

AA, ICP-OES & ICP-MS

Atomic Spectroscopy

A Guide to Selecting the
Appropriate Technique and System

WHAT IS ATOMIC SPECTROSCOPY?

Atomic spectroscopy is the technique for determining the elemental composition of an analyte by its electromagnetic or mass spectrum. Several analytical techniques are available, and selecting the most appropriate one is the key to achieving accurate, reliable, real-world results.

Proper selection requires a basic understanding of each technique since each has its individual strengths and limitations. It also requires a clear understanding of your laboratory's analytical requirements.

The following pages will give you a basic overview of the most commonly used techniques and provide the information necessary to help you select the one that best suits your specific needs and applications.

Primary Industries

Many industries require a variety of elemental determinations on a diverse array of samples. Key markets include:

- Environmental
- Food
- Pharmaceutical
- Petrochemical
- Chemical/Industrial
- Geochemical/Mining
- Biomonitoring
- Agriculture
- Semiconductor
- Nuclear Energy
- Renewable Energy
- Nanomaterials

COMMONLY USED ATOMIC SPECTROSCOPY TECHNIQUES

- Flame Atomic Absorption Spectroscopy
- Graphite Furnace Atomic Absorption Spectroscopy
- Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES)
- Inductively Coupled Plasma Mass Spectrometry (ICP-MS)

Flame Atomic Absorption Spectroscopy

Atomic Absorption (AA) occurs when a ground state atom absorbs energy in the form of light of a specific wavelength and is elevated to an excited state. The amount of light energy absorbed at this wavelength will increase as the number of atoms of the selected element in the light path increases. The relationship between the amount of light absorbed and the concentration of analytes present in known standards can be used to determine unknown sample concentrations by measuring the amount of light they absorb.

Performing atomic absorption spectroscopy requires a primary light source, an atom source, a monochromator to isolate the specific wavelength of light to be measured, a detector to measure the light accurately, electronics to process the data signal and a data display or reporting system to show the results. (See Figure 1.) The light source normally used is a hollow cathode lamp (HCL) or an electrodeless discharge lamp (EDL). In general, a different lamp is used for each element to be determined, although in some cases, a few ele-

There are three widely accepted analytical methods - atomic absorption, atomic emission and mass spectrometry - which will form the focus of our discussion, allowing us to go into greater depth on the most common techniques in use today:

ments may be combined in a multi-element lamp. In the past, photomultiplier tubes have been used as the detector. However, in most modern instruments, solid-state detectors are now used. Flow Injection Mercury Systems (FIMS)

are specialized, easy-to-operate atomic absorption spectrometers for the determination of mercury. These instruments use a high-performance single-beam optical system with a low-pressure mercury lamp and solar-blind detector for maximum performance. Whatever the system, the atom source used must produce free analyte atoms from the sample. The source of energy for free-atom production is heat, most commonly in the form of an air/acetylene or nitrous-oxide/acetylene flame. The sample is introduced as an aerosol into the flame by the sample-introduction system consisting of a nebulizer and spray chamber. The burner head is aligned so that the light beam passes through the flame, where the light is absorbed.

The major limitation of Flame AA is that the burner-nebulizer system is a relatively inefficient sampling device. Only a small fraction of the sample reaches the flame, and the atomized sample passes quickly through the light path. An improved sampling device would atomize the entire sample and retain the atomized sample in the light path for an extended period of time, enhancing the sensitivity of the technique. Which leads us to the next option - electrothermal vaporization using a graphite furnace.

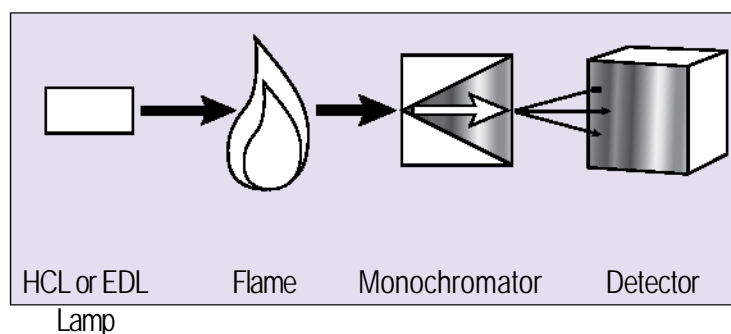


Figure 1. Simplified drawing of a Flame AA system.

Graphite Furnace Atomic Absorption Spectroscopy

With Graphite Furnace Atomic Absorption (GFAA), the sample is introduced directly into a graphite tube, which is then heated in a programmed series of steps to remove the solvent and major matrix components and to atomize the remaining sample. All of the analyte is atomized, and the atoms are retained within the tube (and the light path, which passes through the tube) for an extended period of time. As a result, sensitivity and detection limits are significantly improved over Flame AA.

Graphite Furnace analysis times are longer than those for Flame sampling, and fewer elements can be determined using GFAA. However, the enhanced sensitivity of GFAA, and its ability to analyze very small samples, significantly expands the capabilities of atomic absorption.

GFAA allows the determination of over 40 elements in microliter sample volumes with detection limits typically 100 to 1000 times better than those of Flame AA systems.

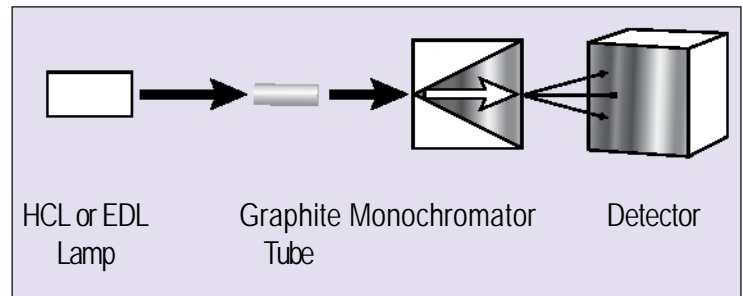


Figure 2. Simplified drawing of a Graphite Furnace AA system.

