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Supelco Edition

radiello is patented by FONDAZIONE SALVATORE MAUGERI-IRCCS
Centro di Ricerche Ambientali - via Svizzera, 16 - 35127 PADOVA

595 North Harrison Road, Bellefonte, PA 16823 USA
www.sigma-aldrich.com/radiello
how does the **diffusive sampler** work?

The diffusive sampler is a closed box, usually cylindrical. Of its two opposite sides, one is “transparent” to gaseous molecules which cross it, and are adsorbed onto the second side. The former side is named diffusive surface, the latter is the adsorbing surface (marked with $S$ and $A$ in the figure).

Driven by the concentration gradient $dC/dl$, the gaseous molecules cross $S$ and diffuse towards $A$ along the path $l$, parallel to the axis of the cylindrical box. The molecules, which can be trapped by the adsorbing material, are eventually adsorbed onto $A$ according to the equation:

$$\frac{dm}{dt} = DS \frac{dC}{dl} \quad [1]$$

where $dm$ is the adsorbed mass during time $dt$ and $D$ is the diffusion coefficient.

Let $C$ be the concentration at the diffusive surface and $C_0$ the concentration at the adsorbing surface, the integral of $[1]$ becomes

$$\frac{m}{t} = D \frac{S}{l} (C-C_0) \quad [2]$$

If the concentration at the adsorbing surface is negligible, the equation can be approximated to

$$\frac{m}{tC} = D \frac{S}{l} = Q \quad \text{and then} \quad C = \frac{m}{tQ} \quad [3]$$

$Q$ is the **sampling rate** and has the dimensions of a gaseous flow (if $m$ is expressed in μg, $t$ in minutes and $C$ in μg·l$^{-1}$, $Q$ is expressed in l·min$^{-1}$).

Therefore, if $Q$ is constant and measured, to calculate the ambient air concentration you need only to quantify the mass of analyte trapped by the adsorbing material and to keep note of the time of exposure of the diffusive sampler.

To improve the analytical sensitivity the collected mass $m$ should be increased by enlarging $Q$. As $D$ is a constant term, one can only try to improve the $S/l$ ratio, namely the **geometrical constant** of the sampler. Unfortunately, in the common axial symmetry sampler, if $S$ is enlarged, the adsorbing surface $A$ must be enlarged too, in order to keep the two parallel surfaces at a fixed distance. Since the analytes can be recovered from the axial sampler only by solvent extraction, any increase of $A$ lead to a proportional increase of the extraction solvent volume, thus the improvement of $Q$ is canceled out by the effect of dilution.

The value of distance $l$ could also be reduced, but under the critical value of about 8 mm the diffusion law is no longer valid in the case of low air velocity values, since adsorption rate becomes higher than supplying rate of analyte molecules at the diffusive surface.

Cannot we improve $Q$ then?

The answer is to improve the sampler geometry to a **radial** design.

From this idea the **radiello** sampler has been developed, its cylindrical outer surface acting as diffusive membrane: the gaseous molecules move axially parallel towards an adsorbent bed which is cylindrical too and coaxial to the diffusive surface.

When compared to the axial sampler, **radiello** shows a much higher diffusive surface without increase of the adsorbing material amount. Even if the adsorbing surface is quite smaller then the diffusive one, each point of the diffusive layer faces the diffusion barrier at the same distance.
As $S=2\pi rh$ (where $h$ is the height of the cylinder) and the diffusive path is as long as the radius $r$, we can then express equation [1] as follows

$$\frac{dm}{dt} = D \frac{2\pi h r}{dr} \frac{dC}{dr}$$ \hspace{1cm} [4]$$

The integral of equation [4] from $r_d$ (radius of the diffusive cylindrical surface) to $r_a$ (radius of the adsorbing surface) becomes

$$\frac{m}{t C} = D \frac{2\pi h}{ln \frac{r_a}{r_d}} = Q$$ \hspace{1cm} [5]$$

the ratio

$$\frac{2\pi h}{ln \frac{r_a}{r_d}}$$

is the geometrical constant of \textit{radiello}. The calculated uptake rate [5] is therefore proportional to the height of the diffusive cylinder and inversely proportional to the logarithm of the ratio of diffusive vs adsorbing cylinder radii.

The microporous sintered polyethylene diffusive barrier of \textit{radiello} photographed at the electron microscope; the path length is much longer than the membrane thickness due to the tortuosity of the pores.

While $r_a$ can be easily measured, $r_d$ can only be calculated by exposure experiments. Actually the diffusive membrane has been designed with a thick tubular microporous layer. The actual diffusive path length is therefore much longer than the distance among the diffusive and adsorbing surfaces due to the tortuosity of the path through the pores. A diffusive cylinder of external diameter 8 mm, thickness 1.7 mm and average porosity of 25 μm, coupled to an adsorbing cartridge with radius 2.9 mm creates a diffusive path of 18 mm instead of the straight line path estimation of (8-2.9) = 5.1 mm.

The sampling rate $Q$ is function of diffusive coefficient $D$, which is a thermodynamic property of each chemical substance. $D$ varies with temperature ($T$) and pressure ($p$); therefore also the sampling rate is a function of those variables according to

$$Q = f (T, p)$$

$Q$ values that will be quoted in the following have been measured at 25 °C and 1013 hPa. As a consequence, they should be corrected so as to reflect the actual sampling conditions.

The correction of $Q$ for atmospheric pressure is usually negligible since its dependence is linear and very seldom we face variations of more than 30 hPa about the average value of 1013 hPa. In the worst case, if corrections for pressure are ignored you make an error of ±3%, usually it is within ±1.5%.

On the other hand, $Q$ depends exponentially on temperature variations, therefore more relevant errors can be introduced if average temperature is significantly different from 25 °C. Moreover, when chemiadsorbing cartridge are used kinetic effects (variations of reaction velocities between analyte and chemiadsorbing substrate) can be evident, apart from thermodynamic ones (variation of $D$).

It is therefore very important to know the average temperature in order to ensure accuracy of experimental data. See how you can perform on-field temperature measurements on page B3.

Even if some cartridges adsorb large quantities of water when exposed for a long time in a wet atmosphere, generally this does not affect sampling by \textit{radiello}. Some consequences, nevertheless, can sometimes be felt on the analysis. As an example, a very wet graphitised charcoal cartridge could generate ice plugs during cryogenic focusing of thermally desorbed compounds or blow out a FID flame.

It is therefore important to protect \textit{radiello} from bad weather. See page B1 how this can be easily done.
The diffusive sampling does not involve the use of heavy and encumbering pumping systems, does not have energy power supply problems, does not require supervision, is noiseless, is not flammable and does not represent an explosion hazard, can be performed by everybody everywhere and with very low costs.

Moreover, it is not subject to the breakthrough problem, which can be serious when active pumping is performed.

**In pumped sampling** the adsorbed compound behaves as a chromatographic peak (top): air flow displaces it along the adsorbent bed and its concentration is distributed as a gaussian function. Eventually, the compound comes out from the opposite end. When its concentration in the outlet air is 10% of the concentration in the sampled air we say that the **breakthrough** has been reached or, with a misleading expression, that the tube has been saturated. Any further pumping leads to a loss of analyte and a consequent underestimation of the environmental concentration. The extent of this phenomenon depends weakly on the concentration of target compound but rather on the value of air flow, the overall sampling volume and the chemical compound involved.

In the graph the case of benzene is displayed, sampled at 25 °C onto an activated charcoal adsorbent bed of the same volume of a code 130 radiello cartridge. The breakthrough is reached after 35, 44 or 49 liters of sampled air depending on benzene concentration in air (10, 50 or 100 μg·m⁻³ respectively).

An apparently similar phenomenon is shown by radiello also. In this case, however, we cannot speak of breakthrough, since no actual air flow is involved, but rather of backdiffusion. This consists of a decrease of the value of m·Q⁻¹·t⁻¹ (which is equal to the measured concentration, see eqn. [3] on page A1). This term is constant and equal to the actual concentration until the adsorbed mass of analyte is far from the maximum amount allowed by the adsorbing medium capacity. The extent of backdiffusion depends on concentration and exposure time but a decrease of 10% in the m·Q⁻¹·t⁻¹ term is observed along with equivalent sampling volumes of magnitude bigger than those seen before: 1600, 2300 and 3050 liters at the concentration of 10, 50 and 100 μg·m⁻³.

Why diffusive sampling has not been so extensively adopted up to now?

This is due to the fact that the traditional axial symmetry sampler has generally poor sensitivity and reproducibility because of the limits set by its geometry. On one side, uptake rate values are generally low, on the other, they often vary depending on environmental conditions.

These limitations have been overcome by radiello.

By virtue of radial symmetry, uptake rate is:

- **high**, since it does not vary linearly but exponentially with the ratio diffusive surface vs diffusive path length (see eqn. [5]). With the same dimensions, radiello’s uptake rate is at least three times higher than that of any axial diffusive sampler;

For a traditional axial symmetry sampler the uptake rate increases linearly with the ratio of diffusive surface vs diffusive path length, while for the radial symmetry sampler, the corresponding increase is exponential. This means that, let the diffusive surface vs diffusive path length ratio be 8:1, for the axial sampler the uptake rate value is 8 (regardless of dimensions) while for the radial one it is 45.
✓ **constant**, due to the great adsorbing capacity of the adsorbing cartridge;

✓ **reproducible**, by virtue of the stiffness of the diffusive membrane and the cartridge and of the close tolerances characterizing all the components of *radiello*;

✓ **invariable with air speed**, due to the tortuosity of the diffusive path inside the microporous diffusive cylindrical surface;

✓ **precisely measured**, because it is not calculated but experimentally measured in a controlled atmosphere chamber in a wide range of concentration, temperature, relative humidity, air speed conditions and with or without interferents....

Moreover, *radiello*

► able to work properly also with bad weather conditions due to the water-repellent diffusive body

► has blank values lower than three times the instrumental noise due to the complex conditioning procedures of the bulk adsorbing (or chemiadsorbing) materials and to the repeated quality controls along the whole production

► has low detection limits and high adsorbing capacities that allow exposure time duration from 15 minutes to 30 days and concentration measurements from 1 ppb to over 1000 ppm

► offers high precision and accuracy over a wide range of exposure values

► allows thermal desorption and HRGC-MS analysis without interferents

► is suited to the sampling of a vast range of gaseous pollutants

► is though and chemically inert, being made of polycarbonate, microporous polyethylene and stainless steel

► is indefinitely reusable in all of its components apart from the adsorbing cartridge; the latter can be recovered if thermal desorption is employed

► it comes from the efforts of one of the main European scientific research institutions that produces it directly by high technology equipment and continuously submits it to severe tests and performs research and development in its laboratory in Padova

All the images in the manual concern the Environmental Research Center of Padova of the Fondazione Salvatore Maugeri-IRCCS
The essential parts of *radiello* are the adsorbing cartridge, the diffusive body, the supporting plate and the adhesive label with the bar code indication. Apart from the adsorbing cartridge, if not differently stated, all of the other components can be repeatedly used for several sampling experiments.

**The adsorbing cartridge**

Depending on the polluting compound to be sampled, many different adsorbing or chemiadsorbing cartridges have been developed. Their dimensions are nevertheless the same for all: 60 mm length and 4.8 or 5.8 mm diameter.

They are contained in glass or plastic tubes wrapped up in a transparent polyethylene thermowelded bag.

The code number, printed onto the bag along with the lot number and expiry date indicates the kind of cartridge.

Apart from the thermal desorption cartridges, all of the other kinds are for single use only. See the application section at the back for codes relevant to the different analytes.

*Available in 20 pieces per package.*

*The cartridge has to be introduced into the diffusive body.*

**The diffusive body**

Four kinds of diffusive bodies are available, with like outer dimensions: 60 mm height and 16 mm diameter.

The *white* diffusive body, **code 120**, of general use, is made of microporous polyethylene 1.7 mm thick and average porosity 25 ± 5 μm. Diffusive path length is 18 mm.

The *blue* diffusive body, **code 120-1**, has the same properties of the white one but is opaque to light: it is suited to the sampling of light-sensitive compounds.

The *yellow* diffusive body, **code 120-2**, should be used whenever the sampling rate must be reduced; it is made of microporous polyethylene 5 mm thick and average porosity 10 ± 2 μm. Diffusive path length is 150 mm.

The *permeative* diffusive body, **code 120-3**, is a 50 μm thick silicone membrane strengthened by a stainless steel net and a microporous polyethylene cylinder. It is employed for anaesthetic gases and vapours sampling.

*Available in 20 pieces per package.*

*The diffusive body has to be screwed onto the supporting plate.*

**The supporting plate**

It is identified by the **code 121**. Made of polycarbonate, it acts both as closure and support for the diffusive body, which has to be screwed onto the thread. It comes along with a clip and a transparent adhesive pocket to hold the label. The three parts are to be assembled before use (see page A6).

*Available in 20 pieces per package.*

**The label**

Self-adhesive, with printed barcode number. Since each barcode number has been printed in only one copy, it allows an unmistakable identification of the sampling tube on field and in the laboratory for the subsequent analysis.

*Each package of 20 adsorbing cartridges contains also 21 labels.*

*If the labels are ordered separately, they are shipped in 198 pieces per package.*
**how to use radiello**

**before sampling**

Before using radiello, you have to assemble the supporting plate with the clip, necessary to suspend it, and the adhesive label pocket.

1. Insert the clip strip in the slot, with the peg facing upwards
2. Peel the strip and insert the peg into the hole
3. Peel off the transparent pocket and place it onto the plate in a central position; if you prefer, the pocket can be applied to the rear of the plate, but **BE CAREFUL**, always with the label insertion slot on the side (otherwise, if it starts raining the label can get wet)
4. Keep the diffusive body in a vertical position, to screw it onto the support plate

**on-field to start the sampling**

Open the plastic bag, draw the cartridge out from the tube and put it in the diffusive body. Keep the glass or the plastic tube and stopper in the original plastic bag.

The lower part of the diffusive body holds a seat for the central positioning of the cartridge. **A correctly centered cartridge should not stick out even by half a millimeter.** If it does, the cartridge is not correctly positioned and out of axis. **BE CAREFUL:** do not hold the diffusive body horizontally when you screw it onto the plate, otherwise the cartridge could come out from its seat and stick out.

As a consequence, when the diffusive body is screwed onto the supporting plate the cartridge is bent, the geometry of the sampler is disturbed and the results obtained become unreliable. **To place the cartridge centrally you need only to tap on the diffusive body.**

Insert a label in the pocket without peeling it off. Keep note of the date and time and expose radiello. Sampling has started.

