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Gas Analysis by Mass Spectrometry

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Overview

General Uses

- Qualitative and quantitative analysis of bulk and trace inorganic and organic compounds and simple mixtures, field measurements, process gases

Examples of Applications

- Gas purity, contaminants, and isotope ratios
- Process gas monitoring (industrial, petroleum, steel)
- Environmental gases (air, SO_2, CO_2, underwater, volcanic)
- Volatile organics (fermentation, pharmaceutical)
- Rapid analysis
- Continuous monitoring
- Internal atmospheres of sealed components
- Gases in inorganic and geologic materials

Samples

- Form: Primarily gases, but volatile liquid from headspace sample can be analyzed
- Size: 1×10^{-4} mL (STP) or larger
- Sample can be collected in a compatible vessel or directly sampled by the instrument from a flowing gas stream or sample environment

Limitations

- Target detection limits, measurement speed, and mass resolution must be matched with instrument capabilities
- Reactive gases are difficult to introduce intact and detect
- Complex mixtures might not be resolved
- Species must have some volatility and, for gas analysis, be less than ~500 amu

Estimated Analysis Time

- Milliseconds to minutes, not including sample preparation and calibration

Capabilities of Related Techniques

- Gas chromatography (GC): may require larger sample size
- Gas chromatography-mass spectrometry (GC-MS): greater capability for compound identification in complex organic mixtures
- Liquid chromatography-mass spectrometry (LC-MS): can measure larger molecular weight and less volatile species
- Infrared/Raman spectroscopy: requires larger sample size; infrared spectroscopy does not detect some inorganic gases

Introduction

Gas analysis by mass spectrometry, or gas mass spectrometry, is a general technique using a family of instrumentation that creates a charged ion from a gas phase chemical species (atomic or molecular) and measures the mass-to-charge ratio (m/z). Typical ionization and measurement occur in a vacuum, and, therefore, samples must comprise permanent gases or volatile species, where larger molecules must use alternative vaporization-ionization methods. Because each empirical molecular formula has a different mass, gas mass spectrometry has the potential to both identify and quantitate the components within a sample. This article covers gas analysis applications that do not use chromatographic separation to physically isolate components of the sample prior to analysis.

Typical applications of gas mass spectrometry fall into two categories: static and continuous. In static analysis, a measurement is made on a fixed or static gas volume, and a plot of signal intensity versus m/z value for each species in the gas is assembled by the instrument. In some cases, fragmentation occurs, which can complicate data interpretation. Static analysis is used for both qualitative and quantitative compositional analysis of individually captured samples. In the category of continuous analysis, specific m/z values are monitored (when analytes are known) or the instrument is scanned repeatedly across an m/z range. Output is typically a plot of analyte m/z versus time or total ion signal (per scan) versus time. Continuous analysis is used for applications such as reactions, industrial processes, and environmental monitoring and can be qualitative or quantitative.

This article is intended to provide an understanding of gas analysis instrumentation and terminology so informed decisions can be made in choosing an instrument and methodology appropriate for the data needed.

General Principles

Every gas mass spectrometer requires the same common functions to perform an analysis: sample introduction, ionization, mass separation, and detection (Fig. 1). Each function can be achieved using a variety of methods and techniques based on the target data goal and sample particulars. In addition to these common functions, general principles that should be considered in matching instrumentation to an analysis goal include, but are not limited to:

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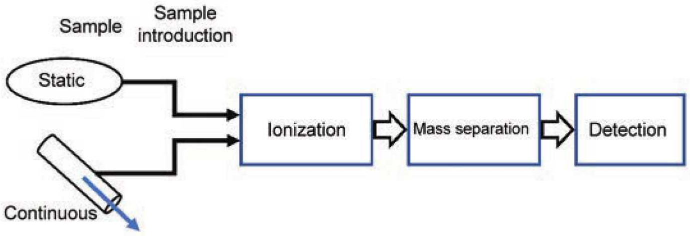

Fig. 1 Schematic of common instrument functions for a gas mass spectrometer

- It is important that the gas volume measured by the instrument is representative of the desired sample, or that the relationship is understood. Sampling bias can be an advantage or disadvantage.
- The complexity of the sample must be considered. A complex gas stream might require advanced sampling techniques to provide adequate data output.
- The mass range of the gases or potential targets should be properly estimated. This can affect the cost of the instrumentation needed.
- The measurement goal should be considered, in conjunction with complexity and mass range, in relation to the sampling frequency. For static measurements sampling frequency relates to the quantity of gas required, while for continuous measurements, sampling frequency relates to the time resolution needed. For example, a sampling frequency of one minute would likely be adequate for environmental monitoring, but not for a reaction monitoring application.

Considerations common to all instrument types are mass resolution, cost (and associated size, weight, and power), and robustness. These factors have a tremendous range in the instrumentation for gas mass spectrometry. Mass resolution is the numeric factor that defines the ability to differentiate between different *m*/*z* and, thus, different analytes apart. Sample complexity and data goals can determine whether an inexpensive, small, low-resolution instrument is suitable.

These general principles are overarching and apply regardless of system details. The following sections discuss some instrument options in the context of these principles to choose appropriate methodology to achieve the data goals.

Sample Introduction

The introduction system serves a common function among instruments; i.e., to bring sample gas into the ionization region of the mass spectrometer in a controlled quantity and controlled pressure. A wide variety of sample pressures ranging from vacuum to >100 psi (> 5000 torr) can usually be accommodated. These goals are accomplished differently for static and continuous sample configurations. In all cases, the mass analyzers require low ($<10^{-4}$ torr) pressures; thus, the fraction of sample gas being analyzed is often small.

Static gas introduction systems vary from a simple valve and effusive leak orifice to complex automated transfer systems that perform evacuation, dilution, and transfer. The primary consideration for choosing an introduction system is to preserve sample gas mixture ratios. Moisture and reactive gases can interact with tubing and sample vessels, therefore vessels and tubing are coated with an inert material ("passivated"). If transferring gas samples in a system below about 0.1 torr, note that as gases transition into a molecular flow regime, the gas mixtures can fractionate, with lighter/faster molecules moving ahead of heavier/slower ones; which requires some extra time to allow equilibrium to be established. Molecular leaks can also bias gas transfer due to mass-dependent flow and pumping efficiency, so care is taken with gas mixtures of diverse gases to characterize this effect if applicable. For quantitative work, it is usually necessary to know both pressure (P) and volume (V) of the sample gas; therefore, typical introduction systems often measure P and use a controlled V for the gas that enters the ionization region. Static gas measurements are typically used in situations where the sample gas volume is small (microliters to liter), or where pressure is low (few torr or lower), and where gas is emitted from a fixed size material (mineral, sealed component, etc.).