The Periodic Table of the Elements

| 1 | | | | | | | | | | | | | | | | 2 | | | | | | | | | | | | | | | |
|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|
| H Hydrogen 1.00794 | | | | | | | | | | | | | | | | He Helium 4.003 | | | | | | | | | | | | | | | |
| 3 | | | | | | | | | | | | | | | | 4 | | | | | | | | | | | | | | | |
| Li Lithium 6.941 | | | | | | | | | | | | | | | | Be Beryllium 9.012182 | | | | | | | | | | | | | | | |
| 11 | | | | | | | | | | | | | | | | 12 | | | | | | | | | | | | | | | |
| Na Sodium 22.989770 | | | | | | | | | | | | | | | | Mg Magnesium 24.3050 | | | | | | | | | | | | | | | |
| 19 | | | | | | | | | | | | | | | | 20 | | | | | | | | | | | | | | | |
| K Potassium 39.0983 | | | | | | | | | | | | | | | | Ca Calcium 40.078 | | | | | | | | | | | | | | | |
| 37 | | | | | | | | | | | | | | | | 38 | | | | | | | | | | | | | | | |
| Rb Rubidium 85.4678 | | | | | | | | | | | | | | | | Sr Strontium 87.62 | | | | | | | | | | | | | | | |
| 55 | | | | | | | | | | | | | | | | 56 | | | | | | | | | | | | | | | |
| Cs Cesium 132.90545 | | | | | | | | | | | | | | | | Ba Barium 137.327 | | | | | | | | | | | | | | | |
| 87 | | | | | | | | | | | | | | | | 88 | | | | | | | | | | | | | | | |
| Fr Francium (223) | | | | | | | | | | | | | | | | Ra Radium (226) | | | | | | | | | | | | | | | |
| 89 | | | | | | | | | | | | | | | | 90 | | | | | | | | | | | | | | | |
| Ac Actinium (227) | | | | | | | | | | | | | | | | Rf Rutherfordium (261) | | | | | | | | | | | | | | | |
| 104 | | | | | | | | | | | | | | | | 105 | | | | | | | | | | | | | | | |
| Db Dubnium (262) | | | | | | | | | | | | | | | | Sg Seaborgium (263) | | | | | | | | | | | | | | | |
| 106 | | | | | | | | | | | | | | | | 107 | | | | | | | | | | | | | | | |
| Bh Bohrium (264) | | | | | | | | | | | | | | | | Hs Hassium (265) | | | | | | | | | | | | | | | |
| 108 | | | | | | | | | | | | | | | | 109 | | | | | | | | | | | | | | | |
| Mt Meitnerium (266) | | | | | | | | | | | | | | | | Ds Darmstadtium (269) | | | | | | | | | | | | | | | |
| 110 | | | | | | | | | | | | | | | | 111 | | | | | | | | | | | | | | | |
| Rg Roentgenium (272) | | | | | | | | | | | | | | | | Cu Copper 63.546 | | | | | | | | | | | | | | | |
| 112 | | | | | | | | | | | | | | | | 113 | | | | | | | | | | | | | | | |
| Au Gold 196.96655 | | | | | | | | | | | | | | | | Hg Mercury 200.59 | | | | | | | | | | | | | | | |
| 180 | | | | | | | | | | | | | | | | 181 | | | | | | | | | | | | | | | |
| Tl Thallium 204.3833 | | | | | | | | | | | | | | | | Pb Lead 207.2 | | | | | | | | | | | | | | | |
| 202 | | | | | | | | | | | | | | | | 203 | | | | | | | | | | | | | | | |
| Bi Bismuth 208.98038 | | | | | | | | | | | | | | | | Po Polonium (209) | | | | | | | | | | | | | | | |
| 208 | | | | | | | | | | | | | | | | 209 | | | | | | | | | | | | | | | |
| At Astatine (210) | | | | | | | | | | | | | | | | Rn Radon (222) | | | | | | | | | | | | | | | |
| 210 | | | | | | | | | | | | | | | | 211 | | | | | | | | | | | | | | | |
| Th Thorium 232.0381 | | | | | | | | | | | | | | | | Pa Protactinium 231.03588 | | | | | | | | | | | | | | | |
| 232 | | | | | | | | | | | | | | | | 233 | | | | | | | | | | | | | | | |
| U Uranium 238.0289 | | | | | | | | | | | | | | | | Np Neptunium (237) | | | | | | | | | | | | | | | |
| 238 | | | | | | | | | | | | | | | | 239 | | | | | | | | | | | | | | | |
| Pu Plutonium (244) | | | | | | | | | | | | | | | | Am Americium (243) | | | | | | | | | | | | | | | |
| 242 | | | | | | | | | | | | | | | | 243 | | | | | | | | | | | | | | | |
| Cm Curium (247) | | | | | | | | | | | | | | | | Bk Berkelium (247) | | | | | | | | | | | | | | | |
| 246 | | | | | | | | | | | | | | | | 247 | | | | | | | | | | | | | | | |
| Cf Californium (251) | | | | | | | | | | | | | | | | Es Einsteinium (252) | | | | | | | | | | | | | | | |
| 250 | | | | | | | | | | | | | | | | 251 | | | | | | | | | | | | | | | |
| Fm Fermium (257) | | | | | | | | | | | | | | | | Md Mendelevium (258) | | | | | | | | | | | | | | | |
| 256 | | | | | | | | | | | | | | | | 257 | | | | | | | | | | | | | | | |
| No Nobelium (259) | | | | | | | | | | | | | | | | Lr Lawrencium (262) | | | | | | | | | | | | | | | |
| 258 | | | | | | | | | | | | | | | | 259 | | | | | | | | | | | | | | | |
| 260 | | | | | | | | | | | | | | | | 261 | | | | | | | | | | | | | | | |
| Ta Tantalum 180.9479 | | | | | | | | | | | | | | | | Hf Hafnium 178.49 | | | | | | | | | | | | | | | |
| 181 | | | | | | | | | | | | | | | | 182 | | | | | | | | | | | | | | | |
| W Tungsten 183.84 | | | | | | | | | | | | | | | | Rf Rutherfordium (262) | | | | | | | | | | | | | | | |
| 184 | | | | | | | | | | | | | | | | 185 | | | | | | | | | | | | | | | |
