

Determination of the concentration of per- and polyfluoroalkyl compounds (PFAS) in a guided gas stream

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1 PURPOSE AND SCOPE

This procedure describes a method for the quantitative determination of per- and polyfluoroalkyl compounds (PFAS) in a guided gas stream. It includes the concentration determination in mass per unit gas volume (ng/Nm³) of polar (semi-)volatile and particle-bound PFAS (boiling point >100°C, >C4) via LC-MS/MS analysis of samples resulting from a sampling train (see schematic representation in Figure 1):

- Probe rinse and filter holder rinse
- Filter
- Condenser rinse
- XAD2 cartridges: 1 at the beginning (primary) and 1 at the end (secondary/breakthrough) of the sampling train
- Condensate from condensate flask
- Impinger water
- Impinger rinse

The procedure is aimed at the quantitative analysis of 28 PFAS compounds that were subject to a validation test based on 4 repeated measurements (+ field blank) with spiked sampling trains during an interlaboratory test (ILC) in February, 2024 (Hofman et al., 2025a). The sampling trains were equipped with media (filter/XAD2 cartridge/impinger water) spiked with native PFAS (50 cpds) at representative concentration levels. The associated measurement uncertainty (U, k=2) according to WAC/VI/A/002 and total train recovery for each of these compounds is shown in Table 1. For quantitative analysis, a U of <50% and total train recovery of 70- 120% are required for both the sampling (LUC/VI/003) and analysis (WAC/IV/A/025) are required. The LOQs were determined per analytical fraction as 10x the standard deviation based on 5 repeated measurements (n=5) at both low (0.05 ng/fraction) and higher (3 ng/fraction) spiked fractions. The resulting LOQs are provided in Table 1.

Most PFAS compounds only have a linear form. Several branched isomers (same molecular formula, different structural formula) can occur for a number of perfluorinated compounds (PFOA, PFHxS, PFOS, PFOSA, MePFOSA, EtPFOSA, MePFOSAA and EtPFOSAA). In this procedure, L-PFOA, L-PFHxS, L-PFOS, L-PFOSA, L-MePFOSA, L-EtPFOSA, L-MePFOSAA and L-EtPFOSAA refer to the linear form. The total concentration (sum of linear and branched compounds) is reported separately as respectively T-PFOA, T-PFHxS, T-PFOS, T-PFOSA, T-MePFOSA, T-EtPFOSA, T-MePFOSAA and T-EtPFOSAA.

Table 1 Measurement uncertainty (U), total spike recovery (%) and limit of quantification (LOQ) of the quantitative PFAS compounds as determined by a validation test. For 8 compounds a distinction is made between the linear form (L-) and the sum of linear and branched isomers (T-)

COMPOUND	CAS	REC (%)	U (k=2)	LOQ*		
				XAD2	Filter	OW
		%	%	ng	ng	ng
PFBA	375-22-4	120%	34%	ND	0.9	0.01
PFPeA	2706-90-3	100%	2%	3	0.8	0.01
PFHxA	307-24-4	98%	10%	1	1.3	0.01
PFHpA	375-85-9	93%	14%	0.9	0.9	0.01
L-PFOA	335-67-1	91%	19%	5	0.1	0.01
PFNA	375-95-1	92%	20%	0.8	0.01	0.01
PFDA	335-76-2	99%	15%	2	0.05	0.01
PFUnDA	2058-94-8	104%	28%	0.2	0.04	0.01
PFDoDA	307-55-1	107%	33%	0.5	0.04	0.01
PFTeDA	376-06-7	96%	50%	0.3	0.01	0.01
PFBS	375-73-5	96%	7%	0.4	0.8	
PFPeS	2706-91-4	91%	13%	0.03	0.03	0.01
L-PFHxS	355-46-4	92%	15%	0.05	0.05	0.01
PFHpS	375-92-8	86%	26%	0.07	0.04	0.01
L-PFOS	1763-23-1	101%	8%	3	0.8	0.01
PFNS	68259-12-1	90%	21%	0.08	0.04	0.01
PFDS	335-77-3	85%	28%	0.1	1.2	0.01
4:2FTS	757124-72-4	98%	3%	0.02	0.4	0.01
6:2FTS	27619-97-2	93%	11%	2.7	0.8	0.01
8:2FTS	39108-34-4	93%	22%	0.1	0.5	0.01
PFBSA	30334-69-1	100%	5%	6	1.8	0.01
MePFBSAA	159381-10-9	103%	5%	0.8	0.1	0.01
PFHxSA	41997-13-1	97%	14%	0.4	0.8	0.01
L-MePFOSAA	2355-31-9	94%	21%	0.05	0.01	0.01
L-EtPFOSAA	2991-50-6	97%	22%	0.05	0.7	0.01
HFPO-DA	13252-13-6	102%	8%	3.5		0.01
DONA	919005-14-4	89%	17%	0.1	0.02	0.01
PFECHS	646-83-3	88%	22%	0.1	0.04	

* The LOQs were determined per analytical fraction as 10x the standard deviation based on 5 repeated measurements (n=5) at both low (0.05 ng/fraction) and higher (3 ng/fraction) spiking levels.

The 14 compounds listed in Table 2 can be determined indicatively. During the ILC, these compounds showed a higher measurement uncertainty (>50%), deviating total train recoveries (<70% or >120%), or are listed as indicative in the WAC/IV/A/025 analysis procedure.

Table 2 Measurement uncertainty (U), total spike recovery (%) and limit of quantitation (LOQ) of the indicative PFAS components as determined by a validation test. For 8 components a distinction is made between the linear form (L-) and the sum of linear and branched isomers (T-).

COMPOUND	CAS	REC (%)	U (k=2)	LOQ		
				XAD2	Filter	OW
		%	%	ng	ng	ng
PFTTrDA	72629-94-8	109%	34%	0.1	0.01	
PFHxDA	67905-19-5	80%	59%	0.5	0.03	0.01
PFODA	16517-11-6	51%	117%	ND	0.7	
PFUnDS	749786-16-1	81%	34%	0.09	0.03	
PFDoDS	79780-39-5	79%	36%	0.03	0.7	
PFTTrDS	791563-89-8	72%	51%	0.02	0.02	
10:2FTS	120226-60-0	108%	29%	0.1	0.7	0.05
MePFBSA	68298-12-4	55%	140%	ND	1.4	0.01
L-PFOSA	754-91-6	56%	85%	0.08	0.8	0.01
L-MePFOSA	31506-32-8	1%	273%	0.2	1.4	0.01
L-EtPFOSA	4151-50-2	0%	289%	ND	0.7	0.01
6:2diPAP	57677-95-9	92%	47%	0.09	0.005	
6:2/8:2diPAP	943913-15-3	81%	63%	0.1	0.05	0.05
8:2diPAP	678-41-1	67%	72%	0.7	0.08	0.01

* The LOQs were determined per analytical fraction as 10x the standard deviation based on 5 repeated measurements (n=5) at both low (0.05 ng/fraction) and higher (3 ng/fraction) spiking levels.