Controlling the quantity and pressure of sample gases are primary considerations for continuous gas introduction systems, which can vary from simple pulsed, fixed-volume valves to multistream samplers, capillary transfer lines, molecular leaks, of membrane inlets. Sampling frequency of continuous introduction must balance source/analyzer pressure requirements with the flow rate entering the instrument. For example, a long capillary inlet enables continuous measurement, but the capillary transit time delays the measurement with respect to the flowing sample. Membrane barriers between the sample gas and the ionization region can be beneficial, reducing the pressure load and/or providing chemical selectivity, such as in the monitoring of hydrocarbons within seawater. The membrane rejects the liquid while allowing hydrocarbons to pass. Therefore, the tradeoff consideration is that the membrane must be permeable to the analytes of interest. Membranes can also create a delay time due to analyte diffusion, which may be an important consideration in reaction and process gas monitoring.

Ionization Source

The ionization source converts the neutral analyte species into charged species, which can be manipulated using magnetic or electric fields for mass analysis. In research environments, ionization techniques use plasmas, lasers, and surfaces under vacuum or atmospheric pressure. Methods to create negative ions are mature, but are needed only in special applications like explosives detection and other niche areas in which the analytes have physical or electronic properties favoring negative ionization; this is outside the discussion of this article. Two methods in widespread use in the context of gas analysis, electron ionization (EI) and chemical ionization (CI), are discussed here. A specific variant of CI called proton-transfer reaction (PTR) is enjoying increased use (Ref 1).

Electron Ionization

Electron ionization is the most common method for creating positive ions of analyte species within the ionization region. Electrons are generated by passing current through a tungsten or rhenium filament and are accelerated and focused into a beam that intersects the cloud of neutral gas brought into the vacuum by the sample introduction system. A kinetic energy (ionization peak) of 70 eV, which has been adopted as the standard condition, creates consistent fragmentation of the analyte species, enabling spectral comparison across systems and generation of standard libraries for identification. In some cases, a lower energy can be used to reduce the observed fragmentation, but results in reduced ionization efficiency and, thus, reduced signal. The electron energy is sufficient to interact with neutral atoms and molecules, stripping an electron and resulting in a positive analyte ion as in the reactions:

$$\text{analyte} + e^- \rightarrow [\text{analyte}]^+ + 2e^- \qquad \text{(Eq 1)}$$

and

$$\text{analyte} + e^- \rightarrow [\text{analyte}]^{2+} + 3e^- \qquad \text{(Eq 2)}$$

Analyte fragmentation results in a charged fragment ion species (fragment) and neutral product (neutral) in the reaction:

$$\text{analyte} + e^- \rightarrow [\text{fragment}_1]^+ + \text{neutral}_1 + 2e^- \qquad \text{(Eq 3)}$$

Because the electron cloud has a distribution of energies, other fragmentation pathways also occur (generating fragment_2, fragment_3, etc.). While there are some species that have relatively low ionization probabilities, EI is considered a universal ionization method.

Chemical Ionization and Proton-Transfer Reaction Ionization

The goal of CI is to reduce the probability of fragmentation by reducing the excess energy of the ionization process. The result can be increased signal as the analyte signal is no longer distributed among $[\text{analyte}]^+$ and some number of fragments $[\text{fragment}_n]^+$. Implementation of CI typically uses EI (sometimes other methods) to create a reagent ion, which interacts with the analytes to produce a charged analyte. Proton-transfer reaction (PTR) ionization is a specific version of CI that limits the reaction, as the name implies, to exclusively proton transfer as:

$$\text{analyte} + H_3O^+ \rightarrow [\text{analyte} + H]^+ + H_2O \qquad \text{(Eq 4)}$$

Both CI and PTR provide the advantage of tuning this reaction using different reagents to provide selectivity. Data is simplified and sensitivity can be increased by ionizing a single species in a mixture. To capitalize on these advantages, CI and PTR are usually used for known targets. PTR instruments also use alternative reagent ions such as NO^+ and O^{2+} to achieve reaction selectivity for particular analyte targets.

Mass Analyzer

The mass analyzer manipulates the charged analyte species to determine their *m*/*z*. For applications and instrumentation described in this article, the objective typically is to generate a single positive charge. Mass-analyzer technologies commonly used for gas mass spectrometry include quadrupole mass filters (also called quad-MS), magnetic sector mass filters (also called sector-MS), and time-of-flight mass analyzers (also called TOF-MS). The first two are technically filters; i.e. they allow only one *m*/*z* value to be detected at a given moment and, therefore, are scanned across an *m*/*z* range to obtain a spectrum. Common factors to consider in choosing an analyzer for static or continuous gas measurement are mass range; resolution (*m*/*z*) and sensitivity; analysis frequency/scanning speed; and size, weight, and power (SWAP).

Mass Range

General-use systems generate primarily singly charged analytes (or fragments), so the mass analyzer needs to span only the atomic or molecular weight range of the targets. For example, an air (O_2, N_2, Ar) or CO_2 measurement only requires a range containing *m*/*z* from 28 to 44, a Xe isotope measurement requires a range of *m*/*z* up to 136, and a volatile organic compound analysis might need to analyze a range of *m*/*z* up to 250 or more.

Resolution (*m*/*z*) and Sensitivity

Resolution of a mass analyzer is the effective separation between two *m*/*z* values in relation to the width of the peaks (Fig. 2). The separation can be defined with respect to the height of the overlap between the peaks (valley) and is often related to the full width at half of the maximum height (FWHM) (Ref 2). The mass-resolving power can be defined for a single peak using its *m*/*z* value divided by width at FWHM, expressed as $m/\Delta m_{50\%}$.

Sensitivity refers to the concept of the number of ions detected relative to the number of atoms or molecules within a volume of the sample gas. Many factors contribute to the sensitivity of a given combination of sample introduction, ionization source, mass analyzer, and ion-detection components including gas transport, ionization efficiency, ion extraction efficiency, and ion transmission through the system. Because of the complexity of these factors, a clear understanding of the sample stream (or gas volume) and measurement requirements is required to evaluate whether a system has appropriate sensitivity.

Analysis Frequency/Scanning Speed

The frequency of measuring a particular *m*/*z* value relates directly to the mass range scanned (quads and sectors) or the pulse frequency of a times-of-flight (TOF) analyzer. This is important in static measurements, because measurements are desired at intervals faster than gas can change due to evacuation. Continuous gas measurements can be slow-changing process gases where one data point per minute might be suitable, but a reaction-monitoring process might require a data point per second. Instrument scan modes can vary by application, so it is important to resolve the desired data rate with the effective rate provided by the analyzer.