| Re Rhenium 186.207 | | | | | | | | | | | | | | | | Sg Seaborgium (263) | | | | | | | | | | | | | | | |
| 187 | | | | | | | | | | | | | | | | 188 | | | | | | | | | | | | | | | |
| Os Osmium 190.23 | | | | | | | | | | | | | | | | Bh Bohrium (264) | | | | | | | | | | | | | | | |
| 192 | | | | | | | | | | | | | | | | 193 | | | | | | | | | | | | | | | |
| Ir Iridium 192.217 | | | | | | | | | | | | | | | | Hs Hassium (265) | | | | | | | | | | | | | | | |
| 194 | | | | | | | | | | | | | | | | 195 | | | | | | | | | | | | | | | |
| Pt Platinum 195.078 | | | | | | | | | | | | | | | | Mt Meitnerium (266) | | | | | | | | | | | | | | | |
| 196 | | | | | | | | | | | | | | | | 197 | | | | | | | | | | | | | | | |
| Au Gold 196.96655 | | | | | | | | | | | | | | | | Ds Darmstadtium (269) | | | | | | | | | | | | | | | |
| 198 | | | | | | | | | | | | | | | | 199 | | | | | | | | | | | | | | | |
| Hg Mercury 200.59 | | | | | | | | | | | | | | | | Rg Roentgenium (272) | | | | | | | | | | | | | | | |
| 201 | | | | | | | | | | | | | | | | 202 | | | | | | | | | | | | | | | |
| Tl Thallium 204.3833 | | | | | | | | | | | | | | | | Cu Copper 63.546 | | | | | | | | | | | | | | | |
| 203 | | | | | | | | | | | | | | | | 204 | | | | | | | | | | | | | | | |
| Pb Lead 207.2 | | | | | | | | | | | | | | | | Zn Zinc 65.39 | | | | | | | | | | | | | | | |
| 208 | | | | | | | | | | | | | | | | 209 | | | | | | | | | | | | | | | |
| Bi Bismuth 208.98038 | | | | | | | | | | | | | | | | Ga Gallium 69.723 | | | | | | | | | | | | | | | |
| 209 | | | | | | | | | | | | | | | | 210 | | | | | | | | | | | | | | | |
| Po Polonium (209) | | | | | | | | | | | | | | | | Ge Germanium 72.61 | | | | | | | | | | | | | | | |
| 210 | | | | | | | | | | | | | | | | 211 | | | | | | | | | | | | | | | |
| At Astatine (210) | | | | | | | | | | | | | | | | As Arsenic 74.92160 | | | | | | | | | | | | | | | |
| 211 | | | | | | | | | | | | | | | | 212 | | | | | | | | | | | | | | | |
| Rn Radon (222) | | | | | | | | | | | | | | | | Se Selenium 78.96 | | | | | | | | | | | | | | | |
| 212 | | | | | | | | | | | | | | | | 213 | | | | | | | | | | | | | | | |
| Th Thorium 232.0381 | | | | | | | | | | | | | | | | Br Bromine 79.904 | | | | | | | | | | | | | | | |
| 232 | | | | | | | | | | | | | | | | 233 | | | | | | | | | | | | | | | |
| Pa Protactinium 231.03588 | | | | | | | | | | | | | | | | Kr Krypton 83.80 | | | | | | | | | | | | | | | |
| 233 | | | | | | | | | | | | | | | | 234 | | | | | | | | | | | | | | | |
| U Uranium 238.0289 | | | | | | | | | | | | | | | | Rb Rubidium 85.4678 | | | | | | | | | | | | | | | |
| 238 | | | | | | | | | | | | | | | | 239 | | | | | | | | | | | | | | | |
| Np Neptunium (237) | | | | | | | | | | | | | | | | Sr Strontium 87.62 | | | | | | | | | | | | | | | |
| 237 | | | | | | | | | | | | | | | | 238 | | | | | | | | | | | | | | | |
| Pu Plutonium (244) | | | | | | | | | | | | | | | | Y Yttrium 88.90585 | | | | | | | | | | | | | | | |
| 244 | | | | | | | | | | | | | | | | 245 | | | | | | | | | | | | | | | |
| Am Americium (243) | | | | | | | | | | | | | | | | Zr Zirconium 91.224 | | | | | | | | | | | | | | | |
| 243 | | | | | | | | | | | | | | | | 246 | | | | | | | | | | | | | | | |
| Cm Curium (247) | | | | | | | | | | | | | | | | Nb Niobium 92.90638 | | | | | | | | | | | | | | | |
| 247 | | | | | | | | | | | | | | | | 247 | | | | | | | | | | | | | | | |
| Bk Berkelium (247) | | | | | | | | | | | | | | | | Mo Molybdenum 95.94 | | | | | | | | | | | | | | | |
| 247 | | | | | | | | | | | | | | | | 248 | | | | | | | | | | | | | | | |
| Cf Californium (251) | | | | | | | | | | | | | | | | Tc Technetium (98) | | | | | | | | | | | | | | | |
| 251 | | | | | | | | | | | | | | | | 251 | | | | | | | | | | | | | | | |
| Es Einsteinium (252) | | | | | | | | | | | | | | | | Ru Ruthenium 101.07 | | | | | | | | | | | | | | | |
| 252 | | | | | | | | | | | | | | | | 252 | | | | | | | | | | | | | | | |
| Fm Fermium (257) | | | | | | | | | | | | | | | | Rh Rhodium 102.90550 | | | | | | | | | | | | | | | |
| 257 | | | | | | | | | | | | | | | | 257 | | | | | | | | | | | | | | | |
| Md Mendelevium (258) | | | | | | | | | | | | | | | | Pd Palladium 106.42 | | | | | | | | | | | | | | | |
| 258 | | | | | | | | | | | | | | | | 258 | | | | | | | | | | | | | | | |
| No Nobelium (259) | | | | | | | | | | | | | | | | Ag Silver 107.8682 | | | | | | | | | | | | | | | |
| 259 | | | | | | | | | | | | | | | | 259 | | | | | | | | | | | | | | | |
| Lr Lawrencium (262) | | | | | | | | | | | | | | | | Cd Cadmium 112.411 | | | | | | | | | | | | | | | |
| 262 | | | | | | | | | | | | | | | | 262 | | | | | | | | | | | | | | | |