2 PRINCIPLE & SETUP

For the measurement of PFAS (>C₄, boiling point >100°C) in emissions, a sampling train is used based on EPA's OTM-45 method (published 1/13/2021) and as shown in Figure 1. This OTM-45 method was published by EPA to promote consistency in the sampling and analysis of PFAS in conducted emissions and is considered best available technology. Gaseous and particulate PFAS (>C₄, boiling point >100 °C) are sampled isokinetically (same magnitude and direction of gas velocity) from the chimney using a heated probe. Particle-bound PFAS are collected on a heated glass wool or quartz filter (120 °C or at least 10 °C above chimney temperature), after which gaseous PFAS are captured via a primary adsorbent (XAD-2) cartridge, a condensation bottle, a series of impingers with absorption reagent (ultrapure water) and then a secondary adsorbent (XAD-2; breakthrough) cartridge.

2.1 OTM-45 SAMPLING TRAIN

The OTM-45 sampling train is shown in Figure 1 and consists of:

- a heated probe with quartz or glass wool filter
- a condenser

- a primary adsorbent (XAD-2) cartridge
- a condensate flask
- a series of 3 impingers filled with ultrapure water
- a secondary adsorbent (XAD-2) cartridge (breakthrough)
- a drying tower (silica or equivalent desiccant) with pump

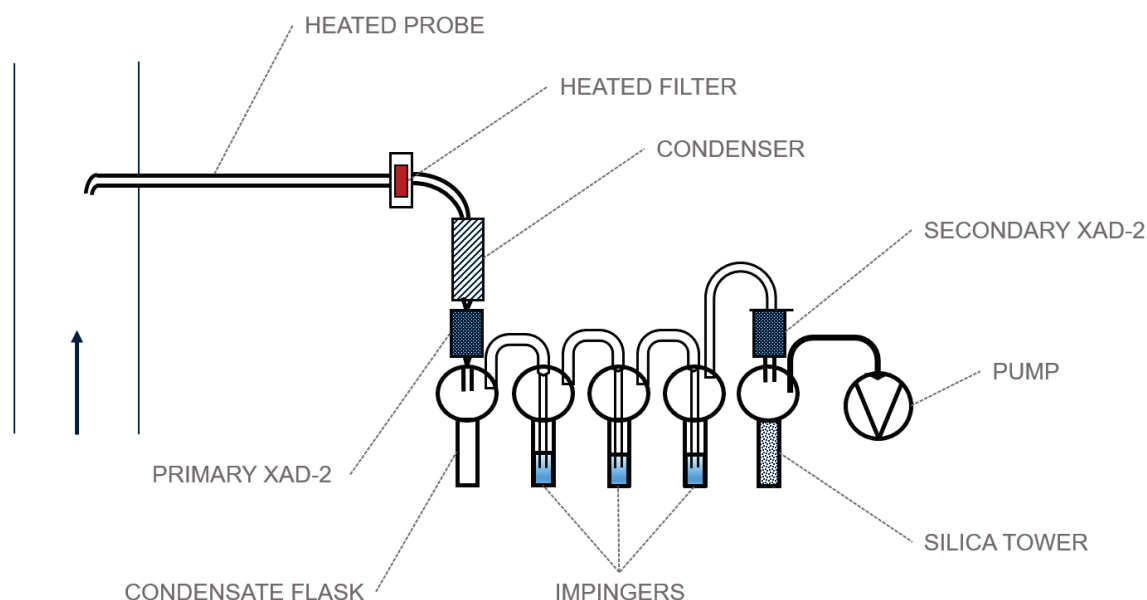


Figure 1 Schematic representation of OTM-45 sampling train

The sampling train consists of borosilicate or quartz glass (probe, filter holder, condenser, condenser bottle, impingers, etc.). Although Teflon (PTFE) should be avoided as much as possible (risk of contamination), it can be used in connection, O-rings and/or coatings. Polypropylene (PP) or polyethylene (PE, HDPE) products can be used to replace PTFE. Any contamination in the media or sampling train used can be determined in the respective medium and field blanks.

Further specifications for the different parts of the sampling train include:

- The quartz filter has an efficiency of at least 99.95% (<0.05% penetration) for 0.3 μm particles and is kept at a temperature of $120 \pm 12^\circ\text{C}$ during the chimney measurement to avoid condensation/moisture on the filter. This temperature must be measured in the filter housing.
- Tubing, condenser, and XAD2 cartridges should be oriented vertically in the sampling train to facilitate maximal flow and avoid moisture buildup inside the train compartments.
- Adsorbent cartridges consist of water-jacketed glass cartridges containing 20-40 g of solid adsorbent (XAD-2).
- The temperature of the incoming gas flow at the XAD-2 cartridges must be kept below 20°C . This (incoming) temperature is measured at the primary XAD-2 cartridge. An ice bath can be used to circulate pump-cooled water to the condenser and adsorbent cartridges. If the ambient temperature is $>20^\circ\text{C}$, the XAD-2 cartridges are required to be cooled.
- Impingers are of the standard type.
- The adsorbent (XAD-2) is stored and transported in glass cartridges or clean wide mouth HDPE jars.
- During sampling, the XAD-2 cartridges are wrapped with aluminum foil to protect the adsorbent from radiant heat and sunlight

- The impingers are filled with approximately 100 ml ultra pure water

Recovery of the samples takes place in existing cartridges (e.g. Table 2)

Since the condensate in the sampling train described above is sent through the primary XAD-2, the adsorbent cartridge can become very wet in stacks with a high moisture content. This could possibly have an effect on the capture efficiency of the adsorbent cartridge or the required underpressure in the sampling train. Two alternative sampling trains were therefore defined in which the condensate is collected in a condensate flask before the sampled gas flow is sent through the XAD2 cartridge, namely the OTM-45 variant (§8.2.1) and the cooled probe method (§8.2.2). The equivalence of these sampling variants was demonstrated for 3 PFAS compounds (PFBA, T-PFOA and PFHxA; C4-C8) by means of simultaneous stack measurement with multiple laboratories (interlaboratory test). The equivalence of these sampling trains will be further investigated for the entire WAC/IV/A/025 scope by means of a new interlaboratory test in 2024.

