1

The Analytical Approach

LEARNING OBJECTIVES

- To be aware of the different types of contamination that can cause problems in trace elemental analysis.
- To know about Health and Safety in the working environment.
- To be able to carry out a Risk Assessment for safe laboratory and in-field practice.
- To appreciate the units used in analytical chemistry.
- To be able to report numerical data with the appropriate assignment of significant figures.
- To be able to present numerical data with correct units and be able to interchange the units as required.
- To know how to present and report laboratory information in an appropriate format.
- To be able to determine the concentration of an element from a straight-line graph using the equation $y = mx + c$.
- To be able to calculate the dilution factor for a liquid sample and a solid sample, and hence determine the concentration of the element in the original sample.
- To appreciate the concept of quality assurance in the analytical laboratory.
- To be aware of the significance of certified reference materials in elemental analysis.
- To develop an understanding of reporting and interpreting the data generated in its appropriate context.

1.1 Introduction

Trace elemental analysis requires more than just knowledge of the analytical technique to be used; in this case, inductively coupled plasma spectrometry. It requires knowledge of a whole range of disciplines that need to come together to create the result. The disciplines required can be described as follows:

- Health and Safety in the laboratory (and external environment);

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- sampling, sample storage and preservation and sample preparation methodologies appropriate to sample type;
- analytical technique to be used;
- data control, including calibration strategies and the use of certified reference materials (CRMs) for quality control and data assurance;
- data management, including reporting of results and their interpretation, context and meaning.

While most of these are covered to some extent in this book, the reader should also consult other resources; for example, books, scientific journals and the web.

1.2 Essentials of Practical Work

The perspective that is required when faced with trace element analysis are the additional precautions required in terms of management of contamination, choice of reagents and acids and cleanliness of the workspace. For example, the grade of chemical used to prepare calibration standards is a major concern when working at (ultra) trace element analysis levels (sub-$\mu g\,ml^{-1}$). Chemicals are available in a range of grades from 'reagent grade' or 'technical grade' through to 'analytical reagent grade', for example, ACS reagent, AristaR®, >99% purity or PUROM™, Optigrade®, picograde® and ReagentPlus®. For 'analytical reagent grade' materials, the manufacturer has characterized the identity and concentration of impurities by subjecting it to stringent chemical analysis. Therefore, the use of sample and reagent blanks in the analytical procedure is essential to identify 'problem elements' that could interfere and to analyse and report data accordingly.

The risk of contamination is a major problem in trace element analysis. Apart from the analytical reagent used to prepare standards, as discussed previously, contamination can also be experienced from sample containers used for storage or quantitative analysis, for example, volumetric flasks, pipettes and so on. For example, metal ions can adsorb onto glass containers and then leach into the solution under acidic conditions, thereby causing contamination. This can be minimized by cleaning the glassware prior to use by soaking for at least 24 hours in a 10% nitric acid solution, followed by rinsing with 'clean' deionized water (three times). The cleaned vessels should then either be stored upside down or covered with Clingfilm® to prevent dust contamination.

For ultra-trace element analyses it will be necessary to perform all laboratory work in a cleanroom. Cleanrooms are designed to maintain extremely low levels of particulates, such as dust, airborne organisms or vaporized particles that could otherwise contaminate the sample or standard during its preparation

and analysis. Ultimately, such contamination leads to an error in the reporting of the analytical result.

1.3 Health and Safety

It is a legal requirement for institutions to provide a working environment that is both safe and without risk to health. In the UK, the *Health and Safety at Work Act 1974* provides the legal framework for Health and Safety. The introduction of the *Control of Substances Hazardous to Health (COSHH)* Regulations in 2002 imposed specific legal requirements for risk assessment when hazardous chemicals (or biological agents) are used. This is often evidenced by the provision of training and information on safe working practices in the laboratory. For the student, this is often done by attending an appropriate safety briefing, the reading (and subsequent signing) of the safety booklet acknowledging an understanding of safety and their role in protecting themselves and other students as well as receiving appropriate training in the use of scientific equipment (e.g. the instrumentation described in this book).

Prior to undertaking any laboratory work, a *Risk Assessment* must be undertaken by an appropriately identified person (e.g. supervisor, academic or technical staff). The purpose of the Risk Assessment is to identify laboratory activities that could cause injury to people and then to provide control measures to ensure that the risk is reduced. Important considerations are:

- substance hazards
- how the substance is to be used
- how it can be controlled
- who is exposed
- how much exposure and its duration

It is important to distinguish between the hazard of a substance and its risk from exposure. This can be done by doing a *Risk Matrix Analysis (RMA)*. The RMA allows a prioritization of the *likelihood* and *severity* to the individual from the hazard identified. All manufacturers of hazardous chemicals are required to provide a *Material Safety Data Sheet (MSDS)* for the stated chemical. The MSDS will contain information about the chemical including:

- manufacturer
- name of chemical
- chemical components
- hazards associated with the product (including a Hazard Statement and a Precautionary Statement)
- first aid measures

- firefighting measures
- handling and storage
- accidental release procedures
- exposure control and personal protection
- physical and chemical properties
- stability and reactivity
- toxicological and ecological information
- disposal practices
- other miscellaneous information

With this information the user must then complete a COSHH form (Table 1.1). As part of the COSHH process specific details of the Hazard Statement and Precautionary Statement, for each chemical, must be included (Table 1.2). Then, assess the *likelihood* of harm coming to pass given the amount/nature of the chemical to be used and the environment/manner it is to be used in; at this stage, the likelihood is assessed on the basis that no specific control measures are being taken. The likelihood therefore assesses the highest risk. After assessing the likelihood, the next stage is to consider the *severity* of the risk. This is done by considering the substance-specific risk (rather than the activity specific risk). Again, like the likelihood this considers the highest severity. By then performing the RMA (*Risk* = *Likelihood* × *Severity*) (Table 1.3) you arrive at the risk for using the chemical.

The individual working in the laboratory is also a major source of contamination. Therefore, as well as the normal laboratory safety practices of wearing a laboratory coat and safety glasses, it may be necessary to take additional steps such as the wearing of 'contaminant-free' gloves and a close-fitting hat as well as working in a fume cupboard or for ultra-trace elemental analysis a cleanroom.

