Draft

Annali di Chimica, 87,1997,by Società Chimica Italiana

TRACEABILITY OF TRACE ANALYSIS

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Summary - Traceability provides the terminology, concepts and strategy for ensuring that analytical chemical measurements are comparable. At present the reference points are often internationally agreed methods; they can also be reference materials. Ideally there should be a single reference point, which in the case of chemistry is the SI Unit the mole but much work will be required to achieve such a situation. Traceability does not imply high accuracy and levels of certainty consistent with fitness for purpose criteria is the goal. This paper discusses the relevance of the concept of traceability and reviews developments leading to a conceptual model for analytical chemistry. It also reports some recent work and considers future needs.

INTRODUCTION

The theme of the EUROANALYSIS IX session at which this paper will be presented is "Reducing Disputes Over Trace Analytical Measurements". The scale of disagreement between laboratories can be in excess of three orders of magnitude, a level which is unheard of in other areas of chemical analysis or other fields of measurement. Whilst perfect agreement between laboratories is neither feasible nor necessary, a better level of comparability is required than is commonly attained. Traceability is a concept and a measurement strategy which provides a means of anchoring measurements in both time and space and is particularly pertinent to the problems of trace analysis. Measurements made at different times or in different places are directly related to a common reference. Applying the concept of traceability to chemical measurements is not easy but it has the potential to provide a means of assessing and controlling the level of (dis)agreement.

The causes of disagreement in trace analysis are manifold. Contamination from the environment, sample containers, reagents and interfering substances result in a positive bias whilst incomplete separation, decomposition, plating-out and suppression effects lead to low results. One of the early reports of the scale of the problem was a paper by J C Sherlock[1] et al in 1985 which showed that of 27 laboratories that participated in an interlaboratory study of lead in cabbage, only 3 laboratories obtained acceptable results. The analysis was not considered particularly difficult and all the participating laboratories had experience of that type of analysis. Other studies[2,3] have shown similar problems with little or no correlation between quality of the results and analytical technique, or the eminence of the laboratory.

The factors leading to poor data are well known by experienced analysts and guidance has recently been provided for the inexperienced[4]. However it is clear from recent interlaboratory comparisons[3,5] that even experienced analysts cannot agree at a level that is often required. There is also a lack of clarity concerning what constitutes agreement and what constitutes fitness for purpose.

The results from three studies of trace elements in water summarised in Table 1 illustrate the unsatisfactory situation we find ourselves in. Which if any of these results could be considered satisfactory? Although there is some commonality between the analytes and concentration ranges there is no common reference and it is difficult to compare the data. The CCQM[6] (all abbreviations are detailed at the end of the paper) results were produced by laboratories participating in a metrology exercise where the target for agreement was ± 1%. The coefficients of variation of the results were comparable with those predicted by the Horwitz. equation[7] which might be considered a disappointing outcome for this relatively simple exercise conducted by laboratories who have the time and resources to make reference measurements. The inferior IMEP results relate to significantly lower concentrations where greater difficulty can be expected but again the CVs are comparable with those predicted by Horwitz. The CONTEST results may illustrate the inexperience of some of the participating laboratories, whilst the relatively good performance of AQUACheck laboratories no doubt reflects the depth of experience of most of the routine water laboratories. The above comments are speculative but if the studies were linked to a common reference, it would facilitate comparison and, if needed, help identify strategies for improvement. Also the reference level measurements could be used to calibrate/validate the working level measurements.

TABLE 1 Comparison of Intercomparisons of Trace Elements in Water

Scheme	CCQM	IMEP	CONTEST	AQUAcheck
Concentration (µg/g)	25-50	0.026,0.052	0.05-14	0.2-2
Elements	Mg Pb Cd Li Mo Fe	Pb Fe	Cd Pb Cr	Pb Cr Fe
No of Labs	8	60	40	120
% of Labs within 10% of assigned value	93	33,35	20, 65, 70	80, 70,83

Sources of data:
CIPM-CCQM interlaboratory study 1994
IMEP-IRMM Study
Contest-UK Proficiency Testing Scheme for Contaminated Land Study (1993)
AQUAcheck UK-Proficiency Testing Scheme for water

A number of authors[8-15] have approached the issue of traceability from different perspectives and constructed apparently different models. It is this author's view that none of the models provides a comprehensive description but each provides an element of a framework within which the debate can be conducted and an international chemical measurement system constructed. The fact that different authors use different similes and place emphasis on different issues, enriches rather than impoverishes the overall description.

This paper builds on earlier[16,17] attempts to describe an international chemical measurement system. It discusses the relevance of the concept of traceability of trace analysis and reviews developments leading to a conceptual model for analytical chemistry. It also reports some work in progress to establish an international framework of reference measurements and considers future needs.

TRACEABILITY AND THE MOLE

Traceability is a term that is not much used by analytical chemists but physicists have made good use of it for many years to ensure that measurements of mass, length, time, etc made in different parts of the world are comparable. The following definition[18] applies to all types of measurements including chemical ones.

> **Traceability:** Property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties.

The key issues are: "related to stated references", "unbroken chain of comparisons" and "stated uncertainties". The first issue to consider is the "stated references". By common practice these may be reference methods, reference materials or, when feasible, the preferred references are the SI units. The seven SI base units provide a basis for sound measurement and the international programme of work led by GCPM under the Convention of the Metre, 1875, provides the internationally recognised measurement standards (references) such as the kilogram. Only in the case of the kilogram, the unit of mass, is the measurement standard a material artefact. For other units the quantity, for example length, is realised through a measurement method of a fundamental constant such as the wavelength of radiation corresponding to a specified atomic transition. The mole is the SI unit which underpins chemical measurements although other units such as the kilogram or Ampere are also employed in chemical measurement. The mole was accepted as a base unit by CGPM in 1971 and is defined as:

> **Mole:** The mole is defined as the amount of substance of a system which contains as many elementary entities as there are atoms in 0.012 kilogram of carbon 12. When the mole is used, the elementary entities must be specified and may be atoms, molecules, ions, electrons, other particles or specified groups of such particles (14th CGPM 1971).