3 SAMPLING PROCEDURE

3.1 PREPARATION

All glassware must be uniquely marked in advance, so that traceability of contamination is possible. Depending on the (re)use of the glassware, there are 2 different cleaning procedures. The sampling probe liner and filter housing are replaced with each measurement and rinsed with methanol.

The following applies to new glassware:

- The glassware (except probe liner) is rinsed with warm water a maximum of 2 weeks before sampling, then rinsed with methanol and dried at 150°C. Pending sampling, the glassware is stored in a closed container.
- The glass probe liner is rinsed with methanol

The following applies to existing glassware that is reused:

- The glassware (except liner) is cleaned with warm water a maximum of 2 weeks before sampling and rinsed successively with methanol and cyclohexane.
- After cleaning with methanol and cyclohexane, the glassware is oven dried at at least 450°C for at least 3 hours. The glassware is now ready for sampling. Pending sampling, the glassware is stored in a closed container.
- Sampling probe liner and filter housing are replaced with each measurement and rinsed with methanol beforehand

The various parts of the sampling train are cleaned in advance with methanol so that they are free of PFAS.

- Adsorbent: The adsorbent (XAD-2) is extracted overnight (16 hours) with methanol by means of a soxhlet extraction before sampling. Afterwards, the XAD-2 cartridges are dried at 40°C in an oven and stored (wrapped in aluminum foil) in a sealed glass jar. The cleaning of the XAD-2 is carried out a maximum of 1 week before sampling. The cartridges are filled with 20-40 g of purified XAD-2, with a minimum aspect ratio of 2. Sampling standards (SS) are spiked inside the primary XAD-2 (13C3-PFBA, 13C8-PFOA, 13C8-PFOS; Hamilton syringe) and filter (13C2-PFUnDA, 13C2-PFDoDA). For the cooled probe sampling train variant, 13C2-PFUnDA and 13C2-PFDoDA are not spiked on the filter, but inside the condensate flask. Typically the XAD-2 pattern is doped with 30 µg of each standard. The XAD-2 is secured in the cartridge by means of purified glass wool.

- Glass wool: Glass wool is purified with methanol and dried at room temperature with N₂.

3.2 SAMPLING

The sampling procedure depends on the sampling train used (OTM-45 (§2.1), OTM-45 variant (§8.2.1) or cooled probe variant (§8.2.2)) and consists successively of:

- Set up a sampling train, perform a leak test and collect field blank samples (6, Appendix 1)
- Heating (or cooling) of probe and filter housing;
- Installation of the sampling probe in the gas duct;
- Register gas meter readings;
- Starting the pump and setting required isokinetic suction flow rates;
- Sampling of the exhaust gas duct for at least 3 hours (~2 Nm³);
- Perform a new leak test after sampling to ensure that no leaks were created during the measurement.

The necessary attention must be paid to prevent the contents of the impingers from being sucked back as a result of a negative pressure in the gas channel or as a result of pressure variations in the sampling line when starting the pumps.

- Check the flow rates regularly and adjust them if necessary. Register the pressure, temperature, flow rates and gas meter readings. If sampling is to be performed at different points (traverse), move the sampling probe from point to point without stopping the pump and set the sampling parameters depending on isokinetic sampling. When changing the measuring opening, the pump must be switched off.
- Then the pump is stopped. Register the gas meter readings again. Remove the sampling probe from the gas channel.
- Proceed to the recovery of the field samples (11; §3.5)
- Rinse the glassware again and recover the post-rinse blank samples (6; § 6.1.1)

3.3 CONTROLS

The following checks are carried out during a stack measurement:

- Check the gas velocities at the sampling points and calculate the sampling parameters to be set at each point (flow rate, sampling duration) if necessary;
- Check the sampling train for leak-tightness before each sampling (see also procedure essential quality requirements LUC/0/005);
- For each series of measurements and at least once a day, a blank must be taken from the equipment (field blank);
- Install the probe in the gas channel and condition the sampling system for at least 10 minutes so that the entire sampling train is at operating conditions and check the proper functioning of the probe;
- During the inspection measurement, check the temperature of:
- Filter: the temperature at the filter (filter housing or directly in the outgoing gas flow) is 120±12°C. Monitor the temperature of the filter during the chimney measurement;
- XAD-2 cartridges: the temperature of the XAD-2 cartridges must be lower than 20°C for efficient capture of the target components.
- Recover the field samples immediately after removing the probe from the chimney;

3.4 OTHER PARAMETERS TO BE REGISTERED

To convert the quantified mass (ng/analysis fraction) into normalized stack emissions (ng/Nm³), it is

necessary to measure additional stack parameters during the sampling period (LUC/0/005):

- Volume flow rate (m³) and temperature (°C) of the emitted gases, together with a continuous measurement of these parameters at a reference point if the flow rate is not constant.
- Water content (%)
- O₂ concentration (%)

3.5 COVERY AND AGGREGATION OF FIELD SAMPLES

Each emission measurement consists of 20 samples (Appendix 1), including medium blank samples (5), field (7) and field blank samples (6) and post-rinse blank samples (2). Treatment of the field samples (S11-17 in Appendix 1) is explained below:

Probe rinse + front half rinse (S12 in Appendix 1): After sampling (in the field), the front part of the filter holder and probe are rinsed 3 times with alkaline methanol (methanol/1% NH₄OH) and this rinsing liquid is supplied to the laboratory in an HDPE recipient (S11).

Filter (S14 in Appendix 1): The loaded filter is removed from the sampling train and delivered to the laboratory in an aluminum-packed petri dish.

Water fraction (S17 in Appendix 1): The condensate from the condensate flask and the water from the impingers are transferred as a mixed sample into a cleaned HDPE recipient and delivered to the laboratory.

MeOH rinse fraction (S15 in Appendix 1): The glassware from the rear part of the filterholder up to the impingers (filter holder, condenser, condensate flask, impingers and connectors) are rinsed 3 times with alkaline methanol (methanol/1% NH₄OH) and delivered to the laboratory in an HDPE recipient.