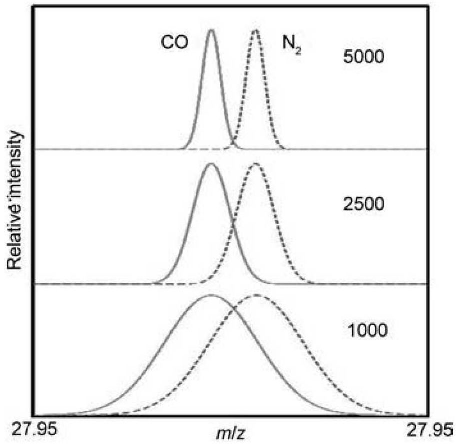

Fig. 2 Simulated peaks for nitrogen (N_2) and carbon monoxide (CO) at instrument mass resolving powers of 1000, 2500, and 5000. *m*/*z*, mass-to-charge ratio

SWAP (Size, Weight, and Power)

Analyzers used for gas analysis vary widely in size, weight, and power requirements, which are proportional to analyzer vacuum requirements, inlet system and somewhat proportional to mass resolution. Simple quadrupole analyzers can be benchtop (~0.02 m^3) and even small enough to use in underwater probes and unmanned aerial vehicles. Process gas sector instruments can be large (~0.2 m^3) due to industrial protections (temperature, vibration, fire); dual-sector instruments are typically even larger due to their electromagnet and vacuum systems. It is important to balance analyzer size, weight, and power restrictions with the data requirements. Types of analyzers discussed here include quadrupole, time-of-flight, and magnetic sector and double focusing.

Quadrupole Analyzer

The quadrupole mass analyzer consists of typically four (or greater even number) parallel rods shown schematically in the center of Fig 3. The rods are axially precision aligned, with opposing rods electrically coupled. An electric field is created by applying a dc potential bias and an RF oscillating potential between the pairs. The dynamic electrical field creates a stable trajectory for a particular *m*/*z* value such that it travels through the length of the rods from ion source to detector. At that potential, the trajectory of all other *m*/*z* values prevents them from reaching the exit of the rods (i.e., unstable trajectories). For this reason, the quadrupole mass analyzer is really an *m*/*z* filter. The dc and RF amplitudes are scanned so different *m*/*z* values exit at different times. "Jump" scans can also be performed to

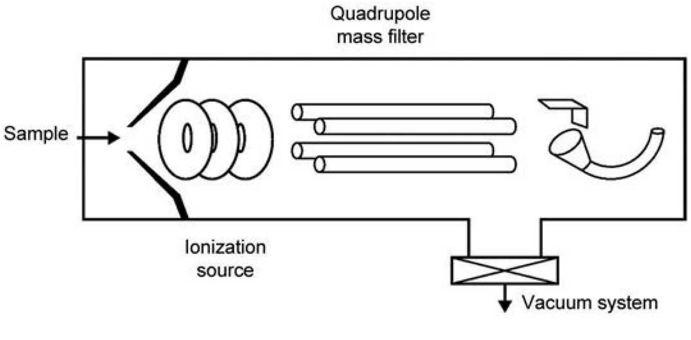

Fig. 3 Schematic of a quadrupole mass spectrometer with four parallel rods

reduce the time required for an analysis. Mass resolution is related to the amplitude of applied potentials, rod lengths, and rod radii and diameters. Ideal fields require hyperbolic rods, so there is a practical compromise in using simple rods between manufacturability and efficiency losses. Typical performance parameters are listed in the analyzer comparison table at the end of this section.

Advantages of quadrupole mass filters compared with other analyzers include:

- Relatively small size and cost
- Wide range of performance available
- Possibility to be configured with EI and CI ion sources

Disadvantages compared with other analyzers include:

- Slower scan speed
- Lower mass resolution

Time-of-Flight (TOF) Analyzer

Time-of-flight (TOF) analyzers consist of a field-free region into which all ions produced in the ionization source are introduced with constant kinetic energy by a pulsed voltage. Because kinetic energy is defined as KE = $\frac{1}{2}mv^2$, ions having different masses have different velocities. Therefore, each value of m/z analyte ion requires a different time to travel the distance of the flight tube (time-of-flight) (Ref 2). The difference can be in the nanosecond or larger time regime. Therefore, the TOF analyzer is a pulsed system (rather than scanning like the quadrupole), so the repetition rate depends on the quality of the electronics and the upper m/z to be analyzed. The repetition rate should not allow the slowest ion of pulse n be overtaken by the fastest ion of pulse $n + 1$. In practice, this still enables kHz acquisition rates; a rate where data analysis and data storage might be a consideration. Additional details and a schematic of this type of analyzer can be found in the article "Solid Analysis by Mass Spectrometry" in this volume.

Typical performance parameters are listed in Table 1. Because mass resolution is related to flight time, TOF analyzers are typically larger than quadrupole analyzers.

Advantages of TOF analyzers include:

- Nonscanning, rapid (kHz) acquisition
- Higher m/z resolution than quadrupoles

Disadvantages include:

- Larger in size than quadrupoles
- Typically not configured for permanent gas analysis

Magnetic Sector and Double Focusing Analyzers

The magnetic sector analyzer also functions as a mass filter. After ions are formed in the ionization source, they are equally accelerated and focused into a magnetic field. Because of their charge, the magnetic field exerts a force of magnitude $qv\mathbf{B}$ (the force direction being orthogonal to the velocity and magnetic field vectors); the product of the magnitude of the charge (q), the velocity (v), and the strength of the magnetic field ($\mathbf{B}$). The force produces a curved flight path, which has a radius defined as:

$$r_{\mathrm{m}} = \frac{mv}{q\mathbf{B}} \qquad \text{(Eq 5)}$$

This radius is created only in the x-y plane, but clever design of the magnet edges provides fringe focusing, which creates focusing in the z plane as well. At a given magnetic field, only one m/z value travels fully to the detector, functioning as a filter, sending other m/z values to the vacuum chamber walls (Ref 2).

A double-focusing magnetic sector analyzer adds a curved electrostatic analyzer as shown in Fig. 4. While there are other geometries and other tandem analyzer arrangements, the EB double-focusing configuration is the most common double-focusing type available for gas analysis.

The curved electrostatic analyzer applies an electric force (qE) that defines another radius of curvature according to the expression:

$$r_{\mathrm{e}} = mv^2/qE \qquad \text{(Eq 6)}$$

This radius is related to the kinetic energy of the ions, thus becoming an energy filter, because only those ions satisfying Eq 6 travel fully to the magnetic sector for m/z separation.

The electrostatic sector produces a narrower ion energy distribution, which has the effect of removing ions that might have been indirectly generated near (but not within) the source's intended ionization region. Examples of indirect ions are those created by charge transfer, bimolecular ion-molecule reaction, and delayed ion dissociation/fragmentation. The energy-resolved nature of the ion beam entering the magnetic sector generates a cleaner dispersion, thus resulting in a higher mass-resolving power. In practice, both electrostatic and magnetic sectors are scanned together across the m/z range desired. Because both sectors create a physical dispersion for their filtering, physical size options are limited. Therefore, the double-focusing class are typically the largest form factor of the systems considered in this article.

Advantages of a double-focusing analyzer include:

- Quantitative results (1% relative or better)
- Much higher m/z resolution than typical quads

Disadvantages include:

- Large and expensive
- Scanning speeds can be slow

Typical performance parameters are listed in Table 1.