**user tip**

Assemble the supporting plate in your laboratory before the sampling campaign to save time in the field

**user tip**

Do not touch the cartridge with your fingers if possible, particularly if it is impregnated with reactive
after the sampling

Keep note of the date and time of the end of exposure.
Place the cartridge into the tube, peel off the label and stick it onto the tube such that the barcode is parallel to the axis of the tube.
If you have performed the sampling of different polluting compounds at the same time, BE CAREFUL NOT TO MIX UP THE TUBES: place the exposed cartridge in its original tube, identified by the code printed on the plastic bag.

IMPORTANT
Always stick the label such that the barcode is parallel to the axis of the tube: any other position will compromise the barcode automated reading by the optic reading device.

radiello maintenance

When exposed outdoors or in a workplace environment, the diffusive body may get dirty from airborne dust. Fine particles (PM$_{10}$) are especially harmful to yellow diffusive bodies since they can obstruct the pores. When the diffusive bodies are dirty you can wash them as follows.
Immerse the diffusive bodies in a beaker with a soapy solution (e.g. dish detergent) and sonicate them for 20 minutes. As the diffusive bodies float, you may make them sink by putting a smaller beaker on them, with water inside enough to dip it a few centimeters. Rinse the diffusive bodies with plenty of water and then deionized water; let them finally dry in the air.

IMPORTANT: NEVER USE SOLVENTS TO CLEAN THE DIFFUSIVE BODIES!!!

After four or five washings, diffusive bodies need to be replaced: repeatedly adsorbed dust may have penetrated the so deeply that they cannot be removed by washing anymore.
The following table shows the advised washing schedule:

<table>
<thead>
<tr>
<th>PM$_{10}$ concentration ($\mu$g·m$^{-3}$)</th>
<th>&lt;30</th>
<th>40</th>
<th>&gt;50</th>
</tr>
</thead>
<tbody>
<tr>
<td>Washing after days of exposure</td>
<td>45</td>
<td>30</td>
<td>15</td>
</tr>
</tbody>
</table>

user tip

even if you can write date and time of the sampling start and end on the adhesive label, we suggest you to keep note of these parameters also separately: after a week exposure with bad weather conditions, your writing might have become illegible!

DO NOT USE MARKER PENS to write on the label: they contain solvents that are sampled by radiello!
The ready-to-use version may be advantageous when you prefer not to assemble all of the components on field. It can be purchased as it is or in separate parts to be assembled by the customer. In the ready-to-use version the adsorbing cartridge is already contained in a diffusive body closed with a polycarbonate screw-thread cap. The whole is closed in a polypropylene airtight container. Just before use draw the diffusive body out of the container and fit it to the special snapping vertical adapter fixed to the supporting plate. After the end of exposure, the diffusive body with its content is placed again in the polypropylene airtight container to be shipped to the laboratory for analysis. The ready-to-use radiello (polycarbonate cap, glass or plastic tube, special snapping vertical adapter, barcode label and polypropylene container) is available for the sampling of the following compounds:

<table>
<thead>
<tr>
<th>code</th>
<th>sampling of</th>
<th>contains</th>
</tr>
</thead>
<tbody>
<tr>
<td>123-1</td>
<td>BTEX and VOCs</td>
<td>white diffusive body and cartridge code 130</td>
</tr>
<tr>
<td>123-2</td>
<td>BTEX and VOCs</td>
<td>yellow diffusive body and cartridge code 145</td>
</tr>
<tr>
<td>123-3</td>
<td>$\text{NO}_2$, $\text{SO}_2$ and HF</td>
<td>blue diffusive body and cartridge code 166</td>
</tr>
<tr>
<td>123-4</td>
<td>aldehydes</td>
<td>blue diffusive body and cartridge code 165</td>
</tr>
<tr>
<td>123-5</td>
<td>ozone</td>
<td>blue diffusive body and cartridge code 172</td>
</tr>
<tr>
<td>123-6</td>
<td>hydrogen sulfide</td>
<td>white diffusive body and cartridge code 170</td>
</tr>
<tr>
<td>123-7</td>
<td>ammonia</td>
<td>blue diffusive body and cartridge code 168</td>
</tr>
<tr>
<td>123-8</td>
<td>HCl</td>
<td>white diffusive body and cartridge code 169</td>
</tr>
</tbody>
</table>

**IMPORTANT:** for the ready-to-use version the supporting plate needs to be ordered separately. The ready-to-use samplers are stable for 3 months.

If you prefer to assemble it by yourselves, you should order:

- ✔ diffusive bodies (of the required type, see following chapters)
- ✔ adsorbing cartridges (of the required type, see following chapters)
- ✔ polycarbonate caps, code 124-1
- ✔ special snapping adapters, code 122-1
- ✔ polypropylene containers, code 124-2
- ✔ supporting plates, code 121

**user tip**

the ready-to-use version of radiello is very useful in the workplace sampling campaigns but is not advised if very low concentrations in outdoor or domestic environments are to be measured.
accessories for radiello

vertical adapter

code 122

The diffusive body can be fitted to the supporting plate either in a vertical or horizontal position, the vertical one being more comfortable when radiello is used for personal sampling.

To assemble radiello in vertical position you have to screw it to the vertical adapter code 122, fitted to the supporting plate.

Available in 20 pieces per package

Assembling the vertical Adapter

place the vertical adapter over the mounting point on the plate

press the adapter onto the plate with your thumbs till the ridge fits the edge of the plate.

The adapter can be removed from the plate by lifting the ridge.

IMPORTANT
when mounting the diffusive body be careful to keep it vertical with the thread upside (see page A6).

shelter

code 196

For outdoor exposures a mountable polypropylene shelter is available which can be hung from lamp posts.

It has been designed to be mounted easily and without any tools on field, so that it is not cumbersome when you transport it from your laboratory. Once assembled, it ensures the best compromise between protection against bad weather and ventilation.

It can house up to four radiello and is able to fit a wide range of pole diameters.

Its colour is quite similar to that of the majority of lampposts: being less visible, it is less subject to acts of vandalism.

Available in 10 pieces per package
**how to assemble the shelter**

All of the components are snap-on assembled.

1. First of all, insert on this panel (the roof) the two supports that will be used to suspend the samplers.

2. Then fix the two walls on the sides of the roof panel. The whole becomes rigid by insertion of the two spacers. Fit them to the slots on bottom of the side panels and turn them by 90° (performing this rotation you may feel some resistance, but go on until you hear a clicking sound).

3. Finally, insert two plastic strips in the rear vertical slots of the side panels. The strips are also available as spare parts, in 100 pieces per package, identified by the code 198.

Suspend the shelter to the pole by closure of the strips, but **DO NOT DRAW SO MUCH THAT THE SHELTER IS DEFORMED**. If the pole has diameter larger than 20 cm, the shelter leans on the curved edges on the rear of the side-walls. If the pole has a smaller diameter, it leans against the curved edge of the roof panel and the rear spacer. If the diameter of the pole is very small the shelter bows down, the wind may make it go round, or the shelter may even slip down to ground. It is then advisable to choose another pole.

**user tip**

If the pole diameter is larger than the strip length, you can put two or more strips together to extend the fastening system. If the sampling site is very windy, do not introduce more than two radiello samplers in each shelter, otherwise rain could dampen the outermost samplers.
On-field temperature measurements

codes 126 e 127

Since the uptake rate values of radiello depend on temperature, the concentration values obtained will be more accurate if precise temperature measurements are performed during the sampling.

To get reliable temperature data you may ask the local weather station, if there is one, and if the measurements are performed nearby your sampling sites. Bear in mind that you should take into account the urban heat island: did you know that there can be a difference of even 4-5 °C between the center and the suburbs of a big town?

With radiello you can create your own temperature measurement station.

A thermometer with precision ± 0,5 °C between -20 and 80 °C and equipped with a data logger capable of recording 2048 data points has been fixed to a vertical adapter (code 126; 126-1 for ready-to-use sampler). It is tiny enough (< 1 cm³) to go perfectly unobserved. It has no battery to replace, needs no maintenance and works properly even with bad weather conditions.

Its memory allows you to record one temperature value every 15 minutes for 22 days, or every 30 minutes for 43 days, or every 60 minutes for 85 days, or... it lasts ten years or a million readings!

The thermometer is fitted to the supporting plate of radiello: use the sampler normally and measure temperature and pollution at the same time.

A very simple reader (code 127), connected to your PC by a serial port, allows you to program the temperature sensor for the measurements on field, to download the acquired data and to perform data statistical and graphic processing by a very user-friendly software.

user tip

When performing urban monitoring install a thermometer every ten sampling sites. If this may help you, contact us to discuss sampling strategies.
**Filtration Kit**

**Code 174**

Code 174 filtration kit is composed by 20 single use plastic syringes and 20 single use micropore hydrophilic polypropylene filters with diameter 13 mm and 0.45 μm porosity. Both filter and syringe are suited to filtration of aqueous solutions with pH in the range of 0 to 12 with commonplace eluents for ion chromatography and reverse phase HPLC.

**Calibration Solution for H₂S**

**Code 171**

Code 171 relieves you from the task of preparing the sodium sulfide standard solution for the calibration curve used for the determination of H₂S by the cartridge code 170 (see page H1).

Since sodium sulfide is deliquescent, its weight is not a primary standard and sodium sulfide solution need titration once prepared. Moreover, titration must be repeated often due to the instability of diluted solution (one hour time is sufficient to decrease sulfide content by 10%).

Code 171 is a methylene blue concentrated solution that, once diluted 1:50, provides the same absorbance value at 665 nm of a sodium sulfide solution of with concentration 1.145 μg·ml⁻¹ sulfide ions.

This concentration value has been chosen to obtain the highest absorbance value within the linearity range of the spectrophotometer.

To obtain a complete calibration curve, just dilute the mother solution as shown in the table.

Code 171 contains 100mL solution that allows you to prepare as many as 50 calibration curves. Kept closed at room temperature, code 171 solution is stable for at least one year.

**Calibration Solution for Aldehydes**

**Code 302**

Calibration curves for aldehydes are obtained with standard solutions of the corresponding 2,4-dinitrophenylhydrazones (see page C1). Although their synthesis is straightforward, their purification is tricky and time-consuming.

Code 302 offers a certified and convenient choice: a solution of nine 2,4-dinitrophenylhydrazones in a solvent compatible with HPLC eluents and with concentrations suitable for the preparation of calibration curves in the range usually spanned by radiello samples.

Code 302 is delivered as 10 ml of acetonitrile solution of the nine 2,4-dinitrophenylhydrazones formed by the aldehydes listed in the table, contained in a pierceable-septum crimped cap vial. The listed concentration values are indicative, actual ones are certified for each lot.

Kept tightly capped in a dark place at 4 °C, the solution is stable for at least four months.
calibration kit for BTEX (CS₂ desorption)

code 405

Code 405 calibration kit has been conceived for the analysis of BTEX sampled in urban environments by the cartridge code 130 and chemically desorbed by carbon disulfide (see page D1).

The kit may be used both for routine calibration and for scheduled quality control of the calibration procedure described on page D4.

It is composed of 12 code 130 cartridges, three of which are blanks and nine, divided into three groups of three, preloaded with BTEX to simulate 7 days exposures (10,080 minutes) to the concentrations listed in the table. The values shown are indicative, actual ones are certified for each lot.

The mass of each analyte deposited onto the cartridge spans the whole range of concentrations usually found in urban environments, extreme values included.

BTEX loading is performed by injection of precisely known amounts of vaporized standard solutions in CS₂ of the five compounds under nitrogen flow.

Kept at 4 °C, the cartridges are stable for at least four months.

<table>
<thead>
<tr>
<th>code 405</th>
<th>simulated concentrations in μg·m⁻³ (7 days exposure equivalent)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Group 1</td>
</tr>
<tr>
<td>benzene</td>
<td>1</td>
</tr>
<tr>
<td>toluene</td>
<td>2</td>
</tr>
<tr>
<td>ethylbenzene</td>
<td>1</td>
</tr>
<tr>
<td>m-xylene</td>
<td>1</td>
</tr>
<tr>
<td>p-xylene</td>
<td>1</td>
</tr>
<tr>
<td>o-xylene</td>
<td>1</td>
</tr>
</tbody>
</table>

calibration kit for VOCs in workplace environments

code 406

The code 406 kit has been conceived for scheduled quality control of the calibration procedure for the analysis of volatile organic compounds (VOCs) sampled by code 130 cartridges in workplace environments (see page D4).

It is composed of 12 code 130 cartridges, three of which are blanks and nine, divided into three groups of three, preloaded with VOCs to simulate 8 hours exposures (480 minutes) to the concentrations listed in the table. The values shown are indicative, actual ones are certified for each lot.

The composition of the mixture is simple but it includes compounds with different polarity. The loaded mass is calculated in order to represent exposures to 0.5, 1 and 2 times the TLV value for the mixture.

VOCs loading is performed by injection of precisely known amounts of calibrated mixtures of the eight compounds under nitrogen flow.

Kept at 4 °C, the cartridges are stable for at least four months.

<table>
<thead>
<tr>
<th>code 406</th>
<th>simulated concentrations in mg·m⁻³ (8 hours exposure equivalent)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Group 1</td>
</tr>
<tr>
<td>benzene</td>
<td>0.1</td>
</tr>
<tr>
<td>toluene</td>
<td>19</td>
</tr>
<tr>
<td>ethylbenzene</td>
<td>12</td>
</tr>
<tr>
<td>m-xylene</td>
<td>12</td>
</tr>
<tr>
<td>p-xylene</td>
<td>12</td>
</tr>
<tr>
<td>o-xylene</td>
<td>12</td>
</tr>
<tr>
<td>butanol</td>
<td>15</td>
</tr>
<tr>
<td>2-etoxyethyl acetate</td>
<td>2.5</td>
</tr>
</tbody>
</table>
calibration kits for BTEX (thermal desorption)

<table>
<thead>
<tr>
<th>Code 407</th>
<th>Simulated concentrations in μg·m⁻³ (7 days exposure equivalent)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Group 1</td>
</tr>
<tr>
<td>benzene</td>
<td>1</td>
</tr>
<tr>
<td>toluene</td>
<td>2</td>
</tr>
<tr>
<td>ethylbenzene</td>
<td>1</td>
</tr>
<tr>
<td>m-xylene</td>
<td>1</td>
</tr>
<tr>
<td>p-xylene</td>
<td>1</td>
</tr>
<tr>
<td>o-xylene</td>
<td>1</td>
</tr>
</tbody>
</table>

The kit may be used both for routine calibration and for scheduled quality control of the calibration procedure described on page E5. It is composed of 12 code 145 cartridges, three of which are blanks and nin, divided into three groups of three, preloaded with BTEX to simulate 7 days exposures (10,080 minutes) to the concentrations listed in the table. The values shown are indicative, actual ones are certified for each lot.

