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Transforming the electricity network

PCB Sniffer

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Western Power Distribution 2021

Contents

1. Executive Summary

The project was funded through the NIA (Network Innovation Allowance) with a budget of £110,000 with a timescale of eleven months starting September 2019, the project was proposed by the ENA (Electricity Networks Association) PCB (Polychlorinated Biphenyl) working group. The project partners were Willow Innovation, RAL Space (Rutherford Appleton Laboratory) and NPL (National Physical Laboratory).

The literature review carried out within this project found that there is currently no safe method of extracting oil from a transformer at height whilst the asset remained operational, however a system could be developed to analyse the transformer headspace for PCB vapour. This project analysed the headspace of a known contaminated asset and the conclusion was that not all PCB molecules could be present within the vapour.

PCB molecules are made up of 209 different compositions (which are called congeners), and these are determined by how many chlorine substituents make up that molecule, these substituents range from one chlorine substituent to a maximum of ten per biphenyl. The lower end (between one to three chlorine substituents) more likely to be present in oil vapour as they are more volatile than the higher end. Each chemical composition from one chlorine to ten chlorines are called a homologues, a homologue is a group of PCB molecules with a slightly different spectrum but have identical number of chlorines, each group has a range of congeners, and these congeners are labelled PCB-01 to PCB-209.

For a PCB congener to be present in oil vapour, it first needs to rise to the surface of the oil and then transfer into the headspace as vapour, congener PCB-209 which has ten chlorine substituents is far less volatile and therefore highly unlikely to be present in vapour at normal operating conditions, to vaporise this congener, the assets would have to be heated considerably outside their safe operating temperatures well above 60°C.

As a result of cross contamination of DNO (Distribution Network Operator) assets by transformer manufactures, there is no way of knowing which PCB congeners were used and therefore present within our assets, as we cannot detect the full range of PCB congeners the testing of the headspace is therefore not an accurate form of testing due to the chances of undetectable PCB congeners. The only way to definitively quantify the amount of PCB within a transformer is to extract a physical oil sample for which there is currently no safe method of extraction whilst the asset is in situ at the top of a pole and live.

Mass spectroscopic analysis did prove to be a useful form of testing for PCBs, the limitation is that we need existing data on all 209 PCB congeners, this could be achieved through analysing each individual congener and recording all IR (Infrared) fingerprints but this data set does not currently exist and would take a significant amount of time, effort and resources to do so, this method of analysing would still require a physical oil sample for accurate results.

2. Project Background

Existing Practices

To date there is no method of testing pole mounted transformers without interrupting customers supplies to safely extract a sample of oil, this method is extremely time consuming, costly and disruptive. With our assets estimated to be around 94,000 which are potentially contaminated, this process could take many years to complete, with a deadline to remove contaminated assets by 2025 we have to find an innovative solution to detect PCBs in OH (Overhead) assets which is safe, quick, and cost efficient.

Proposed changes to European Regulations on Polychlorinated Biphenyls (PCBs) have the potential to require all UK DNOs to test or replace all of their pre-1987, potentially contaminated, oil filled assets (the vast majority of which are transformers) by 2025. These assets were accidentally contaminated with PCBs before the Stockholm Convention banned them in 1987 (The 'Stockholm Convention' is an international environmental treaty that aims to eliminate or restrict the production and use of persistent organic pollutants). This would be in excess of 300,000 pole mounted and ground mounted items across the UK, of which around 94,000 are owned by us. While the ground mounted items could be tested in situ without considerable cost and inconvenience, the vast majority of the 300,000 items are pole mounted and essentially inaccessible.

Most UK DNOs use simple "Clor-N-Oil" test kits to sample a small quantity of oil for the presence of the chlorine within the PCB. This test removes the chloride from the PCB parent molecule which can then be colorimetrically determined (Colorimetric analysis is a method of determining the concentration of a chemical compound in a solution with the aid of a colour reagent. However, nothing is available to test live equipment either by accessing the oil or by testing vapours/emissions from the overhead equipment.