1.4 SI Units and Their Use

The Systeme International d'Unites (SI) uses a series of base units (Table 1.4) from which other terms have been derived. Some of the most commonly used SI derived units are shown in Table 1.5. When using units, it is standard practice to keep numbers between 0.1 and 1000 using a set of prefixes, based on multiples of 10^3 (Table 1.6). It is an extremely useful skill to be able to interchange these units and prefixes. For example, $1\,\mathrm{mol\,l^{-1}}$ can also be expressed as $1000\,\mu\mathrm{mol\,ml^{-1}}$, $1000\,\mathrm{mmol\,l^{-1}}$ or $1000\,\mathrm{nmol\,\mu l^{-1}}$. However, for practical purposes a $1\,\mathrm{mol\,l^{-1}}$ solution is the most useful term.

Table 1.1 An example Control of Substances Hazard to Health (COSHH) form.

Section 1: Overview

Names of chemicals to be used:	*Enter the name of each hazardous chemical to be used*		
Title of activity:	*Enter the title of the activity*		
Brief description of the activity:	*Briefly describe the activity to be undertaken*		
Responsible person:	*Enter name of the member of staff responsible for your work e.g. supervisor*		
Faculty / Department	*Enter the name of your Faculty / Department*		
Date of assessment	*Enter the date*	**Date of Re-assessment**	*Enter the date one year from now*
Location of work:	*Enter the name of Building / Laboratory in which the work will be carried out.*		

Section 2: Emergency Contacts (e.g. project supervisor).

Name	Position	Contact Telephone Number
Enter the name	*Enter their position*	*Enter their telephone number*

Section 3: Hazard Identification

3.1 For hazardous substances in this activity, click all that apply.					
	☐ Toxic		☐ Severe Health Hazards		☐ Health Hazards
	☐ Explosive		☐ Flammable		☐ Oxidising
	☐ Corrosive		☐ Gases Under Pressure		☐ Environmental

3.2 Select the hazard phrases (H-phrases) for each hazardous substance.			
1.	*Select a Hazard phrase*	e.g.	H302-Harmful if swallowed
e.g.	H226-Flammable liquid and vapour	e.g.	EUH014 - Reacts violently with water

(*Continued*)

Table 1.1 (Continued)

Section 4: Hazard Properties

Name of substance	Physical form	Quantity	Frequency	Route of exposure
Enter substance name	*Enter physical form*	*Enter the quantity*	*Enter the frequency*	*Select route*
e.g. Chemical name	solid dust	1 g	weekly	Ingestion

Section 5: Identifying Those at Risk

5.1 Who might be at risk? Select all that apply.		
☐ Staff/PGRs	☐ Taught Students	☐ Young persons (under 18 years old)
☐ New or expectant mothers	☐ Others:	

5.2 Assessment of risk to human health before control measures are in place.
Select the likelihood and severity of harm in the presence of the identified hazards **before** the control measures outlined above are implemented. Calculate the risk rating and act accordingly.

Likelihood of harm	Severity	Risk Rating and Outcome (likelihood x Severity)
e.g. 2. Unlikely	*2. Minor Injury*	*5. Good lab practice required.*

Section 6: Control Measures (Specify control procedures to each hazardous substance identified in section 4.)

6.1 Physical or engineering controls.				
☐ Laboratory	☐ Controlled area	☐ Total containment	☐ Glove Box	☐ Fume cupboard
☐ Microbial safety cabinet	☐ Local exhaust ventilation	☐ Access control	☐ Other: *Enter details*	
You must also specify below at which point in the work activity they are to be used.				
Specify at which point the control measures should be implemented				
6.2 Administrative controls.				
Describe administrative controls				

Table 1.1 (Continued)

6.3 Personal protective equipment (PPE).			
	☐ Eyewear protection (Minimum standard CE EN166)		☐ Disposable lab coat
	☐ Lab coat		☐ Chemical suit
	☐ Specialised footwear. (Minimum standard EN ISO 20345) State type: *Enter details here*		☐ Hearing protection (Minimum standard EN352-1) State type: Enter details here
	☐ Gloves State minimum standard: ☐ BS EN455 – single use for chemical hazards. ☐ BS EN374 – single use for chemicals hazards and microorganisms. State type used: Enter details here		☐ Respirator State type: ☐ Disposable P3 (Minimum standard EN149) ☐ Replaceable filter (Minimum standard EN140) ☐ Powered respirator. State type used: *Enter details here*
	☐ Full-face visor		☐ Other State: *Enter details here*
6.4 Storage requirements.			
Describe storage conditions			
6.5 Transport of hazardous substances.			
Describe how you will transport the hazardous substances			
6.6 Disposal of waste. If specialised waste is to be generated, you must discuss this with a member of technical staff and consult the university waste policy.			
Waste type	**Waste subtype**	**Detail method of disposal**	
Select waste type e.g. liquid	*Select a waste sub-type e.g. Inorganic waste*	*Describe the method of disposal e.g. down the sink with plenty of water*	
6.7 Emergency procedures.			
Minor spillage (for less than 250 mL / 250 g of materials with a low-medium risk rating).		**Major spillage (for greater than 250 mL / 250 g of materials with a low-medium risk rating, or any high risk materials).**	
☐ Secure the spill area.		☐ Evacuate and secure the laboratory/area.	
☐ Inform a competent person (e.g. a member of technical staff or your supervisor).		☐ Inform a competent person (e.g. a member of technical staff or your supervisor).	