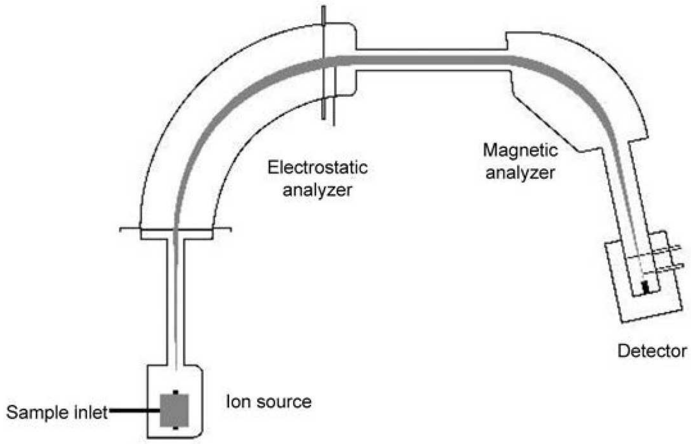

Fig. 4 Schematic of a double-focusing-sector mass spectrometer

Table 1 Performance parameters for analyzer types used in gas analysis

	Quadrupole mass filter	Time-of-flight	Magnetic sector	Double-focusing sector
Ionization mode(a)	EI, PTR	PTR	EI	EI, CI
Mass range	2–300	1–500	1–300	1–200
Mass resolution	100–3000	~12,000	60–5000	1000–60,000
Mass accuracy, ppm	10^2–10^5	10	<10	<5
Scan rate, amu/s	1–200	Nonscanning instrument	0.05–1	0.1–10,000
Detection limit	ppm–ppb	ppm–ppb	1 ppm	1 ppm
Dimensions (volume), m^3	0.02	0.44	0.2	2.7

(a) EI = electron ionization; PTR = proton transfer reaction ionization; CI = chemical ionization.

Ion Detection

The final stage of any mass spectrometer is a detector that can provide a current proportional to the number of ions entering. Often, some level of amplification is required to obtain the necessary sensitivity to enable useful detection limits (optimal signal to noise) for trace analysis. Even strong ion signals on the order of high pA to nA range use basic current amplifiers to put the signals into an easily measurable range to be digitized with accuracy. Ion detectors can have as much variation between each other as the mass analyzers discussed previously.

Faraday Cup

The Faraday cup is possibly one of the simplest ion detectors used in mass spectrometers. The Faraday cup, consisting of a conductive metal cup (element of the circuit) residing in the vacuum chamber, is designed to catch charged ions guided to the surface through the magnetic and/or electric fields produced by the mass spectrometer. The charged particles are neutralized due to electron flow within the metal. Upon striking the metal cup, electric current flow through the metal circuit can be measured and amplified. It is designed with an entrance such that nearly any incoming ion is neutralized within its boundary by wall collisions, and any secondary electrons produced from high-energy collisions are contained by a negative voltage bias at the Faraday cup entrance; loss of these electrons would falsely induce a larger ion current. The signal produced by wall collisions is directly proportional to the number of ions hitting the Faraday cup, where one charge is approximately 1.6×10^{-19} C (coulombs).

Faraday cups can also measure electrons in the vacuum. In those cases, a current is produced in the circuit when electrons hit the metal cup. One of the main advantages of Faraday cup ion detectors is its quantitative accuracy, where the number of ions can be directly calculated from the measured current, with a 1 nA current corresponding to six billion singly charged ions hitting the Faraday cup each second. However, Faraday cups have relatively low sensitivity, providing no direct signal gain like other ion detectors, such as electron multipliers.

Electron Multiplier

While more complex, electron multipliers have become one of the most common detectors in mass spectrometers due to high signal gain and relatively low additional noise compared with other ion detectors. Electron multipliers amplify incident charges to increase the amount of signal from one charged ion. The basic principle focuses on secondary electron emission, which can occur when an electron or charged ion strikes an electrode surface (dynode), typically an active layer on a metal plate, with enough kinetic energy to cause the release of secondary electrons. An avalanche of this process occurs when an electric potential is applied that accelerates the electrons toward another plate, secondary emission occurs, those electrons are accelerated to the next plate, and so on. The final metal plate is an anode that collects the cascade of electrons released, resulting in a current correlating to the electron or ion that triggered the cascade.

Compared with the Faraday cup, electron multipliers have significant advantages, including fast response and increased sensitivity due to the high signal gain and significantly higher signal-to-noise ratio for low intensity signals, thereby lowering some detection limits by several orders of magnitude. Utilizing gated pulse detecting electronics one can even perform discrete ion counting using such detectors. Disadvantages include potential amplification changes due to contamination of the dynode's active layer, analyte saturation of the anode, and mass discrimination caused by variation of the ion velocity. Mass discrimination often results in less signal gain for higher *m*/*z*. Channeltrons, or channel electron multipliers, are a type of electron multiplier with a funnel-shaped input aperture which captures the primary particle that impacts it and emits secondary electrons which further produce an electron cascade in a continuous avalanche down the channel.

Specimen Preparation

Gas sample preparation, transport, and storage can have a large impact on the quality of gas analysis, especially for determining low concentration level components (ppm or less). In general, there is more perturbation of the gas sample with static gas sampling than with continuous sampling. Continuously flowing sample gas of a consistent nature can passivate a transfer line such that the gas makeup is not affected in a measurable way while in transit. However, material of the transfer line could present some background signals, especially when heated (e.g., hydrogen from steel). Some of the best practices and pitfalls of gas sampling are presented here.

Samples from static gas sampling, because they are of limited quantity, are susceptible to contamination that is sufficient enough to affect the results of analysis. They also require containment within a vessel that can range from a classic glass bulb with stopcock, to a steel cylinder with valve welded or threaded on, to specially cleaned and inert-coated metal containers.

The most important consideration with any sample vessel (also referred to as a bottle) is material compatibility with the sample. Also of importance is the level of vessel cleanliness including all internal "wetted" surfaces, particularly the sealing material, which might not be metal but a polymer. Stainless-steel vessels, while common, have a varying effect on the contained gas composition. Certain reactive gases including acidic gases (HCl, HNO_3) and strongly oxidizing or reducing agents (O_3, H_2S) will not remain long in stainless steel cylinders. Other species could have surface-mediated reactions affecting composition distribution over time (isotopic mixing of labile hydrogens, and even of H_2 and D_2 forming HD). There also is the ever-present outgassing of hydrogen from the steel itself (as well as adsorption if the gas sample contains hydrogen), together with lesser amounts of CO and CO_2 depending on the level of cleanliness. Both reactions can be reduced by using a cylinder that has been either internally electropolished to reduce surface area, or a passivated steel (typically by formation of a chromium-rich oxide film) if warranted to reduce reactivity. Containers that have inert coatings can reduce or eliminate these effects. Regardless of the container used, the use of a blank sample bottle can provide insight on background gas levels building up within the bottle and possibly other components of the sampling system (vacuum chamber, transfer lines, and vacuum pump).

There are also common contamination issues that can affect a sample vessel including gas leaks (typically air) into a sample or a slow leak out of a pressurized sample and the presence of internal "virtual" leaks (tight internal volumes that only slowly transfer gas to/from the bulk sample). Cross contamination should also be considered if reusing sample containers. If a sample container is suspect or if trace-level analysis is desired, pretreatment of the sample vessel prior to use is recommended. Such treatment would typically consist of evacuation to high vacuum ($<10^{-6}$ torr, typical of a turbomolecular pumped system) preferably while being heated. If an enclosure or wrapping is not available, the use of a heat gun on metal surfaces helps to remove residual adsorbed water.

