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TECHNICAL GUIDE ON DIRECT-READING DEVICES FOR AIRBORNE AND SURFACE CHEMICAL CONTAMINANTS

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1 INTRODUCTION

1.1 Purpose of this Technical Guide

Direct-reading devices (DRDs) are primarily used to monitor the atmosphere for airborne pollutants, which can be present as gases, vapours, aerosols (including fibres) or fume. They are also used to a lesser, but increasing extent, for the measurement of surface contamination. DRDs include both spot-reading (grab sampling) and real-time monitors, which typically provide continuous measurement.

Within the United Kingdom, there are over a hundred suppliers (manufacturers and their agents) of DRDs and several hundred different instruments available for purchase. Most users require a device which is specific, sensitive, accurate, small, lightweight and trouble-free. However, this is not always practicable and compromises have to be made. This Guide has been developed to provide some general background information and to assist in the selection, application and use of DRDs for workplace monitoring.

The sections in this Guide comprise:

1. Introduction
2. Legislative requirements
3. Methodology
4. Selection criteria
5. Electrical Safety in potentially explosive atmospheres
6. Characteristics of DRDs:
 - a. principle of operation,
 - b. operating characteristics,
 - c. advantages and limitations
7. Performance standards and guides for use
8. The future
9. References
10. Bibliography

Appendix 1 lists most of the types of DRD in common use to help with the selection of the most appropriate device for the monitoring task. Further information can be found in European Standards (see References), NIOSH (2012a and 2012b) and the Bibliography, on the CoGDEM website (www.cogdem.org.uk) relating to gas detection, including the CoGDEM guide (Greenham, 2012) and the BOHS website (www.bohs.org) relating to consultants who have expertise in use of DRDs.

1.2 General usage of DRDs

DRDs can be used in a variety of ways but the correct selection of an appropriate DRD is essential, otherwise the exposure control strategy can be compromised, employees exposed to contaminants and their health and safety put at risk.

DRDs can be personal, portable, transportable or located in a fixed position. They can be used for a variety of purposes, including:

- providing warning of a situation which is potentially hazardous (oxygen deficiency or the presence of a flammable or toxic atmosphere or surface);

- measurements in confined spaces;
- testing the effectiveness of health risk control measures;
- area monitoring;
- spot-reading measurements;
- measurement of personal exposure;
- measurement of peak exposures;
- assisting a health risk assessment process;
- measurement of exposure for comparison with a short term exposure limit (STEL);
- measuring changes in the concentration of airborne or surface contaminants over time;
- boundary fence monitoring;
- video exposure monitoring (see Rosén et al (2005) for a review).

'Traditional' air monitoring and measurement methods involve the collection of airborne contaminants by drawing air through collection devices such as filters or sorbents at a steady flow rate for a fixed period of time. This is followed by gravimetric or chemical analysis which can be resource- and/or capital-intensive. A sampling device is normally worn by the person whose exposure is being measured and the results compared with relevant occupational exposure limits (OELs), defined as workplace exposure limits (WELs) in Great Britain. This enables those involved in health protection activities to establish whether exposure to hazardous substances is likely to present a health risk. The results normally represent the mean exposure over the measurement period, that is, the time-weighted average (TWA), but do not provide information about the nature of variation in concentration during the measurement period.

Some air monitoring DRDs can be used in place of traditional measurement, where the device samples the atmosphere in the breathing zone (defined as a personal monitor) and determines specific components. In some cases, frequent readings can be taken at predetermined intervals and the results stored in the device's datalogger. This stored data can be subsequently downloaded and information on the mean exposure and variation in exposure with time can be obtained. With such applications, various data management facilities are normally made available for presenting the information as required. For example, the data can be displayed in a spreadsheet or as a graph, either using software supplied with the DRD or other proprietary software.

Hand-held air monitoring DRDs can be used in a similar way. They do not provide direct information on personal exposure, as they are not usually located in the breathing zone, but on the concentration of airborne contaminants at certain locations. They can therefore be used for regular "walk through" surveys in order to establish spatial or temporal changes in the concentration of airborne contaminants. In most cases, these devices are used to measure specific components. However, depending on their level of sophistication, they may be susceptible to varying degrees of interference from other substances which may also be present in the atmosphere.

As a rule, portable and transportable DRDs tend to be larger and more sophisticated than personal devices. They can be used to take multiple measurements over a period of time and discriminate between several different types of components.

Fixed-position air monitoring devices (for area monitoring, also known as static monitoring) are generally used to detect leaks at selected sites (e.g., hazard warning, fugitive emission monitoring, checking the effectiveness of control) and can offer the user varying degrees of sophistication. They may be connected to a control room to initiate preventative action (alerts) or initiate control measures, such as ventilation or emergency shut down.

With the move in the EU to employment in smaller companies, more emphasis is being placed on control banding and advice on suitable control systems to complement compliance with Occupational Exposure Limits. Control banding groups workplace hazards into risk ‘bands’ and identifies appropriate controls to reduce the level of risk. This has led to new roles being identified for DRDs in ensuring that systems deployed to control exposure to airborne gases/vapours and dusts are actually effective.

It is impractical to exhaustively outline the relative advantages and disadvantages that DRDs have over conventional sampling and analysis methods as there are many different variants offering different levels of performance. Generally, the advantages include:

- convenience (no sample handling or storage);
- direct readout of results in real-time;
- information on the variation in concentration with time;
- data on short-term exposures;
- data on peak exposures and peak exposure patterns;
- high or low level alarms;
- long-term, calibration-free operation.

A major disadvantage of air monitoring DRDs is that few devices enable direct and reliable comparison of results with OELs because there can be interferences (chemical or physical) which introduce bias into the measurement. Consequently, there is insufficient specificity or accuracy for the compound(s) of interest. Nevertheless, for certain contaminants, e.g. many gases, DRDs are the technique of choice. Despite any disadvantages, DRDs are useful tools that assist health and safety practitioners in assessing occupational health and safety risks from air and surface contaminants within working and ambient environments.

2 LEGISLATIVE REQUIREMENTS

2.1 General

Within the UK, the principal regulations governing substances hazardous to health in the workplace are the Control of Substances Hazardous to Health (COSHH) Regulations, and DRDs can play an important role in assessing compliance. The Confined Space Regulations cover another important area where DRDs have an impact for monitoring both toxic and flammable gases. The use of flammable gases and dusts is governed by the Dangerous Substances and Explosive Atmospheres Regulations (DSEAR) while for offshore installations, the Offshore Installations (Prevention of Fire and Explosion, and Emergency Response) Regulations (PFEER) apply. However, as DRDs are used to aid risk management, they may be used in support of other health and safety legislation which may involve measurement of chemical agents.

2.2 COSHH Regulations

In the UK, the Control of Substances Hazardous to Health (COSHH) Regulations 2002 (as amended), and the Approved Code of Practice and guidance (HSE, 2005), provide a framework for protecting people from hazardous substances. The basic principles of occupational hygiene underlie the COSHH Regulations:

1. Assess risks to health arising from work and identify what precautions are needed.
2. Introduce appropriate measures to prevent or control risk.

3. Ensure that control measures are used and that such equipment is properly maintained and relevant procedures observed.
4. Where necessary, monitor exposure of workers and carry out appropriate health surveillance.
5. Inform, instruct and train employees about health hazards presented and the precautions implemented to reduce risks to an acceptable level.

COSHH (Regulation 10) requires that the exposure of workers should be monitored when any of the following circumstances apply, unless suitable procedures for monitoring do not exist, or cannot be devised, or it is immediately obvious whether control is adequate:

- when failure or deterioration of the control measures could result in a serious health effect, either because of the toxicity of the substance or the extent of potential exposure, or both;
- when measurement is necessary so as to be sure that the Workplace Exposure Limit (WEL) or any self-imposed working standard is not exceeded; or
- when necessary as an additional check on the effectiveness of any control measure provided in accordance with the Regulations, and always in the case of the substances or processes specified in Schedule 5 of these Regulations (i.e. vinyl chloride monomer and spray given off from vessels at which an electrolytic chromium process is carried out, except trivalent chromium).

The employer must assess the degree of exposure and the risks and devise and implement adequate control measures; these control measures must be checked and maintained. Regulation 9 of COSHH specifies the frequency of examination and testing for some controls, such as local exhaust ventilation (LEV) which must be at least once every 14 months; others should be thoroughly examined and tested "*...at suitable intervals...*".

Guidance on LEV has been published by HSE. HSG258 (HSE, 2008a) is specifically aimed at suppliers of LEV goods and services, while INDG408 (HSE, 2008b) and INDG409 (HSE, 2008c) are aimed respectively at employers buying and running LEV systems and employees using them. The guidance clarifies a number of design, installation, maintenance and examination issues. In particular, measurement methods to establish the effectiveness of LEV by use of 'air quality' monitors, e.g. gas or dust detectors, will be especially useful in ensuring that LEV provides adequate control of exposure as required by COSHH.

2.3 Confined Space Regulations

The correct use of DRDs can be crucial in determining whether the atmosphere within a confined space is safe to breathe, both prior to entry and throughout the period that a worker remains within that space. Ensuring safe levels of oxygen and toxic or flammable gases is a legal requirement, covered by the Confined Space Regulations (CSR). The HSE has produced guidance in the Approved Code of Practice, Regulations and Guidance (HSE, 2009), while INDG258 (HSE, 2006a) is a shorter industrial guidance note, helping to define particular hazards and suggesting techniques for 'testing the air'.

2.4 Compressed Air Regulations

Working under compressed air, i.e. in hyperbaric conditions, is covered by the Work in compressed air regulations and code of practice (HSE, 1996). Pressurization levels are typically up to 2 bar (gauge), i.e. 3 bar absolute, although the legal maximum working pressure in Great Britain is 3.5 bar (gauge). WELs are used as part of a regulatory approach to the control of workplace exposure to toxic gases. However, WELs listed in EH40 (HSE, 2005a) are approved only for use where the atmospheric pressure is between 900 and 1100 mbar. This covers the normal range of meteorological variations in Great Britain and slightly pressurised workplaces such as clean rooms, but not hyperbaric conditions in tunnelling or diving. A generic approach to occupational exposure limits for hyperbaric conditions

has concluded that extrapolation of 8-hr time weighted average WELs should be on the basis of partial pressure to take into account the increase in absolute pressure i.e. the limit expressed in ppm units should be linearly adjusted to ensure that the same partial pressure is maintained under all hyperbaric conditions (HSE, 2000). This can also be achieved by adherence to the WEL expressed in mass per unit volume units, e.g. mg m^{-3} , referenced to 1.013 bar and 20°C. Note that flammability limits do not change significantly over typical hyperbaric pressure ranges.

The use of portable and fixed atmospheric gas monitoring equipment for monitoring toxic (typically carbon monoxide, hydrogen sulphide and oxides of nitrogen) and flammable gases (typically methane and petrol vapour) and oxygen in pressurized tunnels is widespread. Oxygen sensors are required to check for both deficiency (health risk) and enrichment (fire risk). The effects of elevated pressure on the accuracy of typical multi-gas detectors have been reported (Walsh et al, 2002).

2.5 DSEAR and PFEER Regulations

Dangerous substances are any substances used or present at work that could, if not properly controlled, cause harm to people as a result of a fire or explosion. They can be found in nearly all workplaces and include solvents, paints, varnishes, flammable gases/vapours such as liquid petroleum gas (LPG), dusts from machining and sanding operations, and dusts from foodstuffs. DSEAR (HSE, 2003a) requires employers to eliminate or control the risks from dangerous substances which may involve the use of flammable gas or dust detection (see also Section 5 - Electrical safety in potentially explosive atmospheres).

For offshore installations, the Offshore Installations (Prevention of Fire and Explosion, and Emergency Response) Regulations (PFEER) apply (see HSE, 1997). Specifically, Regulation 10 "Detection of incidents" states that the duty holder shall take appropriate measures with a view to (a) detecting fire and other events which may require emergency response, including the provision of means for detecting and recording accumulations of flammable or toxic gases; and identifying leakages of flammable liquids; and (b) enabling information regarding such incidents to be conveyed forthwith to places from which control action can be instigated.

3 METHODOLOGY

3.1 Personal monitoring

An important role for the occupational hygienist is to assess exposure to hazardous substances, select appropriate remedial action where necessary and to check the effectiveness of that action. For many substances, adequate control can be assessed by comparing exposure with the WELs published in EH40 (HSE, 2005a). These limits relate to personal exposure, (the exception is vinyl chloride monomer), averaged over a suitable reference period, i.e. 8 hr for long-term exposure and 15 min for short-term exposure. However, the absence of a substance from the list of WELs should not be regarded as an indication that it is safe. In these circumstances, employers should determine their own in-house standards for controlling exposure. Further information can be found in the HSE publication, HSG173, "Monitoring strategies for toxic substances" (HSE, 2006). Personnel undertaking exposure measurements should be familiar with, and competent to implement, EN 689 "Workplace Atmospheres - Guidance for assessment of exposure to chemical agents for comparison with limit values and measurement strategy" (BSI, 1996), see Section 7.2.

DRDs used for personal exposure monitoring should be small, lightweight and unobtrusive. While there are a variety of devices that can be used for the measurement of personal exposures, in practice, only a limited number of airborne contaminants can be measured. The types of DRD include:

- direct-reading chemical detector devices, for example, detector tubes;
- chemical detector devices with read-out facilities, for example, paper tape cassette monitors

- direct-reading electronic devices for gases and aerosols
- direct-reading electronic devices for gases and aerosols with dataloggers.