Cyclohexane rinse fraction (S13 in Appendix 1): The glassware from the probe up to and including the condensate flask (nozzle, probe liner, filter holder, condenser, condensate flask and connectors) are rinsed 3 times with cyclohexane and delivered to the laboratory in an HDPE recipient (S13).

XAD-2 (S16+S18 in Appendix 1): The XAD2 cartridges are recovered from the sampling train. The cartridges are closed at both sides using cut glass caps (or collected in an HDPE jar) and are supplied to the lab as separate samples (S16 and S18 in Appendix 1). As more data on breakthrough occurrence is collected, the analysis requirements of the XAD-2 cartridges as individual fractions may be relaxed.

If the cooled lance probe setup (§8.2.2) is applied, any deposition of particulate PFAS in the condensate will be taken into account by carrying out an additional filtration of the water, after which the residue is added to the filter sample (S14*) and the filtrate is added to the water fraction (S17).

All collected field samples are stored and transported in the dark (shielded from UV light) and on ice (~4°C). To avoid contamination of the media and field samples, special attention should be paid to hygiene during transport, field handling, sampling, recovery and laboratory analysis, as well as during the preparation of the XAD-2 cartridges.

Each sampling results in **20 samples** (Appendix 1) that are aggregated into 6 analytical fractions that are further processed and analyzed (Table 3).

Table 3 Aggregation of field samples into analytical fractions (F1-F6) with the 3 variant setups (OTM-45, OTM-45 variant and cooled probe). The references of the field samples refer to the described treatment of the field samples above (§3.5).

FRACTIE	OTM-45	OTM-45 variant	Gekoelde lans
F1	Filter (S14) + probe rinse (S12)	Filter (S14) + probe rinse (S12)	Filter (S14) + Residu filtration (S14*)
F2	Rinse condenser up to and including impingers (S15)	Rinse condenser up to and including impingers (S15)	Rinse condenser up to and including impingers (S15)
F3	Primary XAD-2 (S16)	Primary XAD-2 (S16)	Primary XAD-2 (S16)
F4	Condensate + water impingers (S17)	Condensate + water impingers (S17)	Condensate + water impingers (S17)
F5	Secondary XAD-2 (S18)	Secondary XAD-2 (S18)	Secondary XAD-2 (S18)
F6	Cyclohexane rinse probe up to condenser (S13)	Cyclohexane rinse probe up to condenser (S13)	Cyclohexane rinse probe up to condenser (S13)

3.6 TRANSPORT AND STORAGE

All field samples are transported on ice (4°C) and in the dark (shielded from UV light). In the laboratory, the analytical fractions (F1-F6) are stored in the dark and cooled (<6°C) and extracted within 28 days after sampling. The extracts can then be refrigerated (<4°C) and stored in the dark for up to 1 year.

Remarks:

- Contact with Teflon or other fluorine-containing polymers should be avoided.
- The concentration of >C10 PFAS in water samples can decrease with increasing storage time due to sorption to recipient walls or deposition (WAC/IV/A/025).

4 ANALYSIS PROCEDURE

The quantitative analysis of the analysis fractions is done in accordance with WAC/IV/A/025. The content of the various PFAS is calculated using the internal standard method. The per- and polyfluoroalkyl compounds and internal standards are identified based on the retention times and ion ratio criteria stated in WAC/VI/A/003.

If a high level of PFAS is expected, the samples can be pre-screened, e.g. through a non-target analysis. To this end, a small part (max 2%) of the XAD-2 cartridge and/or of the condensate is taken for analysis.

4.1 MATERIALS AND REAGENTS

For the material, reagents, standards and solutions used, refer to WAC/IV/A/025

4.2 EXTRACTION FILTER (FRACTION F1)

- Transfer the filter to a (PP) tube.
- Add an appropriate amount of the standard solution of internal standards (IS) so that the theoretical concentration of the IS in the measurement extract is equal to that in the calibration standards.
Add 10mL of the probe and front half rinse, making sure the filter is completely submerged. Add additional alkaline methanol (MeOH/1% NH₄OH) if necessary. Evaporate the remaining rinsing liquid to a few mL.
- Vortex
- Sonicate for 1 hour
- Decant the liquid into another (PP) tube.
- Evaporate the extract to approximately 2 ml
- Centrifuge and transfer MeOH fraction to a new PP tube without taking over the filter residue
- Wash the filter residue with MeOH, vortex, centrifuge and transfer MeOH to the same PP tube
- This washing step is repeated again
- Add the remaining rinsing liquid that was evaporated (a few mL).
- Evaporate extract to 500 µL (MeOH fraction)
- Vortex regularly to prevent the compounds from depositing on the wall of the test tube
- Add 500 µl MeOH and vortex well
- Transfer to a measuring vial

Typically 10 µl of the extract is injected into the LC-MS.

The storage time of extracts is 1 month when stored in the refrigerator. Extracts that have been in the refrigerator are vortexed before injection.

4.3 EXTRACTION MEOH RINSE (FRACTION 2)

- If desired, the extract can be divided into 2 subfractions and one subfraction can be saved for reanalysis.
- Add an appropriate amount of the standard solution of internal standards so that the theoretical concentration of the internal standards in the measurement extract is equal to that in the calibration standards.
- Evaporate to approximately 2 mL
- The sample is transferred to a 15 ml PP tube and the recipient is rinsed 4 times with MeOH
- Further evaporation to 500 µL
- Vortex regularly to prevent the compounds from depositing on the wall of the test tube
- Add 500 µl MeOH and vortex well

Typically 10 µl of the extract is injected into the LC-MS.

The storage time of extracts is 1 month when stored in the refrigerator. Extracts that have been in the refrigerator are vortexed before injection.

4.4 EXTRACTION OF THE XAD2 CARTRIDGES (FRACTION F3 AND F5)

- Before extraction, any water present in the XAD2 cartridge is purged for 2 minutes under a N₂ flow. The drops of water from the cartridge are added to the water fraction (F4). Register the amount of purged water by pre- and post-weighing the XAD-2 cartridge. The secondary XAD2 cartridge and blank XAD2's do not contain water and can be extracted as such.