BTEX loading is performed by injection of precisely known amounts of vaporized standard solutions in methanol of the five compounds under nitrogen flow. During the analysis the chromatographic peak of methanol will be visible. Kept at 4 °C, the cartridges are stable for at least four months.

Empty cartridge
Can be loaded by the customer with the desired adsorbent. It is delivered with the two end caps and the glass tube.
Available in 20 pieces per package.

Code 175
Stainless steel net, 100 mesh, 5.9 mm diameter

Code 176
Stainless steel net, 100 mesh, 4.8 mm diameter

Code 177
Stainless steel net, 3x8 μm, 4.8 mm diameter

Barcode adhesive label
Code 190
Available in 198 pieces per package.

Clip
Code 195
Available in 20 pieces per package.

Strip
Code 198
Useful for repositioning of radiello shelter. Lenght 75 cm.
Available in 100 pieces per package.

Tubes
Available in 20 pieces per package.

Code 199-1
Glass tube, working volume 2.8 ml

Code 199-2
Polypropylene tube, working volume 12 ml

radiello is patented by
FONDAZIONE SALVATORE MAUGERI-IRCCS
Centro di Ricerche Ambientali · via Svizzera, 16 · 35127 Padova
595 North Harrison Road,
Bellefonte, PA 16823 USA
www.sigma-aldrich.com/radiello
**Aldehydes**

**Radiello components to be used:**
- Blue diffusive body code 120-1
- Supporting plate code 121
- Vertical adapter code 122 (optional)
- Chemicadsorbing cartridge code 165
- Filtration kit code 174 (only for analysis)

**Or:** *radiello-ready-to-use sampler* code 123-4 (also see page A8)

**Principle**

Code 165 is a stainless steel net cartridge filled with 2,4-dinitrophenylhydrazine (2,4-DNPH) coated Florisil®. Aldehydes react with 2,4-DNPH to give the corresponding 2,4-dinitrophenylhydrazones.

\[
\begin{align*}
\text{O}_2\text{N} & \quad \Phi-\text{NH-NH}_2 + \text{O}=\text{C} & \quad \text{O}_2\text{N} \\
& \quad R & \quad \Phi-\text{NH-N}=\text{C} + \text{H}_2\text{O} \\
\text{2,4-DNPH} & \quad \text{aldehyde} & \quad \text{2,4-dinitrophenylhydrazone}
\end{align*}
\]

The 2,4-dinitrophenylhydrazones are then extracted with acetonitrile and analyzed by reverse phase HPLC and UV detection.

**Sampling rates**

Sampling rates values \( Q \) at 298 K (25 °C) and 1013 hPa are listed below:

<table>
<thead>
<tr>
<th>Substance</th>
<th>( Q_{298} ) (ml·min(^{-1}))</th>
<th>Linearity range (µg·m(^{-3})·min)</th>
<th>Limit of quantitation (µg·m(^{-3}))</th>
<th>Uncertainty at 2( \sigma ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acetaldehyde</td>
<td>84</td>
<td>1,000±12,000,000</td>
<td>0.1</td>
<td>15.9</td>
</tr>
<tr>
<td>Acrolein</td>
<td>33</td>
<td>3,000±3,000,000</td>
<td>0.3</td>
<td>16.5</td>
</tr>
<tr>
<td>Benzaldehyde</td>
<td>92</td>
<td>1,000±8,000,000</td>
<td>0.1</td>
<td>17.2</td>
</tr>
<tr>
<td>Butanal</td>
<td>11</td>
<td>9,000±10,000,000</td>
<td>0.9</td>
<td>23.5</td>
</tr>
<tr>
<td>Hexanal</td>
<td>18</td>
<td>5,000±15,000,000</td>
<td>0.6</td>
<td>20.2</td>
</tr>
<tr>
<td>Formaldehyde</td>
<td>99</td>
<td>1,000±4,000,000</td>
<td>0.1</td>
<td>13.8</td>
</tr>
<tr>
<td>Glutaric aldehyde</td>
<td>90</td>
<td>1,000±3,000,000</td>
<td>0.1</td>
<td>14.5</td>
</tr>
<tr>
<td>Isopentanal</td>
<td>61</td>
<td>1,500±12,000,000</td>
<td>0.2</td>
<td>17.0</td>
</tr>
<tr>
<td>Pentanal</td>
<td>27</td>
<td>4,000±12,000,000</td>
<td>0.4</td>
<td>22.9</td>
</tr>
<tr>
<td>Propanal</td>
<td>39</td>
<td>3,000±8,000,000</td>
<td>0.3</td>
<td>17.1</td>
</tr>
</tbody>
</table>

1 after 7 days exposure

**Effect of temperature, humidity and wind speed**

Sampling rate varies from the value at 298 K on the effect of temperature (in Kelvin) as expressed by the following equation

\[
Q_K = Q_{298} \left( \frac{K}{298} \right)^{0.35}
\]

where \( Q_K \) is the sampling rate at the temperature \( K \) and \( Q_{298} \) is the reference value at 298 K. This produces a variation of ± 1% for 10 °C variation (upwards or downwards) from 25 °C.

Sampling rate is invariant with humidity in the range 15-90% and with wind speed between 0.1 and 10 m·s\(^{-1}\).
Calculations

The average concentration \( C \) over the whole sampling time (in \( \mu g \cdot m^{-3} \)) is calculated according to the expression:

\[
C \ [\mu g \cdot m^{-3}] = \frac{m \ [\mu g]}{Q \ [ml \cdot min^{-1}] \cdot t \ [min]} \times \frac{1,000,000}{1}
\]

where:
- \( m \) = mass of aldehyde in \( \mu g \)
- \( t \) = exposure time in minutes

Exposure

The optimum exposure duration varies with the expected concentration. Taking formaldehyde as an example, concentration values of 5-30 \( \mu g \cdot m^{-3} \) are usually found in outdoor urban measurements while 20-200 \( \mu g \cdot m^{-3} \) are expected in workplace environments. In workplace environments concentrations may be as high as 2,000-3,000 \( \mu g \cdot m^{-3} \) for short time intervals: it can therefore be interesting to evaluate the peak value (usually referred to by \( STEL \)). The corresponding advised exposure time is shown in the table below:

<table>
<thead>
<tr>
<th>Advised exposure times</th>
</tr>
</thead>
<tbody>
<tr>
<td>outdoor environment</td>
</tr>
<tr>
<td>minimum</td>
</tr>
<tr>
<td>maximum</td>
</tr>
</tbody>
</table>

Do not expose all of the cartridges belonging to the same lot: keep at least two cartridges as blanks.

Storage

The cartridges need to be kept in a dark place at 4 °C. Closed in their bags, they are stable at least six months from the production date. Each cartridge has a blank value of formaldehyde less than 0.1 \( \mu g \), corresponding to a concentration in air less than 0.1 \( \mu g \cdot m^{-3} \) over one week of exposure or 2 \( \mu g \cdot m^{-3} \) over 8 hours. The blank value may increase with time. The expiry date (printed onto the plastic bag) indicates when the expected content of formaldehyde (for a correctly stored cartridge) will probably exceed 0.2 \( \mu g \).

Formaldehyde stability in the cartridge after the sampling (on top) and in solution (left). The stability tests were performed upon cartridges exposed for one week in a standard atmosphere chamber at 25 °C and with 50% relative humidity and at two different concentration levels. Each bar in the plot represents the average and error from the analysis of six samples.
After exposure keep the cartridges well capped at 4 °C, they are stable for 60 days. After solvent desorption (see Analysis) and extraction of the cartridge from the tube, the resulting solution, well capped and stored at 4 °C, is stable for at least 42 days (see on page C2).

**Analysis**

**Desorption**

**Materials**
- HPLC or spectroscopy grade acetonitrile
- class A volumetric pipette, capacity 2 ml
- micropore filter membranes, porosity 0.45 μm, solvent resistant

**Procedure**

Introduce 2 ml acetonitrile directly in the cartridge tube, recap and stir from time to time for 30 minutes. Discard the cartridge. Filter the resulting solution and keep it well capped until analysis time. If analysis has to be delayed, store the solution at 4 °C.

**Instrumental analysis**

The method suggested below is only indicative; the analyst can choose an alternative method, on the basis of its personal experience.

**Materials**
- reverse phase C₁₈ HPLC column, length 150 mm, 4.6 mm diameter, 5 μm packing particle size (e.g. Ascentis C18, Supelco cat.no. 581324-U)
- HPLC apparatus capable of elution gradient and UV detection

**Procedure**

Set the detector at the wavelength of 365 nm. Inject between 10 and 50 μl of solution and elute as follow:
- flow: 1.9 ml·min⁻¹
- Isocratic elution with acetonitrile/water 38:62 v/v for 10 minutes, up to acetonitrile/water 75:25 v/v in 10 minutes, reverse gradient to acetonitrile/water 38:62 v/v in 5 minutes.

On the right: the chromatogram of a real sample analyzed under the described conditions.

**IMPORTANT**

*Acrolein* gives place to three chromatographic peaks, two of them are unresolved. Calculate the concentration basing onto this most abundant peak and ignore the others.

*Isopentanal* appears as two unresolved peaks: its concentration should be obtained by integration of both peaks as a sum.

**USER TIP**
For extracting the cartridges use SPECTRANAL Acetonitril Fluka Cat. No. 34921 with low aldehyde content.
For a reliable and rapid filtration employ the filtration kit code 174.
To obtain an accurate calibration curve we offer you the calibration solution code 302.

---

**IMPORTANT:** verify the presence and the abundance of the 2,4-DNPH chromatographic peak: otherwise, the cartridge could be saturated.

---

**HPLC chromatogram of aldehydes sampled by radiello**
Interferences

Other carbonyl compounds

All carbonyl compounds, ketones included, react with 2,4-DNPH but do not interfere in the analysis if proper chromatographic parameters are selected. In the described chromatographic conditions acetone-2,4-DNPH peak is well resolved from acrolein-2,4-DNPH. Nevertheless, if acetone concentration is higher than 50,000 μg·m⁻³, acrolein-2,4-DNPH peak intensity is depressed by 25%.

Ozone

Examples of ozonolysis of dinitrophenylhydrazones on active supporting materials as silica gel are found in the literature.

On code 165 cartridge, packed with coated Florisil®, ozonolysis is much less important than on any other commercial aldehyde sampling device, either diffusive or pumped, and becomes appreciable only if ozone concentration, averaged over the whole exposure time interval, is higher than 100 ppb. Since this is not usually the case, generally no correction is needed to take into account ozone concentration. If there is firm evidence that ozone concentration is equal or higher than 100 ppb over the whole exposure time, make use of the corrected sampling rate values shown in the table below, where [O₃] is ozone concentration in ppb.

<table>
<thead>
<tr>
<th>Analyte</th>
<th>Corrected sampling rate Q₂₉₈ ml·min⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acetaldehyde</td>
<td>84 - 0.018[O₃]*</td>
</tr>
<tr>
<td>Acrolein</td>
<td>33 - 0.027[O₃]</td>
</tr>
<tr>
<td>Benzaldehyde</td>
<td>92 - 0.05[O₃]</td>
</tr>
<tr>
<td>Formaldehyde</td>
<td>99 - 0.02[O₃]</td>
</tr>
<tr>
<td>Hexanal</td>
<td>18 - 0.02[O₃]</td>
</tr>
<tr>
<td>Isopentanal</td>
<td>61 - 0.06[O₃]</td>
</tr>
<tr>
<td>Pentanal</td>
<td>27 - 0.01[O₃]</td>
</tr>
<tr>
<td>Propanal</td>
<td>39 - 0.03[O₃]</td>
</tr>
</tbody>
</table>

*Apply for ozone concentration higher than 50 ppb

Sampling rate as a function of ozone concentration normalized to 100 for [O₃] equal to zero. Apart from acetaldehyde, ozone effect becomes relevant only at concentration levels higher than 100 ppb as an average over the whole exposure time interval.

The listed values are referred to the temperature of 298 K (25 °C), for deviations larger than ± 10 °C substitute the base value (e.g. 99 ml·min⁻¹ for formaldehyde) with the corrected value calculated according to equation on page C1.

No experimental data is available for butanal and glutaric aldehyde.

USER TIP

If you perform several analyses, a barcode reader will greatly improve productivity in your laboratory and will also minimize the possibility of errors in the copying of sample labels.

Please contact us to help you in the implementation of the reader.

We have also developed software solutions for the analytical data processing and automated production of analysis reports.
Volatile organic compounds (VOCs) chemically desorbed with \( \text{CS}_2 \)

**Radiello components to be used:**
- White diffusive body code 120
- Supporting plate code 121
- Vertical adapter code 122 (optional)
- Adsorbing cartridge code 130

**Or:** radiello-ready-to-use code 123-1 (also see page A8)

**Principle**

Code 130 cartridge is a stainless steel net cylinder, with 100 mesh grid opening and 5.8 mm diameter, packed with 530 ± 30 mg of activated charcoal with particle size 35-50 mesh. Volatile organic compounds are trapped by adsorption and recovered by carbon disulfide displacement, analysis is performed by FID gas chromatography.

**Sampling rates**

The table on page D2 lists sampling rate values at 298 K (25 °C) and 1013 hPa, experimentally measured in a standard atmosphere chamber. For other compounds, whose diffusion coefficient \( D \) is known, sampling rate can be calculated according to equation [5] on page A2, taking into account that white diffusive body and code 130 cartridge give the geometric constant of radiello the value of 14.145 ± 0.110 cm. Several experiments performed in the standard atmosphere chamber demonstrate that the calculated sampling rates seldom deviate by more than ± 10% from the experimentally measured values.

**Effect of temperature, humidity and wind speed**

Sampling rates varies from the value at 298 K on the effect of temperature (in Kelvin) as expressed by the following equation

\[
Q_K = Q_{298} \left( \frac{K}{298} \right)^{1.5}
\]

where \( Q_K \) is the sampling rate at the temperature \( K \) and \( Q_{298} \) is the reference value at 298 K. This produces a variation of ± 5% for 10 °C variation (upwards or downwards) from 25 °C.

Sampling rate is invariant with humidity in the range 15-90% and with wind speed between 0.1 and 10 m·s\(^{-1}\).