The electronic devices can include alarm facilities that can be set by the user or pre-set by the manufacturer.

There are relatively few, if any, devices that are entirely substance-specific and without interferences. Care must be exercised to ensure that the worker's breathing zone atmosphere is sampled. Importantly, any devices that are employed for detecting exceptionally high risk conditions, such as oxygen deficiency or highly toxic atmospheres, must have a rapid response and a recognisable alarm.

3.2 Portable and transportable air monitoring

Portable air monitoring instruments, which include hand-held monitors, are probably the most common type of DRD. Devices used for area monitoring tend to be technically more sophisticated than personal monitors. They are generally larger and some are able to sample, separate and detect more than one compound, e.g. multi-gas instruments. They can be used for monitoring the effectiveness of control measures or for leak detection and tend to offer greater sensitivity than personal monitors. Sampling must be undertaken at positions that are representative of the condition being monitored. For example, sampling should ideally be undertaken at head height to approximate personal exposure, whereas leak detection should be undertaken at whatever locations leaks are possible.

It should be recognised that area monitoring results only provide an indication of personal exposure and should never be used for testing compliance with (personal) WELs.

3.3 Fixed position air monitoring

3.3.1 General

Fixed position monitoring (also known as static or area monitoring) systems are commonly employed to detect flammable, oxygen deficiency and toxic hazards. They are also used to monitor nuisance dust levels. These systems can be single devices or multiple sensors connected to one or more central control or display units. The detectors can either be point samplers or, for optical-based systems, open-path detectors (also known as line-of-sight or beam detectors)¹. Open-path aerosol detectors are also known as obscuration detectors as they detect the reduction in (infrared) transmitted light caused by light scatter and absorption by the aerosol particles (e.g. oil mist). Alternatively, fixed monitors can consist of a sampling line system (in a sequence for multipoint sampling) in which the gas or aerosol is transported to a central (point) measurement and control station by an aspiration system.

The degree of technical sophistication will vary depending on requirements. Information on alarm handling can be found in the EEMUA guide (EEMUA, 2007), which approaches the topic from a control and instrumentation (C&I) viewpoint.

Most WELs refer to personal exposures (the exception is vinyl chloride). However, fixed position monitoring, can be employed to obtain information on the likely sources contributing to the exposure. Fixed position monitoring, however, does not usually reflect the amount that could be breathed in, which determines the risk to health.

¹ Open-path gas monitors measure the spectral absorption (typically in the infrared region although ultraviolet is also used) by gases/vapours over extended optical paths, ranging typically from 1 m to a few km. They measure the integral concentration of the absorbing gas over the optical path in units such as LEL.meter for flammable gases or ppm.meter for toxic gases. Monitors comprise either an optical transmitter and receiver, located at either end of a path through the atmosphere to be monitored, or an optical transceiver (i.e. combined transmitter and receiver) and a suitable reflector, which may be a topographic feature or a retroreflector, located at either end of the path.

Fixed position monitoring is used:

- to warn of leaks in an infrequently occupied area and to warn personnel outside the monitored area of any leaks inside;
- to check the effectiveness of control measures;
- to identify emission sources;
- to determine background workplace contaminant concentrations;
- if there are no suitable personal monitoring methods available;
- when wearing personal monitoring equipment may introduce additional hazards;
- when continuous monitoring alarm systems are installed; and
- for vinyl chloride monitoring as part of the regulations.

The principal considerations for any fixed system are:

- calibration of the analyser or sensors, which affects accuracy;
- failure rate and false alarms;
- response time, which for a sample line system, comprises the sample extraction time, analyser response time and, for multi-point sampling, the time taken to cycle around the sample loop;
- integrity of the sampling system, e.g. leaks, blockages, pump performance;

Further information can be obtained from BS EN 60079-29-2 (flammable gas and oxygen detection) and BS EN 45544-4 (toxic gas detection).

3.3.2 *Response time*

The effective response time of the system, in combination with the alarm levels has to be able to provide sufficient protection for personnel in workspace. There is a compromise between setting a low alarm level, which would provide a more advanced warning, and setting the alarm level sufficiently high to minimise spurious trips and false alarms. Such occurrences result in the loss of confidence in the system with a subsequent lack of use. The risk assessment has to take into account foreseeable events and knowledge of the rate at which a gas release fills the space from a leak allows calculation of the time to reach a hazardous level. The time at which an appropriate alarm level is reached should also incorporate a safety factor to allow for delays in evacuating the area. Typically, two alarms levels are set: a low alarm to warn or initiate an investigation and a high alarm to initiate immediate evacuation or action, which can be either automatic (e.g. valve shut off, activate ventilation) or manual.

There are various ways to minimize the effective response time of the monitoring system. They include:

- using sensing heads instead of sampling points (electronic signals travel faster than gas), although calibration and maintenance is more onerous for multiple sensors;

and for sampling systems:

- minimizing the number of samples on the loop, although adequate coverage must be maintained;
- sampling from all points simultaneously by mixing the gas from each line. This gives an average concentration for the space. However the analyser may require enhanced sensitivity because of increased dilution;

- setting the sequence of samplers on the loop to minimize the cycle time for the more hazardous areas;
- using an additional bypass pump in a sequential sampling manifold to flush the next sample line out in readiness for analysis while the previous sample is being analysed;
- minimizing the sample line length;
- maximizing the sample line flow rate;
- minimizing the analyzer response time;

3.3.3 *Sampling system*

The sampling points should be appropriately located, taking into account:

- obtaining a representative sample;
- speed of response, for example considering likely release direction, gas density, location of personnel;
- ease of function checking and calibration;
- avoidance of damage or reduced effectiveness due to blockage.

The provision of a leak-free and adequate flow rate through the sample lines is crucial for effective operation of the system. Filters are usually required to prevent ingress of unwanted solid or liquid material but may reduce the flow. They also have a limited lifetime dependent on the amount of material deposited.

The sample line material should be selected to minimize adsorption, absorption and reaction with the atmosphere being sampled. Water condensation, if it occurs, can block the sample line; water traps may therefore be required. If vapour is being sampled, it too may condense in the line and so heated sample lines may have to be used.

There is a need to monitor the flow in each sample line, for example with upper and lower flow alarm levels for an acceptable sample line flow. This would check for pump failure and blockage (lower than normal flow) and leaks (higher than normal flow).

3.3.4 *Checking and calibration*

There are two methods of verifying DRD accuracy: a functional or bump test and a full calibration, each appropriate under certain conditions. A bump test verifies calibration by exposing the DRD to a known concentration of test gas. The DRD reading is compared to the actual quantity of gas present (e.g. as indicated on the gas cylinder). If the DRD's response is within an acceptable tolerance range of the actual concentration, then its calibration is verified. Users should check with the DRD manufacturer for the acceptable tolerance ranges. DRDs should be "zeroed" before the bump test. Bump testing gases are generally at above the alarm level points but below the limits for oxygen depletion. More information can be found on the US OSHA site (OSHA, 2004).

If the bump test results are not within the acceptable range, a full calibration must be performed. A full calibration is the adjustment of the DRD's reading to coincide with a known concentration (generally a certified standard) of test gas. For verification of accuracy, calibration gas should always be certified by and traceable to standards. In most cases, a full calibration is only necessary when an DRD fails a bump test or after it has been serviced. The full calibration and bump test should be conducted in a clean fresh air environment.

"Bump testing" is the recommended route for testing many types of DRD's used for the detection of gases. Some manufacturers incorporate the bump test into the charging/test stations so the instrument is tested with the bump gas before removal for use. Often the bump test gas will be a mixture of gases

in a single mix enabling a check of all the gases on multi-gas detectors. It has been good practice in many industries to bump test a gas detector before and after use, thereby ensuring the DRD was functioning correctly during usage.

Bump testing can also be applied to dust monitors, e.g. using aerosol sprays, although it is not as quantitative a method as for gas detectors because of the greater uncertainties in the generation method.

Calibration should always be carried out in line with the manufacturer's instructions but it should be noted that many gas DRDs do not offer high accuracy and the use of bump testing is the recommended method, which tends to indicate repeatability rather than absolute calibration accuracy.

When using calibration gases and equipment, care must be taken when using pressurised gas. Also, some gases are supplied in nitrogen only, whereas DRDs generally work in air: this can affect the calibration value. The calibration may entail using higher values of gas than required and a dilution and blending system needs to be used which can increase errors of calibration.

The calibration periods should be agreed between the user and the DRD supplier. Full, documented records of the results of such actions should be kept. The latest generation of infrared gas detectors have the facility to self-check so reducing the intervals for actual gas testing.

The use of a single analyser with multiple sampling line(s) allows automatic checking and calibration using calibration gases. However, this only checks the analyzer itself and not the whole system. The other components of the system are the sampling line(s) and the alarm and control system to which the analyzer is connected. The sampling line requires checking at suitable intervals, using for example a gasbag and flow meter connected to each sampling point. The integrity of the control system also requires checking to ensure that the readings at the analyzer are accurately transmitted and displayed at the control room.

3.4 Surface contamination monitoring

Surface contamination monitors take readings directly from surfaces without the need for samples to be obtained by methods such as wipe or tape lift, which are then returned to a laboratory for analysis. The monitor results are usually available in either seconds or minutes making surveys of surface contamination both quick and accurate. A surface monitor can either be a portable device that can be placed on the surface to be examined or a wipe or swab that gives an instant colour change reaction.

The type of surface monitor to be used in each instance will depend on a number of factors including the contaminant being assessed and the type and accessibility of the surface to be assessed. The need for instant quantitative results should also be considered.

3.5 General requirements

3.5.1 Preparation

When a DRD is initially acquired it is important that the user reads the manufacturer's instruction manual thoroughly and follows the instructions on testing, calibration and maintenance. Most DRDs are complex and require function tests, maintenance and recalibration to be carried out at regular intervals by a competent person. Recalibration usually requires specialist equipment and reliable methods for generating known reference concentrations of gases, vapours, aerosols or surface contaminant material. Further information on gases can be found in the SIRA Guide (SIRA, 2005). For a DRD to give reliable measurements over a long working life they have to be handled and maintained with care.

Immediately before use, the DRD should be subjected to routine inspection and function tests. In general, the user should:

- a) check that the DRD is within its calibration period as determined by quality assurance/ quality control schedules or procedures, for example, BS EN ISO 9000. Note that some personal monitoring DRDs, e.g. for CO, require no calibration until they reach the end of their life, typically a few years;
- b) for personal, portable and transportable DRDs, visually inspect the carrying case, DRD case or sensor housing for damage;
- c) check that all accessories, such as cables and sample probes, are in good condition and free from contamination;
- d) for an aspirated (i.e. having a manual or automatic pump) DRD, check that the flow rate is within the operating range recommended by the manufacturer and there are no leaks;
- e) check that the batteries are fully charged;
- f) check the zero reading in clean uncontaminated air. A significant non-zero reading can indicate a drift in sensor response or malfunction of the electronics;
- g) carry out a simple function (response) test on the sensor, also known as a “bump test”. This could be done using a test kit, if supplied, or a gas, vapour or aerosol to which the sensor responds;
- h) for DRDs fitted with alarms, check the alarm (audio and/or visual) is operating correctly.

The results of these checks should be recorded.

3.5.2 *Field measurements*

Certain precautions have to be observed when making field measurements. Factors to consider are:

- a) *Condensation.* Avoid water vapour condensation on electrical DRDs as this can cause shorting out or other malfunction. Condensation can easily occur when taking an DRD from a cool to a warm 'wet' environment, such as when transporting the DRD by motor vehicle in cold winter months and immediately using it in a warm workplace with high relative humidity.
- b) *High concentrations.* Avoid inadvertent exposure of gas-detecting DRDs to very high concentrations of gases and vapours as this can saturate or overload the sensor which can result in impaired performance. If accidental exposure occurs remove the DRD and place in a clean air environment. Allow a reasonable time for the DRD to recover and then carry out the function checks and, if possible, a calibration check;
- c) *Environmental conditions.* Users should ensure that the DRD is suitable for use in the expected environmental conditions, such as temperature and humidity.
- d) *Precipitation and dust.* Gas-detecting DRDs should be protected from precipitation such as rain and snow, or dusts.
- e) *Sampling pumps.* Where sampling pumps are used, it is good practice to use water filters or traps to prevent the intake of water.
- f) *Electromagnetic interference.* Avoid the use of mobile telephones and radio communicators in the close vicinity of electrical DRDs since they might interfere with the operation of the DRD.

3.5.3 *Storage conditions*

It is important that DRDs are stored in appropriate conditions, especially if they are used infrequently. Factors to consider include:

- a) cleanliness of the storage environment;

- b) temperature and humidity of the storage environment;
- c) possibility of parts of the DRD, such as the sensor or batteries, deteriorating with age;
- d) testing of the DRD on a planned, regular basis;
- e) the charging and discharging of batteries, if appropriate.

After prolonged storage it would be appropriate to carry out a full check and recalibration according to the manufacturer's recommendation.

3.5.4 Waste Electrical and Electronic Equipment (WEEE) Directive

At the end of the DRD's useable life, it must be disposed of in accordance with regulations that comply with the Waste Electrical and Electronic Equipment (WEEE) Directive, 2002/96/EC amended by 2003/108/EC.