The mole is the relative number of particles of a specified substance and is the macro measure equivalent to the number of elementary particles. The concept of chemical equivalence is implicit in the definition and it leads to relative atomic masses based on 12 for carbon 12. The definition follows on from the work of 19th century scientists who established the principles of chemical stoichiometry leading to atomic and molecular weights. Thus the measure or quantity, the mole, recognises the particulate nature of matter and relates atomic/molecular entities to a macro measure which can be determined by mass measurement. Classical chemical reactions provide the basis for analytical techniques such as gravimetry, titrimetry and electro chemical measurements. Modern chromatographic and spectroscopic methods have greatly extended the capability of analytical chemistry, particularly in the fields of trace analysis but the underlying principles of measurement remain largely unchanged. Chemical, spectroscopic or physical separation is used to isolate a specific entity (analyte). The amount of (specific) substance is then measured either by an absolute method (gravimetry) or relative to a chemical standard (reference). The weighing process links the measurement to the SI unit, the kilogram and the chemical stoichiometry, and relative atomic masses of the analyte and standard (reference) link the measurement to the mole. Thus chemical measurements can be traceable to SI including to the mole. Whether they are or not depends on the strength of the links in the chain of comparisons.

The view expressed by Thompson[10], that most chemical measurements are not traceable to the mole (or the kilogram), is not an uncommon misconception amongst analytical chemists. It is claimed correctly that typically chemical measurements are traceable to either a reference material or to a (reference) method. Indeed this paper (see above and below) takes a similar view. However it does not follow that traceability to SI is irrelevant now or in the future. The key issues are the strengths of the links (currently often weak) and the added value (potentially large). The concepts, the quantities and the units underpin measurement. In particular, the concepts underpinning the mole provide a basis for chemical measurement. For example, the particulate nature of matter, stoichiometry/chemical equivalence and relative atomic masses underpin both classical and modern methods of chemical measurement. It was for that reason that scientists, not just chemists, accepted the need for a seventh base unit, the mole. The mole provides a unifying quantity and unit which relates all (chemical) substances and provides a universal measure for amount of (specified) substance.

There are two related issues which are sometimes confused. First is the importance of the quantity the mole. It is, or should be, accepted by the scientific community that the mole is essential for chemical measurement and it seems to me that traceability to the mole has the potential to provide a universal (unchanging with time or place) anchor for chemical measurement. The second issue is the practical use of the mole as a unit. Chemists commonly use non-standard units ranging from ppm to mass per unit volume. Metrologists argue (correctly) that it is better to use SI units where possible. Hence mole per mole is preferred or mole per kilogram would also be acceptable. Whatever the merits of the case it is relatively straightforward to make the conversion and it will probably not be easy to convince analytical chemists to make the change. Which units to use in practice is a separate argument from the one about the quantity, the mole, underpinning chemical measurements. The atomic clock is an essential part of the traceability chain for time. It does not follow that someone running to catch a train needs to be aware of all the steps leading to the universal system of time measurement. Similarly there may be a case for chemists to consider the mole as something they do not have to pay much attention to, but that would be a pity and make the teaching of chemistry more difficult.

Despite my arguments above I have to accept that although the mole has been an SI unit for 25 years it is rarely used and the quantity the "amount of substance" is virtually never used. Perhaps we need to look again at the definition and the terminology[19].

LINKS IN THE CHAIN

Traceability requires an "unbroken chain of comparisons" between a measurement and the "stated references". In the case of physical measurements (mass, length, time, etc) a comprehensive international system of metrology exists providing a readily available means of tracing measurements to SI. For example, the laboratory balance is calibrated with standard masses which are in turn calibrated against the international kilogram standard held by BIPM in Sèvres near Paris through a series of comparisons involving national and secondary standards. The links in the chemical traceability chain are less well defined and the support systems at best only partly in place. Implicit in the definition of the mole is the existence of an unlimited number of different types of entities (analytes). Hence, unlike mass where there is only one fundamental chain, in chemistry there are millions of chains each with its own links.

The potential burden of establishing the links by "unbroken chains of comparisons" is enormous and remains one of the key issues in establishing traceability to SI for the many millions of different types of chemical analysis carried out in working laboratories.

One way of considering the links in a generic way is as follows:

- SI units eg kg, mole, etc
- International standards eg Kg
- Atomic masses
- Pure chemical reference materials

- Primary methods
- Primary matrix reference materials
- Secondary methods and reference materials
- Working methods and reference materials

The purity of pure chemical reference materials must be high and the uncertainty known. For example if the purity is 99 ± 1% the uncertainty of any linked measurement will be at least that level. Hence to carry out an assay at a level of uncertainty of 0.1% requires a primary standard of better than 99.9% purity. For trace analysis however this is not the central issue. Rather it is the validity of the method and the uncertainties resulting from factors such as contamination, interferences, incomplete extraction, etc which lead to poor quality results and breaks in the traceability chains..

A hierarchy of methods can be established such that a primary method is used to validate or calibrate a secondary method which in turn can be directly linked to a working level method. Whereas the primary method will often be expensive and time consuming a typical working level method will be simple but more uncertain. CCQM defined a primary method in 1995 as:

> **Primary Method:** A primary method of measurement is a method having the highest metrological qualities, whose operation can be completely described and understood and for which a complete uncertainty statement can be written down in terms of SI units.

Clearly a primary method must uniquely measure the "specific entity" (analyte) of interest and the relationship between the amount of substance (analyte concentration) and the measured property be free from or corrected for interferences. At its meeting in 1995 CCQM considered that the following methods have the potential to be considered primary:

- isotope dilution with mass spectrometry (IDMS)
- coulometry
- gravimetry
- titrimetry
- determination of freezing point

Further consideration of IDMS is given later in this paper.

Other methods based on elevation of boiling point, osmotic pressure and gas law measurements could also be considered primary but are likely to be of limited application.

A typical chemical measurement involves a number of steps as illustrated in Figure 1. Loss of control of the link at any one of these steps results in a break in the traceability chain. That is the chain is as good as its weakest link.

Analytical chemists are well aware of the complications and difficulties presented by issues such as sample inhomogeneity and sample preparation/separation and in trace analysis the uncertainties arising from these parts of the process are usually much greater than those originating at the final measurement step. It therefore follows that if the introduction of measurement traceability to the field of trace analysis is to be of value it must address all the steps in the process not just the end measurement.