**Calculations**

The listed sampling rate values already take into account for the desorption efficiency with carbon disulfide. The average concentration over the exposure time interval is therefore calculated from the mass of analyte found onto the cartridge and exposure time without introducing any corrective factor, apart from corrections due to average temperature different from 25 °C.

Average concentration over the whole exposure time is calculated according to the following expression

\[
C [\mu g \cdot m^{-3}] = \frac{m [\mu g]}{Q_K [mL \cdot min^{-1}] \cdot t [min]} \times \frac{1,000,000}{1}
\]

where:
- \( m \) = mass of analyte in \( \mu g \)
- \( t \) = exposure time in minutes
### Sampling rate values $Q$ at 25°C (298 K)

<table>
<thead>
<tr>
<th>Compound</th>
<th>$Q_{298}$ ml·min$^{-1}$</th>
<th>linearity range $\mu$g·m$^{-3}$·min$^{-1}$</th>
<th>uncertainty at 2$\sigma$ %</th>
<th>notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>acetone</td>
<td>77</td>
<td>$10,000$-$600$·$10^6$</td>
<td>7.0</td>
<td>a</td>
</tr>
<tr>
<td>acetonitrile</td>
<td>73</td>
<td>$10,000$-$6$·$10^6$</td>
<td>8.2</td>
<td>b</td>
</tr>
<tr>
<td>acrylonitrile</td>
<td>75</td>
<td>$1,000$-$50$·$10^6$</td>
<td>2.2</td>
<td></td>
</tr>
<tr>
<td>benzyl alcohol</td>
<td>37</td>
<td>$1,000$-$800$·$10^6$</td>
<td>6.5</td>
<td></td>
</tr>
<tr>
<td>amyl acetate</td>
<td>52</td>
<td>$1,000$-$800$·$10^6$</td>
<td>3.4</td>
<td></td>
</tr>
<tr>
<td>benzene</td>
<td>80</td>
<td>$500$-$500$·$10^6$</td>
<td>1.8</td>
<td></td>
</tr>
<tr>
<td>bromochloromethane</td>
<td>70</td>
<td>$50,000$-$1,000$·$10^6$</td>
<td>1.4</td>
<td></td>
</tr>
<tr>
<td>butanol</td>
<td>74</td>
<td>$1,000$-$500$·$10^6$</td>
<td>5.0</td>
<td></td>
</tr>
<tr>
<td>sec-butanol</td>
<td>64</td>
<td>$1,000$-$300$·$10^6$</td>
<td>5.2</td>
<td></td>
</tr>
<tr>
<td>tert-butanol</td>
<td>62</td>
<td>$1,000$-$300$·$10^6$</td>
<td>5.5</td>
<td></td>
</tr>
<tr>
<td>butyl acetate</td>
<td>60</td>
<td>$1,000$-$1,000$·$10^6$</td>
<td>3.0</td>
<td></td>
</tr>
<tr>
<td>2-butoxyethanol</td>
<td>56</td>
<td>$1,000$-$100$·$10^6$</td>
<td>5.7</td>
<td></td>
</tr>
<tr>
<td>2-butoxetyl acetate</td>
<td>41</td>
<td>$1,000$-$100$·$10^6$</td>
<td>5.5</td>
<td></td>
</tr>
<tr>
<td>carbon tetrachloride</td>
<td>67</td>
<td>$100,000$-$60$·$10^6$</td>
<td>9.0</td>
<td></td>
</tr>
<tr>
<td>cyclohexane</td>
<td>54</td>
<td>$500$-$500$·$10^6$</td>
<td>4.5</td>
<td></td>
</tr>
<tr>
<td>cyclohexanone</td>
<td>68</td>
<td>$5,000$-$120$·$10^6$</td>
<td>4.2</td>
<td></td>
</tr>
<tr>
<td>cyclohexanol</td>
<td>54</td>
<td>$5,000$-$120$·$10^6$</td>
<td>4.5</td>
<td></td>
</tr>
<tr>
<td>chlorobenzene</td>
<td>68</td>
<td>$1,000$-$1,000$·$10^6$</td>
<td>3.6</td>
<td></td>
</tr>
<tr>
<td>chloroform</td>
<td>75</td>
<td>$100,000$-$60$·$10^6$</td>
<td>9.7</td>
<td></td>
</tr>
<tr>
<td>n-decane</td>
<td>43</td>
<td>$500$-$1,000$·$10^6$</td>
<td>1.1</td>
<td></td>
</tr>
<tr>
<td>diaceton alcohol</td>
<td>43</td>
<td>$500$-$1,000$·$10^6$</td>
<td>4.5</td>
<td></td>
</tr>
<tr>
<td>1,4-dichlorobenzene</td>
<td>51</td>
<td>$1,000$-$1,000$·$10^6$</td>
<td>7.7</td>
<td></td>
</tr>
<tr>
<td>1,2-dichloroethane</td>
<td>77</td>
<td>$1,000$-$500$·$10^6$</td>
<td>8.2</td>
<td></td>
</tr>
<tr>
<td>1,2-dichloropropane</td>
<td>66</td>
<td>$500$-$250$·$10^6$</td>
<td>4.5</td>
<td></td>
</tr>
<tr>
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<td>methyl-tert-butyl ether (MTBE)</td>
<td>65</td>
<td>$500$-$200$·$10^6$</td>
<td>2.5</td>
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</tbody>
</table>
Notes:

a = weakly adsorbed compound. If its concentration is higher than the TLV for the workplace environments it may be partially displaced by other compounds that are more strongly trapped if their concentration is also high. If this is the case, it is advisable to reduce sampling time under 8 hours.

b = prolonged exposure of charcoal cartridges at relative average humidity higher than 80% causes adsorption of up to 100 mg of water. Water does not interfere with adsorption mechanisms but is displaced by carbon disulfide and gives rise to a separate layer. Some very water soluble polar compounds will distribute between the two solvents, thus provoking an underestimation of the actual air concentration since only the carbon disulfide is injected in the gas chromatograph. When the concentration of polar compounds has to be determined, the calibration curve should be prepared by spiking 50 μl of water in each tube containing the cartridge and the 2 ml of carbon disulfide standard solution (see Analysis).

c = better reproducibility obtained by use of methanol as extraction solvent instead of carbon disulfide.

Limit of quantitation

The limit of quantitation depends on the instrumentation and on the analytical conditions. The minimum revealable environmental concentration can be estimated on the basis of the equation on page D1, where \( m \) is the minimum revealable mass, experimentally measured for each compound. Under the analytical conditions described on page D4, the limit of quantitation for 7 days exposure usually ranges from 0.05 to 1 μg·m\(^{-3}\), depending on the compound.
Exposure

Code 130 cartridge has a very large loading capacity: about 80 mg, corresponding to an overall VOCs concentration of 3,000-3,500 mg·m$^{-3}$ sampled for 8 hours or 70,000-80,000 μg·m$^{-3}$ sampled for 14 days. Nevertheless, if the quantified overall adsorbed mass should be near 80 mg, sampling rate could have deviated from linearity. If this is the case, it is advisable to repeat the sampling experiment reducing exposure time.

Workplace environment

In workplace environments complex mixtures of airborne solvent vapours are often found at concentrations of 2,000-3,000 mg·m$^{-3}$. The outstanding adsorbing capacity of code 130 cartridges allows you to sample them for the whole working shift of 8 hours. On the other hand, the very high values of sampling rates for a variety of compounds allow you to perform accurate concentration measurements even after very short exposures. For example, 15 minutes are enough to measure 0.1 mg·m$^{-3}$ of benzene.

radiello can therefore be employed to evaluate both TWA and STEL concentrations.

Other indoor sampling experiments and outdoor campaigns

High sampling rates of radiello ensure very low limits of detection also for short exposure time intervals. For example, you may measure benzene concentrations as low as 2 μg·m$^{-3}$ with an error not exceeding 4% after 8 hours of exposure. If radiello is exposed for 7 days, limit of quantitation becomes 0.1 μg·m$^{-3}$.

Generally speaking, we suggest exposure time duration ranging from 8 hours to 30 days, the ideal value being 7 days.

Storage

The activated charcoal cartridges have undergone a complex conditioning process that ensures an outstanding chromatographic blank level, never exceeding three times the instrumental noise of a FID detector at the lowest attenuation.

Kept in a cool place and away from volatile organic compounds, the cartridges maintain an unchanging blank level and adsorbing capacity for at least two years. Expiry date and lot number are printed onto the plastic bag wrapping each cartridge: its integrity stands as warranty seal.

After exposure the cartridges, well capped and kept in a cool and solvent-free place, maintain their content unaltered for at least six months.

Analysis

Extraction

Introduce 2 ml of CS$_2$ and 100 μl of internal standard solution (see next page) directly in the radiello glass tube without drawing out the cartridge. Always use class A volumetric pipettes or dispensers. Stir from time to time for 30 minutes. If analysis is not performed soon after, draw out the cartridge and discard it.

Calibration

Outdoor environment sampling

If benzene, toluene, ethylbenzene and xylenes (BTEX) have to be analyzed, prepare three or four standard solutions in CS$_2$ having decreasing concentrations of the analytes in the following ranges (in mg·l$^{-1}$):

- benzene 0.04-17.6
- toluene 0.09-34.8
- o-xylene 0.04-17.6
- m-xylene 0.04-17.7
- p-xylene 0.04-17.2

It is advisable to proceed via consecutive dilutions, starting for example from a stock solution containing 1 ml of each compound in 100 ml. Always use class A volumetric glassware. Introduce 2 ml of each standard solution, along with 100 μl of internal standard, onto a blank code 130 cartridge in its glass tube.

IMPORTANT
always use high purity grade CS$_2$, for example Fluka Cat. No. 84713 or Aldrich Cat. No. 34,227-0

BE CAREFUL
even refrigerated, CS$_2$ permeates the tube plastic cap: its volume decreases by 4-5% a day. If the internal standard has been added, it is only matter of unpleasant odour...

radiello is patented by
FONDAZIONE SALVATORE MAUGERI-IRCCS
Centro di Ricerche Ambientali - via Suisse, 16 - 35127 PADOVA

Supelco Edition
**Analysis of unknown samples**

Identify the sample that has been exposed for the longest time or at the highest expected concentration. Introduce 2 ml of CS₂ but do not add the internal standard, stir and let the sample stand for 30 minutes. Without discarding the cartridge, inject the CS₂ solution in the gas chromatograph with FID detector (see below), identify the compounds appearing in the chromatogram and make an estimation of the order of magnitude of their concentrations.

Prepare a CS₂ solution of the identified compounds with doubled concentration with respect to the sample. Dilute this solution in order to obtain standard solutions of concentration respectively about 0.1, 0.5 and 1 times the concentration estimated in the sample. Introduce 2 ml of each standard solution onto a blank code 130 cartridge in its glass tube, along with the chosen internal standard solution.

The chosen internal standard should have a retention time that does not interfere with other compounds in the chromatogram. Compatibly with this requirements, we suggest to employ a solution of 2-fluorotoluene (e.g. Aldrich F 1,532-3 or Fluka 47520) in CS₂ with concentration of 100 μl·l⁻¹ for outdoor samples and 2 ml·l⁻¹ for workplace samples. Add 2 ml of CS₂ and the internal standard to all of the samples, stir, let the samples stand for 30 minutes and discard the cartridges prior to the analysis.

**Instrumental analysis (advised)**

Capillary gas chromatography with FID detection

**Outdoor environment samples:** 100% dimethylpolysiloxane column 50m x 0.2mm, film thickness 0.5 μm; (e.g. Petrocol DH 50.2, Supelco Cat.No. 24133-U) split injection of 2 μl; split ratio 25:1; nitrogen carrier gas at constant pressure of 20 psi; injector temperature 240 ºC; oven initial temperature 35 ºC for 5 minutes, 5 ºC/min up to 90 ºC, maintain for 3 minutes, 10 ºC/min up to 220 ºC, final isotherm for 5 minutes.

**Workplace samples:** 100% dimethylpolysiloxane column 0.2 mm·50 m, film 0.5 μm; split injection of 3 μl, split ratio 100:1; carrier N₂ at constant pressure of 20 psi; injector temperature 240 ºC; oven initial temperature 50 ºC for 5 minutes, 5 ºC/min up to 80 ºC, 15 ºC/min up to 135 ºC, 20 ºC/min up to 220 ºC, final isotherm 10 minutes. Total time: 29 minutes. The retention times for several compounds analyzed under the described conditions are listed in the table on next page.
What makes the code 130 cartridge incomparable?

**the container**

The container is made of stainless steel cloth AISI 316 with 100 mesh grid opening. It is electric welded with no supply of foreign materials. It has tolerance of ± 0.05 mm diameter and of ± 0.1 mm length.

**the contents**

The cartridge is packed with vegetal activated charcoal with a very large adsorbing surface. Its exceptionally low blank is obtained by conditioning it in a nitrogen stream fluidised bed at 450 °C for 16 hours. The fluidised bed technique does not only guarantee the thorough purification of adsorbing material but also performs an accurate selection of its granulometry, by ventilation separations of the fraction under 50 mesh and over 35 mesh.

**the production**

The cartridge is filled up with charcoal by a very complex automated apparatus that was designed and realised in our laboratory. It avoids any contamination of the adsorbing material during the delicate process of cartridge production and ensures a very accurate dosing of the material itself, providing a variability of less than 2% of the weight of the activated charcoal among the cartridges.

**the quality control**

Each cartridge batch undergoes statistical quality control of the blank level. If amounts higher than 20 ng of each of the BTEX compounds are found, the entire lot is discarded.

---

**the sampling rate measurements**

The sampling rate is measured in a standard atmosphere chamber unique in Italy (and one of the few found all over Europe) that allows the dynamic generation of high flows of controlled concentration gas mixtures from 1 µg·m⁻³ to 1,000 mg·m⁻³ (dynamic range from 1 to 10⁶) of each investigated compound alone or mixed with others. The chamber allows temperature control from -20 to 60 °C, relative humidity control from 5% to 100% and air speed variation from 0.1 to 10 m·s⁻¹.

All of the gas flows are measured as mass flows and have therefore the properties of primary standards. All of the operating parameters (gas flows, temperature, relative humidity, ...) are recorded and the records are available along with the certification documents.
Volatile organic compounds (VOCs) thermally desorbed

Radiello components to be used:
Yellow diffusive body code 120-2
Supporting plate code 121
Vertical adapter code 122 (optional)
Adsorbing cartridge code 145

Or: radiello-ready-to-use code 123-2 (also see page A8)

Principle

Code 145 is a stainless steel net cylinder, with 3x8 μm mesh grid opening and 4.8 mm diameter, packed with 350 ± 10 mg of graphitised charcoal (Carbograph 4), particle size is 35-50 mesh.