If the equipment was bought before 13/08/2005 and is being replaced with new equipment fulfilling the same function, then the producer of the new equipment is responsible for the collection, treatment and recycling of the old equipment, regardless of whether they were the original manufacturer.

If the equipment was bought before 13/08/2005 and is not being replaced, then the user is responsible for financing and arranging treatment in accordance with the WEEE Regulations and existing waste management legislation, including the Duty of Care and the Hazardous Waste Regulations.

If the equipment was bought after 13/08/2005, then the producer of the equipment is responsible for its collection, treatment and recycling when it is disposed of.

If equipment is leased or rented, the producer is usually responsible for its disposal.

The regulations allow producers and business users to agree 'alternative arrangements', whereby the business user agrees to take on some or all of the future costs of the end-of-life treatment of the equipment that is bought.

4 SELECTION CRITERIA

The selection of the most appropriate measurement technique will depend on the measurement task. A decision must be made on which type of measurement to perform: whether to sample and laboratory analyse or whether to use a DRD. Section 1 outlines, in general terms, where DRDs can be used and their advantages and disadvantages. Where the measurement task allows the use of a DRD, then selection of the most appropriate device depends on many factors related to the type of measurement (see section 1.2); ambient and working conditions; conformity to regulations etc. Further information can also be obtained from the SIRA Calibration Guide (SIRA, 2005).

Factors to be considered when selecting a DRD include:

1. **The measurement task.** Various measurement tasks are outlined in sections 1.2 and 7.3.
2. **The type of DRD required (personal, portable, transportable or fixed).** This depends on the measurement tasks to be performed.
3. **The limits of operation and sensitivity to environmental changes.** While a high proportion of workplace measurements will be performed within "normal" environmental ranges (typically, at temperatures between 5 and 40°C; atmospheric pressures between 95 and 110 kPa; relative humidity between 20 and 90% and air speeds between 0.5 and 4 m/s), some measurements will not. In the latter case, the DRD may not comply with the performance requirements, particularly with regard to levels of reliability. DRDs can exhibit a change in output with ambient temperature changes. In some cases, where the temperature drift is known, it is possible to apply correction factors when calculating the concentration of a toxic gas or vapour. DRD manufacturers can supply the user with such

correction factors and advise on their use. Similar considerations also apply to the effects of humidity and pressure changes.

4. **Robustness, durability and shock-resistance.** This will depend on the workplace environment.
5. **Other gases and vapours to be detected, (for gas detectors).** Instruments are available, known as multi-gas detectors, which combine several sensors in one instrument, e.g. for flammable gas, oxygen, toxic gas sensors such as carbon monoxide or hydrogen sulphide, and volatile organic compounds (VOCs).
6. **Sampling site.** Particular requirements of the site not covered elsewhere in this section could affect selection of the most suitable instrument.
7. **Visual or audible alarm warning levels.** It is imperative that any warning signals are set appropriately and seen or heard in order that action is taken as quickly as possible.
8. **Use in potentially flammable atmospheres.** See Section 5 for more details.
9. **Signal output.** Most instruments will offer a range of outputs, such as audible and visual alarms, digital (e.g. RS232 or USB), 4-20 mA, alarm relays, voltage, etc. Selection will depend on the particular application. In some cases, it may be useful to select a monitor with a digital or analogue output (voltage or 4-20 mA) as this can be connected to a datalogger (if the DRD does not have one on-board) or chart recorder, and the data analysed at a later stage.
10. **Concentration range required.** DRDs are only accurate to a given specification over a particular concentration range because of, for example, non-linearity of response or saturation. If the concentration is outside this range then the manufacturer's specification will not apply and any conformity to a performance standard may be invalid.
11. **Limit of detection.** This determines the lowest level at which the device will reliably measure. A device should be chosen with a limit of detection, or lower detectable limit (LDL), which should take into account the use to which the device will be put. For example, if it is required to measure below the WEL, the LDL could be 0.25 WEL or 0.1 WEL.
12. **Accuracy and precision or overall uncertainty.** These determine the uncertainty (error) of the result given by the device. The combination of accuracy (bias) and precision is known as the overall uncertainty (see BS EN 482 for definitions). It is important that the precision is acceptable over short- and long-term time intervals and appropriate for the measurement task (See Section 7.3, Table 1).
13. **Selectivity to the target gases or vapours and sensitivity to interfering gases and vapours (for gas detectors).** This determines how sensitive the device will be to interference from substances other than the one of interest. The response of gas detection instruments can be enhanced or diminished by the presence of other gases. It is particularly important that the cross-sensitivity is checked if the instrument is to be used in areas where other species may be present.
14. **Particle size selectivity (for aerosol detectors).** This will determine the size fraction that the detector responds to. For example, photometers respond approximately to the respirable range, are relatively insensitive to particles above this range and therefore are generally unsuitable for the inhalable fraction.
15. **Selectivity to substance (for surface contamination detectors).** Ideally, the instrument should only be sensitive to the target species. It is particularly important that the cross-sensitivity is checked if the instrument is to be used in areas where other compounds may be present.

16. **Operating principle and parameters of the sensor or instrumental technique.** See Section 6 for more details.
17. **Response and recovery time.** These will depend very much on the system used. For example, the use of sampling probes will increase the response time. Usually, the manufacturer will supply information on any response time change if the DRD is used with a manufacturer-supplied sampling line or probe. In general, higher sensitivity usually requires a longer response time. The response time of the system will also be dictated by the gas to be detected, for example reactive gases may take time to equilibrate with the surfaces of the internal and any external sampling system, high molecular weight vapours which diffuse slowly if the sampling system relies on diffusion during any part of the sampling process. The use of gas monitoring DRDs with long sample times may be the only practicable way of measuring some gases.
18. **Warm-up time.** The warm-up time of a device is important for personal, portable and transportable DRDs in situations where measurements are required quickly after turning on the DRD. Ideally, DRDs should be switched on and left to run for an extended period; however, there may be difficulties in obtaining power over the whole of this period because of limited battery life, for example.
19. **Long-term stability.** The long-term stability of the DRD is an important factor in determining the function check and calibration periods. Extended long-term stability gives confidence in the device and reduces calibration and maintenance costs.
20. **Mains or battery powered.** Sometimes both options are offered. Battery powered instruments offer more flexibility for field operation, but they generally have fewer features. Units powered by mains electricity can be a severe limitation in the field but this can sometimes be overcome by the use of an inverter, allowing the use of a DC source. Mains-powered instruments are usually unsuitable for use in potentially explosive atmospheres, see Section 5 for more details.
21. **Operating time for battery powered DRD.** Where possible, battery powered instruments should enable full-shift operation, that is, for up to eight hours. Care should be taken with rechargeable batteries to ensure that full charge is attained.
22. **Frequency of function checks.** This is dependent on the lifetime, long-term stability and history of usage, for example, high exposures, wear and tear.
23. **Frequency and cost of maintenance and calibration.** These are very important considerations when selecting a monitoring device. The device can only be as good as the calibration allows. A badly calibrated device is useless as the results obtained will be meaningless. All devices should be calibrated according to the manufacturer's instructions. It is good practice to calibrate before and after each period of use, even though this can be time consuming. Calibration intervals need to be established by the user depending on the type of device and the application. Some instruments have an electronic form of test to check general instrument functions, including a warning when sensors are out of calibration.
24. **Fitness for purpose.** For example, size, shape and weight.
25. **Training requirements for reliable operation, maintenance and calibration.** Training is vital to ensure proper use and can be carried out in-house or externally (for example, by the DRD supplier or third party), and ideally using a suitably accredited organisation.
26. **Cost of ownership.** This is a frequently neglected area and purchasers often consider only the capital cost of a system and not the life cycle costs including disposal. Continuing running costs should be considered, as they can be significant over the lifetime of the device. Low capital costs in the short term can lead to high running costs in the long term.

The cost of service and replacement parts should be assessed, as should the cost of calibrating, adjusting and generally maintaining the system.

27. **Compliance with national or international performance standards and appropriate national regulations.** See Section 7 for standards.
28. **Conformity to the user's quality control/assurance system.** For example, certification to ISO 9000 and, in certain applications, UKAS accreditation.

5 ELECTRICAL SAFETY IN POTENTIALLY EXPLOSIVE ATMOSPHERES

5.1 General

Electrical safety is an extremely important consideration when sampling and measuring gases, vapours and dusts in potentially explosive atmospheres. The information given here should be considered as basic and of general application only. Guidance on the required certification for a particular application should be sought from the DRD supplier.

Electrical and non-electrical equipment and installations in potentially explosive atmospheres must be specially designed and constructed so that the risks of ignition are eliminated or reduced. There are two EU Directives: ATEX 95 (94/9/EC) and ATEX 137 (99/92/EC) concerning, respectively, the supply and use of equipment in potentially explosive atmospheres. ATEX 95 (also known as 100a) concerns the supply of equipment, protective systems, components etc, where these are for use in potentially explosive atmospheres. The “user” directive, ATEX 137, is implemented by HSE under The Dangerous Substances and Explosive Atmosphere Regulations, 2002 (DSEAR). ATEX 137 concerns worker health and safety in those workplaces where potentially explosive atmospheres may be present. Most new equipment being sold in the UK for use in potentially explosive atmospheres, including electrical DRDs, must have an ATEX certificate. Furthermore, equipment for use in explosive atmospheres should be regularly inspected and maintained to ensure it does not pose an increased risk of causing a fire or explosion. Maintenance of the equipment should only be carried out by competent persons.

For DRDs used to detect combustible gases/vapours and oxygen, there are two independent categories of test:

- electrical tests - to prevent the ignition of explosive atmospheres by the device itself; and
- performance tests - to ensure that devices are suitable for those gases and the ranges for which they are designed, e.g. BS EN 60079-29-1 (which has superseded the BS EN 61779 series).

Certification to both is required. For devices for the detection of toxic gas only, used in potentially explosive atmospheres, only the electrical test is required for certification. The certification is not valid in oxygen-enriched atmospheres, i.e. more than 21 % v/v oxygen.

Guidance on the selection, installation, use and maintenance of combustible gas detectors (for non-mining use) is given in BS EN 60079-29-2. A substantial list of Lower Explosive Limits (LELs) of the more common gases and vapours can be found in the ‘data standard’ PD IEC 60079-20.

Certification is also required for use of electrical equipment in potentially explosive atmospheres of dust, e.g. flour, grain.

Certification of the apparatus depends on the type of hazardous area and the type of protection required against flammable gas/vapour or dust. Hazardous areas are classified into zones (see BS EN 60079-10), based upon the frequency of the occurrence and duration of an explosive atmosphere, as follows:

- a) Zone 0 - an area in which an explosive gas atmosphere is present continuously or for long periods
- b) Zone 1 - an area in which an explosive gas atmosphere is likely to occur in normal operation
- c) Zone 2 - an area in which an explosive gas atmosphere is not likely to occur in normal operation and, if it does occur, is likely to do so infrequently and will exist for a short period only

5.2 Certification codes

The various types of protection concepts can be illustrated by reference to the ATEX marking which electrical equipment is required to have if intended for use in potentially explosive atmospheres.

The required markings are the **CE** logo, and additional markings to enable full identification of equipment, protective systems and safety devices to be made. They must at least contain the following:

- the  explosion protection mark, together with the mark indicating the equipment group and category; and relating to equipment group II, the letter G (concerning explosive atmospheres caused by gases, vapours or mists) and/or D (concerning explosive atmospheres caused by dust) as shown in Fig. 1;
- name and address of manufacturer;
- designation of series or type and serial number;
- year of production;
- restricted or other safety-related conditions of use.

Fig. 1 shows, in addition to the above markings, some other commonly used safety-related markings, which may be encountered on electrical DRDs used in hazardous areas.

ATEX marking

CE  II 2 GD

CE Mark:

Declaration by the manufacturer that the product meets the requirements of the applicable EU Directives, with no. of notified certifying body

Ex Mark:

For explosive protection equipment, showing compliance with requirements of EU standards harmonised with ATEX 95.

Equipment Group:

I – use in mining
II- use in all other explosive atmospheres

Equipment Category:

1 – use in Zone 0 (gases) and Zone 20 (dusts). For very high safety levels.
2 – use in Zone 1 (gases) or Zone 21 (dusts). For high safety levels.
3 – use in Zone 2 (gases) or Zone 22 (dusts). For normal operations

Hazard Type:

G – gas/vapour/mist
D - dust

Certification code

E Ex ib IIC T5

CENELEC standard:

E- certified to the CENELEC standard

Ex protection:

Ex – explosion protected.

Type of ignition protection:

Examples for gas detectors are:
ia – intrinsic safety, two faults for Zones 0,1,2
ib - intrinsic safety, one fault for Zones 1,2
d – flameproof enclosure
e – increased safety
n – for Zone 2.

Explosion group:

I – representative test gas methane (mines only)
IIA - representative test gas propane
IIB - representative test gas ethylene
IIC - representative test gas hydrogen

Temperature class (gas only):

Highest permissible surface temp. for use in gas explosion protected atmosphere.
T1 – 450°C
T2 – 300°C
T3 – 200°C
T4 – 135°C
T5 – 100°C
T6 - 85°C

Additional codes

T100°C IP65

Temp. for dust: T100°C – maximum surface temperature for use in dust explosion protected atmosphere.