For continuous gas monitoring there are various equipment combinations available to bring the sample stream into the ionization source of the mass spectrometer. Various configurations can address common considerations to:

- Step down sample pressure to vacuum levels (sometimes with a membrane)
- Provide pressure adjustment and control
- Measure flow so the signal can be traced to a time-point in the process gas
- Provide the ability to transfer gas volumes from many different gas streams
- Reduce cross contamination with gas flushing and transfer line heating

Because most applications of continuous gas monitoring are in industrial settings, robustness toward the environment and sample stream should also be considered (temperature, reactivity of gases, etc.).

M/Z and Sensitivity Calibration

Quality mass spectrometer data relies on calibration and tuning with appropriate primary standards. Tuning enables determining response factors (sensitivity), mass accuracy, and closure ratio (calculated pressure to measured pressure), indicating overall instrument suitability. Tuning a quadrupole ion source and mass spectrometer is relatively simple and automated, typically using two mass peaks (e.g., nitrogen and argon, substituting hydrogen if low mass is desired). It optimizes maximum sensitivity, resolution, and peak shape with minimum mass discrimination. The TOF mass analyzer can have peak shape tuned in the middle of its relevant mass range, but a broader mixture of the gas mass range should be used. Detailed tuning of sector instruments is rarely needed as it primarily involves adjusting the ion source acceleration, extraction, and focusing voltages to attain good peak shape and intensity. Sector instruments and quadrupole analyzers have very good mass stability and might only require mass calibration once per week, while the TOF could require more frequent tuning as it is based on the accuracy of multiple electronic timing signals. Spiked internal mass calibration is used for high-resolution instruments if the highest mass accuracy is required for the analysis. An accurate mass is helpful in determining the identity of the component(s) when working with unknown compositions.

It is necessary to calibrate a mass spectrometer's response factors (or sensitivity factors) and confirm the linearity of that response to obtain quantitative analytical results. Signal responses are typically based on a maximum peak height, and in sector instruments run at lower resolutions, peak shape is ideally an isosceles trapezoid (a flat peak top), which results in a high-precision response. A set of gaseous compounds representative of permanent gas components analyzed often typically includes H_2, N_2, O_2, CO, CO_2, and He. Use standards that vary gas partial pressures within the mixture, preferably ranging from near the lower detection limit to the upper limit of the detector.

Knowing the gas concentration in a standard mixture often is the limiting factor to quantitative accuracy for sector instruments. If a mixed gas standard is used, it is highly recommended to obtain more than one mixture so they can be cross checked against one another (supplier reliability varies greatly regardless of the certificate). A better alternative, while less convenient, is to perform calibrations (or occasional cross checks) from pure gases, where the gas purity can be initially confirmed by simple absence of any significant other species.

A problem with using pure gas standards is that the pressure required that will not saturate the detector is usually quite low and below the discrimination of the inlet pressure gauge (or one can use a spinning rotor gauge). One method to overcome this situation is to use a pressure-volume division, or divider, within the inlet system, which produces a constant fractional pressure drop with every repeatable cycle. Multiple cycles are used to extend from where the pressure is measurable (to obtain the divider factor itself) to below gauge resolution, but at desired signal levels and pressure is calculated using the measured divider factor. This same method can be extended to determine/confirm response factor to gas pressure linearity.

Note that the mass calibration mixture need not be a well-quantified mixture as this tuning is distinct from sensitivity calibration to be discussed.

Data Analysis and Reliability

Interpretation of gas analysis mass spectrometer data can be complicated. As indicated previously and in the article "Solid Analysis by Mass Spectrometry" in this volume, ionization sources can introduce multiple types of species to the mass spectrometer from a single gas species, including fragments, multicharged species, and reaction products if the source pressures are high. Stemming from the ideal gas law:

$$\rho = p/\mathrm{k}T, \text{or density} = \text{partial pressure}/(\text{Boltzmann constant})(\text{temperature}) \quad \text{(Eq 7)}$$

signal peak heights (and sometimes areas) are proportional to the concentration of gas within the sample.

Mass spectrometry reliability depends heavily on tuning, mass calibration, and gas introduction. Peak shape, resolution, and sensitivity are important in selecting the appropriate mass spectrometer technique for a given application.

To achieve precise quantitative measurements in gas analysis by MS, it is important to consider both sample- and instrument-related factors. Sample-related factors include ionization efficiencies, concentration, preparation, and detection interferences. Instrument-related factors include transmission and detection efficiency, contamination, source parameter tuning, and calibration.

A common difficulty is the presence of contaminant species, and a concern of whether such potential isobaric (same unit mass) signals can be resolved; i.e., mass resolution must be sufficient to discriminate the potential interference peak if present (Fig. 2). Use of the naturally occurring isotopes can sometimes provide further insight on the presence or absence of a convoluted spectrum (Ref 3). For example, it is possible to discriminate the mass difference between a molecule containing sulfur with one containing two oxygen atoms (e.g., CS and CO_2 with a $\Delta m = 0.018$ amu) using a resolution of 2500. It can easily be achieved using most sector and TOF MS if mass stability is on the order of 0.001 *m*/*z*. However, there is doubt as to its precise mass using a relatively low-resolution quadrupole or if only one peak is present; finding the ~4% isotopic peak for $C^{34}S$ can confirm its identity (CO_2 has a much smaller isotopic signal of ~0.4% for $CO^{18}O$). In similar ways, the fragmentation of a parent species can help elucidate the composition of that parent ion.

Applications and Interpretation

Common applications relate to the factors of analysis speed, *m*/*z* resolution, size, and cost discussed previously. For a particular application, these factors are not equally weighted, and there is significant overlap among the capabilities of the different analyzer types. The systems covered here do not use separation schemes, and therefore can require more complicated data interpretation when multiple species are ionized at the same time. The more complex the sample stream, the more complex the data generated. This can be exacerbated with EI sources, which create potentially many fragment signals for each species in the sample stream; yet simplified in CI/PTR sources where a single *m*/*z* can be produced per species.

Quadrupole-based systems can be small, rapid, and relatively inexpensive, and so are used in portable applications such as environmental monitoring (e.g., pollution, volcanic emissions, and in-situ seawater contamination).

Sector-based systems are stable but slower, and are used for many process measurement scenarios including gas monitoring (O_2, CO_2, H_2, NH_3, and CH_4) in fermentation, iron and steel production, and natural gas; and monitoring larger molecules (hydrocarbons and volatile organics and solvents) in pharmaceutical and polymer production. In combination with array detectors, they are ideal for precise, simultaneous measurement of isotopic ratio distributions.

TOF-based systems in the context of gas analysis (typically PTR ionization source-based) are similar in speed and more sensitive, but much larger compared with quadrupole systems. Higher resolution and a simplified (one *m*/*z* per species) data stream makes these systems ideal in more complex sample streams including complex environmental applications, breath monitoring, and fermentation.