Inductively Coupled Plasma Optical Emission Spectroscopy

ICP is an argon plasma maintained by the interaction of an RF field and ionized argon gas. The plasma can reach temperatures as high as 10,000 °K, allowing the complete atomization of the elements in a sample and minimizing potential chemical interferences.

Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) is the measurement of the light emitted by the elements in a sample introduced into an ICP source. The measured emission intensities are then compared to the intensities of standards of known concentration to obtain the elemental concentrations in the unknown sample.

There are two ways of viewing the light emitted from an ICP. In the classical ICP-OES configuration, the light across the plasma is viewed radially (Figure 3a), resulting in the highest upper linear ranges. By viewing the light emitted by the sample looking down the center of the torch (Figure 3b) or axially, the continuum background from the ICP itself is reduced and the sample path is maximized. Axial viewing provides better detection limits than those obtained via radial viewing by as much as a factor of 10. The most effective systems allow the plasma to be viewed in either orientation in a single analysis, providing the best detection capabilities and widest working ranges.

The optical system used for ICP-OES consists of a spectrometer that is used to separate the individual wavelengths of light and focus the desired wavelengths onto the detector (Figure 4). Older, "direct reader" types of ICP-OES systems used a series of photomultiplier tubes to determine pre-selected wavelengths. This limited the number of elements that could be determined as the wavelengths were generally fixed once the instrument was manufactured. Sequential-type systems can select any wavelength and focus it on a single detector. However, this is done one element at a time, which can lead to longer analysis times. In today's modern ICP-OES systems, solid-state detectors based on charge-coupled devices (CCD) are used, providing very flexible systems and eliminating the need for large numbers of single photomultiplier detectors.

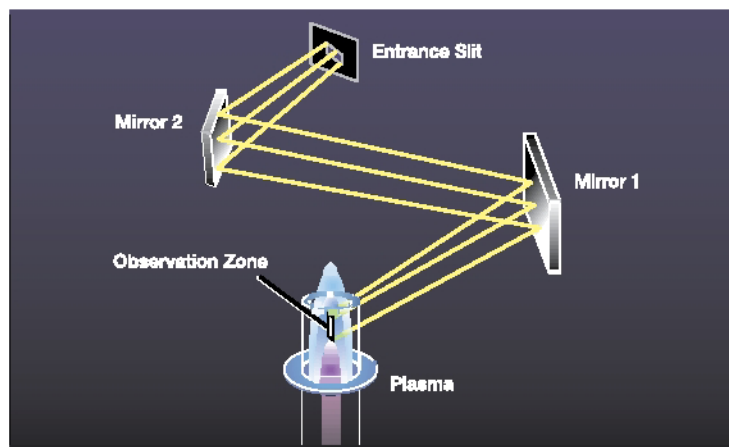


Figure 3a. Radially viewed plasma with a vertical slit image in the plasma.

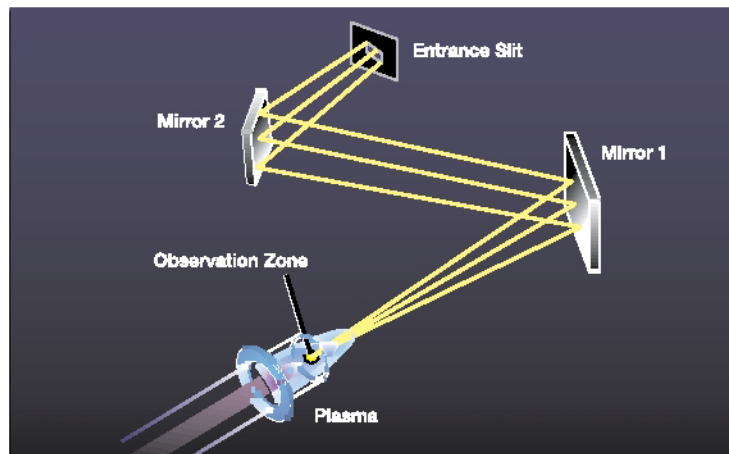


Figure 3b. Axially viewed plasma with an axial slit image in the plasma.

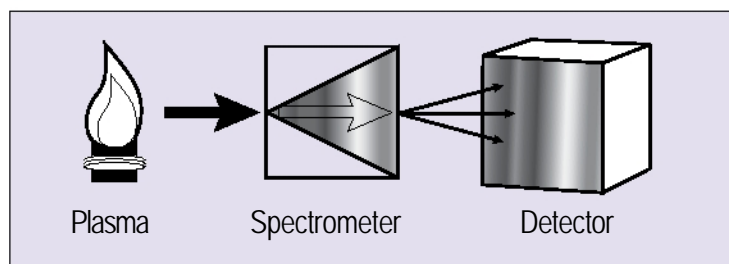


Figure 4. Simplified drawing of a basic ICP system.

Inductively Coupled Plasma Mass Spectrometry

With Inductively Coupled Plasma Mass Spectrometry (ICP-MS), the argon ICP generates singly charged ions from the elemental species within a sample that are directed into a mass spectrometer and separated according to their mass-to-charge ratio. Ions of the selected mass-to-charge ratio are then directed to a detector that determines the number of ions present (Figure 5). Typically, a quadrupole mass spectrometer is used for its ease-of-use, robustness and speed. Due to the similarity of the sample-introduction and data-handling techniques, using an ICP-MS is very much like using an ICP-OES system.

ICP-MS combines the multi-element capabilities of ICP techniques with exceptional detection limits equivalent to or below those of GFAA. It is also one of the few analytical techniques that allows the quantification of elemental isotopic concentrations and ratios, as well as precise speciation capabilities when used in conjunction with HPLC or GC interfaces. This feature enables the analytical chemist to determine the exact form of a species present - not just the total concentration.

However, due to the fact that the sample components are actually introduced into the instrument, there are some limitations as to how much sample matrix can be introduced into the ICP-MS. In addition, there are also increased maintenance requirements

as compared to ICP-OES systems. Generally, ICP-MS systems require that the total dissolved solids content of a sample be below 0.2% for routine operation and maximum stability. There are several items, such as the interface cones and ion lens, located between the ICP torch and the mass spectrometer, that need to be cleaned on a periodic basis to maintain acceptable instrument performance.

Recent developments have led to new technologies to increase the robustness and stability of ICP-MS. Orthogonal ion lens systems increase the ability of the ICP-MS to handle higher total dissolved solids content and dramatically improve long-term stability for high matrix solutions. Interference control has been made even easier by using universal cell technologies that include both collision (using Kinetic Energy Discrimination KED) and Dynamic Reaction Cell (DRC) in a single instrument allowing the analyst to choose the best technique for their samples.