Ingress protection: Protection from dust and water. Hazardous area equipment typically requires a minimum of IP54, the following ratings are available:

Dust: IP5x – dust protected; IP6x – dust tight

Water: IPx4 – splashing water; IPx5 – water jets; IPx6 – powered water jet; IPx7 – temporary immersion; IPx8 – continuous immersion.

Fig.1 ATEX marking and certification codes

6 CHARACTERISTICS OF DRDS

6.1 General

There are many types of DRD which can be used for various tasks as discussed in Section 1. A fundamental characteristic of a DRD is its principle of operation, i.e. the chemical or physical principle on which the sensing mechanism is based. The operating principle influences key measurement characteristics such as typical measurement tasks and range, time of response, selectivity and other limitations which affect its use. The following sections summarise briefly the above characteristics for the major types of operating principle currently used in commercially available DRDs. They are divided into three groups: DRDs for the measurement of concentration of gases and vapours, aerosols and surface contamination.

6.2 Gases and vapours

6.2.1 General

There are a wide range of DRDs for gases and vapours incorporating sensors based on a variety of operating principles. The following tables briefly describe the characteristics of various gas monitoring DRD. However, for a general warning device, the most common types of sensor are electrochemical, catalytic, infrared and photoionization.

6.2.2 *Electrochemical*

Operating principle	Operation of an electrochemical sensor depends upon electrical changes at the electrodes (in contact with a liquid electrolyte) due to redox reactions of the gas or vapour on the surface of the electrodes. Gas diffuses to the sensing electrode and is either oxidised (e.g. CO, H ₂ S, SO ₂ , NO, H ₂ , HCN, HCl) or reduced (e.g. NO ₂ , Cl ₂). Only small quantities of gas or vapour can be consumed and so electrodes and electrolyte are usually confined in semi-permeable membranes to prevent overloading.
Typical measurement tasks	Suitable for a wide range of measurement tasks including personal exposure monitoring, screening measurements, warning.
Typical measurement range	From ppb to thousands of ppm.
Time of response	Response and recovery time usually not less than 30 s, although certain types can be faster.
Selectivity	Not selective; other oxidising or reducing gases and vapours can interfere, although some sensors can achieve a high degree of selectivity, depending on the competing electrode reactions.
Typical calibration frequency	Depends on gas or vapour, from just before use to several months. It depends on exposure and environmental conditions, and is of the order of a few months, typically 6 months is the norm but depends on the environment. For portables, bump testing is used to check before use.
Limitations	a) possibly restricted temperature range due to properties of the electrolyte, for example, -20°C to +40°C; but special types can be configured for extreme climates. b) the electrolyte or the electrode can be affected by other gases resulting in loss of sensitivity or loss of accuracy.

6.2.3 *Semiconductor*

Operating principle	The sensor is based on the change in electrical conductivity associated with chemisorption of gases on a semiconductor surface, i.e. a gas sensitive resistor. Semiconducting material (for example, metal oxide, often based on tin oxide) is electrically heated to a few hundred degrees Celsius. Electrodes are mounted on the surface of the semiconducting material. Resistance changes can be measured when the semiconducting element is exposed to gases or vapours other than air.
Typical measurement tasks	a) used, for example, in alarm-only apparatus and emission source measurements. b) used to measure a wide range of gases and vapours.
Typical measurement range	Sensors are used for the detection of gases and vapours in any concentration but usually in the upper ppm range, for example, 1 to 10000 ppm. However, they tend to have a non-linear response.
Time of response	Depends on gas or vapour, typically 10s of seconds, can be quite slow to respond and recover.
Selectivity	Generally non-specific and susceptible to interference, especially water vapour.
Typical calibration frequency	Frequent calibration usually necessary.
Limitations	a) wide range of sensitivity to different gases and vapours; b) after exposure to high gas concentrations the sensor may need a recovery time of several hours and may have irreversible changes to its zero gas reading and sensitivity; c) exposure to basic or acidic compounds, silicones, organo-lead, sulphur compounds and halogenated compounds can have a significant effect on the sensitivity; d) oxygen concentration can have a significant effect on sensitivity.

6.2.4 Paper Tape (colorimetry)

Operating principle	Gas adsorbs and reacts with a supported chemical reagent, usually in the form of a paper tape or badge, resulting in a colour change of the reagent. The resulting stain is monitored electronically, commonly using a light scattering technique. The reaction can be reversible or irreversible.
Typical measurement tasks	Suitable for a wide range of measurement tasks but not for personal exposure monitoring because of the size/weight of the apparatus. Often used to monitor isocyanates but not selective to different isocyanates.
Typical measurement range	ppb to low ppm.
Time of response	Of the order of minutes in order for a stable colour change to develop.
Selectivity	Depends on the gas or vapour, can be highly selective.
Typical calibration frequency	Depends on the instrument - of the order of weeks.
Limitations	a) chemical cassettes ("chemcassette") for paper tape systems are consumable items; b) typically paper tapes have a shelf-life of up to 12 months and last between 3 – 4 months ; c) bleaching agents can inhibit reaction with the chemical reagent.

6.2.5 Catalytic (Pellistor)

Operating principle	Oxidation of flammable gas occurs at the surface of an electrically heated catalytic element. Sensors are normally constructed as an electrical bridge with two electrically similar elements (beads) mounted close to one another. The elements typically consist of a platinum coil embedded in a ceramic. One (the sensing element) is additionally covered with the catalyst, usually a platinum group metal. The heater maintains the ceramic at a sufficiently high temperature (around 400°C) to ensure combustion of flammable gas. The gas concentration is monitored by measuring the relative change in the resistance of the elements resulting from a temperature increase produced by combustion.
Typical measurement tasks	The measurement of a wide variety of flammable gases and vapours at concentrations up to the lower explosive limit (LEL).
Typical measurement range	0.05% to 5% v/v or 0.1-100% LEL NB: Most OELs for gases and vapours fall well below this measurement range.
Time of response	Depends on gas or vapour, typically 10s of secs.
Selectivity	The sensor response is generally not selective but is selective towards flammable gas.
Typical calibration frequency	Will depend on exposure and environmental conditions, and is of the order of a few months, typically 6 months is the norm but depends on the environment. For portables, bump testing is used to check before use.
Limitations	a) not recommended for the measurement of flammable mixtures above the LEL; b) for the reliable operation of the sensor about 10% v/v of oxygen is required in the measured gas mixture; c) can give false readings in high flammable gas concentrations; c) will detect all other flammable gases and vapours; e) exposure to vapours such as silicones, organo-lead, sulphur compounds, halogenated hydrocarbons and phosphate esters can cause temporary inhibition or permanent poisoning of the sensor.

6.2.6 *Infra-red Spectrometry*

Operating principle	Infrared radiation (from a bulb lamp or LED or, in a limited number of devices, laser, and usually modulated in intensity) is passed through a sample cell and is absorbed by the target gas. The optical path can have a length of several centimetres up to around 0.5 m and can use multiple reflection cells to increase the pathlength to around 20 m. The absorption is measured by thermal, quantum or photoacoustic detectors. The concentration of gas is usually measured by comparing a sample and reference in a single or a double beam apparatus to compensate for changes in beam intensity and the presence of interferents. Non-dispersive (e.g. interference filters, gas correlation cells) and sometimes dispersive techniques (and lasers which emit at a very specific wavelength) are used to select the appropriate infrared wavelength. Fourier Transform spectrometers use the whole spectrum for analysis and portable versions are available having comparatively high sensitivity. Many gases and vapours absorb in the infrared region (2-14 μm). In addition to the point monitors described above, open-path infrared detectors are used for monitoring over long paths up to several 100s meters. They measure the path-averaged concentration and units of measurement are typically LEL.m for flammable gases and ppm.m for toxic gases. Open path Fourier Transform spectrometers (transportable) can also be employed for high selectivity, sensitivity applications.
Typical measurement tasks	Suitable for a wide range of measurement tasks including boundary monitoring. Personal exposure monitoring is also possible for gases such as CO_2 which only require small pathlength cells.
Typical measurement range	ppb to 100% v/v.
Time of response	Seconds. Limited by cell volume and pump speed in aspirated systems. Filters and weather protection housings will increase the time of response.
Selectivity	Depends on gas or vapour and selection of wavelength. Improved selectivity can be obtained by use of several wavelengths or the whole spectrum and chemometrics (pattern recognition) techniques.
Typical calibration frequency	Weeks to months or possibly years where there is continual zero and span self-checking using optical filters to simulate gas. It will depend on exposure and environmental conditions, and is of the order of a few months, typically 6 months is the norm but depends on the environment. For portables, bump testing is used to check before use.
Limitations	a) exposure to high concentration can saturate the instrument for a period; b) cannot detect monatomic and diatomic homonuclear molecules, for example, H_2, Hg, Cl_2 and other halogens c) potential contamination of optical surfaces may preclude use in some arduous applications

6.2.7 Mass Spectrometry

Operating principle	Gases and vapours are injected or continuously aspirated (typically using low flow rates) into a chamber where they undergo ionisation and fragmentation. Fragmented ions are separated according to their mass-to-charge ratio using a quadrupolar field and detected by a Faraday cup or an electron multiplier. Relative intensities of the ions generated from a specific compound are constant under steady operating conditions. The whole system is under high vacuum.
Typical measurement tasks	Measurement of a wide range of gases and vapours. Simultaneous multi-component identification and measurement.
Typical measurement range	Usually from ppb to ppm (depending on the gas or vapour and interferences)
Time of response	Very short time of response and recovery time for directly aspirated apparatus. Slow response if coupled to a gas chromatograph.
Selectivity	High selectivity, even higher if using chemometrics or coupled to a gas chromatograph.
Typical calibration frequency	Daily calibration is usually required.
Limitations	a) bulky and complex apparatus - although size has reduced to suitcase dimensions for transportable applications; b) extensive operator training required; c) high concentrations can saturate the detector and produce memory effects impairing measurements of very low concentrations.

6.2.8 Chemiluminescence

Operating principle	In some chemical reactions (for example, oxidation) intermediates or products are produced in an excited electronic state. Chemiluminescence is the characteristic emission of radiation from this state. The emission can be measured by a photometer and provide a selective means of measuring gas or vapour concentration. Chemiluminescence monitors are primarily used for measurement of oxides of nitrogen and ozone. The apparatus requires a mixing chamber where the target gas interacts with reactant. The reactants are ozone for NO measurement (NO ₂ is determined by prior reduction to NO) and ethylene for ozone measurement.
Typical measurement tasks	Screening in time and space, emission sources.
Typical measurement range	10 ppb to 100 ppm.
Time of response	Seconds to minutes.
Selectivity	High selectivity.
Typical calibration frequency	Weeks to months.
Limitations	Requires reagent gas (e.g. ozone, ethylene). Laboratory type apparatus which is only transportable.

6.2.9 *Paramagnetic*

Operating principle	Some gases, oxygen and, to a lesser extent, nitric oxide are paramagnetic which interact strongly with an applied magnetic field. Various techniques are used to detect oxygen including dumbbell type where torsion induced by the magnetic interaction is detected optically. Others use the temperature dependence of paramagnetism inducing a relative cooling effect.
Typical measurement tasks	Mainly suitable in fixed installations for monitoring oxygen.
Typical measurement range	ppm to 100% v/v
Time of response	1 sec upwards depending on type. Limited by cell volume and pump speed in aspirated systems.
Selectivity	Selective to paramagnetic molecules, for example, oxygen, nitric oxide and nitrogen dioxide.
Typical calibration frequency	Monthly, typically.
Limitations	Depending on the method, may be sensitive to shock and/or vibration; temperature and pressure compensation required.

6.2.10 *Flame Ionization*

Operating principle	This detection principle utilises electrical (ionisation) changes in a hydrogen flame. Ionised atoms or molecules (usually carbon based) generated in the flame are transported by an electrical field and measured as an electrical current. The electrical field is generated by applying a positive potential of up to a few hundred volts to an electrode near the flame (the gas jet acts as the counter electrode). A flame of pure hydrogen (and air) produces a negligible number of detectable ions giving a very low base current. The technique has a linear response over a wide concentration range
Typical measurement tasks	Suitable for a wide range of measurement tasks but not for personal exposure monitoring because of the size/weight of the apparatus.
Typical measurement range	100 ppb to several percent.
Time of response	Fast response, depends on detector volume and pump speed.
Selectivity	Non-selective but can be coupled to a gas chromatograph to increase selectivity.
Typical calibration frequency	Most instruments have a calibration period of weeks.
Limitations	a) external gases (hydrogen and clean air) are required for the flame; b) the sensor is unsuitable for carbon monoxide and inorganic gases; c) the sensor cannot be used with high concentrations of gases that will extinguish the flame, for example, halon; d) halogenated hydrocarbons reduce the response when the apparatus is calibrated for measuring the total carbon content of the gas mixture.