Volatile organic compounds are trapped by adsorption and recovered by thermal desorption, analysis is performed by capillary gas chromatography and FID or MS detection.

General considerations

Thermal desorption is an easy-to-use technique, but it implies some precautions and is of less general use than chemical desorption.

The recovery of adsorbed compounds is based onto the different shape of adsorption isotherms at different temperatures. Since quantitative desorption of trapped molecules should ideally be accomplished at moderate temperatures, only weak adsorbing media are employed, with active adsorbing surface between 10 and 50 times smaller than that of activated charcoal.

Use of thermal desorption requires therefore an accurate preliminary investigation about the adsorbed compound - adsorbing medium pair. Stronger adsorbents are suitable for very volatile compounds, but will yield only partial desorption of heavier compounds.

Anyway, backdiffusion (see page A3) is always lying in wait: due to the adsorbing medium weakness heavier compounds will eventually displace the more volatile ones. Once you have made an accurate choice of the adsorbing material, therefore, you should bear in mind that a real atmosphere is composed by a variety of compounds apart from those you are analyzing at unpredictable concentrations. As a consequence, sampling times can not be as long as those allowed by activated charcoal, otherwise lighter compounds will be lost. With the purpose of allowing reasonable sampling times (up to two weeks) the sampling rate has been dramatically reduced by changing the diffusive body from the white type (code 120) to the yellow one (code 120-2).

When in contact with a solid adsorbing medium, a gaseous compound will be adsorbed following the Freundlich isotherm, that is to say the adsorbed mass will be $x/m = kC^{1/n}$, where $x$ is the mass of gaseous compound adsorbed by the mass $m$ of the solid adsorbent and $C$ is the concentration of the gaseous compound at the equilibrium in the gas phase. $k$ and $n$ depend on temperature and on the adsorbate - adsorbing medium pair. $k$ increases with decreasing temperature and $n$ is the closer to 1 the stronger the adsorbent.

At low temperatures, $x/m$ depends almost linearly on the concentration in air (see the curve at 25 °C): this allows diffusive sampling. At high temperatures, the adsorbent mass is very low whatever the concentration in the gas phase: this allows the recovery of adsorbed compounds by heating (see the curve at 300 °C).

To ensure the best possible recovery yields, $k$ and $n$ have to be small. This, however, will compromise sampling efficiency. In other words, compounds strongly adsorbed at room temperature will be only partially recovered by thermal desorption. On the other hand, compounds that are easily desorbed by heating will be sampled at room temperature with low efficiency.
Smaller average pore size and thicker diffusive membrane make the diffusive path longer and, as a consequence, sampling rates are reduced to less than one third compared to those obtained with white diffusive bodies.

Some compounds, moreover, are thermally unstable. Thermal degradation of such compounds will cause an underestimation of their concentration or the appearance of ghost peaks. Thermal desorption is nevertheless an outstanding analytical technique because it is easy to perform, it does not require the use of toxic solvents as carbon disulfide, it ensures very low limits of detection, is suited to mass spectrometric detection and allows the recovery of the adsorbing cartridges. Basing on our experience, we have chosen Carbograph 4 as the best compromise between sampling efficiency and recovery yields for a wide range of organic compounds.

**Sampling rates**

Sampling rate values at 298 K (25 °C) and 1013 hPa are listed in table on page E3. All of the values shown have been experimentally measured. Exposure tests have been performed up to the levels shown (in μg·m⁻³·min) and sampling rates are guaranteed to be linear up to the limit values and for overall concentration of volatile organic compounds in air not exceeding 2,000 μg·m⁻³.

**Effect of temperature, humidity and wind speed**

Sampling rates varies from the value at 298 K on the effect of temperature (in Kelvin) as expressed by the following equation

$$Q_K = Q_{298} \left(\frac{K}{298}\right)^{1.5}$$

where $Q_K$ is the sampling rate at the temperature $K$ and $Q_{298}$ is the reference value at 298 K. This produces a variation of ± 5% for 10 °C variation (upwards or downwards) from 25 °C.

Sampling rate is invariant with humidity in the range 15-90% and with wind speed between 0.1 and 10 m·s⁻¹. Do not expose directly radiello to rain: even if only small amounts of water are adsorbed by Carbograph 4, they can nevertheless interfere with the analysis.

**Calculations**

The listed sampling rate values take already into account the recovery yields of adsorbed compounds. The average concentration over the sampling period is therefore calculated from sampled mass of analyte and exposure time without introducing any other corrective factor, apart from temperature variations of Q.

Average concentration $C$ in μg·m⁻³ over the whole exposure time is calculated according to the following expression:

$$C [\mu g \cdot m^{-3}] = \frac{m [\mu g]}{Q_K [ml \cdot min^{-1}] \cdot t [min]} \times 1,000,000$$

where:

$m$ = mass of analyte in μg

$t$ = exposure time in minutes

**Exposure**

**Workplace environment**

The weaker adsorbent Cabograph is not recommended for workplace measurements, as high concentrations, that can be expected, would overload the sorbent. A stronger adsorbent, like activated charcoal, is needed (see page D1).
Other indoor sampling experiments and outdoor campaigns

Thermal desorption is exceptionally suited for long exposure times at low concentrations, as in outdoor campaigns and some indoor environments (e.g. homes, schools, etc...), particularly if the subsequent analysis is performed by HRGC-MS. The recommended exposure times range from 8 hours to the upper limits shown in the table below. It is advisable to reduce sampling time if the estimated overall VOCs concentration is higher than 2,000 μg·m⁻³.

### Sampling rate values Q at 25°C (298 K)

<table>
<thead>
<tr>
<th>Compound</th>
<th>Q₂⁹⁸</th>
<th>exposure time upper limit (days)</th>
<th>linear up to μg·m⁻³·min</th>
<th>uncertainty (2σ) %</th>
<th>limit of detection¹</th>
<th>µg·m⁻³</th>
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<tbody>
<tr>
<td>benzene</td>
<td>27.8</td>
<td>7</td>
<td>410,000</td>
<td>8.3</td>
<td>0.05</td>
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<tr>
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<td>14</td>
<td>410,000</td>
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<td>0.05</td>
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<td>10.9</td>
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<td>9.1</td>
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<td>550,000</td>
<td>11.3</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>o-xylene</td>
<td>24.6</td>
<td>14</td>
<td>550,000</td>
<td>9.1</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>p-xylene</td>
<td>26.6</td>
<td>14</td>
<td>550,000</td>
<td>11.3</td>
<td>0.01</td>
<td></td>
</tr>
</tbody>
</table>

¹after 7 days exposure and with MS detection; analytical conditions as described in the Analysis paragraph

²for overall VOCs concentrations not exceeding 500 μg m⁻²

### Storage

The cartridges have undergone a complex conditioning procedure that ensures an outstanding chromatographic blank level. If kept in a cool place without VOCs contamination, blank level and adsorbing capacity stay unaltered for at least eighteen months.

After exposure the cartridges, well capped and kept in a cool and solvent-free place, are stable for at least three months.
Analysis

The analytical methods hereafter described have been set up with the Perkin-Elmer Turbomatrix thermal desorber and Agilent 5973 MSD mass spectrometer detector. They may be implemented on other instruments by introducing minor adjustments as suggested by the analyst’s experience and characteristics of employed instrumentation.

In the following we propose two methods, one for BTEX analysis and another for VOCs. The former is suited to outdoor sampling in urban monitoring, where investigation is usually focussed onto benzene, toluene, ethylbenzene and xylene isomers. The latter is conceived for indoor monitoring, allowing quantification of all the compounds listed on page E3 and also extended qualitative analysis. The two methods differ by a few details, such as the higher desorption temperature for VOCs and the higher cryofocusing temperature for BTEX. The latter caution is introduced to avoid freezing of excess humidity gathered during the sampling in the cryofocusing trap.

Desorption

The thermal desorber is equipped with 1/4” OD SS sample tubes, they have to be hollow and free: discard the stainless steel gauze disk which is fitted to the groove and discard also the springs if present.

Code 145 cartridge has been dimensioned to fit the diameter of Turbomatrix thermal desorption tubes. Its length is such that, when the cartridge is introduced into the tube and is stopped by the groove, it is positioned exactly centrally with respect to the tube length.

Inner diameter of Perkin-Elmer tubes is not always exactly the same; it may be the case therefore that a cartridge code 145 does not slide easily into the tube. Some pushing tool may be helpful then, such as a 500 μl syringe piston, a glass bar or an iron wire 2-3 mm thick.

In some cases the tube inner diameter is slightly larger than the cartridge outer diameter: the cartridge can therefore be pushed out from the tube during desorption due to the desorption gas pressure. If this is the case, make use of the springs provided along with the tubes.

Once capped, the Turbomatrix steel tube has to be positioned in the carousel with the grooves on the bottom.

The described conditions have been optimized for seven days exposures to typical concentrations of urban atmospheres and indoor environments. Shorter exposure times or considerably higher concentrations would require different settings of split flows, with the purpose of ensuring good analytical sensitivity or linearity of response.

### BTEX

**Temperatures and timing**

- Desorption: 320 °C for 10 minutes
- Cryofocusing trap (Tenax TA): during primary desorption maintain 2 °C, secondary desorption at 99 °C/sec up to 290 °C, 1 minute at 290 °C
- Six port valve: 150 °C
- Transfer line: 200 °C

**Flows**

- Carrier gas: helium, 24 psi
- Desorption flow: 100 ml·min⁻¹
- Inlet split: 90 ml·min⁻¹
- Outlet split: 30 ml·min⁻¹

### VOCs

**Temperatures and timing**

- Desorption: at 370 °C for 15 minutes
- Cryofocusing trap (Tenax TA): during primary desorption maintain at -20 °C, secondary desorption at 99 °C/sec up to 290 °C, 1 minute at 290 °C
- Six port valve: 150 °C
- Transfer line: 200 °C

**Flows**

- Carrier gas: helium, 24 psi
- Desorption flow: 100 ml·min⁻¹
- Inlet split: 90 ml·min⁻¹
- Outlet split: 30 ml·min⁻¹
**Instrumental analysis**

Analytical parameters for BTEX and VOCs are the same, apart from the duration of chromatographic run and final temperature.

We recommended the following conditions:

**Column**

100% dimethylpolysiloxane, length 50m x 0.2 mm, film thickness 0.5 μm; (e.g. Petrocol DH 50.2, Supelco Cat.No. 24133-U) the column is directly fitted to the six-port valve of Turbomatrix apparatus.

**Temperatures**

- GC oven: 40 °C for 3 minutes, 8 °C/min up to 80 °C, maintain for 1 minute, 20 °C/min up to 250 °C for BTEX and up to 280 °C for VOCs, final isotherm 1.5 minutes for BTEX and 3 minutes for VOC
- GC-MS interface: 270 °C

**Flows**

- Carrier gas: helium, 0.8 ml·min⁻¹

On page E6 we display two total ion current chromatograms from an outdoor urban site and an indoor sampling respectively.

In the first case, the benzene peak corresponds to an average concentration of 2.2 μg·m⁻³; in the second the concentration of 1,4-dichlorobenzene was 14 μg·m⁻³. Despite the low concentration values, the signal-to-noise ratio is very high in both cases. As a consequence, very reliable mass spectral identification is possible.

**Calibration**

Calibration curves are obtained by gas-phase injection of methanol solutions of the target compounds onto blank cartridges. Injections are performed through a GC injector, where a short piece (10 cm) of wide-bore (0.53 i.d.) deactivated uncoated column is installed. The other end bears a Swagelock reducing connection (1/16”-1/4”). The 1/4” Swagelock nut has to be equipped with a PTFE ferrule instead of the original steel one (use PTFE ferrules that come along with the Turbomatrix caps).

Introduce a blank cartridge in a Turbomatrix tube and fit the tube to the Swagelock nut. Maintain the injector at 200 °C but do not heat the oven. Inject slowly 1 μl of each calibration solution under nitrogen flow (50 ml/min) and let the system purge for 2 minutes. Analyze the cartridge as you would do with a sample.

We suggest you to prepare a complete set of calibration solutions by subsequent dilutions such as they contain, for example, 8, 4, 2, 1, 0.04, 0.02 and 0.01 μg·μl⁻¹ of each compound.

**USER TIP**

If you perform several analyses, a barcode reader will greatly improve productivity in your laboratory and will also minimize the possibility of errors in the copying of sample labels. Please contact us to help you in the implementation of the reader.

We have also developed software solutions for the analytical data processing and automated production of analysis reports.

**USER TIP**

For a very accurate BTEX calibration we offer the preloaded cartridges code 407.
Cartridge recovery

In principle, the thermal desorption analysis leaves a conditioned cartridge that can be used as it is for another sampling. Actually this is not the case since the desorption yield, even if very high, is never quantitative, particularly for compounds with more than six carbon atoms. We recommend therefore to recondition the cartridges after analysis, keeping them at 350 °C for eight hours under nitrogen flow.

Graphitized charcoal is a fragile material that exhibits a tendency to turn to dust under mechanical stress during the use on field and in the laboratory. Even if the stainless steel net mesh grid opening is a few micrometers, dust is lost anyway and the cartridge will eventually become empty. As soon as the mass of graphitized charcoal is reduced by 20% the cartridge has to be discarded. Basing onto our experience, this will occur after at least twenty sampling-and-analysis cycles.

Supelco Edition

TIC chromatograms of an outdoor urban sampling (left) and of indoor air (bottom). Mass spectra of benzene and of 1,4-dichlorobenzene are shown on the bottom of each picture, at concentrations of 2.2 and 14 μg·m⁻³ respectively. Despite the low concentration values, the signal-to-noise ratio is very high in both cases. As a consequence, very reliable mass spectral identification is possible by comparison with mass spectral data libraries with no need of further processing.
Nitrogen and sulfur dioxides (NO$_2$ and SO$_2$)

Radiello components to be used:
Blue diffusive body code 120-1
Supporting plate code 121
Vertical adapter code 122 (optional)
Chemiadsorbing cartridge code 166

Or: radiello-ready-to-use code 123-3 (also see page A8)

Principle
The cartridge code 166 is made of microporous polyethylene coated with triethanolamine (TEA). Nitrogen (NO$_2$) and sulfur (SO$_2$) dioxide is chemiadsorbed onto TEA as nitrite and sulphite or sulphate ions respectively. Nitrite is quantified by visible spectrophotometry while sulphite and sulphate are analysed by ion chromatography (NO$_2$ and SO$_2$ can be analysed together by ion chromatography).