Dual-focusing sector systems are typically used in the highest precision applications where analysis speed is not the main constraint. Small gas volume and high precision requirements (quantitation and *m*/*z* resolution) make dual-focusing sector systems the best choice. However, the precision necessitates higher costs and instrument complexity. Applications include medical and geological isotopic measurements.

The capabilities of the different analyzer types are illustrated in the following examples.

Example 1: Quantification In An Atmospheric-Pressure Plasma Jet Using A Quadrupole MS (Ref 4)

A molecular beam quadrupole mass spectrometer and EI was used to monitor ambient air transport through an atmospheric-pressure plasma jet. The application required the rapid measurement of multiple analyte species and low detection limit capabilities of a quadrupole mass spectrometer.

Sample Preparation

The effect on ambient air species around the plasma jet required no sample preparation. However, it required optimization of the plasma jet and mass spectrometer orifice positions in relation to each other. Due to visible contact between the orifice, plasma emission, and effluent (active plasma flame), interferences were avoided by turning off the plasma jet at separation distances less than 10.5 mm.

Data Reduction

Several factors had to be considered to obtain accurate, reliable analysis of ambient air species in the active plasma region of the atmospheric-pressure plasma jet:

- The technique had to be able to measure multiple analyte species rapidly. A molecular-beam mass spectrometer (MBMS), quadrupole, was used to measure multiple analyte species inside and around the plasma jet. Rapid analysis was possible by scanning a small range for ambient gases.
- It was necessary to calibrate neutral MBMS intensities to correlate them with the different partial pressures of each analyzed particle due to composition distortion effects; i.e., radial diffusion effect of lighter particles versus heavier particles. This was achieved using an airtight, well-defined chamber in front of the MBMS systems with dry compressed air passed through to calibrate ambient air species.
- It was necessary to avoid contact between the plasma jet and mass spectrometer to prevent interferences, as described previously in sample preparation. Therefore, the plasma jet was switched off when closer than 10.5 mm to the orifice of the mass spectrometer.

Data Acquisition

It was determined through calibration of ambient air species (argon, nitrogen, and oxygen) that composition distortion effects were minimal; therefore, intensities and absolute densities were obtained through Eq 7. On-axis measurements of the ambient air species transported through the plasma jet showed different compositions at mass spectrometer distances closer to the jet nozzle versus farther from the nozzle; i.e., argon was higher near the nozzle, but nitrogen and oxygen were higher at greater distances. Figure 5 shows the spectrum observed, with many species being produced inside the plasma jet due to either impurities in the feed gas or formation in the active effluent of the plasma jet through molecular collisions and/or recombination of air species. This includes air fragments, such as O^+, which illustrates the fragmentation occurring in the plasma jet and/or the EI.

Example 2: In Situ Volcanic Plume Analysis Using A Quadrupole MS (Ref 5)

Previously inaccessible, unobtainable data became possible with the development of unmanned aerial systems (UAS), such as miniature mass spectrometers. In this example, both species detection and abundance were determined from in situ volcanic plume analysis. The application required the capability of quadrupole mass spectrometers, including the ability for miniaturization (small and light), large dynamic ranges, and sensitivity.

Sample Preparation and Data Reduction

In situ analysis is the analysis of a material in its original form and position, which requires no sample preparation. However, extensive development of the UAS platforms was required including:

- Integration of a mass spectrometer into small UAS platforms capable of obtaining a 3D chemical map of the volcanic plume. Prior to this development, ground-based, fixed sensors were used to monitor volcanic activity. The UAS-MS systems consisted of a mass analyzer capable of bulk and trace gas analysis and a low-power, miniature scroll vacuum pump.
- A multigas sensor capable of determining chemical species and a large dynamic range. Mass spectrometers can be both qualitative and quantitative, being able to detect components at concentrations less than one ppm. In this case, the appropriate mass analyzer required sensitivity ranging from ppm to 100% concentration, resolution of less than 1 amu between the mass range of 1 to 65 amu, and scan speeds below 2 s/scan. In addition, the small mass range enabled faster scan rates.

Data Acquisition

Prior to analysis of volcano plumes (2014), UAS-mass spectrometry platforms were designed using a small quadrupole mass spectrometer with a direct gas inlet and a sub-ppm limit of detection. Targeted molecular gas species included He, H_2, O_2, CO_2, SO_2, H_2S, and H_2O. Mass spectrometer calibration was accomplished in a laboratory prior to field deployment using calibration mixtures consisting of different compositions of gases, as well as different ppmv (parts per million by volume) and pressure control. Demonstrating sub-ppm limits of detection, good linearity, and high dynamic range, the UAS-mass spectrometry platforms were deployed to multiple volcanic events for plume characterization. Spectra of in situ, direct MS sampling (Fig. 6) of the Las Hornillas, Bocca Nuova, and Bocca Grande volcanic plumes following calibration in multiple-ion mode, showed CO_2 concentrations well above 50%, while H_2S and SO_2 varied more dramatically between each other, as well as the different volcanoes. Advances in mass spectrometer sizes and sensitivity have made the in situ, unmanned analysis of harsh environments possible, even potentially satellite-based remote sensing data.

Example 3: TOF-MS For Fermentation Monitoring (Ref 6)

A PTR ionization source and TOF analyzer was used to monitor the VOC (volatile organic compound) profile during fermentation of beer.

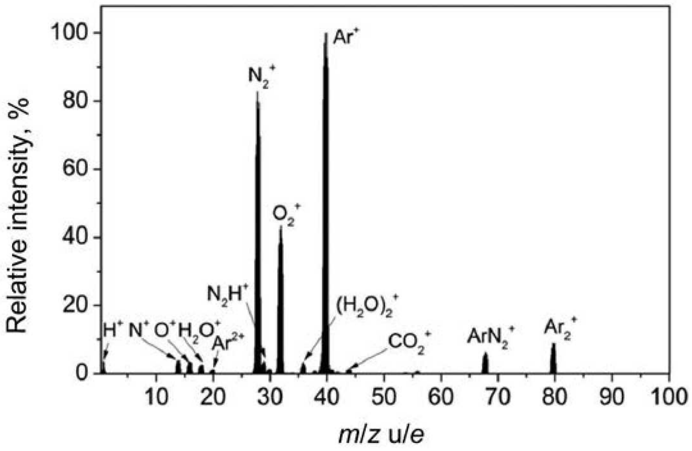

Fig. 5 Positive ion measurements from a quadrupole mass spectrometer illustrate the variety of transported species in ambient air. *m/z*, mass-to-charge ratio. Source: Ref 4

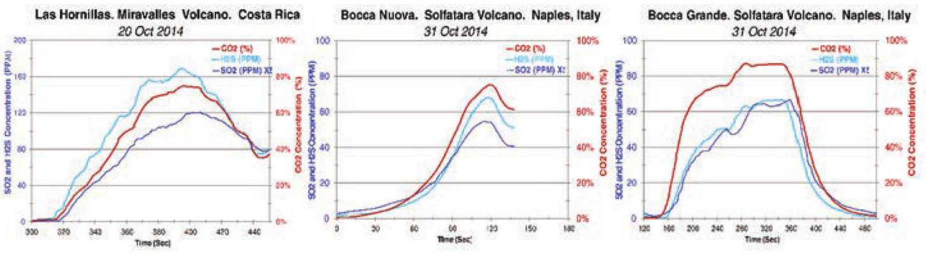

Fig. 6 Volcanic plume analysis of CO_2, H_2S, and SO_2 from in situ direct mass spectrometry sampling of three different volcanic plumes. Source: Ref 5

The range of concentrations and number of species in the vapor phase above the fermentation broth is complex, and PTR (through soft ionization) provides simpler data than would EI. The high mass resolution of the TOF enables potential identification of any volatiles detected.