6.2.11 Photo-ionization

Operating principle	The detection principle is based on ionisation of gaseous compounds by ultraviolet radiation. The gas is irradiated by a uv source, usually a hydrogen lamp with a maximum emission energy of around 10.6 eV. Molecules are photo-ionized and the resulting ion current is measured across an applied electric field. Molecules having an ionisation potential lower than the excitation energy of the lamp are detected. In principle, as the measurements are performed in air, substances having an ionisation potential higher than oxygen (12.1 eV) cannot be detected.
Typical measurement tasks	Suitable for a wide range of measurement tasks including personal monitoring.
Typical measurement range	100 ppb to thousands of ppm.
Time of response	Fast response, depends on detector volume and pump speed.
Selectivity	Non-selective but can be coupled to a gas chromatograph to increase selectivity.
Typical calibration frequency	Most instruments have a short calibration period, typically a day. For portables, bump testing is used to check before use.
Limitations	a) the lamp used as a source of UV radiation has a limited lifetime, especially higher energy (>10.6 eV) lamps; b) cannot detect carbon monoxide. Substances like methane, ethane, propane, acetylene and methanol cannot be detected with commonly available detectors and vapours such as ethanol and ethylene give a low response with a 10.6 eV lamp; c) water vapour can interfere; d) high levels of methane in the presence of the target gas reduce sensitivity by inhibiting ionisation.

6.2.12 Thermal Conductivity

Operating principle	The heat loss characteristic of a heated element is dependent on the thermal conductivity of the gas mixture surrounding the element. Changes in composition of the mixture will change the thermal conductivity of the gas and will result in a change in power dissipation of the element. This can be measured as temperature and electrical resistance changes of the element. Usually there is a compensation element in a reference gas to reduce the influence of external temperature fluctuations.
Typical measurement tasks	Normally used to measure high concentrations of a limited number of gases.
Typical measurement range	0.1% to 100% (v/v).
Time of response	Time of response depends on design of sensor, usually from seconds to minutes.
Selectivity	Non-selective.
Typical calibration frequency	Most instruments have calibration period of weeks to months. For portables, bump testing is used to check before use.
Limitations	a) The technique is only suitable for gases and vapours whose thermal conductivity differs significantly from air, for example, methane, hydrogen; b) The technique is restricted to binary gas mixtures as the net response to more than one toxic gas or vapour is indeterminate unless the proportions of the constituent gases are known. In the worst case, a mixture of high and low conductivity gases could produce no apparatus response.

6.2.13 *Ultraviolet absorption spectrometry*

Operating principle	Ultraviolet radiation is passed through a sample cell and is absorbed by the target gas
Typical measurement tasks	Used for ozone and nitric oxide measurement.
Typical measurement range	ppb to ppm.
Time of response	Seconds. Limited by cell volume and pump speed in aspirated systems.
Selectivity	Depends on gas or vapour and selection of wavelength. Improved selectivity could be obtained by use of several wavelengths or the whole spectrum and chemometrics (pattern recognition) techniques.
Typical calibration frequency	Weeks to months.
Limitations	a) potential contamination of optical surfaces may preclude use in some arduous applications

6.2.14 *Electron Capture*

Operating principle	The sample cell is bombarded with electrons from a radioactive or photoemissive electron source. A standing current is produced by electrons attracted to a collector. When electron-capturing molecules enter the cell, the decrease in current is proportional to their concentration.
Typical measurement tasks	Suitable for measurement of low concentrations of halogenated gases/vapours in air and qualitative leak detection. Not usually suitable for personal exposure monitoring because of the size/weight of the apparatus.
Typical measurement range	1 ppb - 10 ppm
Time of response	Fast response, depends on detector design and pump speed.
Selectivity	Electron affinitive gases/vapours such as chlorinated hydrocarbons.
Typical calibration frequency	Most instruments have a calibration period of weeks.
Limitations	Oxygen gives a positive response.

6.2.15 *Ion Mobility Spectrometry*

Operating principle	Certain compounds are capable of being ionised in air (for example, using a radioactive source such as ^{63}Ni which is a beta-particle emitter, although other methods are possible) to produce characteristic ionic species. Passage of ions into the drift tube (usually a few centimetres in length) is controlled by a gate potential where they migrate in air at around atmospheric pressure under an electrostatic potential gradient of approximately 200 V/cm. The ions are detected at the end of the drift tube using an electrometer. Species can be separated according to their mobility which is a function of their mass, charge and ionic state.
Typical measurement tasks	Screening time and space, emission sources, spot-reading for limited types of compound, for example, isocyanates.
Typical measurement range	ppb to ppm.
Time of response	Fast, of the order of seconds.
Selectivity	High selectivity.
Typical calibration frequency	Short calibration period, typically a day.
Limitations	a) Limited number of gases and vapours detectable; b) Some types of instrument require radioactive source – ^{63}Ni ; c) Water vapour can affect sensitivity.

6.2.16 Conductivity - liquid electrolyte and gold film

Operating principle	Gas or vapour is absorbed into an electrolyte or other absorbent and changes the electrical conductivity. The liquid electrolyte is commonly based on water for measurement of gases such as SO ₂ , NH ₃ . Other gases or vapours can be measured by conversion to acidic/basic products. The gas dissolves in the aqueous phase and the increase in conductivity is directly proportional to the gas concentration. Also, some types of electrical conductivity apparatus can measure mercury vapour or hydrogen sulphide in air by absorption into a solid gold film (mercury forms an amalgam) which irreversibly changes the electrical resistance of the film. A reference film is used to compensate for certain ambient changes.
Typical measurement tasks	Suitable for some measurement tasks but not for personal exposure monitoring because of the size/weight of the apparatus.
Typical measurement range	ppb to 100 ppm.
Time of response	Seconds to minutes.
Selectivity	a) other gases which change electrolyte conductivity interfere; b) the mercury/hydrogen sulphide gold film sensor is highly selective.
Typical calibration frequency	Of the order of days
Limitations	a) Liquid electrolyte requires replenishment; b) Gold film needs a regular cleaning cycle; c) Limited temperature range.

6.2.17 Detector tubes and badges (colorimetry)

Operating principle	A detector tube consists of a sealed glass tube containing an appropriate reagent on a solid matrix. Tubes can be used in pumped systems (using a pump or bellows) to indicate concentration (short term tubes). This process can be automated to improve accuracy using a chip (mini-detector tube) and optical analyser system. Alternatively, they can sample diffusively for measurement of dose from which the TWA can be calculated knowing the exposure time (long term tubes). The ends of the tube are broken off and the sample is drawn through the tube and changes the colour of the reagent. There are two types of end point - stain length, where the length of stain gives an indication of concentration or dose, and colour comparison where the number of strokes of the pump to produce a particular colour is an indication of the concentration. In a badge, the gas is sampled diffusively, reacts with reagent dispersed over an area of a few cm ² and changes its colour. The colour change is monitored by eye, and can be compared with a description of the colour change for various concentrations over a set period or a standard colour chart.
Typical measurement tasks	Short term tubes mainly used for spot tests. Long term tubes and badges used for personal monitoring.
Typical measurement range	From sub-ppm to % levels.
Time of response	Depends on pump, target gas and reagent.
Selectivity	Tubes are cross sensitive to similarly reacting chemical species.
Typical calibration frequency	Tubes come pre-calibrated.
Limitations	a) Tubes can only be used once; b) Need to carefully dispose of glass tubes after use.

6.2.18 Gas Chromatography

Operating principle	Gas chromatography is a technique for separating multicomponent mixtures. A mixture of gases or vapours is injected into a gas stream and separated into individual components by a selected chromatographic column. The individual gases elute from the column at characteristic times (retention time) and are detected by an appropriate non-selective detector. Columns are typically long tubes made of metal, glass, ptfе or silica; either packed or wall-coated (also known as capillary columns) with stationary phase adsorbent. Typically detectors used are flame-ionisation (e.g. for VOCs), photoionisation (e.g. for VOCs), electron capture (e.g. for halogenated VOCs), thermal conductivity (e.g. for hydrogen), mass spectrometry (for various gases/vapours) and flame photometry (e.g. for sulphur, phosphorus).
Typical measurement tasks	A wide range of measurement tasks. Portable and hand-held gas chromatographs are available.
Typical measurement range	Depends on the type of detector used and chromatographic column.
Time of response	Slow response: depends on the time required to elute the gas from the chromatographic column.
Selectivity	Highly selective; depends on type of chromatographic column and operating parameters.
Typical calibration frequency	Stable over short period, frequent calibration (of the order of daily) usually required depending on type of detector.
Limitations	a) Usually requires a 'clean' dry carrier gas, for example, air, nitrogen; b) A complex instrument requiring extensive operator training; c) Non-continuous monitor.

6.2.19 *Flame temperature*

Operating principle	The rise in temperature of a flame burning a constant flow of hydrogen (or other suitable combustible gas) by flammable contaminants in the air sample supporting the flame's combustion is measured by a detector.
Typical measurement tasks	This type of fixed position DRD is used to measure the total amount of flammable gases and vapours below the LEL when a fast response time is required.
Typical measurement range	0-100% LEL
Time of response	The response time of an FTA is mainly determined by time to feed the sample gas to the flame; response times below five seconds can be obtained.
Selectivity	Halogenated hydrocarbons, such as halons at high concentrations may decrease the signal by reduction of the flame temperature.
Typical calibration frequency	Monthly
Limitations	It is non-specific as the response depends only on the calorific value of the sample. At higher concentrations the response is not linear. The analyser is not recommended for measurement in ppm ranges. External gas(es) are required. Hydrogen or another fuel is required for the flame. Either oxygen is required in the gas to be measured, or a separate air supply needs to be provided for the burner. The signal is dependent on the flow rates of sample, fuel, and, where used, combustion air. Therefore, as in FID, pressure of the gas sample, air and flammable gas should be kept constant, but it should be noted that the flame arrestors used in the sampling line can be soiled and difficulty may be experienced in keeping the sample flow constant. Care should be taken in the presence of Halon in the gas to be measured. Gas samples containing halon but not containing combustible gas will reduce the flame temperature; this should be detectable by the apparatus. Halon at high concentrations in the presence of combustible substances may cause a misreading and may even extinguish the flame.

6.3 Aerosols

6.3.1 *General*

The use of DRDs for aerosols can present greater challenges than for gases and vapours because:

- there are three sampling conventions relating to where the aerosol deposits in a human: inhalable, thoracic and respirable (BS EN 481).
- the effectiveness of the sampling system depends on various factors, e.g. air velocity, the particle size distribution. Sampling passively or actively (i.e. with a pump) affects the effectiveness.
- the sensor response may also depend on particle size distribution and other particle characteristics such as refractive index, shape.

Direct-reading aerosol monitors can be classified into the following three main groups:

- Vibrational mass method,
- Beta attenuation method,
- Optical methods.

These methods are typically used for measuring solid particles although optical methods can also be employed for liquid aerosols. Optical methods are the most numerous because of their high sensitivity, especially in the respirable range, and ease of use. For more information on aerosol DRDs refer to Baron and Willeke (2001). Also CEN standards committee TC137 are currently preparing guidance in the form of European standards on the various types of direct-reading aerosol monitors used in occupational hygiene.

The measurement of fibres requires special types of monitoring technique different to those above (see section 6.3.7).

6.3.2 *Photometry - infrared scattering*

Operating principle	The sample is drawn either passively, using natural air movement, or actively (pumped) into a measuring chamber where infrared radiation is scattered and then detected by a photodetector mounted off-axis from the source. The radiation intensity at the detector is proportional to the concentration of aerosol. Scattered light intensity increases as the particles become smaller and the scattering angle is reduced. The aerosol particle size distribution therefore significantly affects the response. Photometers are optimised for measurement of the respirable fraction.
Typical measurement tasks	Personal monitoring. Screening and spot readings using portable monitors.
Typical measurement range	0.01 to 100 mg/m ³ .
Time of response	Of the order of seconds.
Selectivity	For most photometers the scattered light intensity is at a maximum for particles between 1 to 2 µm, and is close to zero for particles greater than approximately 10 µm. They are therefore suited to measurement of the respirable fraction and become more inaccurate for the thoracic and inhalable aerosol conventions. Determination of the mass concentration of the respirable fraction requires on-site calibration for the aerosol being sampled. Pumped models may have an on-line filter that can be used for gravimetric and chemical analysis.
Typical calibration frequency	Photometers are calibrated in mg m ⁻³ of respirable dust. This is normally carried out by the manufacturer using a polydisperse test dust such as A2 fine test dust following procedures in standards such as ISO 12103-1. On-site calibration is performed by comparison with gravimetric sampling using a reference gravimetric sampler, e.g. a personal cyclone positioned immediately adjacent or by comparison with mass concentration obtained by gravimetry using an on-line filter.
Limitations	Response is not directly proportional to mass, but dependent upon particle size, shape and refractive index. Requires factory and on-site calibration for mixed or varying aerosols. Calibration is only valid for identical and stable aerosols and recalibration should be performed when either the aerosol particle characteristics change or the workplace is changed. Response is minimal for particles > 10 µm, therefore only suitable for the respirable fraction. Oversensitive to fine aerosols (e.g. water mist)

6.3.3 *Piezoelectric*

Operating principle	Particles are collected on the surface of a piezoelectric crystal, forming part of a quartz crystal-based oscillating circuit. The mass of deposited particles causes a reduction in the oscillation frequency. The frequency reduction is directly proportional to the particle mass.
Typical measurement tasks	Screening and spot readings using portable monitors.
Typical measurement range	0.02 to 10 mg/m ³ .
Time of response	30 -120 s
Selectivity	Response is independent of chemical composition and particle size (below 10 µm).
Typical calibration frequency	Most instruments have a calibration period of weeks. No on-site calibration required. Each crystal sensor has its own frequency response and typically the instrument is factory-calibrated to give the required mass response. No further calibration is required provided that the crystal is not damaged.
Limitations	Usage limited by dust loading on crystal, i.e. measurement range. Regular cleaning of the crystal is required. The monitor is only suitable for small respirable particles (i.e. low mass).