Sampling is selective for gaseous molecules: any airborne nitrite, sulphite or sulphate will not cross the diffusive membrane.

Sampling rates

NO$_2$
The sampling rate value $Q$ at 298 K (25°C) and 1013 hPa is $0.141 \pm 0.007$ ng·ppb$^{-1}$·min$^{-1}$.

SO$_2$
The sampling rate value $Q$ at 298 K (25°C) and 1013 hPa is $0.466 \pm 0.022$ ng·ppb$^{-1}$·min$^{-1}$.

Effect of temperature, humidity and wind speed
Sampling rate of NO$_2$ varies from the value at 298 K on the effect of temperature (in Kelvin) following the equation:

\[ Q_K = Q_{298} \left( \frac{K}{298} \right)^{7.0} \]

where $Q_K$ is the sampling rate at the temperature $K$ ranging from 263 to 313 K (from -10 to 40 °C) and $Q_{298}$ is the reference value at 298 K.

Sampling rate for SO$_2$ does not vary with temperature between 263 and 313 K (from -10 to 40 °C).

Sampling rate is invariant with humidity in the range 15 - 90% and with wind speed between 0.1 and 10 m·s$^{-1}$ for both gases.

Calculations

NO$_2$
The concentration $C_{NO_2}$ is calculated according to the equation:

\[ C_{NO_2} = \frac{m_{NO_2}}{Q_K \cdot t} \]

where $m_{NO_2}$ is nitrite mass in ng found on the cartridge, $t$ is exposure time in minutes and $Q_K$ is the sampling rate value at the temperature $K$ in Kelvin.

SO$_2$
Convert the sulphite found onto the cartridge into sulphate by multiplying its mass by 1.2, then sum the obtained value to the sulphate found in the cartridge. The concentration in ppb is calculated according to the equation:

\[ C_{SO_2} = \frac{m_{SO_4}}{0.466 \cdot t} \]

where $m_{SO_4}$ is the overall sulphate mass in ng found in the cartridge (sulphate itself and sulphite converted into sulphate) and $t$ is exposure time in minutes.

USER TIP
It is advisable to measure the sampling temperature by the thermometer code 126.
Exposure

Exposure up to 15 days is feasible but if relative humidity is higher than 70% for the entire sampling duration it is not advisable to sample for more than 7 days. Due to the fact that TEA is very hygroscopic in fact, even if water does not actually interfere with sampling or analysis, the excess water adsorbed by the cartridge could cause some loss of adsorbing medium by percolation.

Limit of quantitation and uncertainty

Sampling rate of NO$_2$ and SO$_2$ is linear ranging from 10,000 to 5,000,000 ppb·min. Limit of quantitation after 7 days exposure is 1 ppb for both gases. The uncertainty at 2σ is 11.9% for NO$_2$ and 9.2% for SO$_2$.

Storage

The cartridges are stable for at least 12 months before and 4 months after the sampling, if kept in the dark at 4 °C. Expiry date is printed on the plastic bag.

Do not expose all of the cartridges belonging to the same lot, keep at least two of them as blanks.

Analysis

Add 5 ml of water in the plastic tube with the cartridge and stir vigorously by a vortexer for 1 minute. Do the same with two-three unexposed cartridges.

Colorimetric determination of nitrite ion

Nitrogen dioxide is quantitatively converted to nitrite ion. Prepare the following reagents:

- **sulphanilamide**: dissolve 10 g of sulphanilamide in 100 ml concentrated HCl and dilute to 1,000 ml with water
- **NEDA**: dissolve 250 mg of N-(1-naphthyl)ethylendiamine dihydrochloride in 250 ml of water (discard the solution when it turns brown).

Transfer 0.5 ml (or a different volume, see the table below) of the cartridge extraction solution to a plastic or glass 10 ml tube along with 5 ml of sulphanilamide reactive. Cap tightly, stir and wait for 5 minutes. Add 1 ml of NEDA reactive, stir and wait for 10 minutes. Do the same with unexposed cartridges.

Measure the absorbance of samples at 537 nm using water to zero the spectrophotometer, then subtract the blank value from unexposed cartridges. Prepare the calibration standards in the same way from sodium nitrite solutions of concentration ranging from 0.1 to 20 mg·l$^{-1}$ expressed as NO$_2$.

When nitrite ion concentration is higher than 20 μg·ml$^{-1}$ (corresponding to 7 days of exposure to 70 ppb) the absorbance value is no longer comprised in the calibration curve. To analyse the samples, draw smaller amounts of the extraction solution as shown in the table. In order to maintain the overall volume unaltered, add the listed volume of water.

<table>
<thead>
<tr>
<th>average expected concentration for 7 days exposure in ppb</th>
<th>sample volume ml</th>
<th>water volume to be added ml</th>
</tr>
</thead>
<tbody>
<tr>
<td>up to 70</td>
<td>0.5</td>
<td>0</td>
</tr>
<tr>
<td>from 70 to 150</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>higher than 150</td>
<td>0.1</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Determination of the sulphite and sulphate ions

 Though SO$_2$ is converted into sulphite and sulphate ions with variable ratios, the sum of the two ion equivalents is linear with exposure to SO$_2$. To obtain calibration curves, prepare solutions containing both ions at concentrations ranging from 5 to 50 mg·l$^{-1}$. Perform the ion chromatography analysis of the standard solutions and the extraction solutions from radiello cartridges in the same way according to your usual laboratory practice.
Ozone (O₃)

**Radiello components to be used:**
- Blue diffusive body code 120-1
- Supporting plate code 121
- Vertical adapter code 122 (optional)
- Chemiadsorbing cartridge code 172

**Or:** radiello-ready-to-use code 123-5 (also see page A8)

---

**Principle**

The adsorbing cartridge is formed by a micropore polyethylene tube filled with silica gel coated with 4,4’-dipyridylethylen e and closed, at one end, by a PTFE cap. Upon exposure, acid-catalysed ozonolysis of 4,4’-dipyridylethylene leads to 4-pyridylaldehyde.

Silica gel ensures the presence of water, necessary to complete ozonolysis reactions. In the laboratory, 4-pyridylaldehyde is condensed with 3-methyl-2-benzothiazolinone hydrazone (MTBH) to yield the corresponding azide, yellow coloured. The absorbance of the solution is measured at 430 nm. Production of 4-pyridylaldehyde is a specific reaction of ozone; neither nitrogen oxides nor organic compounds, if present, do interfere.

---

**Sampling rate**

The sampling rate value \( Q \) at 298 K (25°C) and 1013 hPa is \( 24.6 \text{ ml·min}^{-1} \).

Sampling is linear in the exposure range from 10,000 to 4,000,000 \( \mu\text{g·m}^{-3}·\text{min}^{-1} \).

**Effect of temperature, humidity and wind speed**

Sampling rate varies from the value at 298 K on the effect of temperature (in Kelvin) as expressed by the following equation:

\[
Q_K = Q_{298} \left( \frac{K}{298} \right)^{1.5}
\]

where \( Q_K \) is the sampling rate at the temperature \( K \) and \( Q_{298} \) is the reference value at 298 K. Sampling rate is not influenced by humidity or wind speed.

---

**Calculations**

The average concentration over the whole exposure time is calculated according to the equation

\[
C \left[ \mu\text{g·m}^{-3} \right] = \frac{m \left[ \mu\text{g} \right]}{24.6 \cdot t \left[ \text{min} \right]} \cdot 1,000,000
\]

where \( m \) is ozone mass in \( \mu\text{g} \) sampled by radiello and \( t \) is exposure time in minutes.
**Exposure**

Introduce the cartridge in the diffusive body and make sure that the PTFE cap is positioned at the same end of the screw.

In outdoor environments, where typical ozone concentrations range from 2 to 400 μg·m⁻³, we suggest exposure time from 24 hours to 14 days. The ideal range is from 3 to 7 days.

In workplace environments it is advisable to sample over the entire 8 hours shift.

**Limit of detection and uncertainty**

The limit of detection is 2 μg·m⁻³ for 7 days exposures. The cartridge is saturated after 14 days exposure at 400 μg·m⁻³. The uncertainty at 2σ is 14.5% over the whole sampling rate linearity range.

**Storage**

The cartridges need only protection from direct sunlight: keep them in a drawer or a cupboard at room temperature. In these conditions, the blank level does not exceed 0.015 absorbance units for up to six months.

Expiry date is printed onto the plastic bag wrapping each cartridge.

Generally, an increase of blank level does not imply that the cartridge must be discarded. The only consequence is a corresponding increase of the analytical limit of quantification.

After exposure the samples have to be stored in the dark as before, along with three unused cartridges to be analysed as blanks. Analyse them within a week.

**Analysis**

**Reactives and materials**

- 3-methyl-2-benzothiazolinone hydrazone hydrochloride (MBTH): dissolve 5 g per liter in water and add 5 ml of concentrated sulphuric acid; this solution is to be freshly prepared.
- 4-pyridylaldehyde
- micropore filter membrane 0.45 μm

**Procedure**

Draw the cartridge out from the plastic tube, discard the PTFE cap and pour the silica gel into the tube. Add 5 ml of MBTH solution, recap the tube and stir vigorously. **Let the tube stand for at least one hour to react**, stirring from time to time. Filter through the micropore filter (if you make use of the code 174, act as follows: fit the filter to the syringe, transfer the solution from the tube to the syringe and filter it into a second tube or directly into the spectrophotometer measure cell).

Measure absorbance at 430 nm using water to zero the spectrophotometer. The yellow colour is stable for several days if the solution is kept well capped in its tube.

Treat in the same manner three unused cartridges of the same lot and subtract the average blank value from the absorbance values of the samples.

**Calibration**

Dissolve 100 μl (112.2 mg at 20° C) of 4-pyridylaldehyde in 1 liter of water and dilute this solution (e.g. 1:2, 1:5, 1:10) to obtain calibration solutions. Transfer 0.5 ml of each calibration solution in a plastic tube together with 4.5 ml of MBTH solution. Stir and let stand for one hour, then read the absorbance at 430 nm (filtration is not needed). Plot the calibration curve for ozone mass vs measured absorbance, taking into account that:

1 μg of 4-pyridylaldehyde = 0.224 μg of ozone.
Hydrogen sulfide (H₂S)

**Radiello components to be used**
- White diffusive body code 120
- Supporting plate code 121
- Vertical adapter code 122 (optional)
- Chemiadsorbing cartridge code 170

**Or:** radiello-ready-to-use code 123-6 (also see page A8)

**Principle**

The cartridge code 170 is made of microporous polyethylene and impregnated with zinc acetate. Hydrogen sulfide is chemiadsorbed by zinc acetate and transformed into stable zinc sulfide. The sulfide is recovered by extraction with water. In contact with an oxidizing agent as ferric chloride in a strongly acid solution it reacts with the N,N-dimethyl-p-phenylenediammonium ion to yield methylene blue.

![Chemical reaction](image)

N,N-dimethyl-p-phenylenediammonium → Methylene blue

Methylene blue is quantified by visible spectrometry.

**Sampling rate**

Sampling rate \( Q \) at 298 K (25°C) and 1013 hPa is \( 0.096 \pm 0.005 \text{ ng·ppb}^{-1}·\text{min}^{-1} \).

**Effect of temperature, humidity and wind speed**

Sampling rate varies from the value at 298 K on the effect of temperature (in Kelvin) as expressed by the following equation:

\[
Q_K = 0.096 \left( \frac{K}{298} \right)^{3.8}
\]

where \( Q_K \) is the sampling rate at the temperature \( K \) ranging from 268 to 313 K (from -5 to 40 °C).

Sampling rate is invariant with humidity in the range 10 - 90% and with wind speed between 0.1 and 10 m·s⁻¹.

**Calculations**

Once \( Q_K \) at the sampling temperature has been calculated, the concentration \( C \) is obtained according to the equation:

\[
C = \frac{m}{Q_K \cdot t} \times 1,000
\]

where \( m \) is the mass of sulphide ion in μg found onto the cartridge and \( t \) is exposure time in minutes.

**Exposure**

Exposure duration may vary from 1 hour to 15 days. Sampling is linear from 2,000 to 50,000,000 ppb·min of H₂S.
Limit of detection and uncertainty
The limit of detection is 30 ppb for 1 hour exposure or 1 ppb for 24 hour exposure. The uncertainty at 2σ is 8.7% over the whole exposure range.

Storage
The cartridges are stable at least for 12 months before and 6 months after exposure. Do not expose all of the cartridges of the same lot: keep at least two of them as blanks.

Analysis
Reactives
✓ sulphuric acid: slowly add 25 ml of concentrated sulphuric acid to 10 ml water and let the solution cool;
✓ amine: dissolve 6.75 g of N,N-dimethyl-p-phenylendiammonium oxalate in the sulphuric acid solution. Dilute this solution to 1 liter with sulphuric acid - water 1:1 v/v. Kept in a dark bottle and well capped, this solution is stable for at least four weeks. CAUTION: this solution is very poisonous.
✓ ferric chloride: dissolve 100 g of ferric chloride hexahydrate (FeCl₃·6H₂O) in 40 ml of water.
✓ ferric chloride-amine: mix 10 ml of ferric chloride solution with 50 ml of amine solution. This solution has to be freshly prepared;
✓ sulphuric acid for dilution: slowly dissolve 40 ml of concentrated sulphuric acid in 900 ml of water, let the solution cool and make up to 1,000 ml.

Procedure
Add 10 ml of water to the plastic tube containing the cartridge, recap and stir vigorously, preferably by a VORTEX stirrer.
Add 0.5 ml of ferric chloride - amine solution, recap immediately and stir. The tube must be capped immediately in order to avoid that the developed hydrogen sulfide can escape from the tube before reacting.
Wait for 30 minutes and measure absorbance at 665 nm using water to zero the spectrophotometer. The colour is stable for several weeks.
Do the same with two or three unexposed cartridges of the same lot and obtain the average blank value, then subtract it to the samples.

Calibration
Calibration curves may be prepared by sodium sulfide standard solutions, which have to be titrated just before use. As diluted sodium sulfide solutions are very unstable (the sulfide content can diminish as much as the 10% in an hour) it is strongly recommended to make use of the calibration solution code 171, following the instructions included.

IMPORTANT
Absorbance is linear up to 1,200 absorbance units, corresponding to an exposure value of about 80,000 ppb-min. If higher absorbance values are obtained, dilute the samples with the sulphuric acid for dilution.
Be careful to apply the same dilution ratio to the samples and the blanks.
NEVER USE WATER TO DILUTE.