Validation, calibration and quality control are essential to the realisation of traceability

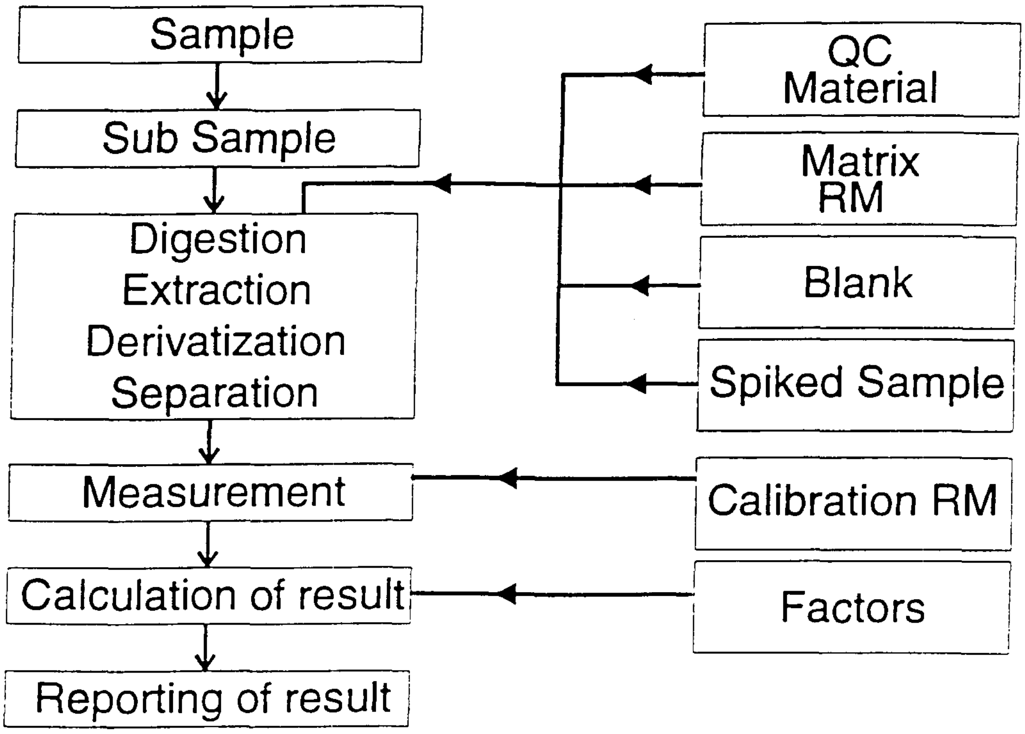


FIGURE 1 **Steps in a Typical Analytical Measurement**

In a typical chemical analysis calibration is carried out by comparing signals obtained from a measurement step for the sample with that obtained for a standard (reference) prepared from a pure specimen of the analyte. Interferences may not be accounted for and losses of analyte due to incomplete extraction or contamination from reagents, for example, may also go unnoticed. In good analytical chemistry circles these issues are addressed during the method validation stage and by making periodic measurements on quality control materials. Analysis of matrix matched reference materials, spiked samples and blanks all contribute to the validation process as does assessment and control of selectivity, specificity, range, linearity, limit of detection, limit of quantitation, ruggedness, bias and precision. The degree of rigor with which these validation, calibration and QC processes are carried out will influence the degree of traceability and whether a method can be considered to be primary.

TRACEABILITY TO STANDARD METHODS

In some instances reference to SI is not feasible, for example in the measurement of fat or fibre in food. The analytes are not sufficiently well defined to be linked to SI and reference to an internationally recognised reference material and or method constitutes the highest form of traceability achievable. In other instances such as the determination of trace levels of pesticides in bread, the method depends on extraction steps which are not completely under control and may involve significantly less than 100% extraction of the analyte from the sample matrix. As a result, an unknown systematic bias exists. There are two ways of treating such methods. The first is to consider traceability to a reference method or reference material so that all laboratories who use the method can obtain comparable results. Providing the bias is not excessive and the qualitative situation is understood in relation to decisions based on the results, such an approach can be reasonable and is certainly common place. A second approach, and probably normally to be preferred, is to attempt to estimate the uncertainty associated with the bias and to build it into the total uncertainty budget. By this means the data is traceable to SI but at a greater level of uncertainty. Although not usually recognised as such by the analytical chemistry community, most trace analysis can be considered to be traceable to a method or reference material. The problem is that the method or reference material is often not firmly anchored. A common problem with standard methods is that they are not fully standardised. Small variations in the measurement procedure employed in different laboratories can result in different results. For example small variations in equipment performance or impurities in reagents can change the method.

REFERENCE LABORATORIES

The final component of the process of maintaining an "unbroken chain of comparisons" are the laboratories who produce the methods, reference materials and measurements. In the physical measurement world there exists a network of laboratories ranging from internationally recognised metrology institutes who develop and maintain international standards or references, to calibration or secondary reference laboratories all of whom provide the transfer standards needed by working level laboratories. This structure which centres on national standards laboratories was largely put in place at the turn of the century. No such structure exists to support chemistry but the concept as illustrated in Figure 2 is clearly also of relevance.

It is, however, necessary to explore in more detail precisely how it might operate. P de Bièvre[8] has written extensively on this subject and explained how different types of laboratories can be fitted into a general model which involves a variety of possible traceability routes: for example, local traceability to a sectoral laboratory and a non-SI reference or traceability via metrology, reference and sectoral laboratories to field or working laboratories. Another of the other possibilities is direct traceability from the SI to field laboratories. The field of analytical chemistry is too large to follow the organisational model established by national physical standards laboratories and greater diversity will be inevitable. Some progress is being made in developing a structure to support analytical chemistry through the work of CCQM, CITAC, EURACHEM and others and this is further discussed later in this paper.

Gas analysis is an area where the international chemical measurement system is probably most highly developed with a fairly extensive network of international comparisons between metrology laboratories now taking place. This area has the advantage of relative simplicity and is often closely associated with the work of national physical laboratories. As a result, work in this area can be expected to stimulate and help lead the development of traceability in chemistry.