Sample Preparation

The goal of the study was to measure volatiles produced under different conditions of yeast strain and hop cultivar, and to monitor the volatile profile over time (four days). A wort mixture was generated through brewing processes involving heating, cooling, and adding ingredients at specified intervals. Each variant treatment was transferred to a headspace vial (20 mL glass with septum cap) for long-term fermentation at 20 °C (68 °F). An autosampler robot transferred a volume of gas from the vial directly into the instrument.

Data Reduction

The signal is from protonated analytes, $[A + H]^+$, which would most likely be polar species such as alcohols, ketones, etc. Principal component analysis and advanced processing of the signal was required to determine correlated and statistically significant differences among the sample set. Even with high mass resolution, specific signals were compared with other fermentation literature (and methods using separation techniques such as GC/MS) to attempt identification or at least classification. For example, three *m/z* values are plotted versus time in Fig 7. Tentative identification for these ions, based on isotope signals and prior fermentation literature, was assigned as: *m/z* 89.057 ($C_4H_8O_2$: acetoin or ethyl acetate), *m/z* 137.131 ($C_{10}H_{16}$: β-pinene, myrcene, α/γ-terpinene, or limonene), *m/z* 173.153 ($C_{10}H_{20}O_2$: isoamyl isovalerate, ethyl octanoate, 2-methylbutyl-2-methyl-butyrate, decanoic acid, or pentyl pentanoate). While it may not seem to be very specific, such a short list would not be possible using a lower resolution analyzer or EI ionization source.

Data Acquisition

At set intervals of six hours, the headspace was flushed with nitrogen, then sampled and 20 spectra averaged. The autosampler allowed for the same time intervals for each variant, and rapid data collection would allow for only minutes or less time between variant measurements. The variants shown are combinations of yeast (CA = California ale, SA = Scottish ale, NY = no yeast) and hops (NS = Nelson Sauvin, MT = Motueka). The signals in Fig. 7 show three types of VOC emission during fermentation: increase over time, decrease over time, and lifecycle variation. Note that the concentration axis is in parts per billion and the time axis is hours. Concentration was calculated using a PTR rate coefficient rather than individual response factors, which is not possible due to the complexity and lack of absolute identification. The data is still very useful for purposes of comparison and contributing to the understanding of the fermentation process.

Example 4: Sector MS For Steel Process Gas Monitoring (Ref 7)

Performed under vacuum, many steel production processes need continuous gas analysis to monitor the composition of the exhaust gas. Detecting variations during the process identifies materials out of specification prior to completion of the process. Using a magnetic sector mass spectrometer illustrates the increased accuracy and precision of magnetic sectors compared with most quadrupoles.

Sample Preparation and Data Reduction

Due to high amounts of dust produced in the materials for the steelmaking process, the integration system connecting the mass spectrometer to the process included two heated sampling probes with built-in filters to clean the probes prior to use.

Achieving reliable, accurate spectra for the analysis of steelmaking processes requires:

- An analysis technique capable of analyzing a system under a range of pressures. Previous methodologies were confined to atmospheric pressure analysis. However, many modern steelmaking processes, including basic oxygen furnaces and electric arc furnaces, have dramatic pressure fluctuations, including down to <0.75 torr. Mass spectrometers operate under vacuum and, therefore, are ideal for the analysis of vacuum processes, but it is important that the pressure within the mass spectrometer remains constant. Therefore, in this case, a variable pressure inlet was used that has two valves, which work in opposition to control the analyzer pressure.

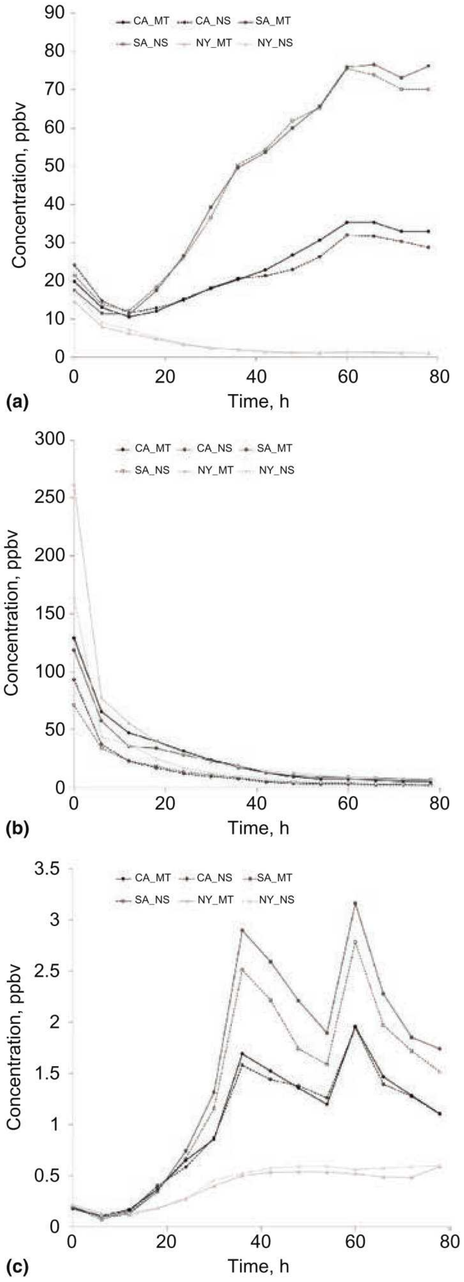

Fig. 7 Signal versus time for mass-to-charge ratio (*m/z*) values of (a) 89.057, (b) 137.131, and (c) 173.153 show different trends based on yeast (CA, California ale; SA, Scottish ale; NY, no yeast) and hops (MT, Motueka; NS, Nelson Sauvin) used in the fermentation of beer. ppbv, parts per billion by volume. Source: Ref 6

- An ability to analyze inert gases with signal stability. The ability of mass spectrometers, such as magnetic sectors, to separate ions based on *m*/*z* enables monitoring of multiple inert gases rapidly. In addition to having slow response, previous experimental methodology required the use of at least three types of non-mass spectrometry analyzers to monitor inert gases and their concentrations.
- Integration of the mass spectrometer to the steelmaking processes, including multiple components discussed previously in the sample preparation section.