6.3.4 TEOM - Tapered Element Oscillating Microbalance

Operating principle	An oscillating frequency is applied to a tapered glass tube with a sampling filter at its narrow end. The filter is held inside a plastic cassette push-fitted onto the glass tube. The top of the tapered tube is coated with an electrically conducting layer and located between two electrodes, which maintain an electric field. An oscillating current flows through the conducting layer, inducing vibration of the tapered tube. The vibration frequency is measured by an optical system. The electrical oscillation frequency depends on the mass of the filter cassette positioned at the narrow end of the tube and, thus, on the mass of deposited particles.
Typical measurement tasks	Screening and spot readings using portable monitors. Static readings.
Typical measurement range	Static: 0.0001 – 5,000 mg/m ³ Personal (US mines only): 0.05-200 mg/m ³
Time of response	Minutes (although static monitor can respond in 10 s depending on mass concentration).
Selectivity	Independent of the physical and chemical properties of the particles. On-site calibration factors are unnecessary. There is no limitation, in principle, on the size of particles that can be detected (unlike the piezoelectric crystal). Different size fractions can be sampled using selective inlets, e.g. cyclones, impactors, porous foam plugs, and PM10, PM2.5 and PM1 fractions.
Typical calibration frequency	Each tapered glass tube sensor has its own frequency response, therefore the instrument is factory calibrated. No further calibration is required provided that the sensor is not damaged and the filter is fitted correctly. Reference filters of known mass can be used as part of a quality control system to check the stability of the sensor.
Limitations	Detector is operated at elevated temperature, 50 °C, to exclude semi-volatiles, e.g. water, organics. Requires > 30 min warm up time at the start of monitoring. The static device is large and not readily portable, although a personal monitor (sample inlet on helmet and monitor on belt) is available for use in US mines.

6.3.5 *Beta mass monitors*

Operating principle	Dust particles sampled on a filter attenuate beta particles (electrons) which are counted using a Geiger-Müller tube. Beta particle attenuation is proportional to the mass of particles collected per filter unit area.
Typical measurement tasks	Fixed monitoring only.
Typical measurement range	0 –10 mg/m ³
Time of response	Approximately 1 hr.
Selectivity	The method is normally limited to the thoracic (PM ₁₀) or respirable particle fractions because the response is affected by the uniformity of particle deposition on the filter. Particle size selective inlets connected to the mass sensing head are used to select the thoracic or respirable fractions. Response is almost independent of chemical composition and particle size.
Typical calibration frequency	Careful calibration against known gravimetric reference samples is required. This is initially carried out by the manufacturer and can then be routinely checked in the laboratory.
Limitations	Radioactive source necessary. Response time is long because an extended integration period is required. Measurement involves comparing numbers of pulses detected by the Geiger-Müller counter before and after sampling which depends on the uniformity of the deposition of particles on the filter and their chemical composition.

6.3.6 *Optical particle counters*

Operating principle	The method involves single particle counting gated through a small illuminated volume. The scattered light intensity from each particle is measured by a photodetector. Signal analysis allows particles to be counted and their size to be estimated. This method requires sampling of the aerosol by a pump. One method uses condensation particle counting (CPC) based on generation of a supersaturated atmosphere of alcohol to produce sufficiently large particles for counting, grown from smaller (e.g. nano) particles.
Typical measurement tasks	Personal monitoring. Screening and spot readings using portable monitors. CPC can be used for nanoparticles (ultrafine particulate matter).
Typical measurement range	0 - 300 particles/cm ³
Time of response	Rapid, of the order of seconds.
Selectivity	Typically, aerosol particles in the size range 0.3 to 10 µm. The mass of a particles classified can be calculated given various assumptions. OPCs are unsuitable for measuring the concentration of the inhalable fraction of workplace aerosols.
Typical calibration frequency	Most instruments have a calibration period of weeks. Optical particle counters require calibration of both the particle count response and the particle diameter response. Calibration of particle count response is usually performed by the manufacturer. Calibration of particle diameter response is calibrated using spherical, individually dispersed particles with a diameter close to the value corresponding to the threshold of the relevant channel.
Limitations	Only low concentrations can be measured using this method because of coincidence errors in the measured volume. The coincidence occurs when two or more particles pass simultaneously through the optical sensing volume. The concentration is thus underestimated.

6.3.7 *Optical fibre counters*

Operating principle	The fibre counting method involves drawing air by an internal pump across a laser beam. This produces a scattering pattern, which the detector can recognize as either produced by fibres or particles (which in most situations greatly outnumber fibres), and each fibre is then counted.
Typical measurement tasks	Background monitoring and leak detection.
Typical measurement range	0 - few hundred fibres/ml
Time of response	Depends on size of fibres: fast (seconds) to detect large fibres in high concentrations, slow (minutes) to detect small fibres in low concentrations.
Selectivity	Increasing concentrations of non-fibrous dust decreases the selectivity of the fibrous component. Also, most regulations specify the length, width and length/width ratio of the fibres, which must be detected.
Typical calibration frequency	All instruments require calibration against fibre and fibre dimension concentrations by the instrument supplier before use. Calibrations generally drift over time.
Limitations	Only high concentrations of fibres of set dimensions can be measured using these instruments. They are not appropriate for carcinogenic fibres, such as asbestos, where the control limits are fairly low - 0.1 fibres/ml over 4 hours, and involve personal sampling. OFCs are not sensitive enough for background measurement to the clearance indicator level of 0.01 fibres/ml. There are two instruments currently available, and while they can be calibrated for amosite asbestos, they usually underestimate chrysotile and crocidolite. The instruments will measure relative fibre concentrations.

6.4 SURFACE CONTAMINATION

6.4.1 *General*

This type of DRD measures pollutant concentration on surfaces rather than the airborne concentration measured by other DRDs discussed in this section. It is accepted that exposure to contaminated surfaces through skin contact can be as significant as inhalation exposure. It is therefore important to be able to measure surface contamination in addition to airborne pollutants in the workplace. Surface measurements also provide a tool for assessing cleaning operations.

One example of assessment of surface contamination would be at a facility handling lead where the workers undergo monitoring for blood lead levels. When the blood lead level of several workers is found to be high, a survey of surfaces throughout the facility can be undertaken, in addition to air monitoring measurements, in order to confirm the effective routes of exposure. If high levels of surface contamination are found in areas expected to be clean, e.g. kitchen or washing facilities, then dermal exposure would be identified as potentially having a significant contribution to total worker exposure.

Surface monitoring can also be used to monitor contamination in clean room areas either when contamination has occurred or by taking random samples as a matter of routine.

6.4.2 X-Ray fluorescence

Operating principle	X-ray fluorescence using either a miniaturised x-ray tube or radio-isotope excitation sources.
Typical measurement tasks	On-site screening of soils and surfaces; for example, contaminated land, potential contamination levels on carpets, textiles including overalls, gloves, towels, cushions. On-site analysis of airborne dust collected on filters.
Typical measurement range	1 - 5000 $\mu\text{g}/\text{cm}^2$. Detection limit 1 $\mu\text{g}/\text{cm}^2$ for most elements, 5 $\mu\text{g}/\text{cm}^2$ for Cd, Sn, Sb and Ba.
Time of response	Analysis time 1 min
Selectivity	Selective to elements from sulphur to uranium
Typical calibration frequency	Radioisotope instruments might require monthly checks for energy calibration, resolution, background and target elements. However, most currently available instruments are factory calibrated and undergo self-calibration when switched on.
Limitations	Stringent legislation applies for transport and custody of radioactive sources present in radioisotope-based instruments. Common sources such as Cd109 and Fe55 need to be changed regularly (half-life of 2.7 years and 1.2 years, respectively) to maintain instrument sensitivity. Maximum power output for current x-ray tube-based instruments is about 50 keV, which limits K-shell excitation to elements below Ba. All PXRF instruments can detect elements deep within the matrix depending on density of the material. Hence, measurements need to be made before <u>and</u> after wiping the surface, the difference providing evidence for the amount of removable contamination present on the surface.

6.4.3 Raman Spectroscopy

Operating principle	Monochromatic light (i.e. a laser) is focused onto the sample. The scattered light from the sample is collected back to the instrument. A small portion of this scattered light is observed at a wavelength longer than that of the incident light: this is the Raman spectrum. It is characteristic of the sample molecular composition. The frequency of the incident light is usually filtered out using a notch filter. Most instruments are equipped with a dispersive element. The detector is an electronic light sensor (i.e. a charge-coupled device). Portable Raman instruments are available for chemical identification in the field.
Typical measurement tasks	Suitable for a wide range of measurement tasks: can be used on bulk solids, liquids, gels, slurries, powders. Measurements can be done remotely through glass and plastic containers, on filters and skin.
Typical measurement range	Raman sensitivity depends on the compound of interest and the host material. Some molecules show no Raman effect (i.e. very low Raman scattering cross-section). Sensitivity depends on the quality of the optics, laser stability and detector sensitivity. As a general rule, the greater the portability, the worse the sensitivity. Hence, going from truly portable to compact instruments, the limit of detection for a particular molecule might well range from ~ 0.1 to 10% by weight.
Time of response	Seconds to few minutes.
Selectivity	Raman spectroscopy is highly molecule specific. With chemometric (pattern recognition) routines, chemicals in a mixture can be identified.
Typical calibration frequency	Daily internal calibration using a standard (typically a silicon wafer). Additional calibration is needed to extract absolute molecular concentration from mixtures. Portable instruments might not all be sensitive or stable enough for quantitative analysis.
Limitations	Not all molecules are Raman active. Some materials exhibit fluorescence under laser excitation. This might over-ride the Raman signal and makes molecular identification difficult. Safety issues and sample thermal stability may be of concern under laser beam illumination, especially when used to identify chemicals on the skin surface.

6.4.4 *Portable surface spectrofluorimeter*

Operating principle	Shortwave UV is used to excite surfaces. A focusing system is used to direct a beam from a xenon flash lamp at the surface requiring examination. A filter is used to select the excitation waveband required. The light emitted from the surface on excitation is then transferred by fibre optics to a spectrometer.
Typical measurement tasks	Coating identification and measurement, occupational hygiene monitoring, cleaning monitoring, tracer studies.
Typical measurement range	Dependant on substance generally 1 – 1000 µg
Time of response	A few seconds
Selectivity	Minimal, by altering the excitation wavelength, the cut off wavelength and the region of interest in the response, it is possible to obtain some selectivity but the instrument does not differentiate between molecules.
Typical calibration frequency	The instrument should be calibrated before each use.
Limitations	The lack of selectivity means that in a mixture of contaminants it is not possible to isolate the one of interest. Also, the readings are taken from a very small area so surveying for very localised contamination can be difficult.

6.4.5 *Colour change indicators*

Operating principle	A wipe or swab is used in conjunction with a developing fluid. The developing fluid is used to wet the wipe or swab, the surface of interest is then wiped. If the substance being tested for is present a colour change takes place. If a quantitative result is required then a known area should be wiped.
Typical measurement tasks	Kits are available for the detection of metals such as mercury, nickel, lead, cadmium and chromate and also for other compounds such as aromatic amines, aromatic isocyanates, aliphatic amines and hydrazine. Can be used to check on housekeeping and cleaning techniques.
Typical measurement range	The lower sensitivities are between 1 and 3 µg dependant on contaminant of interest. No upper limit is documented.
Time of response	Dependant on type generally under 1 minute
Selectivity	Dependant on kit. There are some interferences with the lead and cadmium kits. Also there are some cross-reactants that turn a different colour from the main substance of interest.
Typical calibration frequency	None required.
Limitations	Only gives a qualitative response instantly, quantitative results require the swabs to be sent for analysis by other methods but could be used in conjunction with the PXRF device described above. There are some interferences.

7 PERFORMANCE STANDARDS AND GUIDES FOR USE

7.1 Introduction

The European Committee for Standardisation (CEN) originally introduced two European standards concerned with 'assessment of workplace exposure'. The first standard, BS EN 482 (1994), specifies general performance requirements for procedures for determining the concentration of chemical agents in workplace air. This standard applies to all stages of a measuring procedure: it includes those with separate sampling and analysis stages and also DRDs. The second standard, BS EN 689 (1996), provides guidance for the assessment of exposure to chemical agents in workplace atmospheres and the measurement strategy. Finally, there are performance standards and guides for use of electrical DRDs for gases: BS EN 45544 series (instruments) and BS EN 1231 (short-term detector tubes). Guidance standards on DRDs for aerosols are under development.

Subsequently, BS EN 14042 was published in 2003 and provides guidance on the selection of procedures and the installation, use and maintenance of devices for the determination of concentrations of chemical or biological agents in workplace atmospheres. This standard is based on the guidance in BS EN 689 and the requirements of BS EN 482. Although the emphasis of BS EN 14042 is on sampling methods, for short-term measurements the characteristics of short-term detector tubes are covered, while for continuous/instrumental measurement methods, i.e. DRDs, reference is made to BS EN 45544-4 which provides guidance on the selection, installation, use and maintenance of electrical apparatus used for the direct detection and direct concentration measurement of toxic gases and vapours (see section 7.4.1). General guidance applicable to DRDs can also be found in BS EN 14042 relating to the operation of the measuring devices, e.g. use of personal, portable, transportable and fixed measuring devices.