- Add an appropriate amount of the standard solution of internal standards within the XAD2 so that the theoretical concentration of the internal standards in the measurement extract is equal to that in the calibration standards.
- Add 75 mL of MeOH/1% NH₄OH to the XAD-2 cartridge. The adsorbent must be completely immersed.
- Close the cartridge on both sides with glass caps.
- Sonicate for 1 hour (in recipient filled with water up to the MeOH level)
- The glass caps are replaced by couplings and the extraction liquid is pushed out of the cartridge by means of a N₂ flow for 2 minutes and collected in a 500 mL recipient.
- Rinse XAD2 with approximately 30mL MeOH, flush with N₂ for 2 minutes and add to the rinsing liquid to the same recipient
- Rinse cartridge caps with a few ml of MeOH
- Evaporate the MeOH fraction to approximately 2 mL
- Transfer extract to 15 ml PP tube and rinse the recipient 4 times with MeOH
- Further evaporation to 500 µL
- Vortex regularly to prevent the compounds from depositing on the wall of the test tubeThe cartridge is rinsed with 20 mL of methanol and combined with the 75 mL.
- Add 500 µl MeOH and vortex well
- Transfer to a measuring vial.

Typically 10 µl of the extract is injected into the LC-MS.

The storage time of extracts is 1 month when stored in the refrigerator. Extracts that have been in the refrigerator are vortexed before injection.

4.5 EXTRACTION WATER FRACTION (FRACTION 4)

- Determine the total weight of the water fraction from the XAD-2 cartridge, the condensate and the impinger water.
- The sample bottles are first emptied and then rinsed with sufficient methanol (< 10% methanol), after which the water and methanol are combined before taking a subsample. In this case, the laboratory states on the report that the analysis was carried out on a sub- sample.
- Take a subsample, e.g. 25 mL of the water fraction from the XAD-2 cartridge and condensate and 25 mL of the impinger fraction and combine them (2*25 mL).
- The remainder of the water fractions (XAD-2 water, condensate and impinger water) can be saved for reanalysis.
- Add an appropriate amount of the standard solution of internal standards so that the theoretical concentration of the IS in the measurement extract is equal to that in the calibration standards.
- Vortex the mixture vigorously.
- An SPE-WAX cartridge is used for the extraction. The procedure includes the following steps:
 - o Condition the SPE cartridge with 4 ml MeOH/0.1% NH₄OH solution;
 - o Condition the SPE cartridge with 4 ml of methanol;
 - o Rinse the SPE cartridge with 4 ml of ultrapure water; be careful not to let the cartridge dry;
 - o Transfer the subsample (50 mL) over the SPE cartridge;
 - o Centrifuge the SPE cartridges so that they are dry (20 min, 2000+ rpm)
 - o Rinse the sample recipient with 5 ml methanol and use it to elute the SPE cartridge; capture this fraction;
 - o Rinse the sample recipient with 5 ml MeOH/0.1% NH₄OH solution and use it to elute the SPE cartridge; combine this fraction with the previous one;

- SPE extract is evaporated to 500 µL
- Vortex regularly to prevent the compounds from depositing on the wall of the test tube
- Add 500 µl MeOH and vortex
- Transfer to a measuring vial

Typically 10 µl of the extract is injected into the LC-MS.

The storage time of extracts is 1 month when stored in the refrigerator. Extracts that have been in the refrigerator are vortexed before injection.

4.6 EXTRACTION OF CYCLOHEXANE RINSE (FRACTION 6)

- If desired, the mixture can be divided into 2 subfractions and one subfraction can be saved for reanalysis.
- Add an appropriate amount of the standard solution of internal standards so that the theoretical concentration of the internal standards in the measurement extract is equal to that in the calibration standards.
- Evaporate to approximately 2 ml
- The samples are transferred to 15 ml PP tubes and the recipient is rinsed 4 times with MeOH
- Further evaporate to a few drops
- Vortex regularly to prevent the components from depositing on the wall of the test tube
- Add MeOH until 1 mL
- Transfer to a measuring vial.

Typically 10 µl of the extract is injected into the LC-MS.

The storage time of extracts is 1 month when stored in the refrigerator. Extracts that have been in the refrigerator are vortexed before injection.

4.7 LC-MS/MS MEASUREMENT

The LC-MS/MS measurement is carried out in accordance with WAC/IV/A/025.

5 REPORTING

The analysis report consists of the measured mass concentrations per analytical fraction (ng/fraction) for the field sample and field blank (<10%) and the resulting relative breakthrough (<30%). The emission concentration (C_{emission}) of each compound (summed over the different analysis fractions) is then calculated in ng/Nm³. This is calculated from the sum concentration of the samples (analyzed fractions), normalized by the amount of sampled air (Nm³) and the prevailing O₂ concentration in the chimney. When calculating the sum of the mass fractions (ng), the lower bound method ("lower bound": <LOQ = 0) must be applied in accordance with WAC/IV/A/025. The lower bound method is applied to each individual analysis fraction.

The sampled flow (V_{samp}) is calculated from the monitoring data of the gas counter, temperature and pressure meter according to:

$$V_{\text{samp}} = \frac{(V_{\text{end}} - V_{\text{start}}) * 273,15 * P_{\text{gas}}}{(273,15 + T_{\text{gas}}) * 1013,25}$$

with V_{samp} the sampled volume (Nm^3dr), V_{start} and V_{end} , respectively, the start and end volume as monitored by the gas counter (m^3), P_{baro} the absolute pressure (mbar) at the gas counter and T_{gas} the temperature at the gas counter ($^{\circ}\text{C}$). Furthermore, 273.15 is the reference temperature (Kelvin) and 1013.25 is the reference pressure (mbar).

The quantified fraction masses (ng/fraction) are then summed over the different analysis fractions according to the lower bound method ($<\text{LOQ} = 0$) and finally normalized for the sampled flow rate (V_{samp} in Nm^3) and the oxygen level (O_2 in %) to obtain the emission concentration (C_{emission} in ng/Nm^3) to obtain:

$$C_{\text{emission}} = \frac{C_{\text{mon}}}{V_{\text{samp}}} * \left[\frac{(21 - \text{O}_{2\text{ REF}})}{(21 - \text{O}_{2\text{ stack}})} \right]$$

with C_{emission} the normalized emission concentration ($\text{ng}/\text{Nm}^3 \text{ dr}$), C_{mon} the summed fraction masses (ng) following the lower bound method ($<\text{LOQ} = 0$), $\text{O}_{2\text{ REF}}$ the reference oxygen content (11%) and $\text{O}_{2\text{ stack}}$ the oxygen content in the stack (%).