(*Continued*)

Table 1.1 (Continued)

☐ Other *Describe other emergency procedures*			☐ Evacuate the building using the fire alarm.		
In the event of fire, assuming you are trained in the handling of extinguishers and it is safe to do so, specify which types of fire control may be used:					
☐ Carbon dioxide	☐ Water	☐ Dry powder	☐ Foam	☐ Fire blanket	☐ Automatic fire suppression
☐ Other	*Describe other fire control measures here, if applicable*				
In the event of an accident requiring first aid, seek assistance as soon as possible. Detail below any specific considerations, which must be made for the hazardous substances in use.					
☐ If hazardous material comes into contact with skin, remove any affected clothing and wash the area with copious amounts of water. ☐ For large areas rinse the skin using the emergency shower.			☐ If hazardous material comes into contact with the eyes, rinse the eyes using an eye wash station. ☐ For serious eye burns, use diphoterine station.		
☐ For phenol burns, wash with copious amounts of water and apply polyethylene (PEG) 300 to the area.			☐ For hydrofluoric acid burns, wash with copious amounts of water and apply calcium gluconate gel to the area.		
☐ If cyanide has been inhaled, move the victim to fresh air.			☐ Other. Please state: *Enter details here*		
6.8 Assessment of risk to human health once control measures are in place. Select the likelihood and severity of harm in the presence of the identified hazards after the control measures outlined above are implemented. Calculate the risk rating and act accordingly. Guidance may be found in the appendix by clicking here.					
Likelihood of harm	**Severity**	**Risk Rating and Outcome (Likelihood x Severity)**			
Enter likelihood e.g. 2. Unlikely	*Enter severity e.g. 1. Delay only*	*Enter risk rating e.g. 2. Good laboratory practice only required*			
6.9 Instruction, training and supervision. In consultation with the approver, specify the level of training and supervision required to safely carry out the work described. **Select all that apply.**					
☐ Special instructions are required to safely carry out the work.					
☐ Special training is required to safely carry out the work.					
☐ Work may be carried without direct supervision.			☐ Work may be carried without indirect supervision.		
☐ Work may not be started without the advice and approval of the approver.			☐ Work may not be carried out without close supervision.		

Table 1.1 (Continued)

Section 7: Approval
I hereby confirm that the above is a suitable and sufficient risk assessment for the work activity described.

7.1 The assessor.		
Name	**Signature**	**Date**
7.2 The approver (if required).		
Name	**Signature**	**Date**

Table 1.2 Examples of (a) Hazard[a)] and (b) Precautionary[b)] statements.

(a)

Letter	Type of hazard	Intrinsic properties of the substance	Example
H	2 = Physical	e.g. Explosive properties for codes 200–210; flammability for codes 220–230 etc.	H302 harmful if swallowed
H	3 = Health		
H	4 = Environmental		

(b)

Letter	Type of precaution	Examples
P	1 = General precaution	P102 Keep out of the reach of children
P	2 = Prevention precaution	P281 Use personal protective equipment as required
P	3 = Response precaution	P301 If swallowed:
P	4 = Storage precaution	P404 Store in a closed container
P	5 = Disposal precaution	P501 Dispose of contents/container to …

a) There are 72 individual and 17 combined Hazard statements.
b) There are 116 individual and 33 combined Precautionary statements.

Table 1.3 Risk matrix analysis.[a)]

			Severity					
			6	**5**	**4**	**3**	**2**	**1**
Likelihood			multiple fatalities	single fatality	major injury	lost time injury	minor injury	delay only
	6	certain	36	30	24	18	12	6
	5	very likely	30	25	20	15	10	5
	4	likely	24	20	16	12	8	4
	3	may occur	18	15	12	9	6	3
	2	unlikely	12	10	8	6	4	2
	1	remote	6	5	4	3	2	1

a) *Note: Low risk:* numerical score 1–10. Good laboratory practice (including Personal Protective Equipment of a laboratory coat and safety glasses) required. *High risk:* numerical score 12–18. Specific identified control measures must be used. *Very high risk:* numerical score 20+. Trained personnel only.

Table 1.4 Some commonly used base SI units.

Measured quantity	Name of SI unit	Symbol
Length	Metre	m
Mass	Kilogram	kg
Amount of substance	Mole	mol
Time	Second	s
Thermodynamic temperature	Kelvin	K

Table 1.5 Some commonly used derived SI units.

Measured quantity	Name of unit	Symbol	Definition in base units	Alternative in derived units
Electric charge	Coulomb	C	$A\,s$	$J\,V^{-1}$
Energy	Joule	J	$m^2\,kg\,s^{-2}$	$N\,m$
Force	Newton	N	$m\,kg\,s^{-2}$	$J\,m^{-1}$
Frequency	Hertz	Hz	s^{-1}	—
Pressure	Pascal	Pa	$kg\,m^{-1}\,s^{-2}$	$N\,m^{-2}$
Power	Watt	W	$m^2\,kg\,s^{-3}$	$J\,s^{-1}$

Table 1.6 Commonly used prefixes.

Multiple	Prefix	Symbol
10^{15}	peta	P
10^{12}	tera	T
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p
10^{-15}	femto	f

1.5 Significant Figures

A common issue when recording data from practical work is the mis-reporting of significant figures. This issue is important as it conveys an understanding of the key concepts in data treatment. The following examples illustrate the issues and how they can be interpreted.

For example, when asked to accurately weigh an approximate 0.5 g of sample, how many decimal places should be reported? In this situation it would be expected that a four-figure decimal place analytical balance would be used to accurately weigh out the sample. On that basis, the sample would be recorded as 0.5127 g.

In practical terms, the sample would have been weighed by difference, that is, a sample container would be first weighed on a four-figure decimal place analytical balance, then the sample placed inside the container and the weight again recorded and, finally, the sample transferred to a digestion vessel and the sample container re-weighed. By taking the weights of the container with/without the sample allows an accurate recording of the weight of sample transferred into the digestion vessel.

In addition, for example, if you have a numerical value, representing a weight or concentration, of 276.643 it would be reasonable to represent this as: 276.6 or even 277. If the value was 0.828, then it may be reasonable to round up to 0.83. Whereas for a value of 12763. It would be reasonable to report as 12763 or, in some circumstances, 12760.

Finally, for example, is it appropriate to report the concentration of an element in a solid sample as 25.21345678 mg kg^{-1}? No, a more appropriate reporting of the concentration would be 25.2 mg kg^{-1}.