USER TIP
Code 171 calibration solution relieves you from the task of preparation and titration of the sodium sulfide solutions.
Ammonia (NH₃)

Radiello components to be used
Blue diffusive body code 120-1
Supporting plate code 121
Vertical adapter code 122 (optional)
Chemiadsorbing cartridge code 168

Principle
The cartridge code 168 is made of microporous polyethylene and impregnated with phosphoric acid. Ammonia is adsorbed as ammonium ion. Airborne ammonium salts dispersed as particulate matter do not cross the diffusive membrane of radiello.

Ammonium ion is quantified by visible spectrometry as indophenol: at basic buffered pH ammonium ion reacts with phenol and sodium hypochlorite, with pentacyanonitrosylferrate catalysis (in the following cyanoferrate), to form indophenol. The reaction product is intensely coloured in blue, and its absorbance measured at 635 nm.

\[
\text{HO} - \text{C} = \text{O} + \text{NH}_3 + \text{C}_{6}H_{4}\text{OH} \xrightarrow{\text{NaClO}} \text{Na}_{2}\text{Fe(CN)}_{5}\text{NO}\cdot2\text{H}_2\text{O} \quad \text{(cyanoferrate)}
\]

indophenol

Sampling rate
Sampling rate \( Q \) at 298 K (25°C) and 1013 hPa is 235 ml·min⁻¹.

Effect of temperature, humidity and wind speed
The effect of temperature on sampling rate is negligible (<0.1%/°C) in the range from 275 - 312 K (2 - 39 °C). Sampling rate is invariant with humidity in the range 10 - 90% and with wind speed between 0.1 and 10 m·s⁻¹.

Calculations
The concentration \( C \) in \( \mu g \cdot m^{-3} \) is obtained according to the equation:

\[
C = 0.944 \frac{m}{235 \cdot t} \times 1,000,000
\]

where \( m \) is the mass of ammonium ion in \( \mu g \) found onto the cartridge and \( t \) is exposure time in minutes.

0.944 is the numerical factor necessary to convert ammonium ion into ammonia (see Analysis).

Exposure
Introduce the cartridge in the diffusive body and make sure that the PTFE cap is positioned at the same end of the screw.

Ammonia is sampled linearly in the range from 2,000 - 20,000,000 \( \mu g \cdot m^{-3} \cdot \text{min} \).

Exposure time is allowed to range from 1 hour to 14 days.

IMPORTANT
Do not touch the microporous portion of the cartridge with your fingers: sweat contains ammonium ions.
Limit of detection and uncertainty
The limit of detection is 1 μg·m⁻³ for 24 hour exposure. The uncertainty at 2σ is 6.5% over the whole allowed exposure range.

Storage
The cartridges are stable at least for 12 months before and after exposure if kept at room temperature in an ammonia-free environment. Do not expose all of the cartridges of the same lot: keep at least two of them as blanks.

Analysis

Materials
✓ plastic or glass tube, volume 12 ml, with cap
✓ micropipet with variable volume from 0.1 to 1.0 ml
✓ 5 ml glass pipet

Reactives
✓ buffer solution (pH 10.6): dissolve 1.1 g of NaOH and 3.04 g of NaHCO₃ in one liter of water
✓ phenol: dissolve 10 g of phenol in 100 ml of ethanol
✓ cyanoferrate: dissolve 0.5 g of sodium pentacyanonitrosylferrate dihydrate (Na₂Fe(CN)₅NO·2H₂O) in 100 ml of water and add a few drops of 10% NaOH. Keep this solution in a dark bottle and prepare it freshly.
✓ oxidising solution: sodium hypochlorite with 1% of active chlorine in 0.2 M NaOH. Keep cool in a dark bottle.

Ammonium ion quantification
Open radiello tube and cautiously discard the cartridge PTFE cap (it may have been contaminated with handling). Help yourself with a pair of pliers.
Add 10 ml of deionised water to the cartridge in its tube (make sure that no trace of ammonium ion is found in the water you use). Recap the tube and stir vigorously by a VORTEX stirrer for at least 15 seconds.
Transfer 1 ml of the solution into another tube along with 0.4 ml of phenol, 0.4 ml of cyanoferrate, 5 ml of buffer solution and 1 ml of oxidising solution.
Wait for 1 hour and then measure the absorbance of the solution at 635 nm using water to zero the spectrophotometer.
Do the same with two unexposed cartridges and subtract their absorbance value to the samples. Generally, the blank value does not exceed 0.040 absorbance units.
For exposure value higher than 500,000 μg·m⁻³·min the absorbance value is no longer linear: dilute a known fraction of the coloured solution with the buffer.
Calibration curves are conveniently prepared with ammonium chloride solutions in the range from 0.5 to 10 mg·l⁻¹ as ammonium ion.

IMPORTANT
If sample is too concentrated (absorbance no longer linear) DO NOT DILUTE WITH WATER: the pH value is critical in the determination of the colour intensity.
Hydrochloric acid (HCl)

**Radiello components to be used**
- White diffusive body code 120
- Supporting plate code 121
- Vertical adapter code 122 (optional)
- Chemiadsorbing cartridge code 169

**Or:** radiello-ready-to-use code 123-8 (also see page A8)

---

**Principle**

Code 169 cartridge is made of stainless steel net loaded with silica gel (0.1 to 0.4 mm particle size). Gaseous hydrochloric acid is adsorbed by silica gel and subsequently extracted with water to be quantified by ion chromatography as chloride ion.

Sampling is selective for the gaseous molecules: any airborne chloride salt will not cross the diffusive membrane of radiello.

---

**Sampling rate**

Sampling rate $Q$ at 298 K (25 °C) and 1013 hPa is 103 ml·min⁻¹.

---

**Effect of temperature, humidity and wind speed**

Sampling rate varies from the value at 298 K (25 °C) on the effect of temperature (in Kelvin) as expressed by the following equation:

$$Q_K = Q_{298} \left( \frac{K}{298} \right)^{1.5}$$

where $Q_K$ is the sampling rate at temperature $K$ and $Q_{298}$ is the sampling rate value at the reference temperature of 298 K. This yields a ± 5% variation of $Q$ for a 10 °C variation (upwards or downwards) from 25 °C.

Sampling rate is invariant with humidity in the range 15 - 90% for short exposure time (see Exposure) and with wind speed between 0.1 and 10 m·s⁻¹.

---

**Calculations**

Let $m$ be the mass of chloride ion in μg found onto the cartridge and $t$ the exposure time in minutes, the environmental concentration $C$ of hydrochloric acid in μg·m⁻³ is obtained according to the equation:

$$C = \frac{1.028 \cdot m}{Q_K \cdot t} \cdot 1,000,000$$

where $Q_K$ is the sampling rate at temperature $K$ (in Kelvin) and 1.028 is the ratio between molecular masses of HCl and Cl⁻ (see Analysis).

---

**Exposure**

Hydrochloric acid is sampled linearly in the range from 20,000 - 20,000,000 μg·m⁻³·min.

---

**Workplace environment**

In workplace environment we recommend exposure time from 15 minutes to 8 hours: the ceiling values can be measured.
Outdoor environment
We recommend exposure time from 2 hours to 2 days. Exposure time as long as 7 days is allowed if average relative humidity does not exceed 50%, taking into account the water absorbing properties of silica gel.
We also recommend to protect radiello from rain by the mountable shelter code 196.

Limit of detection and uncertainty
The limit of detection is 10 μg·m⁻³ for 24 hour exposure. The uncertainty at 2σ is 3.5% over the whole allowed exposure range.

Interferents
Gaseous chlorine is adsorbed by silica gel and is revealed as 0.02 ng of chloride ion for 1 μg·m⁻³·min of chlorine.

Storage
Kept in a clean environment free from gaseous hydrochloric acid, the cartridges code 169 are stable for at least 24 months before and after sampling.
If more than six months have passed since you received the cartridges, before environmental sampling campaigns, it is advisable to analyse some cartridges to check for contamination from the background. Discard the cartridges if they contain more than 5 μg of chloride ion.

Analysis
Add 2 ml of deionised water to the cartridge in its tube (make sure that no trace of chloride ion is found in the water you use). Recap the tube and stir vigorously by a VORTEX stirrer for 1-2 minutes. Analyse the solution by ion chromatography. Subtract the blank value obtained from two unexposed cartridges.
Prepare the calibration solutions with sodium or potassium chloride concentrations ranging from 0.5 to 25 mg/liter as Cl⁻.
Hydrofluoric acid (HF)

**Radiello components to be used:**

Blue diffusive body code 120-1
Supporting plate code 121
Vertical adapter code 122 (optional)
Chemiadsorbing cartridge code 166

**Or:** radiello-ready-to-use code 123-3 (also see page A8)

**Principle**

The cartridge code 166 is made of microporous polyethylene coated with triethanolamine (TEA). Gaseous hydrofluoric acid is adsorbed by TEA and subsequently extracted with water to be quantified by ion chromatography or by ion selective electrode as fluoride ion.

Sampling is selective for the gaseous molecules: any airborne fluoride salt will not cross the diffusive membrane of radiello.

**Sampling rate**

Sampling rate $Q$ at 298 K (25 °C) and 1013 hPa is $187 \text{ ml·min}^{-1}$.

**Effect of temperature, humidity and wind speed**

Sampling rate is invariant with humidity in the range 10 - 90% for short exposure time (see Exposure) and with wind speed between 0.1 and 10 m·s$^{-1}$.

The effect of temperature is under investigation.

**Calculations**

Let $m$ be the mass of fluoride ion in μg found onto the cartridge and $t$ the exposure time in minutes, the environmental concentration $C$ of HF in μg·m$^{-3}$ is obtained according to the equation:

$$C = \frac{1.053 \cdot m}{187 \cdot t} \frac{1,000,000}{1}$$

where 1.053 is the ratio between molecular masses of HF and F$^-$ (see Analysis).

**Exposure**

Hydrofluoric acid is sampled linearly in the range from 10,000 to 50,000,000 μg·m$^{-3}$·min.

**Workplace environment**

In workplace environments we recommend exposure time from 15 minutes to 8 hours: the ceiling values can be measured.

**Outdoor environment**

We recommend exposure time from 2 hours to 14 days.

Protect radiello from rain by the mountable shelter code 196.

**Limit of detection and uncertainty**

The limit of detection is 7 μg·m$^{-3}$ for 24 hour exposure. The uncertainty at 2σ is 4.5% over the whole exposure range.
Storage
Kept in a dark place at 4 °C, the cartridges stay unaltered for at least 12 months before exposure and 4 months after sampling. Expiry date is printed on the plastic bag wrapping each cartridge.
If more than six months have passed since you received the cartridges, before environmental sampling campaigns, it is advisable to analyse some cartridges to measure any contamination from the background. Discard the cartridges if they contain more than 2 μg of fluoride ion.
Keep at least two unexposed cartridges for each lot and analyse them as blanks.

Analysis
Ion chromatography
Add 5 ml of eluent solution to the radiello tube. Stir vigorously by a VORTEX stirrer for 1-2 minutes. Let the tube stand for 10 minutes, then stir manually and inject the solution in the ion chromatographic apparatus without further treatment.
Analyse 1-2 unexposed cartridges and subtract the average blank value to the samples.

Ion Selective Electrode
Prepare an ionic strength buffer as follows. Dissolve 57 ml of acetic acid in 500 ml water and add 50 g of sodium chloride and 0.3 g of sodium citrate. When complete solubilisation has been achieved, adjust the pH value to 5-5.5 (ideal value is 5.3) by adding drops of 10 M sodium hydroxide. Make up to 1 liter with water.
Add 5 ml water to radiello tube and stir vigorously by a vortexer for 1-2 minutes, then let stand for 10 minutes. Introduce a magnetic stirring bar in a 20 ml beaker, add 10 ml of ionic strength buffer and 1 ml of the extraction solution of the cartridge. Start the magnetic stirrer and make the potentiometric measurement by an ion selective electrode for fluorides. In the described analytical conditions, the electrode response should be linear in the range from 1 to 1,000 mg·l⁻¹ of F⁻ with slope close to 59 ± 0.5 (if potential is expressed in mV).
Analyse 1-2 unexposed cartridges and subtract the average blank value to the samples.

IMPORTANT
Always use water with fluoride content lower than 0.5 mg·l⁻¹.
Anaesthetic gases and vapours
N₂O, isoflurane, ethrane, halothane and sevorane

Radiello components to be used
Sampling kit code 125, containing 20 single packages each composed of:
1 permeative body (see code 120-3)
   1 supporting plate (see code 121)
   1 vertical adapter (see code 122)
   1 adsorbing cartridge (see code 132)
the listed components are contained in a closed aluminum envelope, which
is wrapped by a thermowelded paper-polyethylene bag.
The whole is sterilized by γ-rays.
The single components are also available non-sterilized in 20 pieces per package.

Principle
Code 132 cartridge is made of stainless steel net loaded with a mixture of molecular sieve and activated charcoal 35-50
mesh.
Nitrous oxide and halogenated anaesthetic gases permeate the silicone membrane and are sampled by the molecular sieve
and by activated charcoal respectively.
The sampled compounds are displaced by a water-methanol mixture and are quantified by capillary gas chromatography
and a headspace sampler.
N₂O, isoflurane, ethrane and halothane are detected by the Electron Capture Detector (ECD) with very good sensitivity;
sevorane can not be quantified by ECD detection and has to be analyzed by mass spectrometry.

Sampling rates
Sampling rate values Q at 298 K (25 °C) and 1013 hPa are listed in
the table on the right.

Effect of temperature, humidity and wind speed
Sampling rate varies from the values at 298 K on the effect of tem-
perature (in Kelvin) as expressed by the following equation:

\[ Q_K = Q_{298} \left( \frac{K}{298} \right)^{1.5} \]

where \( Q_K \) is the sampling rate at temperature \( K \) and \( Q_{298} \) is the sam-
ping rate value at reference temperature of 298 K. This yields a ± 5%
variation of Q for a 10 °C variation (upwards or downwards) from
25 °C.

Sampling rate is invariant with humidity in the range 10 - 90% for exposure time not exceeding 8 hours and with wind speed
between 0.1 and 10 m·s⁻¹.

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<tr>
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<th>( Q_{298} ) (ml·min⁻¹)</th>
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<tr>
<td>N₂O</td>
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<td>(isoflurane)</td>
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<tr>
<td>sevorane</td>
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</table>

Radiello is patented by
FONDAZIONE SALVATORE MAUGERI-IRCCS
Centro di Ricerche Ambientali - via Svizzera, 16 - 35127 PADOVA
Calculations

Concentration in air is obtained by the following equation:

\[ C = \frac{m}{Q_K \cdot t} \cdot \frac{1}{1,000} \]

where:
- \( C \) = concentration in mg·m\(^{-3}\)
- \( m \) = mass of analyte found on the cartridge in μg
- \( Q_K \) = sampling rate in ml·min\(^{-1}\)
- \( t \) = exposure time in minutes

Exposure

Sampling rate is constant for exposure time up to 8 hours at relative humidity up to 80% with N\(_2\)O concentration up to 500 ppm and overall halogenated anaesthetic compounds concentration up to 100 ppm.