6 QUALITY CONTROL

6.1 QUALITY CONTROL SAMPLING

6.1.1 SAMPLING BLANKS

Due to the contamination risk, strict quality control procedures are provided in this LUC method. This follows the OTM-45 quality procedure, but relaxes the blank use depending on the glassware use. Three types of sampling blanks are considered:

- **Medium blank (S1-S5 in Appendix 1):** A blank filter, rinsing fluid (alkaline methanol and cyclohexane), blank XAD2 and ultrapure water (5 samples) are supplied to the laboratory in HDPE containers. Nothing has been done in the field with this blank, just a transfer to the sampling container in the lab. The purpose of the media blank is to determine whether spent media or other interferences are introduced into the sample through transportation, storage, and the field environment.
- **Field blank (S6-S11 in Appendix 1):** The entire sampling train is assembled, the filter house is heated, a leak test conducted and, subsequently, rinsed with alkaline methanol just before sampling. Recovery and aggregation of the field samples follows the same procedure as described in §3.5, with the exception of the secondary XAD2 cartridge. The resulting analytical fractions (6) are delivered to the laboratory in an HDPE container:

- S6: Probe rinse and front half rinse
- S7: Glass wool or quartz fibre filter
- S8: XAD-2 (primary only)
- S9: Impinger water
- S10: MeOH rinse filter back up to condensate flask
- S11: Cyclohexane rinse probe up to condensate flask

The measured field blank concentrations in each fraction are also reported for interpretation of the analysis results.

- **Post-rinse blank (S19-S20 in Appendix 1):** After collecting the field samples (S12-S18), the glassware is rinsed again 3 times with alkaline methanol (S19) and 3 times with cyclohexane (S20). The purpose of the rinse blank is to check whether all PFAS have been adequately captured in the field samples.

The different sampling blanks are collected during each campaign (maximum 3 consecutive measuring days at the same measuring location/company*) or measurement, depending on the glassware use (schedule):

- If the same glassware is used for each measurement, only 1 field blank needs to be collected per campaign, and a post-rinse blank for each measurement.
- If new glassware is used for each measurement, a field blank is required for each measurement and a post-rinse blank per measurement campaign.

To avoid unnecessary lab analysis of medium blanks (4 samples), LC-MS/MS analysis is only required when field blank results exceed 10% of the field sample. When a new stack is sampled at the same location/site, the use of new glassware is required.



*Campagne = max. 3 opeenvolgende meetdagen op eenzelfde meetlocatie

**Nieuwe Schoorsteen = nieuw glaswerk

6.1.2 SAMPLING STANDARDS (SS)

For each stack measurement, isotope-labeled sampling standards (SS) are added to the primary XAD2 ($^{13}\text{C8}$ -PFOA, $^{13}\text{C8}$ -PFOS, $^{13}\text{C3}$ -PFBA) and filter ($^{13}\text{C2}$ -PFUnDA, $^{13}\text{C2}$ -PFDoDA) to control for the entire sampling and analysis process. In this LUC method, sampling standards for C4 ($^{13}\text{C3}$ -PFBA), C8 ($^{13}\text{C8}$ -PFOA and $^{13}\text{C8}$ -PFOS) and $>10\text{C}$ ($^{13}\text{C2}$ -PFUnDA, $^{13}\text{C2}$ -PFDoDA) compounds are considered. The recoveries of these standards, after correction for the recovery of the internal standards (IS), must demonstrate per stack measurement that recovery of the labeled standards meets the required range of 70-130%. Between 50-70% recoveries are still acceptable, but recoveries must be flagged and reported. Below 50% standard recovery, the reason must be investigated and a new measurement might be required.

The percentage recovery (%) should be evaluated on the entire sampling train (sum of analysis fraction recoveries), as migration of the recovery standards throughout the train compartments cannot be excluded.

6.1.3 RELATIVE BREAKTHROUGH

The relative breakthrough (RD; %) of PFAS through the sampling train is evaluated per compound based on the mass ratio between the secondary (breakthrough) XAD2 cartridge (F5) and the sum of all fractions (F1-F6) in the sampling train via the following formula:

$$RD(\%) = \frac{F5_{mass}}{(F1_{mass} + F2_{mass} + F3_{mass} + F4_{mass} + F5_{mass} + F6_{mass})} \times 100\%$$

If the relative breakthrough is lower than 30%, the quantified mass for each PFAS compound from fraction F5 (secondary XAD-2 cartridge) is added to the other fractions to calculate the total PFAS emission concentrations. If the relative breakthrough is greater than 30%, the reason must be investigated and, if necessary, a new measurement might be required.

7 MATERIAL

7.1 SAMPLING

- Heated probe + filter housing
- Filter
- Uniquely engraved glassware + couplings (possibly with glass ball couplings):
- Condenser
- Condensation flask (1)
- Impingers (3)
- XAD2 cartridges (2), spiked with sampling standards (SS)
- Teflon lines (if necessary)
- Drying column with silica
- Pump
- Cooling bath with pump
- Aluminium foil
- Refrigerator box with ice (storage of field samples)
- Solvents: alkaline methanol (methanol/1% NH_4OH) and cyclohexane

- Sufficient HDPE containers (28)

8 ADDITIONS OR DEVIATIONS FROM OTM-45

Based on the acquired practical experience of the reference laboratory with PFAS stack measurements, comparative measurements and bilateral communication with the Environmental Protection Agency (EPA) and Flemish commercial laboratories, a list of allowed deviations from the OTM-45 method (§9.1) and 2 alternative sampling trains (§9.2) are defined (Hofman et al., 2025b).

8.1 DEVIATIONS

An overview of the allowed deviations of this method compared to the OTM-45 procedure, with associated arguments, is shown in Table 4.