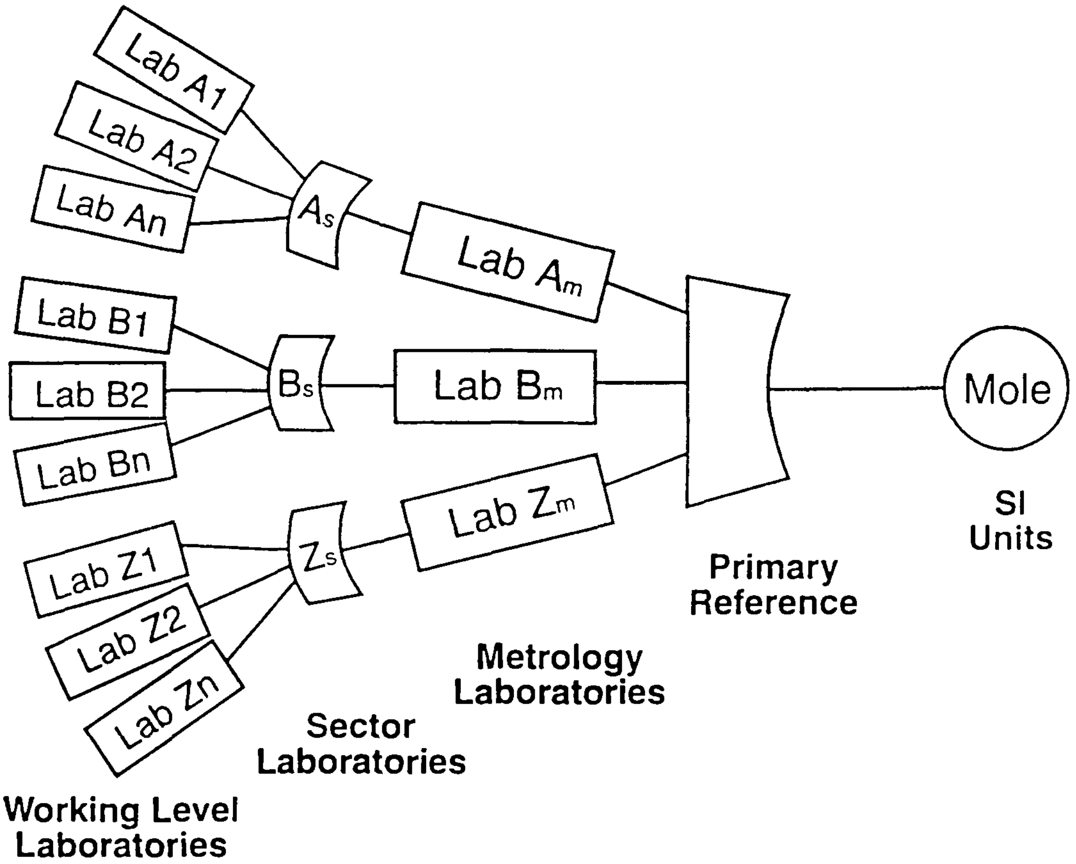


FIGURE 2 Network of Laboratories in Traceability Chain

MEASUREMENT UNCERTAINTY

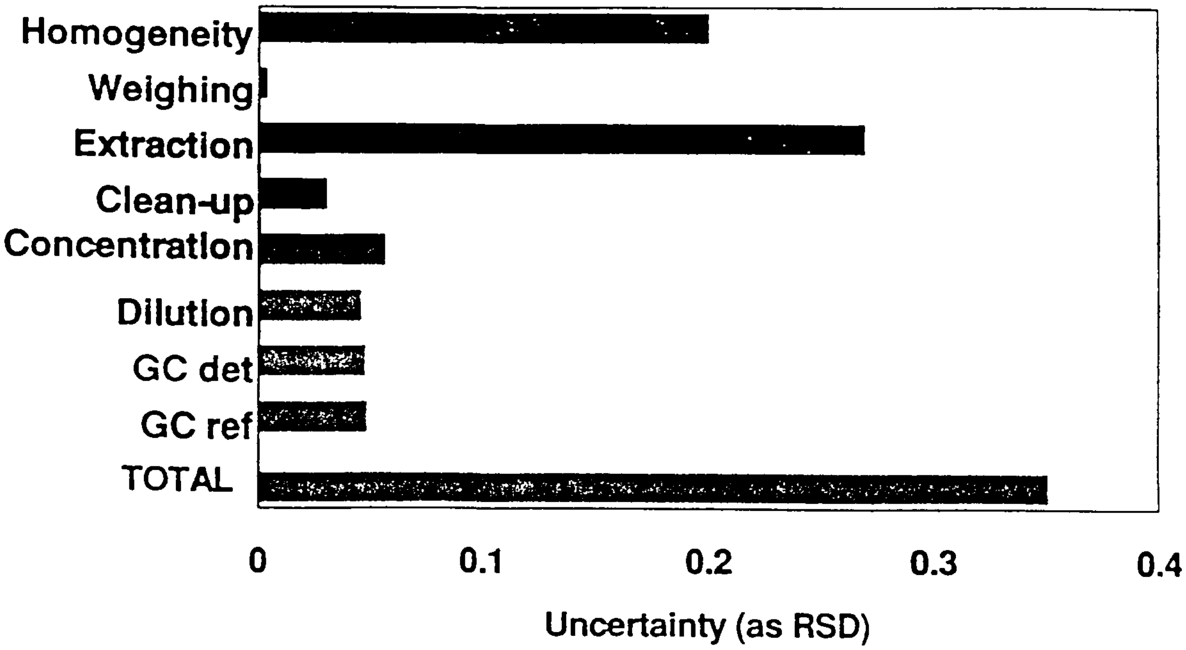
The third requirement for traceability is the availability of "stated uncertainties". Measurement uncertainty is emerging as the preferred means of stating the level of confidence that can be attached to a measurement and offers advantages over other terms such as precision, trueness, etc. It encompasses both random and systematic effects and represents a band within which the true value of a measurement can be expected to lie, with a stated confidence level. It is defined as follows[18]:

> **Uncertainty of Measurement:** parameter, associated with the result of a measurement that characterises the dispersion of the values that could reasonably be attributed to the measurement.

A general strategy for the estimation of measurement uncertainty has been published by ISO[20] and an interpretation which includes four worked examples has been published by EURACHEM[21] The ISO approach to the estimation of uncertainty is to identify individual components such as uncertainty of mass measurements, uncertainty of level of extraction, etc; to quantify each contribution based on estimates derived from experiment, the literature or experience and to combine the components to give a total uncertainty budget. The components (ua-uz) and the combined standard uncertainty Uc are stated as standard deviations and combined as follows:

$$Uc^2 = (ua^2 + ub^2 + ...)^{1/2}$$

Often it is convenient to estimate groups of uncertainty factors within a single uncertainty component and it can be seen from the data presented in Figure 3 that the combined standard uncertainty is dominated by the two largest components. Hence the estimation of uncertainty needs to focus attention on deriving good estimates for the dominant components. To increase confidence Uc is multiplied by a coverage factor. A factor of 2 provides a confidence level of approximately 95% and 2Uc = U, the expanded uncertainty.