7.2 BS EN 689 Workplace atmospheres - Guidance for the assessment of exposure by inhalation to chemical agents for comparison with limit values and measurement strategy

The assessment is based on an occupational exposure assessment and, if necessary, periodic measurements to check that the exposure conditions are unchanged. If the conditions are changed, a reassessment is necessary.

7.2.1 Occupational exposure assessment

The occupational exposure assessment is used to identify potential exposure situations and assess the level of exposure through a sequence of stages with increasing sophistication (initial appraisal, basic survey, detailed survey). At each stage, the possibility exists to conclude the assessment.

The initial appraisal will indicate the likelihood of exposure. It is based on the list of chemical agents that are likely to be present in the workplace atmosphere and on several workplace factors likely to have an influence on the exposure level (tasks, work pattern and techniques, ventilation, emission sources, etc.). If the initial appraisal shows that the presence of an agent in the air at the workplace cannot be ruled out for certain, this agent needs to be considered in the next stage. In practice, this means that if an agent is introduced in the workplace even as an impurity or is produced in the workplace even as a side product or waste, it has to be considered in the basic survey.

The basic survey provides quantitative information about exposure. This information is based on earlier measurements, measurements from comparable installations or reliable calculations on relevant quantitative data. If the information obtained is insufficient to enable valid comparison to be made with the limit value (LV), it has to be supplemented by workplace measurements. If the basic survey shows that the exposure is above the limit value, BS EN 689 requires that immediate action be taken to remedy the situation and a new assessment be conducted. If the basic survey shows that the exposure is well below the limit value and is expected to remain so on a long-term basis, taking into account the stability of conditions at the workplace and the arrangement of the workplace process, the

assessment procedure may be stopped. In BS EN 689 no figure is associated with the concept 'well below the limit value', but it is generally accepted that it concerns time-weighted average concentrations less than 0.1 LV. If neither of those conclusions can be reached, the next stage of the assessment is undertaken.

The detailed survey will provide validated and reliable information on exposure when the exposure is close to the limit value. The information is based on workplace measurements and will lead to the conclusion of the occupational exposure assessment.

According to BS EN 689, the occupational exposure assessment phase will be concluded with one of the three actions listed below:

- a) When the exposure exceeds the limit value, control measures are taken to reduce the exposure and the exposure reassessed.
- b) When the exposure is well below the limit value, a reassessment of the exposure level will be done at periodic intervals. The time interval between assessments will depend on how long the exposure level is likely to remain low.
- c) When the exposure is between a) and b), a periodic measurement scheme should be established to monitor the exposure level.

7.2.2 *Periodic measurements*

The emphasis of periodic measurement is on longer-term objectives, such as checking that control measures remain effective. Information is likely to be obtained on trends or changes in pattern of exposure so that action can be taken before excessive exposure occurs. In this respect, it is important to use a measurement method and strategy that makes it possible to detect trends at a sufficiently early stage.

7.2.3 *Reassessment*

At any time during the assessment and monitoring process, changes in the process or control measures could have a major impact on the exposure level. Therefore, such changes will require a reassessment of the exposure.

7.2.4 *Measurement strategy*

The measurement strategy described is based on an approach which enables the efficient use of resources. It gives instructions on:

- selection of the measurement task and procedure;
- selection of workers for the exposure measurements;
- selection of the measurement conditions and patterns.

BS EN 689 refers to the basic measurement tasks described in BS EN 482.

7.3 *BS EN 482 Workplace atmospheres - General requirements for the performance of procedures for the measurement of chemical agents.*

These requirements apply to all measuring procedures, irrespective of the chemical nature or physical form of the agent and irrespective of the sampling method or analytical method used. BS EN 482 is applicable to measuring procedures with separate sampling and analysis stages and to DRDs. The performance requirements include unambiguity, selectivity and overall uncertainty (a combination of bias and precision) for minimum specified measuring ranges and averaging times. BS EN 482 is a basis for forthcoming standards for specific procedures and devices for workplace measurements. Five basic measurement tasks have been defined in the standard. These are:

- a) Screening measurements of time-weighted average concentration to provide relatively crude quantitative information on the exposure level in order to decide whether an exposure problem exists. These measurements can also be used to determine if the exposure is well below or well above the limit values.
- b) Screening measurements of variation of concentration in time and/or space to provide information of the likely pattern of exposure and to identify locations and periods of "high" exposure. They can also be used to set the duration and frequency of sampling for comparison with limit values.
- c) Measurements near an emission source to provide information on the location and the intensity of the source. In association with other information they can allow the elimination of a suspected source as a significant contributor to exposure.
- d) Measurements for comparison with a limit value to provide accurate and reliable information on the time-weighted average concentration of a specific agent in the air, which can be inhaled.
- e) Periodic measurements to check if the exposure conditions have changed since the last comparison against respective limit values, or whether the control measures remain effective.

Table 1 summarises the performance requirements in BS EN 482 for various measurement tasks.

Table 1. BS EN 482 Specification of performance requirements depending on the measurement task. (LV = Limit Value, e.g. UK Workplace Exposure Limit).

Measurement task	Relative overall uncertainty	Minimum specified measuring range	Averaging time
Screening measurements of time-weighted average (TWA) concentration to provide relatively crude quantitative information on the exposure level in order to decide whether an exposure problem exists at all. These measurements can also be used to determine if the exposure is well below or well above the limit value.	< 50 %	0.1 - 5 LV	less than or equal to LV reference period
Screening measurements of variation of concentration in time and/or space to provide information on the likely pattern of exposure and to identify locations and periods of 'high' exposure. They can also be used to set the duration and frequency of sampling for comparison with limit values.			
Screening in Time:	< 20 %	dynamic range > 10:1	< 5 min
Screening in Space:	< 40 %	dynamic range > 10:1	< 15 min
Measurements near an emission source to provide information on the location and the intensity of the source. In association with other information they may allow the elimination of a suspected source as a significant contributor to exposure.	< 50 %	0.5 - 10 LV	source dependent
Measurements for comparison with limit values to provide accurate and reliable information on the time-weighted average concentration of a specific agent in the breathing zone of the worker.	< 50 %	0.1 - 0.5 LV	less than or equal to LV reference period
	< 30 %	0.5 - 2 LV	
Periodic measurements to check if the exposure conditions have changed since the last comparison with limit values, or to check that the control measures remain effective.	< 50 %	0.1 - 0.5 LV	less than or equal to LV reference period
	< 30 %	0.5 - 2 LV	

Appendix A of BS EN 482 gives a list of measurement tasks referred to in BS EN 689 and involving a combination of the basic measurement tasks:

- a) **Worst case measurements.** Screening measurements in time and space can clearly identify episodes where higher exposures occur, for example, high emissions due to certain work activities. Sampling periods can be selected containing these episodes. This approach is called worst-case sampling. Subsequently, monitoring may be employed either as a screening measurement of time-weighted average concentration or for comparison with limit values. This approach can allow a low cost exposure assessment to be made when the results of a few worst-case measurements are still below the limit value.
- b) **Fixed point measurements.** These can be used for comparison with limit values if the results are representative of personal exposure. In other uses, the initial measurement task is the same as for emission sources and any subsequent monitoring will be a screening measurement of time-weighted average concentration or a periodic measurement.

- c) **Short-term peak measurements.** Screening measurements of variation in time can find short-term peaks. These measurements may be followed by screening measurements of time-weighted average concentration. Where the measurements are of exposure concentration, these can be compared with limit values. Short-term limit values may be important in these cases.

7.4 Electronic DRDs - Performance Standards and Guidance for Use

7.4.1 Toxic gas - occupational and commercial environments

In addition to the general requirements in BS EN 482, DRDs are subject to specific performance requirements related to their construction and mode of operation. European standards for performance requirements, and a guide for use of toxic gas detectors for workplace air measurements have been published as the BS EN 45544 series (i.e. performance standards BS EN 45544-1, -2, -3 and guidance BS EN 45544-4). The following tests are included in the performance standards:

- Calibration and overall uncertainty;
- Mechanical (vibration and drop);
- Environmental (effects of temperature, pressure, humidity, air speed);
- Performance under reference conditions (audible alarm, alarm set point(s), alarm response time, flow failure alarm, warm-up time, time of response, time of recovery, warm-up and time of response for spot-reading DRDs, addition of sampling probes, field verification kit, gas concentrations above the measuring range and electrical fault signal);
- Orientation;
- Electrical (battery capacity, mains power supply, power supply interruptions, voltage transients and step changes of voltage, time-weighted average function, electromagnetic compatibility);
- Drift

The guide, BS EN 45544-4, provides advice on the selection, installation, use and maintenance of devices conforming to the scope of BS EN 45544-1.

Guidance for identifying spillage, leakage or build-up of combustion products from gas-fired equipment in non-domestic premises is given in BS 7967-5 (to be published in 2010). This entails the measurement of carbon monoxide (CO) and carbon dioxide (CO₂) in the atmosphere and in equipment flues by the use of electronic portable combustion gas analysers.

The performance of portable and transportable instruments for the detection of carbon dioxide in indoor air quality, in its most general sense, is covered by BS 8494:2007. A new (European) standard (draft BS EN 50543) having a similar scope but extending it to include carbon monoxide detectors is under development (to be published in 2010/11). Carbon dioxide detectors are employed in applications such as air quality measurement and testing ventilation/extraction system efficiency in workplaces (e.g. commercial kitchens). HSE guidance on gas safety for catering and hospitality businesses (HSE, 2006) refers to measurement of carbon dioxide as part of the catering canopy test methodology.

7.4.2 Toxic gas – domestic premises

The use of DRDs for monitoring carbon monoxide in domestic premises is covered by British Standard BS EN 50291 'Specification for carbon monoxide detectors (electrical) for domestic use'. The guide for use on domestic carbon monoxide detectors is BS EN 50292.

There is also a British standard (BS EN 50379) for portable apparatus designed to detect and measure specific combustion flue gas products, including CO, in domestic, residential and commercial premises. These devices are known as flue gas analysers (FGAs) or, more generally, electronic portable combustion gas analysers.

The use of electronic portable combustion gas analysers, for domestic premises only, is covered by the BS 7967 family of standards (parts 1-4). These standards give guidance on the methodology to adopt when checking ambient air for carbon monoxide when investigating (non-incident related) reports of fumes from heating appliances or the activation of domestic CO alarms. A guide for domestic gas operatives/engineers to assist them with dealing with situations covered by these standards has been published (CORGI, 2006).

7.4.3 *Flammable gas - occupational and commercial environments*

The standards covering the performance, selection, installation, use and maintenance of flammable gas DRDs are BS EN 60079-29-1 and BS EN 60079-29-2.

The contents of these standards include:

- intended applications;
- methods to test the performance of the instrument;
- criteria for selection;
- operation of fixed, portable and transportable gas detection apparatus;
- training;
- physical and chemical principles of operation; and
- guidance on the nature of a flammable gas release.

Functional safety¹ of gas detectors (both flammable and toxic) is covered by BS EN 50402; there is also an equivalent international standard under development by IEC (draft IEC 60079-29-3).

A performance standard for open-path flammable gas detectors is about to be published: BS EN 60079-29-4 "Performance requirements of open path detectors for flammable gas".

HSE has also produced guidance on the use of flammable gas detectors (HSE, 2004).

7.4.4 *Flammable gas - domestic premises*

The use of DRDs for monitoring flammable gases (natural gas and liquefied petroleum gas) in domestic premises is covered by British Standard (BS EN 50194) 'Specification for electrical apparatus for the detection of combustible gases in domestic premises'. The guide for selection, installation, use and maintenance of such domestic combustible gas detectors is BS EN 50244.

7.4.5 *Oxygen - occupational and commercial environments*

BS EN 50104 'Electrical apparatus for the detection and measurement of oxygen. Performance requirements and test methods' relates to portable, transportable and fixed electrical apparatus for the measurement of oxygen concentration in gas mixtures indicating up to 25% (v/v). Guidance on the selection, installation, use and maintenance of oxygen detectors relating to a flammable hazard (e.g. inerting operations) is also contained in EN 60079-29-2 (i.e. as an addition to flammable gas detectors).

¹ Functional safety is defined as part of the overall safety relating to the equipment under control (EUC) and the EUC control system which depends on the correct functioning of the electrical/electronic/programmable electronic safety-related systems (E/E/PES), other technology safety-related systems and external risk reduction facilities. The EUC is the equipment under control or the process that the gas detection system is assuring the safety of. The gas detection system is part of the E/E/PES. The safety function of a gas detection system is the function (inclusive from gas sampling to the output of the gas detection system) implemented by the gas detection system to enable the safety-related system to achieve a safe state of the EUC.

7.4.6 Aerosol monitors – occupational environments

The European standards organisation CEN is currently (2009/10) engaged in producing guidance on the use of direct-reading aerosol monitors in occupational settings. The responsible committee is CEN/TC137/WG3.

7.4.7 Other standards referencing DRDs

Other standards which refer to DRDs include process safety applications and gas analyser requirements. The standards below constitute a non-exhaustive list.

BS EN 378-1 “Refrigerating systems and heat pumps – Safety and environmental requirements. Part 1: Basic requirements, definitions, classification and selection criteria” explicitly requires the installation of fixed leak monitors in refrigeration and air-conditioning machinery rooms, as well as other areas where a sudden leak into an occupied space would cause a hazardous condition. Alarm levels are specified, depending on which group the refrigerant belongs to, and classified according to its flammable and/or toxic hazard.