In general terms the following guidance is provided:

- When rounding up numbers to the fourth decimal place, add one to the last figure if the number is greater than 5; for example, 0.54667 would become 0.5467.
- When rounding down numbers to the fourth decimal place, remove one to the last figure if the number is less than 5; for example, 0.54662 would become 0.5466.
- For a number 5, round to the nearest even number; for example, 0.955 would become 0.96 (to two significant figures) *or* if the value before 5 is even, it is left unchanged; for example, 0.945 would become 0.94 (to two significant figures) *or* if the value before 5 is odd, its value is increased by one; for example, 0.955 would become 0.96 (to two significant figures).
- Zero is not a significant figure when it is the first figure in a number; for example, 0.0067 (this has two significant figures, 6 and 7). In this situation it is best to use scientific notation, for example, 6.7×10^{-3} or, as the number is normally associated with a unit use the prefix milli, m; for example, 6.7 mg.

1.6 Calibration and Quantitative Analysis

Quantitative analysis in plasma spectroscopy requires the preparation of a series of calibration standards from a stock solution. These standards are prepared in volumetric flasks. Calibration solutions are usually prepared in terms of their molar concentrations, that is, mol l^{-1}, or mass concentrations, that is, g l^{-1}, with both referring to an amount per unit volume; that is, concentration = amount/volume. It is important to use the highest (purity) grade of chemicals (liquids or solids) for the preparation of the stock solution; for example, an analytical reagent grade.

For example, the preparation of a $0.1\ \text{mol l}^{-1}$ solution of lead from its metal salt in a 1 l volumetric flask would be done as follows. Using the molecular weight of lead nitrate, $Pb(NO_3)_2$ (331.20) and the atomic weight of lead (207.19) you simply multiply the molecular weight by the desired molarity ($0.1\ \text{mol l}^{-1}$) to give you the exact amount of lead nitrate to be dissolved in 1 l of solution to produce a $0.1\ \text{mol l}^{-1}$ solution of lead.

$$\text{that is, } (331.20\ \text{g mol}^{-1} \times 0.1\ \text{mol l}^{-1}) = 33.1200\ \text{g of } Pb(NO_3)_2 \text{ in } 1\ \text{l}$$

However, it is often the case that 1 l of solution would not be required; a more realistic volume would be 100 ml. In that case, each weight of material would need to be divided by 10. Therefore, 3.3120 g of $Pb(NO_3)_2$ would be dissolved in 100 ml of solution to produce a $0.1\ \text{mol l}^{-1}$ Pb solution.

Similarly, for example, if you wish to prepare a 1000 µg ml^{-1} solution of lead from lead nitrate you simply divide the molecular weight by the atomic weight to give you the exact amount of lead nitrate to be dissolved in 1 l of solution to produce a 1000 µg ml^{-1} solution of lead.

that is, (331.20 / 207.19) = 1.5985 g of $Pb(NO_3)_2$ in 1 l.

However as before, it is often the case that 1 l of solution would not be required; a more realistic volume would be 100 ml. In that case each weight of material would need to be divided by 10. Therefore, 0.1599 g of $Pb(NO_3)_2$ would be dissolved in 100 ml of solution to produce a 1000 µg ml^{-1} stock solution of Pb.

[*Note:* the mass concentration µg ml^{-1} (it could also be expressed as mg l^{-1}, for example) is also referred to as ppm (parts per million).]

1.7 Making Notes of Practical Work and Observations

It is often convenient when carrying out laboratory work to record your data in a laboratory notebook (hardback paper or electronic notebook format). It is important that you always accurately record, in whatever format used, your name, module code, details of what you did, reagents and chemicals used, equipment and instrumentation used, accurate weights and volumes, duration times and practical observations. Some specific tips are provided on recording information in your hardback notebook:

- Record data correctly and legibly (even you may not be able to read your own writing later).
- Write in ink (and not pencil, which fades with age).
- Include the date and title of individual experiments and/or areas of investigation.
- Briefly outline the purpose of the experiment; that is, what you hope to know by the end.
- Identify and record the hazards and risks associated with the chemicals/equipment being used.
- Refer to the method/procedure being used (undergraduate laboratory) or write a full description of the method/procedure and its origins (postgraduate research).
- Record your observations (and note your interpretation at this stage); for example, accurate weights, volumes, how standards and calibration solutions were prepared and instrumentation settings (and the actual operating parameters).

Table 1.7 Recording quantitative data for the analysis of lead by inductively coupled plasma–mass spectrometry (ICP–MS).

Concentration ($\mu g\ l^{-1}$)	^{208}Pb intensity (counts s^{-1})
0	565
10	19887
20	45356
30	59876
40	78543
50	99654

- Record data with the correct units, for example, mg or $\mu g\,g^{-1}$, and to an appropriate number of significant figures, for example, 26.3 mg or 0.48 $\mu g\,g^{-1}$ (and not 26.3423 mg or 0.4837 $\mu g\,g^{-1}$).
- Interpret data in the form of tables and calibration graphs.
- Record initial conclusions.

[*Note:* Example templates for the recording of laboratory information are provided in Chapter 8. Included in the Chapter 8 Appendices are example templates for: Sample pre-treatment; Sample preparation; ICP–AES analysis and ICP–MS analysis.]

A useful approach is to accurately record quantitative laboratory results in tabular format. This is often best done by creating two columns into which the data can be entered. It is essential, however, for future consultation of these data, that the columns are given the appropriate headings, for example, concentration ($\mu g\,l^{-1}$) and signal (mV), to prevent errors occurring later. It is also important to record details of any sample dilutions that have taken place (see Chapter 8, Laboratory Templates). A typical table of data for an experiment to determine the concentration of lead is shown in Table 1.7. In the case of electronic (e)-notebooks laboratory proformas will be available, as per the Laboratory Templates in Chapter 8, that allow information and data to be inserted and recorded in a pre-determined format and style.

1.8 Data Analysis

In quantitative data analysis it is normal to plot a graph using either dedicated instrument software or another commercial computer-based graphics package, for example, Microsoft Excel™, rather than by hand on graph paper. [*Note*: You should remember, however, that you may still need the skill to plot a graph by hand on graph paper in a university examination unless the examination has

gone on-line!] Irrespective of the mode of preparing the graph, it is important to ensure that the graph is correctly labelled and presented. All graphs should have a numerical descriptor and title, for example, 'Figure 5.1 Calibration of Pb by ICP-AES'.