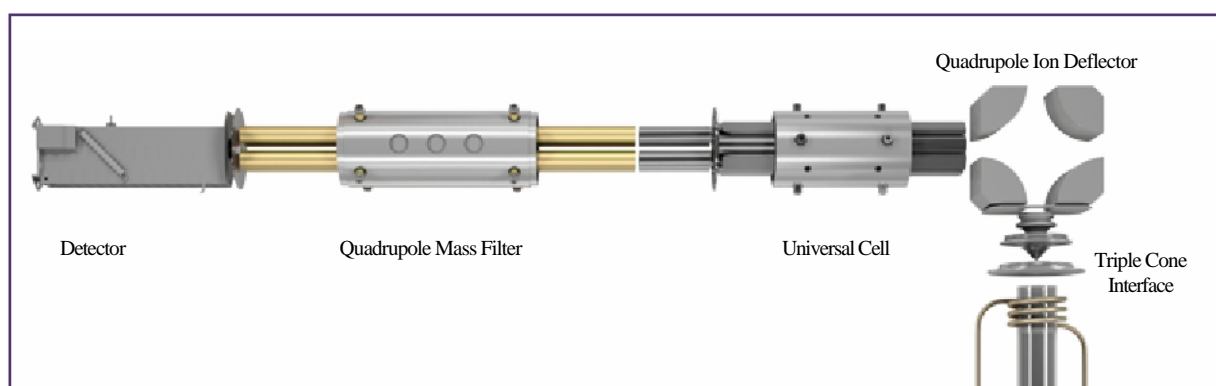


Figure 5. Simplified drawing of ICP-MS system with Universal Cell Technology (UCT).

SELECTING A TECHNIQUE FOR YOUR ANALYSIS

With the availability of a variety of atomic spectroscopy techniques, laboratory managers must decide which of these is best suited to their particular analytical

requirements. Unfortunately, because the techniques complement each other so well, it may not always be clear which is the optimum solution for a particular application.

Selecting a technique requires the consideration of a variety of important criteria, including:

- Detection limits
- Analytical working range
- Sample throughput
- Data quality
- Cost
- Interferences
- Ease-of-use
- Availability of proven methodology

In order to help you narrow your selection, many of these criteria are discussed below for Flame AA, Graphite Furnace AA, ICP-OES and ICP-MS. In simple terms, your choice can be guided by answering the four questions in Table 1.

Detection limits

The detection limits achievable for individual elements are important in determining the usefulness of an analytical technique for a given analytical problem. Without adequate detection-limit capabilities, lengthy analyte concentration procedures may be required prior to analysis.

Typical detection-limit ranges for the major atomic spectroscopy techniques are shown in Figure 6. For a complete listing of detection limits by element for Flame AA, GFAA, ICP-OES (with radial and axial torch configurations) and ICP-MS, see the table on page 14.

Table 1. Technique decision matrix.

| | Flame AA | GFAA | ICP-OES | ICP-MS |
|---------------------------|----------|------|---------|--------|
| How Many Elements? | | | | |
| Single | ■ | | | |
| Few | | ■ | | |
| Many | | | ■ | ■ |
| What Levels? | | | | |
| High ppb | ■ | | ■ | |
| Sub ppb | | ■ | ■ | ■ |
| Sub ppb-ppm | | | | ■ |
| Sub ppt | | | | ■ |
| How Many Samples? | | | | |
| Very few | ■ | ■ | | |
| Few | ■ | ■ | ■ | ■ |
| Many | | | ■ | ■ |
| How Much Sample? | | | | |
| > 5 mL | ■ | ■ | ■ | ■ |
| < 1-2 mL | | ■ | | |

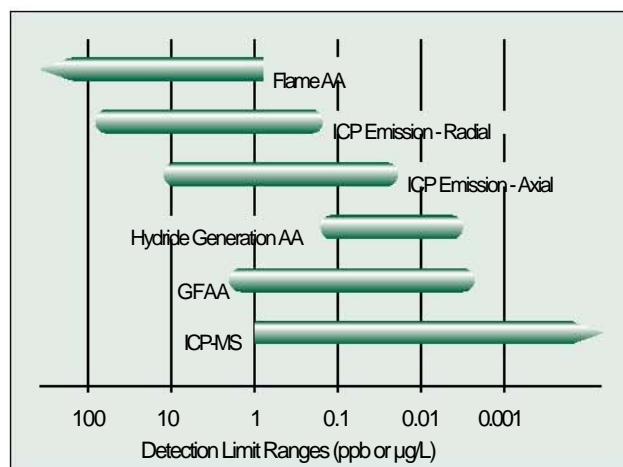


Figure 6. Typical detection limit ranges for the major atomic spectroscopy techniques.

Analytical working range

The analytical working range can be viewed as the concentration range over which quantitative results can be obtained without having to recalibrate the system. Selecting a technique with an analytical working range (and detection limits) based on the expected analyte concentrations minimizes analysis times by allowing samples with varying analyte concentrations to be analyzed together. A wide analytical working range can also reduce sample-handling requirements, minimizing potential errors.

Sample throughput

Sample throughput is the number of samples that can be analyzed or elements that can be determined per unit of time. For most techniques, analyses performed at the limits of detection or where the best precision is required will be more time-consuming than less demanding analyses. Where these factors are not limiting, the number of elements to be determined per sample and the analytical technique will determine the sample throughput.

- Flame AA - Provides relatively high sample throughput when analyzing a large number of samples for a limited number of elements. A typical determination of a single element requires only 3-10 seconds. However, Flame AA requires specific light sources and optical parameters for each element to be determined and may require different flame gases for different elements. As a result, even though it is frequently used for multi-element analysis, Flame AA is generally considered to be a single-element technique.

- Graphite Furnace AA - As with Flame AA, GFAA is basically a single-element technique. Because of the need to thermally program the system to remove solvent and matrix components prior to atomization, GFAA has a relatively low sample throughput. A typical graphite-furnace determination normally requires 2-3 minutes per element for each sample.
- ICP-OES - A true multi-element technique with exceptional sample throughput. ICP-OES systems typically can determine more than 73 elements per minute in individual samples. Where only a few elements are to be determined, however, ICP is limited by the time required for equilibration of the plasma with each new sample, typically about 15-30 seconds.
- ICP-MS - Also a true multi-element technique with the same advantages and limitations of ICP-OES. ICP-MS can typically determine more than 73 elements per minute in an individual sample, depending on such factors as the concentration levels and required precision. Although ICP-MS has a wide working range, the upper linear concentration range is generally less than that of ICP-OES systems and may require that some samples be diluted.

Costs

As they are less complex systems, instrumentation for single-element atomic spectroscopy (Flame AA and GFAA) is generally less costly than that for the multi-element techniques (ICP-OES and ICP-MS). There can also be a considerable variation in cost among instrumentation for the same technique. Instruments offering only basic features are generally less expensive than more versatile systems, which frequently also offer a greater degree of automation. Figure 8 provides a comparison of typical instrument price ranges for the major atomic spectroscopy techniques.