Source: S Ellison, LGC

FIGURE 3 **Uncertainty Components for Measurement of Trace Organophosphorus Pesticide in Bread**

Some of the key sources of uncertainty in chemical analysis are as follows[21]:

- Incomplete definition of the measurand (for example, failing to specify the exact form of the analyte being determined)
- Sampling - the sample measured may not represent the defined measurand, for example a sub-sample may not be representative of the bulk, or the sample tested may have degraded with time since sampling
- Incomplete extraction and/or pre-concentration of the measurand
- Matrix effects and interferences
- Contamination during sampling or sample preparation
- Inadequate knowledge of the effects of environmental conditions on the measurement procedure or imperfect measurement of environmental conditions
- Personal bias in reading analogue instruments
- Uncertainty of weights and volumetric equipment
- Instrument resolution or discrimination threshold
- Values assigned to measurement standards and reference materials
- Values of constants and other parameters obtained from external sources and used in the data reduction algorithm

The data given in Figure 3 has been recently derived by LGC colleagues for the determination of organo phosphorous pesticide residue in bread. The standard method involves homogenisation of a loaf of bread, extraction with organic solvent, liquid-liquid extraction to clean up the extract followed by concentration of the extract by gas blow down, dilution to a standard volume followed by GC measurement relative to a pesticide standard solution. Sample inhomogeneity, resulting from uneven distribution of the pesticide within the loaf combined with what proved to be non-representative sub-sampling of the loaf is one of the major contributions to uncertainty as were a series of random and systematic effects associated with the extraction step. The sample homogeneity uncertainty estimate was derived from modeling studies based on experience of factors such as the thermal degradation characteristics of pesticides during baking and the distribution of unbaked flour on the loaf surface. Significant reduction in this component would require redesign of the sampling and homogenisation part of the standard method. The uncertainty component due to the extraction step was estimated from spiking experiments to estimate the level of recovery and duplicate analysis. The led to a correction factor of 1.1 to correct for incomplete recovery of the spike. The combined uncertainty for the extraction step, including allowance for different extraction behaviours between the real analyte and the spike was 0.27 RSD which is the major contribution to the combined standard uncertainty of 0.35 RSD for the complete analysis. The uncertainty contribution from weighing, volume measurements and GC determination were estimated partly from experimental data such as replicate measurement and partly from uncertainties provided by others such as equipment and reference material suppliers. Hence estimation of measurement uncertainty for a measurement partly depends on the availability of uncertainty data for the variety of references (mass, volume, chemical) used within the total measurement process. Also the uncertainty of the measurement cannot be less than the uncertainty components of the contributing references.

Measurement uncertainty can be considered as the strength of the links in the traceability chain. In the pesticide example it would be relatively easy to reduce the uncertainty associated with weighing and volume measurements for example but this would make little improvement in the overall uncertainty or level of traceability which is dominated by chemical factors. Although the expanded combined standard uncertainty (K factor = 2) is large at 0.7 RSD (± 70%) it is realistic for this type of trace analysis (0.01-1mg kg^{-1}) and the measurement can be considered to be traceable to SI. Use of repeatability data alone and failure to correct for the incomplete extraction would of course break the SI traceability links.

It follows from the discussion so far that the traceability and uncertainty of working level measurements are dependent on the traceability and uncertainty of all the references that contribute to the measurement. It is generally accepted by metrologists that higher level references must have an uncertainty better by a factor of about 5 than the measurements they contributed to. That is a chemical reference material with a measurement uncertainty of ± 1% is required in order to make working level measurements at an uncertainty level of ± 5%.

The approximate situation regarding the hierarchy of uncertainty of chemical references is summarised below:

Atomic weights : 1 part in 10^4 to 10^6 depending on the element

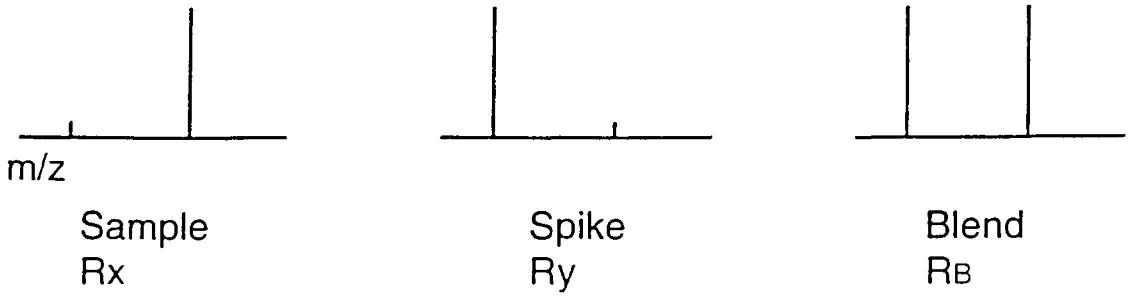
Best metrology laboratories/Reference Material Producers
Assay 1 part in 10^4 - 10^3
Trace 1 part in $2x10^2$ - 10^1

State of art in analytical laboratories
Assay 1 part in 10^3 - 10^2
Trace 1 part in $5x10^1$-10^0

The state of art data represents best practice but there are many instances where laboratory intercomparisons show much greater variability which is largely unrecognised by the participating laboratories. The challenge for those working on traceability is to help improve the visibility of poor quality data and provide support needed for improvement.

ISOTOPE DILUTION MASS SPECTROMETRY (IDMS)

Isotope dilution represents the ideal form of internal standard. The sample is spiked with an isotopically enriched analogue of the analyte which may be elemental or molecular, inorganic or organic. The spike is added as early in the analytical process as possible. In simple terms the unspiked sample (X), the spike (Y) and a blend (B) are analysed by mass spectrometry and the ratios of isotopes measured. The concentration of analyte in the sample can be derived from mass measurements and mass spectrometry isotopic ratio measurements as illustrated in Figure 4. The mass measurements are directly traceable to SI and the isotope measurements are linked to relative atomic masses and hence the mole. Many uncertainty components contributing to multistep analytical processes, such as chemical separation are compensated for in the ratio measurements. Also ratio measurements can be carried out more reproducibly than absolute measurements and thus concentrations can be determined more precisely. Thus the technique has the potential to be a primary method.



$$\frac{N_x}{N_y} = \frac{R_y - R_B}{R_B - R_x} \quad \frac{1 + R_x}{1 + R_y}$$

where Nx and Ny are the number of entities of x and y and RB, Rx and Ry are mass spectrometry ratio measurements

FIGURE 4 Principles of IDMS

The degree to which IDMS compensates for non-quantitative behaviour depends on how closely the spiking process represents the real sample behaviour. For example in Figure 5 situation (a) represents the ideal case where the internal standard (spike) is added to the sample which is digested and completely taken into the solution. This situation generally pertains in inorganic analysis where IDMS is increasingly commonly employed. Situation (b) (Figure 5) is less satisfactory but is sometimes the best that can be achieved in organic analysis. When the analyte is contained within a solid sample and extraction is employed there is the potential for the real analyte to behave differently from the spike during extraction. For example in the case of trace levels of pesticides in bread (see above) the sample pesticide may be bound more strongly than the spike and hence IDMS will not compensate for such effects. Ideally the sample should be totally digested but with organic analysis it can involve a trade off between the vigor of sample treatment and analyte decomposition.