Graphs are normally used to describe a relationship between two variables, for example, x and y. It is normal practice to identify the x-axis as the horizontal axis (abscissa) and to use this for the independent variable, for example, concentration (with its appropriate units, e.g. $\mu g\,ml^{-1}$). The y-axis as the vertical axis (ordinate) is used to plot the dependent variable, for example, signal response (with appropriate units, e.g. mV). The mathematical relationship used for linear straight-line graphs is:

$$y = mx + c \tag{1.1}$$

where y is the signal response, for example, signal (mV), x is the concentration of the working solution (in appropriate units, e.g. $\mu g\,ml^{-1}$), m is the slope of the line of best fit of the graph and c is the intercept on the x-axis.

Then, by a simple re-arrangement allows the determination of the unknown sample concentration (x):

$$(y - c)/m = x \tag{1.2}$$

A typical graphical representation of data (a *direct calibration graph*) obtained from an experiment to determine the level of lead in a sample using inductively coupled plasma–mass spectrometry (ICP–MS) is shown in Figure 1.1a.[1]

An alternative approach to undergoing a *direct calibration*, as described before, is the use of the method of *standard additions*. This may be particularly useful if the sample is known to contain a significant portion of a potentially interfering matrix. In standard additions, the calibration plot no longer passes through zero (on both the x- and y-axes). As the concept of standard additions is to eliminate any matrix effects present in the sample, it should be implicit that the working standard solutions will all contain the same volume of the sample; that is, the same volume of the sample solution is introduced into a succession of working calibration solutions. Each of these solutions containing the same volume of the sample is then introduced into the inductively coupled plasma and the response recorded. However, plotting the signal response (e.g. signal (mV)) against analyte concentration produces a graph that no longer

1 R is known as the *correlation coefficient*, and provides a measure of the quality of calibration. In practice, R^2 (the *coefficient of determination*) is used because it is more sensitive to changes. This varies between −1 and +1, with values very close to −1 and +1 pointing to a very tight 'fit' of the calibration curve.

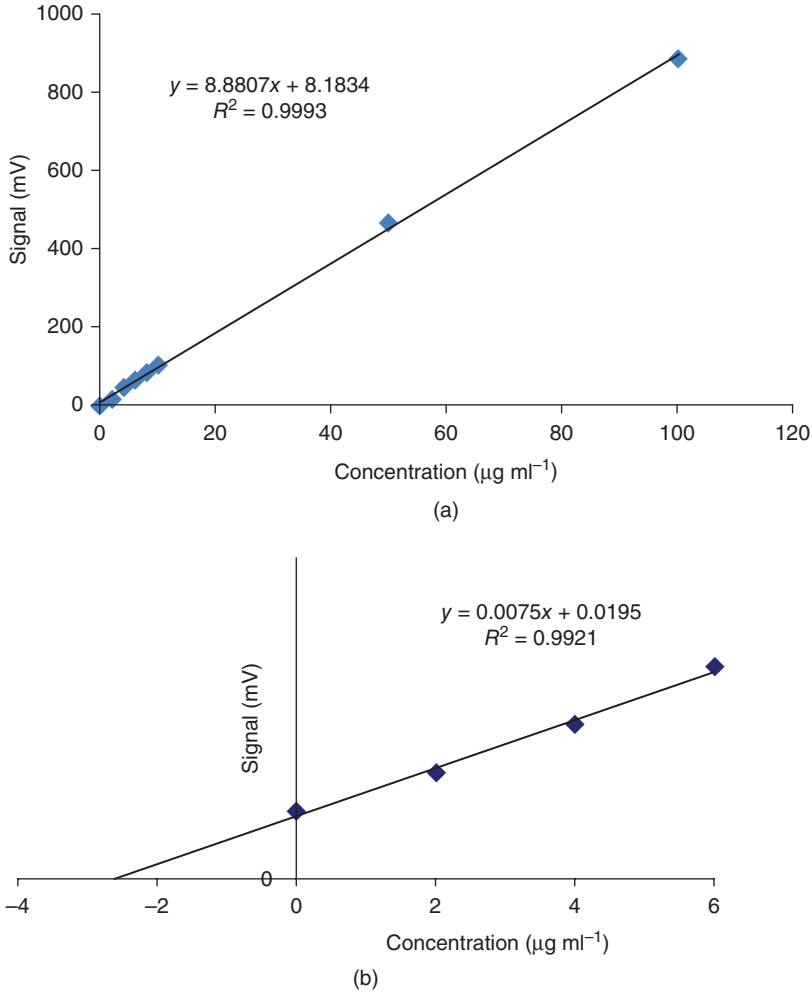

Figure 1.1 Calibration graphs. (a) a direct calibration graph and (b) a standard additions method calibration graph.

passes through zero on either axis, but if correctly drawn, the graph can be extended towards the *x*-axis (extrapolated) until it intercepts it. By maintaining a constant concentration *x*-axis, the unknown sample concentration can be determined (Figure 1.1b).[1] It is essential that this graph is linear over its entire length or otherwise considerable error can be introduced.

The limit of detection (LOD) of an analytical procedure is the lowest amount of analyte in an unknown sample that can be detected but not necessarily quantified, that is, recorded as an exact concentration. The LOD, expressed as

a concentration (in appropriate units), is derived from the smallest measure, x, that can be detected with reasonable certainty for a given procedure. One approach to determine the LOD is to measure the signal of a known concentration at or near the lowest concentration that is observable (normally at least seven times). The value C_L is given by the equation:

$$C_L = C_{LCS} + K.SD_{LCS} \tag{1.3}$$

where C_{LCS} is the mean of the low concentration standard, SD_{LCS} is the standard deviation of the low concentration standard and K is a numerical factor chosen according to the confidence level required (typically 2 or 3).

An alternate format, that uses the signal-to-background ratio (SBR) to calculate the LOD is:

$$C_L = (3 \times C_{LCS} \times RSD_B) / SBR \tag{1.4}$$

where RSD_B is the relative standard deviation of the background signal.