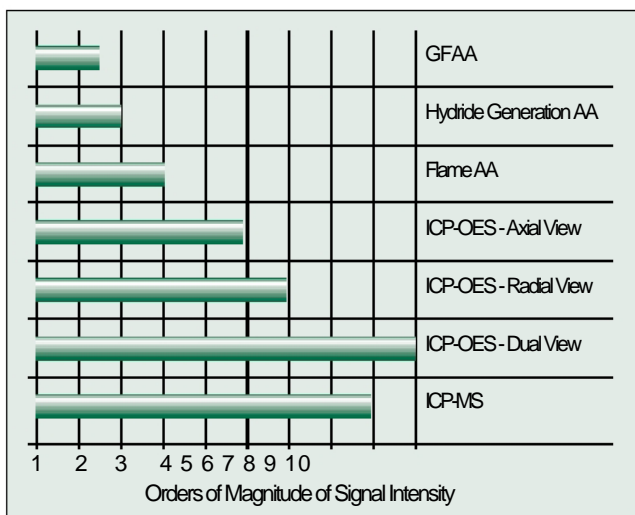


Figure 7. Typical analytical working ranges for the major atomic spectroscopy techniques.

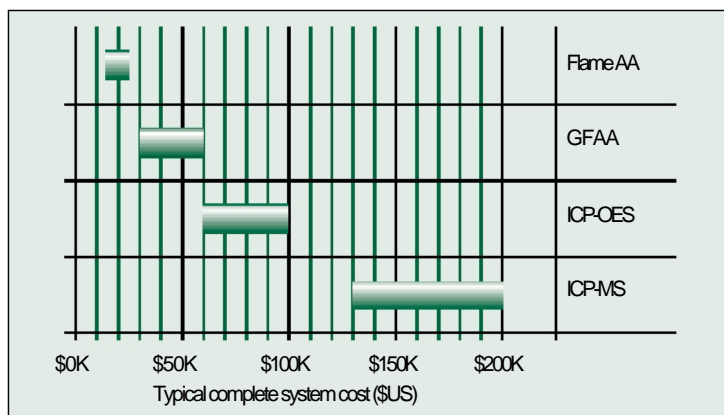






Figure 8. Typical relative purchase prices for atomic spectroscopy systems.

SELECTING A SYSTEM FOR YOUR ANALYSIS

| TECHNIQUE | STRENGTHS | LIMITATIONS | APPLICATIONS | SYSTEM |
|---|--|---|---|---|
| Flame AA - Flame Atomic Absorption Spectroscopy | <ul style="list-style-type: none"> • Very easy-to-use • Widely accepted • Extensive application information available • Relatively inexpensive | <ul style="list-style-type: none"> • Low sensitivity • Single-element analytical capability • Cannot be left unattended (flammable gas) | Ideal for laboratories analyzing large numbers of samples for a limited number of elements and for the determination of major constituents and higher concentration analytes. | AAAnalyst 200/400 AA Spectrometers  |
| GFAA - Graphite Furnace Atomic Absorption Spectroscopy | <ul style="list-style-type: none"> • Exceptional detection limits • Well-documented applications • May be left unattended | <ul style="list-style-type: none"> • Limited analytical working range • Sample throughput somewhat less than other techniques | Ideal for laboratories analyzing a limited number of elements and requiring excellent detection limits. | PinAAcle AA Spectrometers  |
| ICP-OES - Inductively Coupled Plasma Optical Emission Spectroscopy | <ul style="list-style-type: none"> • Best overall multi-element atomic spectroscopy technique • Excellent sample throughput • Very wide analytical range • Good documentation available for applications • May be left unattended • Easy-to-use | <ul style="list-style-type: none"> • Higher initial investment | Ideal for laboratories analyzing multiple elements in a moderate or large number of samples. | Optima ICP-OES Spectrometers  |
| ICP-MS - Inductively Coupled Plasma Mass Spectrometry | <ul style="list-style-type: none"> • Exceptional multi-element capabilities • Ability to perform isotopic analyses • Well-documented interferences and compensation methods • Rapidly growing application information • Detection limits equal to or better than GFAA with much higher productivity • May be left unattended | <ul style="list-style-type: none"> • Highest initial investment • Method development more difficult than other techniques • Limited solids in sample | Ideal for laboratories analyzing multiple elements in a large number of samples and requiring a system capable of determining trace and ultra-trace analyte concentrations. | NexION ICP-MS Spectrometers  |

Once you have identified the best solution for your particular application, read on for more in-depth product details.

Atomic Absorption Spectrometers



You'll discover an easy, affordable and reliable flame atomic absorption (AA) solution. The process of AA analysis, has been simplified from sample introduction to results. It's easy for anyone with a basic understanding of AA to get fast, reliable results every time, and the quality and reliability is available to everyone with these affordable systems.

Easy to use, easy to own, and featuring many of the advances it is the perfect choice for any laboratory needing a reliable, trouble-free solution for flame AA analysis.

Atomic Absorption Spectrometers



The atomic absorption (AA) spectrometers bring AA performance to new heights. Engineered with an array of exciting technological advances, it offers a variety of configurations and capabilities to deliver exactly the level of performance you need:

- Flame only, furnace only, or space-saving stacked designs featuring both
- Flame, furnace, flow injection, FIAS-furnace and mercury/hydride capabilities on a single instrument
- Choice of Deuterium or longitudinal Zeeman background correction
- TubeView™ color furnace camera simplifies autosampler tip alignment and sample dispensing
- Proven WinLab32™ software offering both ease-of-use and exceptional flexibility

And no matter which model you select you'll discover an intuitive, highly efficient system capable of simplifying your journey from sample to results - even with the most difficult matrices.

ICP-OES Spectrometers



With its groundbreaking features and expanded capabilities, it is more than just an evolution of the world's most popular ICP-OES... it's a revolution. Built around the proven design of the Optima platform, the 8x00 series delivers breakthrough performance through a series of cutting-edge technologies that enhance plasma stability, simplify method development and dramatically reduce operating costs:

- Flat Plate™ Plasma Technology - with a patented, maintenance-free RF generator uses half the argon of traditional systems dramatically reducing operating costs.
- Patented Dual View - offers radial and axial viewing of the plasma for effective measurement of elements with high and low concentrations in the same method.
- PlasmaCam™ Viewing Camera - offers continuous viewing of the plasma, simplifying method development and enabling remote diagnostic capabilities for maximum uptime.

