectrophotometry, atomic-absorption spectroscopy, polarography, ion-selective electrodes, etc. Fortunately, many of the newer techniques such as atomic absorption, MECA spectroscopy, candoluminescence spectroscopy etc. readily lend themselves to the analysis of micro samples and it is probably in the application of techniques such as these that the future of inorganic microanalysis lies. Nevertheless, the future may not completely become the monopoly of the machinist, for, as we have seen, some very valuable techniques which require only the simpler equipment were developed during the post-war years and it can also be of great advantage to combine classical and instrumental procedures; the discovery of similar techniques and the successful application of combined procedures cannot be ruled out so long as chemical reactions continue to be studied.

REFERENCES

1. H. Lieb, Microchemical Techniques, p.7. Interscience Publishers, New York (1961).
2. F. Szabadvary, History of Analytical Chemistry, Pergamon Press, Oxford (1966).
3. R. Belcher, Proc. Anal. Div. Chem. Soc., 12, 77 (1975).
4. R. Belcher, Proceedings of the International Symposium on Microchemistry, 1958, p. 558, Pergamon Press (1959).
5. W.I. Stephen, Proc. Anal. Div. Chem. Soc., 14, 183 (1977).
6. H.K. Alber, Mikrokemi Fyra Föredrag av Herbert Alber, p.9, Norstedt and Soners Forlag, Stockholm (1933).
7. R.L. Mitchell, The Spectrochemical Analysis of Soils, Plants and Related Materials, Technical Communications No. 44a, Commonwealth Agricultural Bureau.
8. H. Malissa and E.E. Schöffmann, Mikrochim. Acta, 187 (1955)
9. R.W. Moshier and R.E. Sievers, Gas Chromatography of Metal Chelates, Pergamon Press, Oxford (1965).
10. R. Belcher, Talanta, 15, 357 (1968); Proc. Soc. Anal. Chem., 7, 61 (1970).
11. I.P. Alimarin and N. Petrikova, Inorganic Ultramicroanalysis, Pergamon Press, Oxford (1964).
12. E.I. Conway, Microdiffusion Analysis and Volumetric Error, 2nd Ed. Crosby, Lockwood, London (1957).
13. H. Holness, Inorganic Qualitative Analysis, Pitman, London (1953)
14. R. Belcher, Analyst, 99, 802 (1974).
15. P.W. West, Anal. Chem., 46, 784A (1974)
16. W.I. Stephen, Educ. in Chem. (1969).
17. H. Weisz, Microanalysis by the Ring Oven Technique, 2nd Ed., Pergamon Press, Oxford (1970).
18. I.M. Kolthoff and E. Sandell, Mikrochim. Acta, 1, 9 (1937).
19. K.B. Yatsimirskii, Kinetic Methods of Analysis, Pergamon Press, Oxford (1966).
20. G.G. Guilbault, Enzymatic Methods of Analysis, Pergamon Press, Oxford (1970).