As LODs are often not practically measurable a more realistic value is to use the limit of quantitation (LOQ) of an analytical procedure. The LOQ is the lowest amount of a metal in a sample that can be quantitatively determined with suitable certainty; the LOQ can be taken as 10 times 'the signal-to-noise ratio' or $K = 10$ in Eq. (1.3).

1.9 Data Treatment

In both the direct calibration graph and the method of additions graph, the result obtained from the sample is normally not the final answer of how much of the metal was in the original sample. This is because the sample has normally undergone some form of sample preparation (see Chapter 3). In the case of a solid sample, this might have involved acid digestion (see Section 3.2.1), while in the case of a liquid sample, liquid–liquid extraction (see Section 3.1.1) or other form of extraction (see Section 3.3). What is therefore required is a correction to the concentration data obtained from the calibration; often the application of a dilution or concentration factor that considers the sample preparation procedure. The following provides examples of the general forms of calculations that are necessary in the case of (i) a liquid sample that has been extracted using ammonium pyrrolidine dithiocarbamate (APDC)–methyl isobutyl ketone (MIBK) and (ii) a solid sample that has been acid-digested or extracted.

For example, calculate the concentration ($\mu g\,ml^{-1}$) of copper in a waste water sample obtained from the local waste treatment plant. A waste water sample (150 ml) was extracted with APDC–diethylammonium diethyldithiocarbamate (DDDC) into MIBK (20 ml) using liquid–liquid extraction. The extract was then

quantitatively transferred to a 25.0 ml volumetric flask and made up to the mark with MIBK. What is the dilution factor?

$$25\,\text{ml} / 150\,\text{ml} = 0.167\,\text{ml ml}^{-1} = 0.167 \text{ (with no units)}$$

[*Note:* that the dilution factor only considers the final volume of extract (i.e. 25.0 ml) and the initial sample volume (150 ml of waste water).]

If the solution was then analysed and found to be within the linear portion of the graph (see Figure 1.1a), the value for the dilution factor should then be multiplied by the concentration from the graph, producing a final value indicating the concentration of copper in the waste water sample.

In addition, for example, calculate the concentration ($\mu g\,g^{-1}$) of lead in a soil sample obtained from a contaminated land site. An accurately weighed (5.2456 g) soil sample was acid-digested using nitric acid and hydrogen peroxide, cooled and then quantitatively transferred to a 100.0 ml volumetric flask and made up to the mark with distilled water. This solution was then diluted by taking 10.0 ml and transferring to a further 100.0 ml volumetric flask where it is made up to the mark with high-purity water. What is the dilution factor?

$$[(100.0\,\text{ml}) / (5.2456\,\text{g}) \times (100.0\,\text{ml} / 10.0\,\text{ml})] = 190.64\ \text{ml g}^{-1}$$

If the solution was then analysed and found to be within the linear portion of the graph (see Figure 1.1a), the value for the dilution factor should then be multiplied by the concentration from the graph, so producing a final value indicating the concentration of lead in the contaminated soil sample.

[*Note*: This type of calculation would be used for the use of alternate extraction protocols (see Section 3.3).]

1.10 Data Quality

It is essential to know whether the data obtained is appropriate. Quality assurance is all about getting the correct result. The main objectives of a quality assurance scheme are as follows:

- to select and validate appropriate methods of sample preparation;
- to select and validate appropriate methods of analysis;
- to maintain and upgrade analytical instruments;
- to ensure good record-keeping of methods and results;
- to ensure quality of the data produced;
- to maintain a high quality of laboratory performance.

The following are examples of important aspects of establishing and maintaining such a QA scheme:

- Individual performing the analyses
  - Has the individual been trained in the use of the instrumentation and/or procedures? If so by whom (where they trained or experienced)?
  - Was the training formal (formal qualification or certificate of competency obtained) or done in-house?
  - Can the individual use the instrumentation alone or do they require oversight?
- Laboratory procedures and practices
  - Do the procedures use CRMs to assess the accuracy of the method?
  - Do the procedures use spiked samples to assess recoveries? Samples are spiked with a known concentration of the analyte under investigation and their recoveries noted; this allows an estimate of analyte matrix effects to be made.
  - Do the procedures include analysis of reagent blanks? Always analyse reagents whenever the batch is changed or a new reagent introduced. This allows reagent purity to be assessed and, if necessary controlled, and also acts to assess the overall procedural blank; typically introduce a minimum number of reagent blanks; that is, 5% of the sample load.
  - Do the procedures use standards to calibrate instruments? A minimum number of standards should be used to generate the analytical curve, for example, a minimum of five. Daily verification of the calibration plot should be done using one or more standards within the linear working range.
  - Do the procedures include the analysis of duplicate samples? Analysis of duplicates or triplicates allows the precision of the method to be determined and reported.
  - Do the procedures include known standards within the sample run? A known standard should be run after every 10 samples to assess instrument stability; this also verifies the use of a daily calibration plot.

In implementing a good quality control programme, it is necessary to analyse a CRM. A CRM is a substance for which one or more elements have known values and estimates of their uncertainties, produced by a technically valid procedure, accompanied with a traceable certificate and issued by a certifying body. Typical examples of certifying bodies are the National Institute for Standards and Technology (NIST), based in Washington, D.C., USA, the Community Bureau of Reference (BCR), Brussels, Belgium and the Laboratory of the Government Chemist (LGC), London, UK. The accompanying certificate, in addition to providing details of the certified elemental concentration and their uncertainties in the sample, also provides details of the minimum

sample weights to be used, storage conditions, moisture content and so on. An example of a typical certificate is shown in Figure 1.2. The incorporation of a suitable CRM alongside your unknown samples provides an opportunity for the accuracy (see Section 1.12) of your sample preparation methodology and analysis protocol to be investigated. A large range of CRMs across a broad range of sample matrices are available. It is appropriate to choose a CRM with a similar/same matrix as your sample types. Then, by comparing your obtained element concentration data for the CRM and its certificate value you can decide on whether your sample preparation methodology and analysis protocol are appropriate (or not). Agreement with the element concentration data to within a standard deviation of the certificate data confirms its suitability for application with the unknown samples. If the values obtained are outside the defined certified data range, a re-evaluation of *all* procedures, working practices and reagents used is required to establish any inherent issue(s) that have led to inaccurate data being obtained. Once the situation is resolved, and often this is by trial and error as well as intuition and past experience, the CRM would be re-sampled, prepared and re-analysed until the data obtained is within the defined data limits for each element.