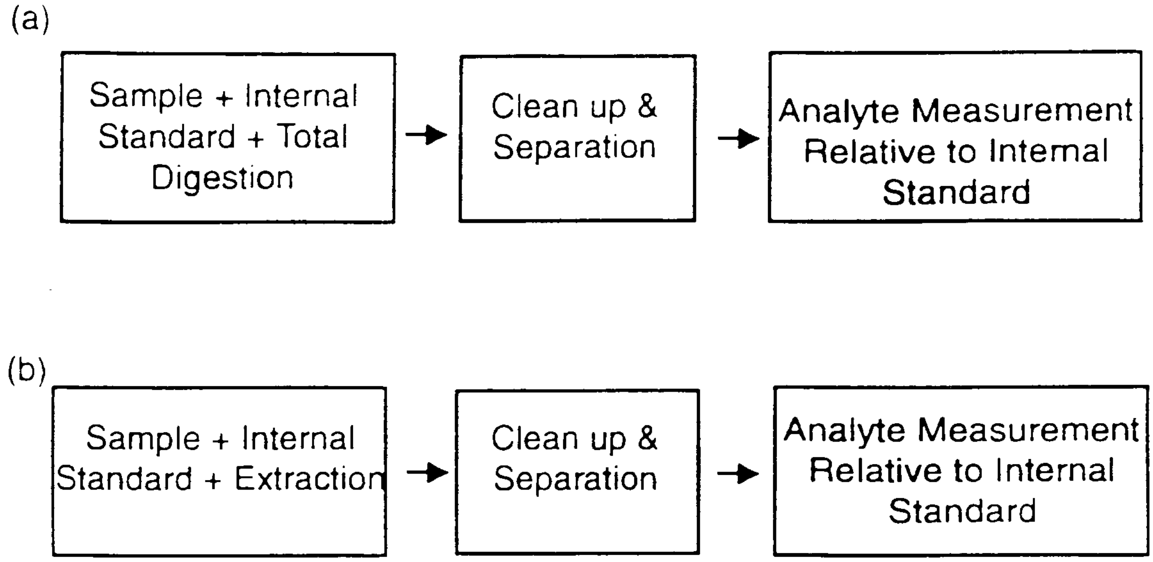
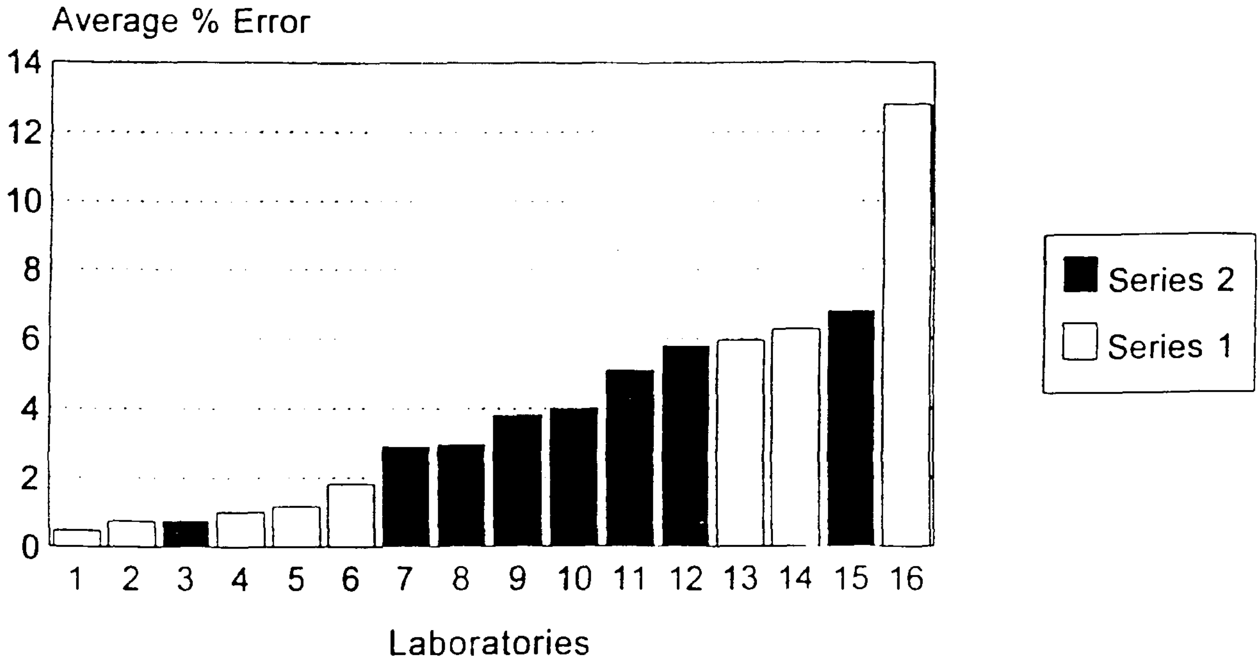