Project Overview

The project was made up of the following elements:

1. A Paper Study to capture the state-of-the-art learning in relation to the problem of optical spectroscopic detection and quantification of PCB molecules.

2. Laboratory measurements of some of the main PCB sub-elements to enable the provision of robust estimates of detection sensitivity of optical spectroscopic methods. This activity was not a specific objective but would have been required if no spectroscopic data on PCB molecules were available. Sufficient spectroscopic data was gathered to enable the provision of robust estimates of spectroscopic detection methods.

3. The results from 1 and 2 helped develop a model of the detection instrument and detection scenario to understand the prospects and limitations of various approaches and select the best solution given cost, timescale, performance and operational constraints in a laboratory environment.

Scale of the project

The project was divided between three project partners, NPL (The National Physical Laboratory) and RAL Space in conjunction with Willow Innovation

The work packages included:

NPL

A literature review on the measurement of polychlorinated biphenyls in transformer oil as part of work package one follwed by; A report on the findings of transformer headspace sampling and analysis for the presence of polychlorinated biphenyls as part of work package two.

RAL Space / Willow Innovation

A feasibility report on spectroscopic detection of polychlorinated biphenyls as part of work package one.

The key to the project's success is identifying current sampling techniques or identifying accurate testing methodologies for the detection of PCBs within transformer oil vapour

The ENA (Electricity Networks Association) PCB Cohort group unanimously agreed that Willow Innovation and National Physical Laboratory provided the greatest understanding of the requirements of the project, how the project might be developed and delivered, while providing best value for money. However, while it was felt that these two organisations should be used to launch phase one, other partners should remain under consideration for later projects, this is because any further projects would look to develop testing equipment based on the learning from this project, other partners may be best suited to fulfil the requirements of this type of project.

3. Scope and Objectives

The scope of this project was to identify a viable non-intrusive solution for the detection of PCBs in transformer mineral oil without the need of a physical oil sample and can be carried out on an overhead asset whilst maintaining customer supplies.

This project had two work packages:

Work package 1

This work package carried out two individual paper studies which included

1. Literature review on existing commercial and non-commercial techniques for the extraction and measurement of PCBs in transformer oil and;
2. A feasibility study on spectroscopic detection of PCBs

Work package 2

Work package two carried out laboratory testing for the detection of Polychlorinated Biphenyls (PCBs) in transformer oil vapour, this package was to test the headspace (area above the oil within the transformer) of a known contaminated asset in a controlled environment to detect PCB molecules.

Objectives

Table 3-1: Status of project objectives

Objective	Status
Solution to identify PCBs in network assets	✓
Develop a central database of known contaminated assets	Ongoing
Share the potential learning	✓

4. Success Criteria

Table 4-1: Status of project success criteria

Success Criteria	Status
Demonstrating a potential solution to the wide scale replacement of assets is achievable	✓
Demonstrating to the wider community that us and the industry are actively investigating solutions to this issue	✓

5. Details of Work Carried Out

5.1. Work Package 1

This work package consisted of a literature review on the measurement of polychlorinated biphenyls in transformer oil and a feasibility report on spectroscopic detection of polychlorinated biphenyls.

This work package was carried out by RAL Space and NPL, the literature review and the feasibility reports were completed independently of each other and had different objectives. The NPL literature review report looked at all available techniques for sampling oil and vapour of a pole mounted transformer whilst remaining operational and also the best detection methodologies of PCBs.

RAL Space focused its feasibility report specifically on spectroscopic detection of PCBs.