Table 4 Overview of additions or deviations from the OTM-45 method

OTM-45	LUC
SAMPLING	
Heated sampling line between filter holder and condenser	No need for heated line between filter holder and condenser
Condensate guided through primary XAD2 cartridge	Sampling train variants (cooled probe, OTM-45 variant)
Analytical fractions (4): • filter + front half rinse • back half rinse + primary XAD2 • condensate + rinse condensate flask + impinger water + impinger rinse • secondary XAD-2	analytical fractions (6): • filter + front half rinse • primary XAD2 • backl half rinse + condensate flask rinse • condensate + impinger water + impinger rinse • secondary XAD-2 • cyclohexane rinse
medium blanks collected in every measurement campaign and field nad post-rinse blanks collected for every measurement	Based on the observed blank concentrations, relaxation of blank collection frequency depening on the glassware use.
Cooled XAD-2 cartridges	XAD2 cartridges are only cooled when temperature requirements (<20°C) cannot be fulfilled.
The OTM-45 method foresees A condensate flask and 3 additional impingers	minimum 1 condensate flask and 2 additional impingers in the sampling train
Concentration of ammonia in methanol is 5%	Concentration of ammonia in methanol can be lowered from 5% to 1%
Filter quality control (3 filters/batch) including extraction/prep. (§7.1.1.1)	Filter QC included in medium blank
Adsorbent (XAD2) QC including sample extraction/prep (§7.1.3)	Adsorbent QC included in medium blank
Minimum sampling volume of 3 Nm³ dr (§8.1.2.1)	Sometimes hard due to underpressure train: minimum 3h of monitoring (~2 Nm³ dr)
Record color (condition) of silicate towers in field report (§8.2.10)	Not required
Rinse blank (Sample Train Field Blank STFB) again consists of a complete used sampling train with new media.	Post-rinse blank consists of a single rinse to check the sampling train
Temperature of the filter (120°C) is measured in the gas flow	Temperature can also be monitored in filter housing
The 1st, 3rd and 4th impinger are of the Greenburg-Smith type with a modified (longer) tip. Only the 2nd impinger is of the Greenburg-Smith type.	Alle impingers are of the standard type
Recovery of filter in glass petri dish closed with HDPE tape or resealable PE bag.	Filter is recovered in a petridish wrapped in aluminum foil

Before use, rinse aluminum foil three times with 5% ammonium hydroxide in methanol and store in a cleaned Petri dish or gauze jar.	After initial laboratory testing, this procedure is no longer used.
Recovery XAD2 in original container, HDPE container with PP or PE lid or in glass container closed with glass lids.	Recovery XAD2 in glass container or HDPE jar
Clean glass wool by immersing it 3 times in 5% ammonium hydroxide in methanol, drying in the oven at 110°C and storing in 5% ammonium hydroxide in methanol rinsed glass jar with PE or PP liner lid.	Glass wool is rinsed with methanol and dried with N2 at room temperature
Ammonium hydroxide, 5% in methanol rinse	After initial laboratory testing, the ammonia percentage can be reduced to 1%
Glassware washing procedure: Hot water + soap - tap water - deionized water - acetone, dichloromethane, methanol - drying at 300°	New glassware: Glassware is rinsed with warm water and methanol and fired for at least 3 hours at +/- 150°C Glassware used: Successively 1 hour sonication with methanol, 1 hour sonication with cyclohexane (fully immersed) and at least 3 hours firing at 450°C.
Seal glassware with glass lids or cleaned aluminum foil	Glassware is stored in a closed container
Rinse glassware again with 5% ammonium hydroxide in methanol before use	Only rinsed with methanol
Filter temperature is maintained at 120°C or 10°C above chimney temperature to prevent condensation on the filter.	Filter housing is kept at 120± 12 °C
Use a brush while rinsing the probe to collect any deposited material.	Only rinsing is applied (No contamination of rinse blanks observed)
SAMPLE PREP/ANALYSIS	
7 sampled samples are aggregated into 4 analytical fractions.	7 sampled samples are aggregated into 5 analytical fractions.
Recovery standards for C8 PFOA and PFOS (13C8-PFOA, 13C8-PFOS)	In addition to standard recoveries for C8 PFOA and PFOS (13C8-PFOA, 13C8-PFOS), also a spike from a C4 component (13C3-PFBA)
18u shaking before extraction.	Following initial lab tests: 1h of sonication can be applied as alternative (+4x shaking)
dilution with water (or methanol) during evaporation	Dilute with methanol during evaporation
Analysis of PFAS compounds (50) described in OTM-45	Analysis of the PFAS components performed via LC-MS/MS analysis in accordance with WAC/IV/A/025. This methodology was validated for 50 components.
QC/ REPORTING	
If the relative breakthrough is greater than 10%, the fraction of the 2nd XAD-2 is added to the sum of the other fractions and reported.	The 2nd XAD2 cartridge concentration is always added to other fractions. Only if >30% should the reason be investigated and a re-measurement may be necessary if necessary.

8.2 SAMPLE TRAIN VARIANTS

8.2.1. OTM-45 VARIANT SAMPLE TRAIN

This sampling train includes the same measurement principle, compounds and sample preparation as the OTM-45 method (§2.1) but collects the condensate in a condensate flask before the gas flow is passed over the primary XAD2 cartridge (see the diagram below in Figure 2). After the primary XAD2 pattern, 3 impingers and a secondary XAD-2 pattern (breakthrough) are connected. The OTM- 45 variant lineup includes:

- a heated probe with quartz filter
- a condenser
- an empty condensation bottle to collect the condensate
- a primary XAD2 pattern (beginning)
- a series of 3 impingers filled with ultrapure water
- a secondary XAD2 pattern (end)
- a drying tower (silica or equivalent desiccant) with pump

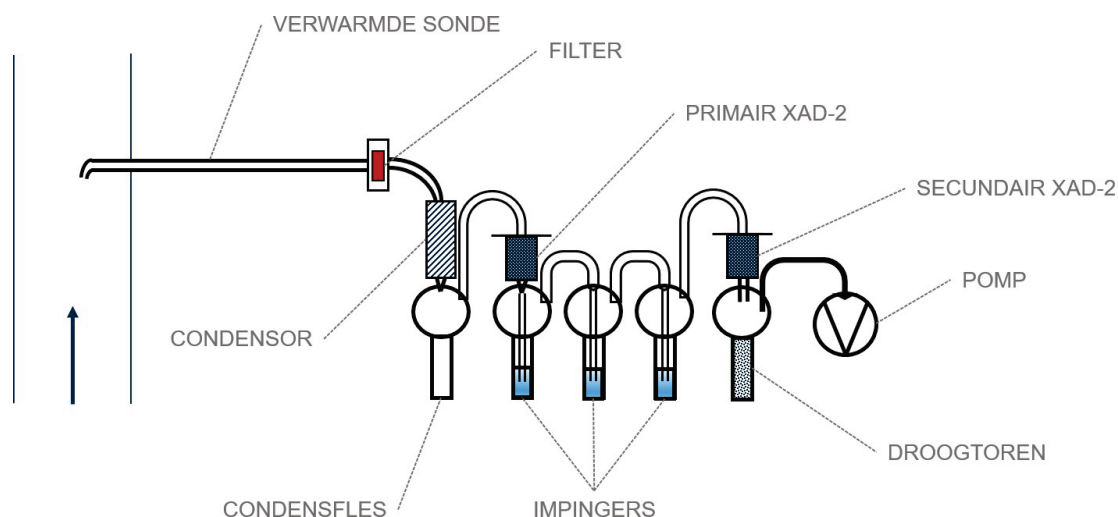


Figure 2 Schematic of the OTM-45 variant setup

The sampling train mainly consists of borosilicate or quartz glass (probe, impingers, filter holder) and although Teflon (PTFE) should be avoided as much as possible (risk of contamination), it can possibly be used in connections, O-rings and/or coatings. Recovery of the samples takes place in existing cartridges (e.g. XAD2 cartridges), polypropylene (PP) or polyethylene (HDPE) bottles and results in 7 different samples (§3.5).