Standards on safety requirements for equipment for dryers, ovens and coating plants in which flammable substances are released specifically refer to fixed, integrated flammable gas monitoring systems based on DRDs, for example, BS EN 1539 (2000). Here, the requirement for fast response detectors is critical.

The code of practice for safety in tunnelling in the construction industry (BS 6164) describes basic performance requirements for flammable, oxygen and toxic gas detectors and guidance for their use.

There are other safety-related standards which refer to the measurement of toxic and flammable gas concentrations. For example, BS EN 61207 'Expression of performance of gas analysers'; Part 1: General is applicable to gas analysers (complete instruments or individual sensor and electronic units, if supplied separately) specified for permanent installation in any location, utilising either a sample handling system or an *in situ* measurement technique. The standard specifies tests for determining the functional performance of such analysers and aims to unify methods used in making and verifying statements on their functional performance. It is applicable to *in situ* and extractive analysers installed both indoors and outdoors. Subsequent parts of the standard are concerned with different types of analysers, for example, Part 2 - Oxygen in gas (utilising high temperature electrochemical sensors; and Part 6 - Photometric analysers.

7.5 Detector tubes - Performance Standards

BS EN 1231 (1997) describes performance requirements and test methods for short-term tubes. The British standard for long-term tubes, BS 5343-2 (1991), is obsolete.

8 THE FUTURE?

8.1 General

Although this section is titled “The future”, most, if not all, of the trends noted below are already happening but may become more widespread as their usefulness or cost-effectiveness becomes generally apparent. Trends in the performance and usage of DRDs may be categorized as follows:

- Improved sensor performance
 - higher sensitivity/lower detection limit
 - improved selectivity
 - greater reliability including self-checking/calibration
- Improved user features which make monitoring easier or more effective/efficient to use, for example:

- Managing fleets of detectors (e.g. on a large site) more effectively through networking and analysis of their logged status data (e.g. calibrations, alarm events);
- greater worker empowerment through instruments which give direct feedback allowing modification of their behaviour or environment to reduce their exposure, though this would have to be managed carefully;
- multi-functional detectors (c.f. mobile phone technology) incorporating heart rate, temperature, gas and dust concentration, GPS (see below); these devices will depend to a large extent on...
- Miniaturization
 - Lower power
 - Smaller size
- New sensors having superior performance/cost over existing types
- New applications which generate new data
 - Exposure data from real-time monitors are collected to identify and control potential hazards, and survey health effects of exposure. With regard to the latter, real-time data are typically too variable for detailed statistical analysis. A single worker's exposure varies considerably depending on the type of work, its duration, day-to-day differences in type, location, duration of work/equipment and environmental changes. An enormous amount of data would need to be analysed to assess the influence of numerous variables and determine the cause and effect.
 - Nevertheless, peak exposure metrics derived from real-time monitors have been developed to characterize exposure to organic solvents (Preller et al, 2004). Peak exposures in the flour processing industry have also been evaluated to provide information on exposure determinants and control measures essential for assessment of intervention strategies real-time monitors (Meijster et al, 2008). These techniques will be increasingly used in the future.
 - The application of gas and aerosol monitors with GPS provides new opportunities for concentration mapping over space in order to better characterize exposure patterns and identify lack of controls (Adams et al., 2009; Hornsby-Myers, 2003).

Specific developments for each of the three types of DRDs covered in this guidance (gas, aerosol, surface contamination) are addressed below.

8.2 Gas/vapour detection

There have been steady gains in the miniaturisation of laboratory-based instrumentation such as gas chromatography-mass spectrometry, and Fourier Transform Infrared (FTIR) and Cavity Ring down spectrometers (Parkes et al., 2003) for speciation of complex mixtures and detection of ppb levels. Transportable and even portable versions are now becoming available.

Also, the development of Ion Mobility Spectrometry, well-known as a fast-response chemical warfare agent detector, as workplace air monitoring continues through variants of the technique: high-Field Asymmetry IMS (FAIMS) and differential mobility spectrometry (DMS), which show promise as sensitive and selective DRDs but at a realistic cost for industrial use (Kolakowski and Mester, 2007).

The advent of low cost lasers should lead to the development of highly selective (possibly tunable) and sensitive detectors for various gases which absorb in the infrared and possibly ultraviolet.

Hydrogen sulphide and benzene detection are active topic areas for development of optical sensors based on IR and UV, with particular applications in the petrochemical industry. These devices have the potential to provide greater selectivity than existing DRDs for these agents but without incurring excessive cost.

Gas imaging cameras, now employed for leak detection especially in petrochemical environments, may become more widespread for other areas of workplace monitoring.

Other areas of sensor research currently in vogue include carbon nanotubes, surface acoustic wave (SAW) devices, electronic noses.

Real-time breath analysis is an area of research in the medical field (e.g. rapid diagnosis of state of health) which would have benefits for occupational health assessment. The monitor must be sufficiently fast and selective (in a high humidity atmosphere) in order to provide meaningful results. Potential candidates include SIFT-MS, selective ion flow tube mass spectrometry (Smith and Španěl, 2005).

Stand-off measurement techniques, i.e. where gas detection in hazardous areas can be achieved without the need for personnel to be present, are under development, stimulated by disaster management. Examples of such techniques include LIDAR (light detection and ranging), drones (also known as unmanned aerial vehicles, UAVs) carrying DRDs (and samplers).

8.3 Aerosol detection

The use of photometers for dust measurements continues to grow steadily with improvements in the effects of size selectivity, humidity, etc. While improvements are being made in terms of size selectivity, there will still be a need to characterize the response of instruments to different aerosol characteristics (e.g. size fractions, dust types) particularly for personal/portable monitors.

The development of agent specific detectors (e.g. advanced optical techniques for shape recognition of bioaerosols which allows identification and quantification) could spill over into improved aerosol monitors for workplace air monitoring.

There is potential for the TEOM, which measures true mass concentration, to be adapted into a portable device for measurement of respirable, thoracic and possibly inhalable fractions. Currently, it is used as fixed position monitor (e.g. for environmental applications) and as a portable (belt-mounted) monitor used in US coalmines where it is powered by the miner's cap-lamp battery (Patashnick et al., 2002).

For direct-reading fibre measurements, the ability of the fibre detectors to measure fibres of interest depends on the size of the fibres, their concentration and the proportion of the fibrous component compared to the non-fibrous component. With regards to asbestos, the control limit is very low (0.6 fibres/ml for peak exposure, 0.1 fibres/ml for personal exposure measured over a 4 hour period and 0.01 fibres/ml for clearance indicator level/background/reassurance). As the concentration of particles and large fibres (i.e. outside the measurement dimension range) often predominate, the ability of fibre monitoring instruments to distinguish scattered light patterns of interest from the other dust patterns diminishes. Such instruments will measure the relative concentrations of fibres (e.g. in leak situations) but are not accurate enough for current control limits. Improvements in fibre sensor technology would therefore be extremely useful.

There is a need to develop standards for performance and use, and industry-specific guidance on use of direct-reading aerosol monitors, which are being undertaken by CEN (see section 7.4.6).

8.4 Surface contamination measurement

The latest generation of powerful miniaturised x-ray tube-based instruments generate x-rays up to about 50 keV. These portable XRF instruments produce a constant x-ray output over their lifetime. They offer an additional advantage over isotope-based instruments in the fact that they only generate x-rays when powered up. Greater sensitivity and resolution for elements as light as magnesium can be achieved when using instruments equipped with large area silicon drift detector technology combined with helium gas purge, tunable x-ray tube and appropriate filters.

Portable infrared spectrometers are currently available for gas and vapour monitoring as well as for the identification of powders, liquids and solids. Minimal sample preparation is required before analysis (i.e. pumping a gas to an appropriate level within detection chamber or recovering first

powders or liquids from a surface). The emergence of new fibre optics equipped with diamond attenuated total reflectance probe heads for the mid-infrared suggests that in-situ measurements on surfaces might become a viable option for portable infrared instruments. With such instrumentation, no sample preparation at all would be required. Moreover, substrate interferences over the infrared spectral region would be very limited.

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APPENDIX 1 - SUMMARY OF VARIOUS DRD CHARACTERISTICS

SENSOR	POTENTIAL BENEFITS*	POTENTIAL LIMITATIONS*
Gases and vapours		
Electrochemical	Wide range of measurement Low power Low cost	Non-selective Restricted temperature range Affected by other gases Can be poisoned
Semiconductor	Long lifespan Relatively inexpensive Easy to use Can be used on O ₂ -depleted atmosphere	Non-specific Low sensitivity Temperature and humidity dependent Slow response and zero return Can be poisoned
Paper tape (chemcassette)	High degree of specificity High sensitivity Cassettes pre-calibrated Physical evidence (colour change)	High cost Limited range of tapes Slow response and recovery Tape shelf life (approx. 3 months)
Catalytic (pellistor)	Low cost Simple operation Response generally indicative of explosive hazard in gas mixture	Non-specific Poisoned Only detects flammable gases Requires oxygen Low sensitivity - LEL ranges
Infra-red spectrometry	Can be very accurate Good sensitivity (depends on pathlength) Suitable for wide range of gases Not poisoned Autochecking	High cost Bulky (for toxic gases except CO ₂) Relatively complex Only suitable for gases with infra-red absorption (e.g. H ₂ , Cl ₂ not detectable) Optical surfaces prone to contamination
Mass spectrometry	Can be highly accurate High sensitivity Can differentiate very accurately Long lifespan	Very high cost Complex - needs trained operator High running costs
Chemiluminescence	High degree of specificity High accuracy Sensitivity good for some gases	Relatively expensive Needs O ₃ generator for NO (hazard) Can be prone to interferences
Paramagnetic	Highly selective for oxygen. Wide dynamic range. High accuracy.	Sensitive to shock/vibration Temperature and pressure compensation may be required Fixed/transportable devices only.
Flame ionisation	Long sensor life High sensitivity Easy to use	Unable to differentiate between gases Needs H ₂ supply (hazard) Halogens impair detector
Photo-ionisation	Easy to use/calibrate Rapid response High sensitivity	Non-specific Cannot ionise some gases (e.g. lower hydrocarbons) Sensitive to water vapour O ₂ has quenching effect High energy lamp has short lifetime
Thermal conductivity	Long sensor life Simple operation Low cost	Unable to differentiate between gases Limited range of gases (good for CH ₄ , H ₂)

SENSOR	POTENTIAL BENEFITS*	POTENTIAL LIMITATIONS*
Ultraviolet absorption spectrometry	High sensitivity	Non-specific (but spectral analysis can improve this) Optical surfaces prone to contamination Fixed/transportable devices only
Electron capture	High sensitivity Long sensor life	Only detects gases with electronegative atoms (including oxygen) Non-specific Relatively expensive Leak detectors have low accuracy
Ion mobility spectrometry	High degree of specificity Hand-held detectors available High sensitivity Fast response	Small range of suitable gases High cost Humidity and temperature sensitive Narrow measuring range
Conductivity – liquid electrolyte/gold film	High specificity High sensitivity Easy to use	High cost Gold film limited to H ₂ S and Hg vapour Gold film needs regular cleaning cycle
Detector tube/badge	Very low cost Easy to use Physical evidence (colour change) Wide range of gases Pre-calibrated	Mainly for spot tests but some long-term tubes available Low accuracy Need to dispose of glass tubes after use
Gas chromatography	Can separate gas mixtures Long sensor life Accurate Good sensitivity	Not continuous Long sample analysis time Needs carrier gas Skilled operator required
Flame temperature	Fast response General hydrocarbon detector	Non-specific Fixed instrumentation only Halogen-containing species may affect reading External gases required, e.g. H ₂
Aerosols		
Photometry (light scattering)	Direct readout in mg/m ⁻³ Portable - can be used for personal sampling Wide range of dusts Easy to use Most sensitive to respirable range Pumped models may have online filter for gravimetric calibration	Response not directly proportional to mass, needs calibrating for different dust particle sizes, shapes etc Does not identify dust Relatively insensitive to thoracic/inhalable convention dust
Piezoelectric	Response directly proportional to mass, i.e. independent of composition and particle size	Dust loading limits measurement range, regular cleaning required. Only suitable for low mass, respirable particles.
TEOM	Response directly proportional to mass Wide range of particle sizes (respirable to inhalable)	Long response time, although the higher the concentration the faster the response No portable monitor for general use, typically large fixed device. Long warm-up time
Beta mass monitors	Response virtually independent of particle size and composition.	Fixed instrumentation only Limited to thoracic or respirable particle fractions Long response time

SENSOR	POTENTIAL BENEFITS*	POTENTIAL LIMITATIONS*
Optical particle counter	Suitable for nanoparticles Fast response	Unsuitable for inhalable fraction Only low concentrations measurable Measurement units in particles per unit volume rather than mass per unit volume (although this may be a useful metric depending on the application)
Optical fibre counter	Real-time measurement suitable for background monitoring and leak detection	Only suitable for high concentrations of fibres with set dimensions Unsuitable for carcinogenic fibres where limits are low. Interference from non-fibrous dust decreases selectivity to the fibrous component
Surface Contamination		
X-ray fluorescence	Simple to use Minimum sample preparation Rapid on-site analysis of surfaces	Currently only configured to analyse metals Needs a surface High cost of source replacement

* These are general benefits and limitations and depend upon the design of the device. It is therefore important to check the manufacturer's specification and consult an expert when considering the intended use of the device.