ICP-MS Spectrometers

To leverage the true power of ICP-MS in your lab, you need a solution that lets any scientist analyze any sample at any time. All while generating clear, reliable, informative results. It requires an instrument that offers a unique level of simplicity, flexibility and sensitivity - exactly what you get with ICP-MS.

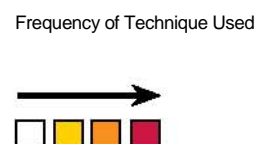
Engineered with an array of ground-breaking technologies to optimize performance and productivity, the face of ICP-MS has been changed by being the first instrument to offer:

- Three cones (sampler, skimmer, and hyper skimmer) to eliminate internal maintenance and provide unrivaled STABILITY
- Three quadrupoles to maximize SENSITIVITY for every element in a run
- Three modes of operation (Standard, Collision, and Reaction) for ultimate application FLEXIBILITY



Atomic Spectroscopy Applications by Market

| MARKET | TYPICAL APPLICATIONS | COMMONLY USED TECHNIQUES | | |
|---------------------|---------------------------------|--------------------------|---------|--------|
| | | A | ICP-OES | ICP-MS |
| Environmental | Water | | | |
| | Soil | □ | ■ | ■ |
| | Air | □ | ■ | ■ |
| Food | Food safety | ■ | □ | ■ |
| | Nutritional labeling | ■ | ■ | ■ |
| Pharmaceutical | Drug development | ■ | ■ | □ |
| | Quality control | □ | □ | ■ |
| Petrochemical | Petroleum refining | □ | ■ | □ |
| | Lubricants and oils | ■ | ■ | ■ |
| Chemical/Industrial | Quality control/Product testing | □ | ■ | □ |
| | Geochemical/Mining | ■ | ■ | ■ |
| Biomonitoring | Exploration | ■ | ■ | ■ |
| | Research | ■ | ■ | ■ |
| Agriculture | Biological fluids | □ | ■ | ■ |
| | Soils | ■ | □ | ■ |
| Semiconductor | Wafers | ■ | ■ | □ |
| | High-purity chemicals | □ | □ | ■ |
| Nuclear Energy | Low-level waste | ■ | □ | ■ |
| | Process water | □ | ■ | ■ |
| Renewable Energy | Biofuels | □ | ■ | ■ |
| | Solar panels | □ | ■ | ■ |
| Nanomaterials | Research | □ | ■ | ■ |
| | | ■ | □ | ■ |



IMPORTANCE OF ATOMIC SPECTROSCOPY TO SPECIFIC MARKETS

Environmental

In the environment we live in, understanding heavy-metal contamination is critical. The accurate measurement of concentrations of these metals is imperative to maintain clean air, water and soil for a safer world.

Food

Accurate analysis of food for nutritional content, contamination or authenticity - the exact geographic source of the product - is critical for regulatory and quality assurance.

Pharmaceutical

Drug research, development and production is dependent on elemental analysis, starting with the testing of individual ingredients and continuing through production to final quality control, as impurities can affect drug efficacy and metabolism.

Petrochemical

From petroleum refining to a broad spectrum of applications using lubricants and oils, many industries require the determination of metals - particularly analytes that can lead to degradation and contamination - to ensure conformity as well as monitor and control processes.

Chemical/Industrial

From the analysis of raw materials and components to finished product testing and quality control, industrial and chemical manufacturers require accurate analytical techniques to ensure the safety and performance of their products.

Geochemical/Mining

With myriad applications from date stamping to precious metals testing, atomic spectroscopy offers a fast, accurate solution for broad geological surveys as well as an invaluable means of testing potential mining areas before incurring the high costs associated with digging.

Biomonitoring

Instrumentation for accurate measurements of metals in biological matrices is vital when assessing human exposures to natural and synthetic chemicals. Speciation is also becoming increasingly important due to its ability to provide additional information on element valence state or molecular form.

Agriculture

Trace metals are essential for plant growth. Atomic spectroscopy also facilitates precise soil analysis to ensure that metals are not at levels that could unduly affect the food source (livestock and/or crops).

Semiconductor

Determining lower and lower values in a variety of materials - rapidly and affordably - has become necessary in the increasingly competitive semiconductor industry.

Nuclear Energy

Operating under constant scrutiny, the nuclear field is required to monitor and measure the levels of a variety of elements to an exacting degree. Atomic spectroscopy is commonly used to determine trace elements in everything from process water to low-level waste.

Renewable Energy

As the world continues to move toward eco-friendly technologies and energy sources, there's an ever-increasing need for accurate elemental analysis. Applications include testing biofuels for batch consistency and quality control, as well as trace elemental analysis on solar panels to ensure optimum performance.

Nanomaterials

As research science defines more novel applications for nanomaterials, the need to eliminate material uncertainty on a particle-by-particle basis continues to grow. Whether there is a need to solve an environmental issue or apply a manufacturing QA/QC solution to a synthesis or formulation process, there is a growing requirement for sensitivity to conduct accurate, precise work.