8.2.2. COOLED PROBE SAMPLING TRAIN

This sampling train provides isokinetic sampling by means of a cooled probe, followed by 2 condensate flasks (see the diagram below in Figure 3). The resulting dry gases then pass through a glass wool filter, a primary XAD2 cartridge, 2 impingers and a secondary XAD-2 cartridge. Any deposition of PFAS particles in the condensate is taken into account by an additional filtration. The residue is added to the filter fraction and the filtrate to the condensate fraction. The cooled probe setup includes:

- a cooled probe
- 2 condensation flasks
- 2 impingers filled with ultrapure water
- a glass wool filter
- a primary XAD2 cartridge
- a secondary XAD2 cartridge
- a drying tower (silica or equivalent desiccant) with pump

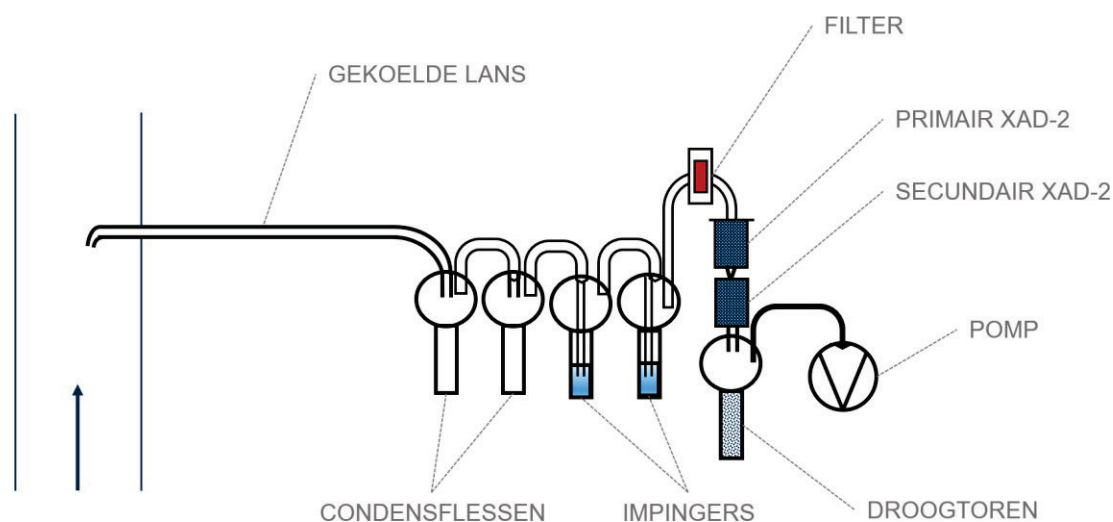


Figure 3 Schematic of cooled probe sampling train

The sampling train mainly consists of borosilicate or quartz glass (probe, impingers, filter holder) and although Teflon (PTFE) should be avoided as much as possible (risk of contamination), it can possibly be used in connections, O-rings and/or coatings. Recovery of the samples takes place in existing cartridges (e.g. XAD2 cartridges), polypropylene (PP) or polyethylene (HDPE) bottles and results in 7 different samples (§3.5).

9 REFERENCES

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10 APPENDIX

Appendix 1: Different samples originating from a PFAS emission measurement campaign, including medium blank, field blank and post-rinse blank.

S1	MEDIUM BLANK	Blank filter
S2		Blank rinse MeOH
S3		Blank rinse Cyclohexane
S4		Blank XAD2
S5		Blank water
S6	FIELD BLANK	Rinse nozzle + probe + filter front (MeOH) – Field blank
S7		Filter- Field blank
S8		XAD2-1+spike- Field blank
S9		Impinger water - Field blank
S10		Rinse filter back + condenser + condensate flask + impinger rinse (MeOH) - Field blank
S11		Rinse nozzle + sonde + filter holder + condenser + condensfles (Cyclohex)- Field blank
S12	FIELD SAMPLE	Rinse nozzle + probe + filter front (MeOH)
S13		Rinse nozzle + probe + condenser + condensate flask (Cyclohex)
S14		Filter
S15		Rinse filter back + condenser + condensate flask + impingers (MeOH)
S16		Primary XAD2 (SS spike)
S17		Condensate + Impinger 1-2-3 Water
S18		Secondary XAD2
S19	POST-RINSE BLANK	Post-rinse nozzle + probe + filter holder + condenser + condensate flask + impingers (MeOH)
S20		Post-rinse nozzle + probe + filter holder + condenser + condensate flask (CycloHex)

Appendix 2: Applied sampling standards (SS)

		COMPONENT	
SS	SS1	Perfluoro-n-(13C8)octanoic acid (M8PFOA)	¹³ C ₈ -PFOA
	SS2	Sodium perfluoro-1-[13C8]octanesulfonate (M8PFOS)	¹³ C ₈ -PFOS
	SS3	Perfluoro-n-(2.3.4-13C3) butanoic acid (M3PFBA)	¹³ C ₃ -PFBA
	SS4	Perfluoro-n-[1,2-13C2]-undecanoic acid (M2PFUDa)	¹³ C ₂ -PFUnDA
	SS5	Perfluoro-n-[1,2-13C2]-dodecanoic acid (M2PFDoA)	¹³ C ₂ -PFDoDA

Note:
 Variants of some isotopically labeled compounds are also available (e.g., 13C4-PFBA, 13C4-PFOA, 13C8-PFOS, 13C9-PFUnDA, 13C12-PFDoDA, etc.). These variants may also be used instead of the compounds listed above, as long as the sampling standards differ from the internal standards used (WAC/IV/A/025).