Figure 1.2 Diagrammatic representation of a certificate as supplied with a Certified Reference Material.

International Organization Name

Type of matrix

Element	Concentration (wt.%)	Element	Concentration (mg kg^{-1})
Calcium	1.504 ± 0.013	Cadmium	(0.011)*
Magnesium	0.251 ± 0.009	Copper	5.34 ± 0.21
Phosphorus	0.140 ± 0.009	Lead	0.560 ± 0.022
Potassium	1.31 ± 0.03	Nickel	0.86 ± 0.09
Sulfur	(0.09)*	Zinc	12.1 ± 0.4

Notes:

The material will be provided in a sealed container alongside this certificate. The certificate, in addition to providing details of the certified (and indicative) elemental concentrations and their uncertainties in the sample, also provides details of the minimum sample weights to be used, storage conditions, moisture content, details of how analysed and so on.

*Values in parentheses are indicative values only.

1.11 Data Interpretation and Context

It is essential that the data obtained is placed in its context and interpreted. For example, the concentration obtained by the analysis and verified by a quality assurance scheme generates a trustworthy and reliable value. However, the interpretation and contextualization of the obtained metal concentration is essential. This might be, for example, against known legislative values that need to be enforced, for food protection and dietary requirements, metallurgical analysis of steel for bridge building and metal impurities in a catalyst for polymer production. So, it might be that the concentration obtained in the original sample is reported or that the concentration obtained is converted into a decision, for example, safe or not safe, good quality or poor quality.

1.12 Analytical Terms and Their Definitions

Finally, some useful analytical terms and their definitions are presented. The most important analytical terms of use in practical inductively coupled plasma spectrometry are:

- *Accuracy*. A quantity referring to the difference between the mean of a set of results or an individual result and the value that is accepted as the true or correct value for the quantity being measured.
- *Acid digestion*. Use of acid (and often heat) to destroy the organic matrix of a sample to liberate the metal content.
- *Aliquot*. A known amount of a homogenous material assumed to be taken with negligible sampling error.
- *Analyte*. The component of a sample that is ultimately determined directly or indirectly.
- *Bias*. Characterizes the systematic error in each analytical procedure and is the (positive or negative) deviation of the mean analytical result from the (known or assumed) true value.
- *Calibration*. The set of operations that establish, under specified conditions, the relationship between values indicated by a measuring instrument or measuring system and the corresponding known values of the measurand.
- *Calibration curve*. Graphical representation of a measuring signal as a function of quantity of analyte.
- *Certified Reference Material (CRM)*. Reference material, accompanied by a certificate, one or more of whose property values are certified by a procedure that establishes its traceability to an accurate realization of the units in which the property values are expressed, and for which each certified value is accompanied by an uncertainty at a stated level of confidence.

- *Coefficient of determination*. The measure of the quality of calibration is often expressed as R^2 because it is more sensitive to changes. Values vary between −1 and +1, with values very close to −1 and +1 pointing to a very tight 'fit' of the calibration curve.
- *Complexing agent*. The chemical species (an ion or a compound) that will bond to a metal ion using lone pairs of electrons.
- *Confidence interval*. Range of values that contains the true value at a given level of probability. The latter is known as the *confidence level*.
- *Confidence limit*. The extreme values or 'end-values' in a confidence interval.
- *Contamination*. In trace analysis this is the unintentional introduction of analyte(s) or other species that are not present in the original sample and may cause an error in the determination. This can occur at any stage in the analysis. Quality assurance procedures, such as analyses of blanks or of reference materials, are used to check for contamination problems.
- *Control of Substances Hazardous to Health (COSHH)*. Regulations that impose specific legal requirements for risk assessment wherever hazardous chemicals (or biological agents) are used.
- *Co-precipitation*. The inclusion of otherwise soluble ions during the precipitation of lower-solubility species.
- *Correlation coefficient*. The measure of the quality of calibration (R). R^2 is known as the *coefficient of determination*.
- *Dilution factor*. The mathematical factor applied to the determined value (data obtained from a calibration graph) that allows the concentration in the original sample to be determined. Frequently, for solid samples, this will involve a sample weight and a volume to which the digested/extracted sample is made up to prior to analysis. For liquid samples, this will involve an initial sample volume and a volume to which the digested/extracted sample is made up to prior to analysis.
- *Dissolved*. Material that will pass through a 0.45 µm membrane filter assembly prior to sample acidification.
- *Dry ashing*. Use of heat to destroy the organic matrix of a sample to liberate the metal content.
- *Error*. The error of an analytical result is the difference between the result and a 'true' value:
  - *Random error*. Result of a measurement minus the mean that would result from an infinite number of measurements of the same measurand carried out under repeatability conditions.
  - *Systematic error*. The mean that would result from an infinite number of measurements of the same measurand carried out under repeatability conditions, minus the true value of the measurand.