ATOMIC SPECTROSCOPY DETECTION LIMITS

| Element | Flame AA | Hg/Hydride | GFAA | ICP-OES | ICP-MS | Element | Flame AA | Hg/Hydride | GFAA | ICP-OES | ICP-MS |
|---------|------------|------------|------------|----------|------------|---------|----------|-------------|-----------|--------------|---------|
| Ag | 1.5 | | 0.005 | 0.6 | 0.00009 | Mo | 45 | | 0.03 | 0.5 | 0.00008 |
| Al | 45 | 0.1 | 1 | 0.0004 * | Na | 0.3 | 0.005 | | 0.5 | 0.0003 As | 150 |
| | 0.03 | 0.05 | 1 | 0.0004 | Nb | 1500 | 1 | | 0.00004 | | |
| Au | 9 | 0.15 | 1 | 0.0001 | Nd | 1500 | 2 | 0.0003 B | 100 | | 20 |
| | 1 | 0.001 | Ni | 6 | | 0.07 | 0.5 | 0.0002* Ba | 15 | | 0.35 |
| | 0.03 | 0.00004 | Os | 6 | 0.00006 | | | | | | |
| Be | 1.5 | | 0.008 | 0.09 | 0.0003 | P | 7500 | | 130 | 4 | 0.04* |
| Bi | 30 | 0.03 | 0.05 | 1 | 0.00002 | Pb | 15 | 0.05 | 1 | 0.00004 * Br | |
| | | | | 0.04 | Pd | 30 | 0.09 | 2 | 0.00003 C | Pr | 750 |
| | | | 2 | 0.00003 | | | | | | | |
| Ca | 1.5 | | 0.01 | 0.05 | 0.0003 * | Pt | 60 | | 2.0 | 1 | 0.0001 |
| Cd | 0.8 | | 0.002 | 0.1 | 0.00007 | Rb | 3 | | 0.03 | 5 | 0.0002 |
| Ce | | | | 1.5 | 0.00005 | Re | 750 | | | 0.5 | 0.0003 |
| Cl | | | | 2 | Rh | 6 | 5 | 0.00004 | | | |
| Co | 9 | | 0.15 | 0.2 | 0.00006 * | Ru | 100 | | 1.0 | 1 | 0.0001 |
| Cr | 3 | | 0.004 | 0.2 | 0.0003 * | S | | | | 10 | 0.9* |
| Cs | 15 | | | | 0.00005 | Sb | 45 | 0.15 | 0.05 | 2 | 0.0002 |
| Cu | 1.5 | | 0.014 | 0.4 | 0.0002 * | Sc | 30 | 0.1 | 0.001 Dy | 50 | 0.5 |
| | 0.0002 | | Se | 100 | 0.03 | 0.05 | 2 | 0.0003 * | | | |
| Er | 60 | | | 0.5 | 0.0001 | Si | 90 | | 1.0 | 10 | 0.09 |
| Eu | 30 | | | 0.2 | 0.00007 | Sm | 3000 | | | 2 | 0.0002 |
| F | Sn | 150 | 0.1 | 2 | 0.0002 Fe | 5 | 0.06 | 0.1 | 0.0005 * | Sr | 3 |
| | 0.025 | 0.05 | 0.00007 Ga | 75 | | 1.5 | 0.00008 | | Ta | 1500 | 1 |
| | 0.00001 Gd | 1800 | | | 0.9 | 0.0003 | Tb | 900 | 2 | 0.00003 Ge | 300 |
| | 1 | 0.0006 * | Te | 30 | 0.03 | 0.1 | 2 | 0.0003 * Hf | 300 | 0.5 | 0.0003 |
| | Th | 2 | 0.00005 Hg | 300 | 0.009 | 0.6 | 1 | 0.001 | Ti | 75 | |
| | 0.35 | 0.4 | 0.0002*Ho | 60 | 0.4 | 0.00004 | Tl | 15 | 0.1 | 2 | 0.00001 |
| I | 0.003 | Tm | 15 | 0.6 | 0.00003 In | 30 | | | 1 | 0.00008 | U |
| | 15000 | 10 | 0.00002 Ir | 900 | 3.0 | 1 | 0.00009 | V | 60 | | 0.1 |
| | 0.5 | 0.00007*K | 3 | 0.005 | 1 | 0.001 | W | 1500 | | | 1 |
| | 0.00003 La | 3000 | 0.4 | 0.00004 | Y | 75 | | | 0.2 | 0.00002 | |
| Li | 0.8 | | 0.06 | 0.3 | 0.00005 | Yb | 8 | | | 0.1 | 0.0001 |
| Lu | 1000 | 0.1 | 0.00004 | Zn | 1.5 | | 0.02 | 0.2 | 0.0007*Mg | 0.15 | 0.004 |
| | 0.04 | 0.0001 | Zr | 450 | | | 0.5 | 0.00007 | | | |
| Mn | 1.5 | | 0.005 | 0.1 | 0.0001 * | | | | | | |

All detection limits are given in micrograms per liter and were determined using elemental standards in dilute aqueous solution. All detection limits are based on a 98% confidence level (3 standard deviations).

All atomic absorption detection limits were determined using instrumental parameters optimized for the individual element, including the use of System 2 electrodeless discharge lamps where available.




All Optima ICP-OES detection limits were obtained under simultaneous multi-element conditions with the axial view of a dual-view plasma using a cyclonic spray chamber and a concentric nebulizer.

Cold-vapor mercury detection limits were determined with a FIAS-100 or FIAS-400 flow injection system with amalgamation accessory.

The detection limit without an amalgamation accessory is 0.2 µg/L with a hollow cathode lamp, 0.05 µg/L with a System 2 electrodeless discharge lamp. (The Hg detection limit with the dedicated FIMS-100 or FIMS-400 mercury analyzers is < 0.005 µg/L without an amalgamation accessory and < 0.0002 µg/L with an amalgamation accessory.) Hydride detection limits shown were determined using an MHS-15 Mercury/Hydride system.

All ICP-MS measurements were performed on a NexION ICP-MS with a quartz sample introduction system using a 3-second integration time and ten replicates in de-ionized water. Detection limits were measured under multi-element conditions in Standard mode, except where denoted by an asterisk (*). Detection limits denoted by * were performed in a Class-100 Clean Room using Reaction mode with the most appropriate cell gas and conditions for that element in de-ionized water.

ATOMIC SPECTROSCOPY ACCESSORIES

| Instrument Capability | |
|---|--------------------|
|  | PinAAcle/AAAnalyst |
|  | Optima |
|  | NexION |

Titan MPS™ Microwave Sample Preparation System



- Flexible, cost-effective solution for pressure digestion of a broad range of samples
- Connection-free and contact-free temperature/pressure sensing for ultimate ease-of-use
- Strong and durable digestion vessels are easy to use and warranted for one year

FIAS



Fully automated flow-injection system

- Simplifies and speeds up analyses requiring complex sample preparation such as Mercury and other hydride-forming elements

Specialized Software



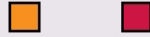
- QC charting
- Tools for 21 CFR Part 11 compliance
- Speciation software

Autosamplers



- Flexible rack configurations
- Fast, accurate random access
- Corrosion-resistant sampling components
- Flow-through rinse station to minimize sample-to-sample contamination

High-Throughput Sample-Introduction System



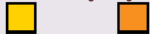
- Minimizes sample uptake and washout time
- Throughput increased up to 2-3 fold
- Eliminates sample contact with peristaltic pump tubing

AA Consumables



- HCL and EDL lamps
- Graphite tubes
- Standards

Mercury Hydride System



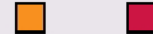
- Highly sensitive determination of Mercury or hydride-forming elements

Graphite Furnace



- Quick, easy interchange between flame and furnace
- Low sample consumption (as low as a few μL)
- Exceptional detection limits, down to the pg range

ICP-OES and ICP-MS Consumables



- Cones
- Torches
- Nebulizers
- Standards