FIGURE 5 **Traceable Analytical Processes**

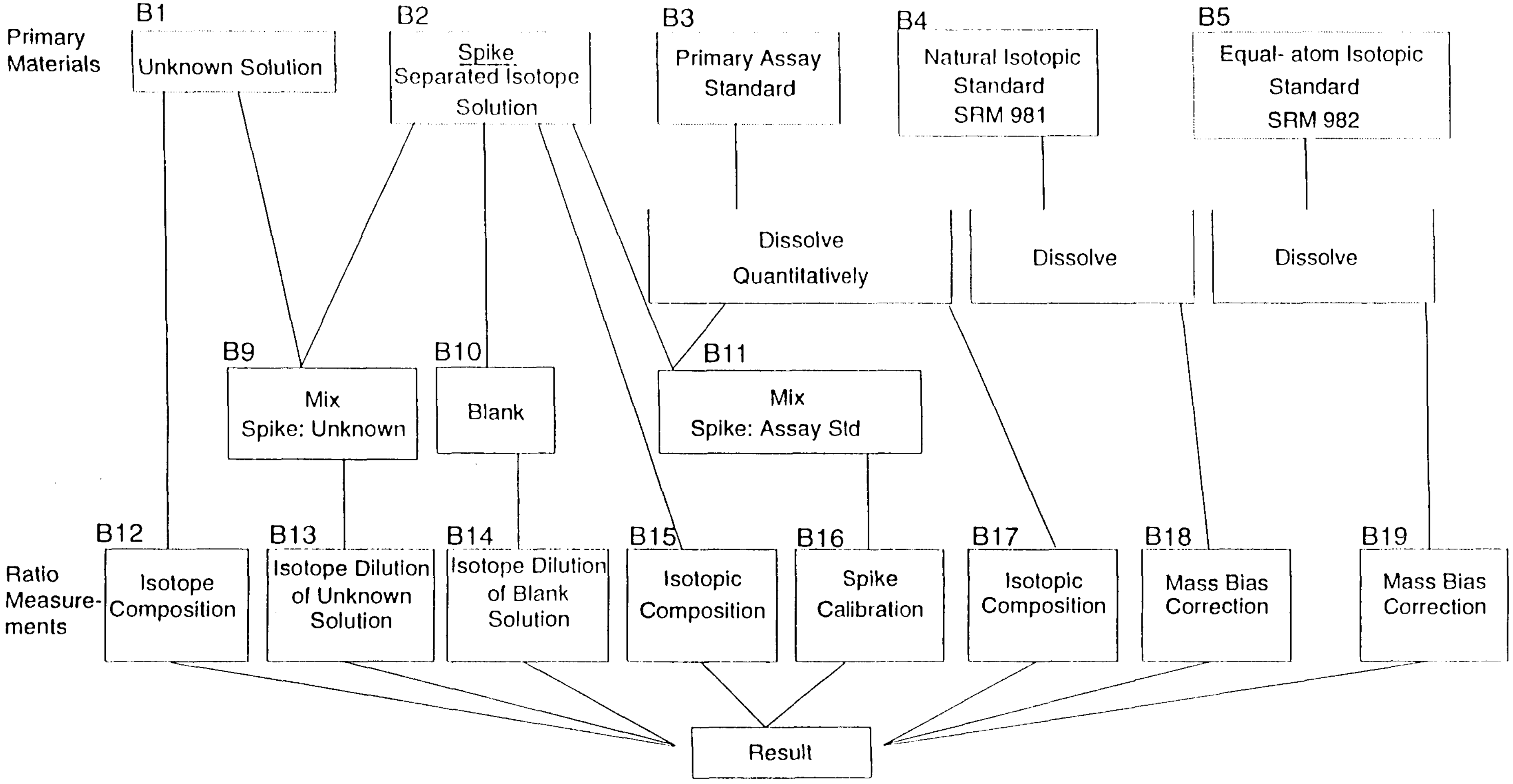
Early elemental analysis work by IDMS was carried out using TIMS which is a difficult and expensive technique limited to a small number of laboratories worldwide. The recent growth in the number of ICPMS instruments has opened up the possibility of IDMS to many analytical laboratories. Whilst TIMS has the potential to produce measurements at 0.01% RSD repeatability compared with 0.1-0.6% RSD for low resolution ICPMS recent work on high resolution ICPMS has closed the gap with repeatability of 0.04% RSD reported[22]. Whilst the potential of IDMS is high we have some way to go before an international support system can be anticipated. The results shown in Figure 6 were obtained by laboratories taking part in a metrological study[6,12] involving trace elements in water (Mg, Pb, Cd, Li Mo, Fe at 25-50$\mu g\ g^{-1}$ levels). The target performance was $\leq \pm 1\%$ relative to the certified value for each element. It is clear from Figure 6 that only five out of sixteen laboratories achieved the desired performance. Whilst five out of the top six laboratories used IDMS, three of the poor performers also employed IDMS. The application of IDMS as a primary method is clearly not without difficulty and Figure 7 illustrates the type of analytical regime that needs to be observed to obtain the best results. Also the technique is critically dependent on the availability of chemically pure (unenriched) reference materials and well characterised and chemically pure isotopically enriched materials. Fortunately despite a declining world nuclear programme isotopically enriched materials for many elements are available and high purity pure substances can also be obtained, certainly at a level appropriate to trace analysis.



Series 1 - IDMS   Series 2 - Other Techniques   February 1994

FIGURE 6 **Average Error per Element for Each Laboratory Participating in CCQM Trace Elements in Water Study (1994)**

Work on organic IDMS has also been in progress for some ye[illegible] The potential advantages of IDMS are illustrated in Table 2 . It is also clear that MS-MS provided no added value for the type of analysis reported and indeed the additional complication resulted in inferior repeatability. In other circumstances where the separating power of MS-MS was needed a different pattern of CVs could be expected. It will be of interest to see the out[illegible]logical interlaboratory study being organised by the LGC on behalf of CCQM. The p[illegible]e (pp'-dichloro-diphenyl) dichloroethylene (pp'DDE) at trace levels is being analysed by a number of laboratories world-wide using IDMS. The results are expected to be available in 1997.



Source R L Watters Jr NIST

FIGURE 7 Steps Involved In IDMS

TABLE 2 **Comparison of IDMS and Conventional Calibration for Trace Pesticides Analysis (pp'-DDE)**

Sample	Method	Mean concentration (μg/g)	CV(%) (N=10)
Solution of pp'-DDE	MS-MS	8.8	39.8
	IDMS-MS	10.05	3.6
	IDMS	10.36	0.6
Bran	MS-MS	0.091	27.2
	IDMS-MS	0.100	4.8
	IDMS	0.100	2.7
Corn Oil	MS-MS	0.220	75.0
	IDMS-MS	0.224	10.4
	IDMS	0.210	3.5

Source: K S Webb & D Carter, LGC 1995

A variation of IDMS being employed for organic analysis is liquid chromatography or gas chromatography linked to a combustion isotope ratio mass spectrometer[25]. Following chromatographic separation the analyte is combusted to carbon-dioxide and water. Modern instruments are capable of determining the $^{13}C/^{12}C$ ratios to a precision of ≈ 10ppm RSD. The overall analytical measurement uncertainty is critically dependent on perfect chromatographic separation and on the quality of reference gases but the technique has considerable potential as a reference method. One of the advantages of the technique is that an isotopically enriched analogue of the analyte is not required.

REFERENCE MATERIALS

Reference materials, sometimes called chemical standards or standard reference materials, are widely employed in chemical analysis for measurement validation, calibration and QC purposes. They may be pure substances characterised for purity, matrix materials characterised for specific compounds, or materials characterised for physico-chemical properties. The highest level of reference materials are certified reference materials (CRM) which are defined as follows[18]:

> **Certified Reference Material (CRM):** reference material, accompanied by a certificate, one or more of whose property values are certified by a procedure which establishes traceability to an accurate realization of the unit in which the property values are expressed, and for which each certified value is accompanied by an uncertainty at a stated level of confidence

Chemical CRMs provide a key link in the traceability chain but at present there is no internationally recognised structure linking CRMs to the 20,00 or so reference materials available world-wide. Many of the materials are produced by national measurement institutes such as NIST or LGC with traceability to these institutions but the linkage between these institutions is only now being put in place through CCQM and CITAC. Table 3 shows proposed classes for reference materials based on the degree of traceability to SI and this or something similar could provide the basis for a standard system. Because of the enormity of the number of required reference materials it will never be possible to produce all that are required. What is needed is a structure which relates high level CRMs to working level materials and the provision of a range of materials to act as beacons for the navigation of the difficult seas of chemical measurement. Just as in nautical navigation the beacons should be placed where the biggest difficulties are expected. A range of materials addressing priority measurement problem areas and covering a selection of matrix types, analytes, sample preparation techniques and end method techniques would provide the basis for such a structure.