Data Acquisition

Analyzing furnace exhaust gas compositions provides information on the development process and defects can be detected prior to process completion. In the case of decarburization, the species of interest were N_2, CO, CO_2, O_2, and Ar. All of these species are below 50 amu. Figure 8 shows an example of a vacuum oxygen decarburization (VOD) real-time monitoring spectrum where rapid changes in composition can be seen. This illustrates the importance of the fast analysis provided by the mass spectrometer. The process pressure also illustrates the variation in pressure, for which many other analyzers would be unable to compensate. With the precision of the magnetic sector (between 2 and 10 times that of a quadrupole) combined with the speed of analysis (only needing to be 200 amu/s) and the inlet pressure control, this work illustrated the utility of mass spectrometers in monitoring the steelmaking process.

Example 5: Double-Focusing Sector MS For Isotopic Xe Gas Measurement (Ref 8)

Double-focusing magnetic sector instrumentation has the largest physical footprint of the gas-analysis mass spectrometers discussed in this article. However, this type of instrument satisfies data requirements in precision applications such as isotope analysis. The abundance of different isotopes of an element can vary by orders of magnitude, and the overall abundance of some isotopes can be very small (<0.1% relative to the highest abundant isotope). Small changes in relative abundance can be meaningful, so the high stability, precision, and resolution provided by dual-focusing instrumentation and multicollector configurations is desirable. This example illustrates precise quantitative comparison between xenon isotopes in the study of earth's formation, using static gas samples of limited volume.

Sample Preparation

Gases and radioactive elements are trapped as molten rock cools and solidifies, with subsequently generated gases created by radioactive decay also being trapped. Xenon has nine stable isotopes, five of which are produced from radioactive decay of other elements. Therefore, the ratio of radiogenic ^{129}Xe and non-radiogenic ^{130}Xe isotopes changes with the age of the rock and how much of the parent atom ^{129}I (iodine) it originally contained. Because Xe is within the rock, a "step-crush" method is used inside the vacuum of the source region of the mass spectrometer. As the rock is crushed, additional gas is released, and another measurement is made. In some cases, the gas is filtered (for reactive gases) and cryo-trapped for controlled introduction into the source region. Care is taken to minimize air contamination of the sample and source.

Data Reduction

To account for potential mass discrimination issues or sensitivity variations that could affect the precision needed, ratios between signals are often used rather than absolute signal intensity. Also, calibration or reference gases can be introduced alternately with sample gas. It is important to use controls and standards to separate instrumental artifacts and detection drift from the variations present in samples. Sample preparation method, sample inlet, ionization methods, and detector sensitivity can all affect the final ratio of isotopes measured, together referred to as mass discrimination, so care is taken to determine instrument and method correction factors. The ^{129}Xe/^{130}Xe ratio change plotted for the Icelandic sample represents only a 6% change in the fractional abundance ratio for ^{129}Xe/^{130}Xe where ^{130}Xe has only 4% natural abundance, thus highlighting the importance of precision potentially needed in isotope ratio measurements.

Data Acquisition

In this example, a multicollector detector is used where multiple xenon isotopes are measured simultaneously. This type of detector eliminates some of the systematic instrumentation mass discrimination effects mentioned above. Measurements are made on many replicates of gas escaping from the rock matrix and span a range of isotopic ratios (partial pressures). Figure 9 demonstrates that mixing of mantle-gas sources with air is a linear relation. The slope of the line created by the ratios of radiogenic to non-radiogenic isotopes provides information about the primordial gas source and early mantle mixing. The two slopes observed show that the molten rocks were geochemically distinct and remained separated 4.45 Gyr when mantle solidification was complete and had not undergone theorized whole mantle convective mixing.

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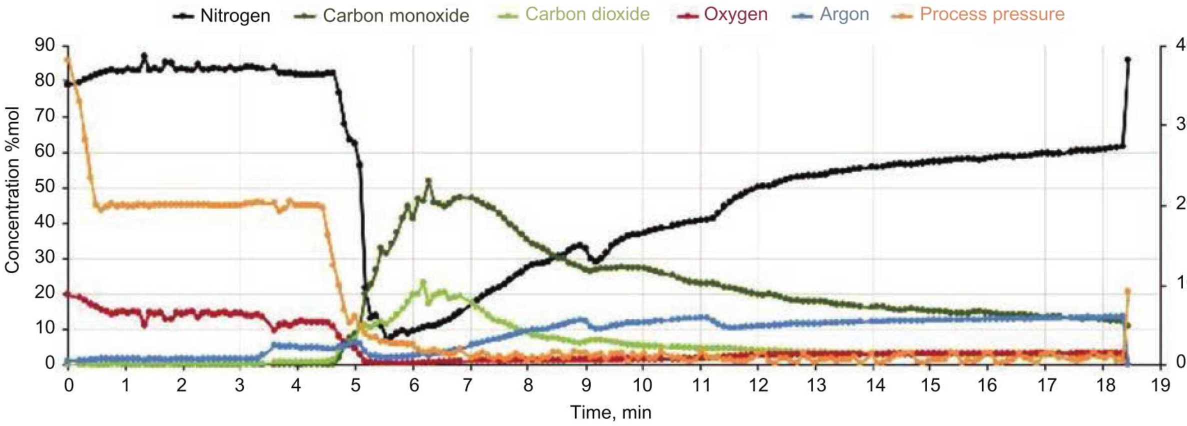

Fig. 8 Typical real-time monitoring spectrum for the vacuum oxygen decarburization steelmaking process illustrates the capability of the mass spectrometer to show the rapid changes in composition. Source: Ref 7

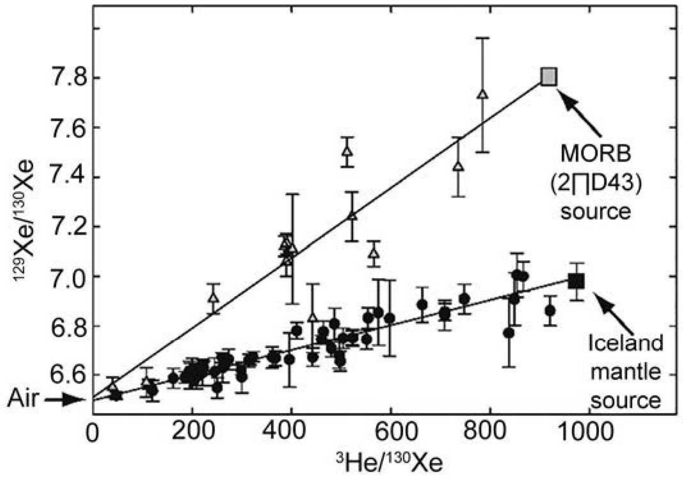

Fig. 9 Plot of isotope ratios for two basalts in geochronology study. MORB, midocean ridge basalt. Source: Ref 8

Revised from Q.G. Grindstaff, J.C. Franklin, and J.L. Marshall, Gas Analysis by Mass Spectrometry, *Materials Characterization*, Vol 10, *ASM Handbook*, ASM International, 1986.

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