- *Extraction*. The removal of a soluble material from a solid mixture by means of a solvent or the removal of one or more components from a liquid mixture by use of a solvent with which the liquid is immiscible or nearly so.
- *Figure of merit*. A parameter that describes the quality of performance of an instrument or an analytical procedure.
- *'Fitness for purpose'*. The degree to which data produced by a measurement process enables a user to make technically and administratively correct decisions for a stated purpose.
- *Heterogeneity*. The degree to which a property or a constituent is randomly distributed throughout a quantity of material. The degree of heterogeneity is the determining factor of sampling error.
- *Homogeneity*. The degree to which a property or a constituent is uniformly distributed throughout a quantity of material. A material may be homogenous with respect to one analyte but heterogeneous with respect to another.
- *Interferent*. Any component of the sample affecting the final measurement.
- *Limit of detection (LOD)*. The detection limit of an individual analytical procedure is the lowest amount of an analyte in a sample that can be detected but not necessarily quantified as an exact value. The LOD, expressed as either the concentration C_L or the quantity Q_L, is derived from the smallest measure, C_L, that can be detected with reasonable certainty for a given procedure. The value C_L is given by Eq. (1.3). For many purposes, the LOD is taken to be $3S_{bl}$ or 3 times 'the signal-to-noise ratio', assuming a zero blank.
- *Limit of quantitation*. For an individual analytical procedure, this is the lowest amount of an analyte in a sample which can be quantitatively determined with suitable uncertainty. It may also be referred to as the *limit of determination*. The LOQ can be taken as 10 times 'the signal-to-noise ratio', assuming a zero blank.
- *Linear dynamic range (LDR)*. The concentration range over which the analytical working calibration curve remains linear.
- *Linearity*. This defines the ability of the method to obtain test results proportional to the concentration of analyte.
- *Liquid–liquid extraction*. A method of extracting a desired component from a liquid mixture by bringing the solution into contact with a second liquid, the solvent, in which the component is also soluble, and is immiscible with the first liquid or nearly so.
- *Matrix*. The carrier of the test component (analyte), all of the constituents of the material except the analyte, or the material with as low a concentration of the analyte as it is possible to obtain.
- *Measurand*. A quantity subject to measurement.
- *Method*. The overall, systematic procedure required to undertake an analysis. This includes all stages of the analysis, and not just the (instrumental) end determination.

- *Microwave digestion*. A method of digesting an organic matrix to liberate metal content by using an acid at elevated temperature (and pressure) based on microwave radiation. Can be carried out in either open or sealed vessels.
- *Organometallic*. An organic compound in which a metal is covalently bonded to carbon.
- *Outlier*. This may be defined as an observation in a set of data that appears to be inconsistent with the remainder of that set.
- *Precision*. The closeness of agreement between independent test results obtained under stipulated conditions.
- *Qualitative analysis*. Chemical analysis designed to identify the components of a substance or mixture.
- *Quality assurance*. All those planned and systematic actions necessary to provide adequate confidence that a product or services will satisfy given requirements for quality.
- *Quality control*. The operational techniques and activities that are used to fulfil requirements of quality.
- *Quality control chart*. A graphical record of the monitoring of control samples which helps to determine the reliability of the results.
- *Quantitative analysis*. This is normally taken to mean the numerical measurement of one or more analytes to the required level of confidence.
- *Reagent*. A test substance that is added to a system to bring about a reaction or to see whether a reaction occurs (e.g. an analytical reagent).
- *Reagent blank*. A solution obtained by carrying out all steps of the analytical procedure in the absence of a sample.
- *Recovery*. The fraction of the total quantity of a substance recoverable following a chemical procedure.
- *Reference material*. This is a material or substance, one or more of whose property values are sufficiently homogeneous and well established to be used for the calibration of an apparatus, the assessment of a measurement method or for assigning values to materials.
- *Repeatability*. Precision under repeatability conditions; that is, conditions where independent test results are obtained with the same method on identical test items in the same laboratory, by the same operator, using the same equipment within short intervals of time.
- *Reproducibility*. Precision under reproducibility conditions, that is, conditions where test results are obtained with the same method on identical test items in different laboratories, with different operators, using different equipment.
- *Robustness*. For an analytical procedure, this is a measure of its capacity to remain unaffected by small, but deliberate variations in method parameters, and provides an indication of its reliability during normal usage. It is sometimes referred to as ruggedness.

- *Sample*. A portion of material selected from a larger quantity of material. The term needs to be qualified; for example, representative sample, subsample and so on.
- *Selectivity (in analysis)*. Qualitative – the extent to which other substances interfere with the determination of a substance according to a given procedure. Quantitative – a term used in conjunction with another substantive (e.g. constant, coefficient, index, factor, number etc.) for the quantitative characterization of interferences.
- *Signal-to-noise ratio*. A measure of the relative influence of noise on a control signal. Usually taken as the magnitude of the signal divided by the standard deviation of the background signal.
- *Solvent extraction*. The removal of a soluble material from a solid mixture by means of a solvent or the removal of one or more components from a liquid mixture by use of a solvent with which the liquid is immiscible or nearly so.
- *Speciation*. The process of identifying and quantifying the different defined species, forms or phases present in a material or the description of the amounts and types of these species, forms or phases present.
- *Standard (all types)*. A standard is an entity established by consensus and approved by a recognized body. It may refer to a material or solution (e.g. an organic compound of known purity or an aqueous solution of a metal of agreed concentration) or a document (e.g. a methodology for an analysis or a quality system). The relevant terms are as follows:
  - *Analytical standard (also known as a Standard solution)*. A solution or matrix containing the analyte which will be used to check the performance of the method/instrument.
  - *Calibration standard*. The solution or matrix containing the analyte (measurand) at a known value with which to establish a corresponding response from the method/instrument.
  - *External standard*. A measurand, usually identical with the analyte, analysed separately from the sample.
  - *Internal standard*. A measurand, like but not identical with the analyte, which is combined with the sample.
  - *Standard method*. A procedure for carrying out a chemical analysis which has been documented and approved by a recognized body.
- *Standard addition*. The addition of a known amount of analyte to the sample to determine the relative response of the detector to an analyte within the sample matrix. The relative response is then used to assess the sample analyte concentration.
- *Stock solution*. This is generally a standard or reagent solution of known accepted stability, which has been prepared in relatively large amounts of which portions are used as required. Frequently, such portions are used following further dilution.

- *Sub-sample*. This may be either (i) a portion of the sample obtained by selection or division, (ii) an individual unit of the lot taken as part of the sample or (iii) the final unit of multi-stage sampling.
- *True value*. A value consistent with the definition of a given quantity.
- *Uncertainty*. A parameter associated with the result of a measurement that characterizes the dispersion of the values that could reasonably be attributed to the measurand.

1.13 Summary

The methodology for trace elemental analysis requires an understanding of a whole range of inter-related issues centred around the sample, sample preparation, analysis, data interpretation/presentation and quality assurance. This chapter has highlighted some of the most important aspects. In addition, the main strategies for calibration are discussed, including the preparation of a standard solution.