TABLE 3 **Classes of Reference Materials Determined by their Traceability**

Class	**Description a;nd Criteria in Terms of Traceability to SI**
0	Pure Specified Entity Certified to SI at the Smallest Achievable Uncertainty
I	Certified by Measurement Against Class 0 RM or SI with Defined Uncertainty by Methods without Measurable Matrix Dependence
II	Verified by Measurement Against Class I or 0 RM with Defined Uncertainty
III	Described Linkage to Class II, I or) RM
IV	Described Linkage Other than to SI
V	No Described Linkage

Within the UK VAM Initiative it is expected that reference materials will be increasingly certified by use of primary methods such as IDMS and in the current programme it is expected that materials ranging from drugs in freezer dried urine to organo metalic compounds in fish tissue will be certified by primary methods. What is now required is the direct international comparisons.

As part of the traceability structure for reference materials it will be necessary to put in place accreditation and certification processes to provide assurance and transparency. Work in this area is also taking place through ISO REMCO and the publication of ISO guide 34. The next step is to establish a mechanism for implementation which links country to country and high level reference materials to working level ones.

COST BENEFIT

Traceability and measurement uncertainty provide a quantitative measure of quality, a basis for fitness for purpose assessments and a basis for cost-benefit analysis. The level of uncertainty and traceability required should be driven by the decision making process. High costs can be incurred by making poor decisions based on inadequate data. Also improved measurement uncertainty can lead to cost reduction in manufacturing processes and in pollution control. At the other end of the spectrum unnecessarily high quality measurements are also costly. Traceability and uncertainty provide the basis for at least a semi-quantitative understanding of measurement quality and cost. By the same analysis it should be possible to show the added value of the high level references in the traceabiity chain.

In the author's laboratory we have experience of undertaking trace element analysis in a wide variety of matrices at performance levels varying from semi-quantitative surveys to high performance metrological measurements. The time and cost varies enormously ranging from 15 minutes to undertake a semi-quantitative (± 10-20%) multielement ICPOES analysis to one week per element for state of the art metrological measurements.

CONTRIBUTING ORGANISATIONS

The feasibility of establishing a traceability system to underpin chemcial measurment is under investigation by a number of international networking groups such as EURACHEM, EUROMET, CITAC, CCQM, ISO, IUPAC and AOAC International. These activities are supported by input from government laboratories, academe and industry and projects ranging from research into new methods and reference materials to interlaboratory studies, conferences, workshops, papers and guides are in progress. A number of countries (UK, USA, Canada, Mexico, Germany, The Netherlands, France, Italy, Sweden, Russia, Japan, Korea and Australia are known to the author) have or are building up robust chemical metrology programmes. The Commission of the European Community through its Joint Research Centre and Framework Programme is also keenly interested in such work. Although there is much to do, good progess is being made. Some examples of significant developments are summarised below.

EURACHEM

- Traceability Workshop 1992
- Measurement Uncertainty Guide
- Strategy papers for the Commission of the European Community

CITAC

- Directory of reference materials in the pipe line
- Directory of chemical metrology activities worldwide
- Definition of criteria for establishing traceability to the mole
- Working level interlaboratory comparisons

CCQM

- Definition of primary method of measurement and studies of the potential of selected methods such as IDMS, gravimetry, etc
- Interlaboratory studies concerned with gas, trace elements and trace organic analysis

THE FUTURE

A great deal of progress has occurred in recent years and although we cannot claim to have even completed the design of an international system, there is an emerging consensus about the key issues, a skeletal framework and even some building blocks. Perhaps the key thing to put in place next is a demonstrator project which actually establishes, for the first time, for selected priority measurements an international network to provide traceable links between working level laboratories in different parts of the world. The main aim would be to test the feasibility and the added value of different ways of establishing traceable links. Such a project would build a cascade network of the type shown in Figure 2 to link primary measurements undertaken, say, by IDMS to standards produced by "sector laboratories" and hence to large numbers of working level laboratories. Measurement of trace elements in clean water would make a good demonstrator project. Water analysis is a topic of practical and regulatory importance in all countries. It has also been established that water measurements made in different laboratories often do not agree (see Table 1). Finally it is an area where research has been conducted to develop primary measurement methods and is simple enough to be used as a metrological model. The hope is that Europe may take a lead and initiate such a programme.

The gap in thinking between metrologists and analytical chemists is also an important issue. The gap is partly conceptual and partly terminological. There is a danger of the cultural gap widening with unhelpful consequences and it is important that greater collaboration and cross-fertilisation is engineered. There is a need for a promotional programme to sell metrolgoy to chemists and to involve more analytical chemists in the work.

It is already clear that traceability is relevant to analytical chemistry but much more work is required to clarify and harmonise concepts, models and systems and to put in place the tools (methods, etc) needed to establish an international system of traceability.

Demonstrator projects will be vital to both the optimisation of systems and to the promotion of the strategy. Also work focused on the areas of large uncertainty (sample and sampling preparation) will be crucial to progress.

In summary the aims of traceability work should be as follows:

- To provide support by provision of traceable reference materials and reference methods
- To ensure that primary references are relevant and linked to working level measurements
- To raise awareness of the importance of traceability amongst analytical chemists and their customers

ACKNOWLEDGMENT

Some of the work described in this paper was carried out with the financial support of the DTI UK Government Valid Analytical Measurement initiative.

ABBREVIATIONS

CCQM	Comité Consultatif pour la Quantity de Matiére
IMEP	International Measurement Evaluation Programme
SI	Systéme International d'Unités
GCPM	Conference génèrale des poids et measures
CITAC	Cooperation on International Traceability in Analytical Chemistry
EURACHEM	A focus for analytical chemistry in Europe
IDMS	Isotope Dilution with Mass Spectrometry
TIMS	Thermal Ionisation Mass Spectrometry
ICPMS	Inductively Coupled Plasma Mass Spectrometry
LGC	Laboratory of the Government Chemist (UK)
NIST	National Institute of Standards and Technology (USA)
ICPOES	Inductively Coupled Plasma Optical Emission Spectroscometry
VAM	UK Valid Analytical Measurement Initiative funded by government

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