Exposure time longer than 8 hours in presence of relative humidity higher than 80% leads to the loss of the nitrous oxide already sampled by the effect of competing water vapour adsorption on the molecular sieve sites.

Limit of detection and uncertainty

The cartridges are conditioned to ensure a chromatographic blank level lower than three times the instrumental noise at the minimum attenuation.

If a well conditioned ECD is employed, 4 hours of exposure ensure the following analytical sensitivities: 0.5 ppm of N\(_2\)O, 0.002 ppm of forane, 0.01 ppm of ethrane and 0.002 ppm of halothane. **Sevorane is not detected by ECD.** The Flame Ionisation Detector (FID) can be employed instead with acceptable sensitivity, but if nitrous oxide and the other halogenated compounds have to be quantified at the same time, a mass spectrometry detector must be used. Acquiring by the SIM (Single Ion Monitoring) technique detection limits close to the ECD performances can be achieved for N\(_2\)O, forane, ethrane and halothane. For sevorane, 1 hour exposure allows to detect 0.1 ppm.

The uncertainty at 2\(\sigma\) is: 5.5% for N\(_2\)O, 4.7 - 5.6% for forane, ethrane and halothane with ECD detection, 6.2% for N\(_2\)O and 5.5 - 6.2% for forane, ethrane, halothane and sevorane with MS detection.

Storage

The sampling kit code 125 is sterilized by \(\gamma\)-rays. Use of the sampler makes it no longer sterile. With the exception of the adsorbing cartridge, the sampler is indefinitely re-usable. After the first sampling, if you can arrange for sterilization by yourselves you only need to re-order code 132 cartridges to perform other sampling campaigns. Adsorbing cartridges need not to be sterile.

If kept in a dry place free from chemical contamination, the cartridges are stable for at least 12 months. After the sampling, the cartridges are stable for 30 days if stored with the same precautions.

Analysis

**Materials needed for the analysis**

✔ 20 ml headspace glass vials with open-top aluminum crimp caps and rubber/PTFE septa
✔ water/methanol mixture 60/40 v/v
✔ usual laboratory glassware

---

**IMPORTANT**

DO NOT STERILIZE THE SAMPLER BY AUTOCLAVING. Autoclaving treatment **permanently** damages the silicone permeative membrane.
Materials needed for the calibration curve

- pure N₂O in a gas cylinder
- halogenated anaesthetic compounds
- gastight syringe (volume 500 μl) and other syringes (volume 100 and 10 μl)
- 1 liter glass bottle with threaded neck, equipped with open-top screw cap and rubber/PTFE septum (the volume of the bottle must be precisely measured and the bottle must be rinsed with dry nitrogen before use)
- magnetic stirrer with large magnetic stirring bar (about 30-40 mm long)
- usual laboratory glassware

Extraction

Introduce 10 ml of water/methanol mixture in a headspace vial by a volumetric pipette. Add the radiello cartridge and cap immediately. Stir and let equilibrate, place the vial in the headspace bath and let equilibrate for one hour at 45 °C.

Instrumental analysis

ECD detection (sevorane is not detected)

- vial pressurization gas: N₂ at 1.2 atm
- loop volume: 1 ml
- gas chromatographic column: polystyrene-divinylbenzene PLOT, 30m x 0.32mm, film 20μm (e.g. Supel-Q-PLOT, Supelco cat.no. 24242) (allows quantification of nitrous oxide and other anaesthetic gases in one chromatographic run)
- carrier gas: N₂ at 1.0 atm
- split ratio: 10/1
- make-up gas: Ar-CH₄ (CH₄ 10% v/v) at 30 ml·min⁻¹
- GC oven: 40° C for 2 min, 10° C·min⁻¹ up to 150° C, 6° C·min⁻¹ up to 200° C, final isotherm for 5 minutes
- injector temperature: 150° C
- detector temperature: 300° C

In the described analytical conditions chromatogram similar to the one in the figure are obtained. In the example shown, exposure time was 4 hours at the concentration values indicated and with relative humidity of 70%.

MS detection

The instrumental conditions are as described above, with the exception of the carrier gas (helium has to be used instead) and the make-up gas, which is not employed. Acquire by SIM (Single Ion Monitoring) focussing the detector on the following signals (the base peak is underlined):

N₂O: 44; forane and ethrane: 51, 67, 117; halothane: 117, 198, 179; sevorane: 33, 131, 181

If high concentrations of CO₂ interfere (it gives a strong signal at m/z 44), N₂O can be quantified basing on the signal at m/z 30. On page L4 a typical GC-MS chromatogram (as total ion current) is displayed. It can be observed that, as an effect of the vacuum applied on the detector end of the column, retention times are shorter with respect to those obtained with ECD detection.

Calibration

Calibration curves for N₂O and halogenated anaesthetics can be prepared simultaneously.

Draw pure N₂O in a gas sampling bulb. Transfer 20 ml of pure N₂O in the 1 liter bottle through the septum by a gastight syringe. Switch on the magnetic stirrer and let the mixture equilibrate for 30 minutes.
Standard solutions of the halogenated compounds must be prepared in water/methanol 60/40 v/v in order to contain from 0.05 to 3.0 mg/l of each compound; five calibration levels are recommended. For each level pipet 10 ml of calibration solution in an empty vial, add a blank code 132 cartridge and cap immediately.

Add also a precisely measured volume of diluted N₂O drawn from the bottle by a gastight syringe (usually added volume ranges from 50 to 1,000 μl), stir and let equilibrate at 45 °C for 1 hour.

The values above generally comprise the usual conditions of operating theatres. The analyst may choose different values if needed, but equivalent exposure values should not exceed 400,000 mg·m⁻³·min for nitrous oxide and 50,000 mg·m⁻³·min for each of the halogenated compounds.

Pay attention: the ECD response may not be linear. If this should be the case, use a second order calibration curve.

---

**Useful data**

<table>
<thead>
<tr>
<th>name</th>
<th>chemical formula</th>
<th>molecular weight</th>
<th>1 mg·m⁻³ at 25°C = ppm</th>
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<tbody>
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<td>N₂O</td>
<td>44</td>
<td>0.556</td>
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<tr>
<td>forane</td>
<td>CHF₂-O-CHCl-CF₃</td>
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<td>ethrane</td>
<td>CHF₂-O-CF₂-CHClF</td>
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<td>halothane</td>
<td>CF₃-CHBrCl</td>
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<td>sevorane</td>
<td>CH₂F-O-CH(CF₃)₂</td>
<td>200</td>
<td>0.123</td>
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</tbody>
</table>
phenol, methylphenol and dimethylphenol
(thermally desorbed)

Radiello components to be used
White diffusive body code 120
Supporting plate code 121
Vertical adapter code 122 (optional)
Adsorbing cartridge code 147

Principle
Code 147 cartridge is a stainless steel net cylinder with 100 mesh grid opening and 4.8 mm diameter, packed with 250 ± 10 mg of Tenax-TA, particle size 20-35 mesh. Phenols are trapped by adsorption and recovered by thermal desorption, analysis is performed by capillary gas chromatography and MS detection. The method has been optimized for the following compounds:

![Chemical structures](image)

Sampling rates
Sampling rate values $Q$ at 298 K (25 °C) and 1013 hPa are listed in the table on the right. All of the values shown have been experimentally measured.

**Effect of temperature, humidity and wind speed**
Sampling rate varies from the value at 298 K on the effect of temperature (in Kelvin) as expressed by the following equation:

$$Q_K = Q_{298} \left( \frac{K}{298} \right)^{1.5}$$

where $Q_K$ is the sampling rate at the temperature $K$ and $Q_{298}$ is the reference value at 298 K. Sampling rate is invariant with humidity in the range 15 - 90% and with wind speed between 0.1 and 10 m·s⁻¹.

<table>
<thead>
<tr>
<th>Compound</th>
<th>$Q_{298}$ ml·min⁻¹</th>
<th>limit of detection μg·m⁻³</th>
<th>uncertainty at 2σ %</th>
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<td>phenol</td>
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<td>m-cresol</td>
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<td>8.0</td>
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<tr>
<td>p-cresol</td>
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<td>2,5-dimethylphenol</td>
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<td>2,6-dimethylphenol</td>
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<tr>
<td>3,5-dimethylphenol</td>
<td>61</td>
<td>0.4</td>
<td>22.2</td>
</tr>
</tbody>
</table>

After 24 hours exposure and with MS detection; analytical conditions as described in the Analysis paragraph.
Calculations

The listed sampling rate values take already into account the recovery yields of adsorbed compounds. The average concentration over the sampling period is therefore calculated from sampled mass of analyte and exposure time without introducing any other corrective factor, apart from temperature variations of Q.

Average concentration \( C \) in \( \mu g \cdot m^{-3} \) over the whole exposure time is calculated according to the following expression:

\[
C \ [\mu g \cdot m^{-3}] = \frac{m \ [\mu g]}{Q \ [ml \cdot min^{-1}] \cdot t \ [min]} \times \frac{1,000,000}{1}
\]

where:
- \( m \) = mass of analyte in \( \mu g \)
- \( t \) = exposure time in minutes
- \( Q \) = sampling rate at temperature K

Exposure

Workplace environment

Exposure time can range from 2 to 8 hours.

Other indoor sampling experiments and outdoor campaigns

The recommended exposure times range from 8 hours to 7 days.

Storage

If cartridges are kept in a cool place without phenol and related compounds contamination, blank level and adsorbing capacity stay unaltered for at least 24 months.

After exposure the cartridges, well capped and kept in a cool and solvent-free place, maintain their content unaltered for at least three months.

Analysis

The analytical method hereafter described have been set up by the Perkin-Elmer Turbomatrix thermal desorber and Agilent 5973 MSD mass spectrometer detector. They may be implemented on other instruments by introducing minor adjustments as suggested by the analyst’s experience and characteristics of employed instrumentation.

Desorption

The thermal desorber is equipped with 1/4” OD SS sample tubes, they have to be hollow and free: discard the stainless steel gauze disk which is fitted to the groove and discard also the springs if present.

Code 147 cartridge has been dimensioned to fit the diameter of Turbomatrix thermal desorption tubes. Its length is such that, when the cartridge is introduced into the tube and is stopped by the groove, it is positioned exactly centrally with respect to the tube length.

Inner diameter of Perkin-Elmer tubes is not always exactly the same; it may be the case therefore that a cartridge code 147 does not slide easily into the tube. Some pushing tool may be helpful then, such as a 500 μl syringe piston, a glass bar or an iron wire 2-3 mm thick. In some cases the tube inner diameter is slightly larger than the cartridge outer diameter: the cartridge can therefore be pushed out from the tube during desorption due to the desorption gas pressure. If this is the case, just press slightly one end of the cartridge to make it oval.

Once capped, the Turbomatrix steel tube has to be positioned in the carousel with the grooves on the bottom.
Temperatures and timing

- Desorption: 280°C for 10 minutes
- Cryofocusing trap (Tenax TA): during primary desorption maintain at 2 °C, secondary desorption at 99 °C/sec up to 290 °C, maintain at 290 °C for 1 minute
- Six port valve: 150 °C
- Transfer line: 200 °C

Flows

- Carrier gas: helium, 24 psi
- Desorption flow: 100 ml·min⁻¹
- Inlet split: 80 ml·min⁻¹ (flow from tube to cryofocusing trap: 20 ml·min⁻¹)
- Outlet split: 25 ml·min⁻¹

Instrumental analysis

Column

100% dimethylpolysiloxane, length 50m x 0.2mm, film thickness 0.5 μm; (e.g. Petrocol DH 50.2, Supelco Code 24133-U) the column is directly fitted to the six-port valve of Turbomatrix apparatus

Temperatures

- GC oven: 50 °C for 2 minutes, 8 °C/min up to 160 °C, 12 °C/min up to 260 °C, final isotherm 2 minutes
- GC-MS interface: 260 °C

Flows

- helium carrier gas: 0.8 ml·min⁻¹

In the figure on the right a typical chromatogram (as total ion current) is shown.

Calibration

Calibration curves are obtained by gas-phase injections of methanol solutions of the analyzed compounds onto blank cartridges. Injections are performed through a GC injector, where a short piece of wide-bore (0.53 mm i.d.) deactivated uncoated column is installed. The other end bears a Swagelock reducing connection (1/16” to 1/4”). The 1/4” Swagelock nut has to be equipped with a PTFE ferrule instead of the original steel one (use PTFE ferrules that come along with the Turbomatrix caps).

Introduce a blank code 147 cartridge in a Turbomatrix tube and fit the tube to the Swagelock nut. Keep the injector at 200 °C but do not heat the oven. Slowly inject 1 μl of each calibration solution under nitrogen flow (50 ml·min⁻¹) and let the system purge for 2 minutes. Analyze the cartridge as you would do with a sample.

We suggest you to prepare a complete set of calibration solutions by subsequent dilutions such as they contain, for example, 4, 2, 1, 0.05 and 0.010 μg·μl⁻¹ of each compound.
Cartridge recovery

Recovery yield of phenol and related compounds is higher than 98%. Nevertheless, traces of analyzed compounds remain on the cartridge, but a thorough regeneration can be performed as follows.

Wash the cartridge with methanol (5 ml in a glass tube are enough) stirring from time to time. Let it dry in the air and finally condition it at 300 °C for two hours under nitrogen or helium flow.

Thermal stability of Tenax-TA is good enough to allow a great number of sampling, analysis and conditioning cycles, provided that conditioning temperature does not exceed 300 °C and nitrogen or helium employed do not contain more than 10 ppm of oxygen.

Analytical service for radiello diffusive sampler

Analytical services are also available to European users directly through the Fondazione Salvatore Maugeri. Users can send the sampled cartridges in for analysis and results. For more information on prices and conditions of this service, please contact directly

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e.mail fsmpd@fsm.it
web www.radiello.com
<table>
<thead>
<tr>
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<td>RAD121</td>
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m-xylene, B5, B6, D2, D5, E3, E4
o-xylene, B5, B6, D2, D5, E3, E4
p-xylene, B5, B6, D2, D5, E3, E4
xylenol (see dimethylphenol)