Literature Review on polychlorinated biphenyls in transformer oil NPL[1]

The objective of the literature review was to understand the techniques available, both commercially and non-commercially, for measuring PCBs in the oil of pole-mounted transformers techniques of how to extract the oil from a pole mounted transformer safely. From extensive internet, literature and patent searches, it was found that a high number of the techniques that may give rapid results and that may be suitable for this application are in the developmental phase and not yet at a stage where they could be deployed for the work under consideration. Furthermore, many require an oil sample to be taken for analysis. The method for obtaining a sample of oil described in the US patent 5,131,283 appeared promising, this method involved piercing the side of a transformer whilst operational and re-sealing once finished, this technique has been tainted by past industry practices which resulted in corrosion and premature failure.

The SERS (Surface-Enhanced Raman Scattering) technique has the potential to have very high sensitivities but how it would be applied in the field is unclear. The principal technique found that may meet the requirement of detecting PCBs remotely from a transformer or transformer breather tube, is PTR-TOF-MS (Proton Transfer – ‘’Time of Flight’’ Mass Spectrometry). This method has been used in a laboratory setting to measure PCBs in the vapour phase. SIFT-MS (Selected Iron Flow Tube – Mass Spectrometry) is another potential technique which in theory should be able to measure PCBs, however, this has not yet been investigated. Both techniques would require coupling with either special heated inlet hoses or live-line rods for sampling the air from the transformer headspace and PCB concentrations of approximately 5 pptv (parts per trillion volume) must be present in the headspace. Current and potential commercially available techniques are summarised in Table 5-1, segregated by their application. The red box represents current practices while the green box represents the techniques which may allow determination of PCBs via headspace analysis.

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[1] https://www.westernpower.co.uk/downloads-view-reciteme/367933

Table 5-1: Characteristics of the options for determining PCBs in the oil of live, pole-mounted transformers and off-line transformers

Sampling Location	Live Transformer		Off-Line Transformer	
	Real-Time	Laboratory	Real-Time	Laboratory
Headspace / Gas	Fast sampling time and detection with sensitivity to measure headspace of a 50-ppm sample	Complex, long sampling time and long analysis; very sensitive	N/A	Long sampling which may require heating and long analysis; analytical method is very sensitive
Oil	Complex sampling and fast analysis; measure qualitatively 50-ppm or below		Simple sampling and fast analysis; measures qualitatively 50-ppm or below	

Feasibility report on spectroscopic detection of polychlorinated biphenyls [2]

This report describes the activity and findings from the RAL Space Spectroscopy Group during a scoping study for polychlorinated biphenyl (PCB) analysis.

This report focused on optical spectroscopic detection techniques, with emphasis on mid-infrared (mid-IR) wavelengths (2 to 20 µm). General advantages of mid-IR spectroscopic methods and instrumentation relevant to the intended application include:

- Sensitive detection as a result of strong interaction of molecules with mid-IR light
- Limited interference from atmospheric water vapour
- Reliable quantitative measurement method
- Ready identification of chemical identity via the mid-IR ‘fingerprint’
- Discrimination between congeners
- Stand-off detection capability
- No major consumables
- Frequent calibration unnecessary

Additional potential advantages of spectroscopic instruments based on quantum cascade lasers (QCLs), a type of semiconductor chip laser, include:

- Devices can be compact & rugged
- Low power requirements
- Mid-IR QCL systems are generally eye-safe

The study consists of an analysis of the state-of-the-art on PCB analysis as publicly available. The case of gas phase and liquid phase detection and quantification are considered. A first estimate of instrumental requirements is derived, followed by a short review of possible technologies and implementation approaches to consider.

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[2] https://www.westernpower.co.uk/downloads-view-reciteme/367936

5.1.1. Key conclusions on spectroscopic data

Availability of quantitative spectroscopic data for PCBs appears extremely limited, such that a necessary first step in the development of any spectroscopic analysis device would be a laboratory measurement campaign to obtain quantitative spectra of ideally all 209 PCB congeners, or at least a significant subset of these known to be spectrally distinguishable.

This means that the spectroscopic data currently available is limited and therefore this methodology cannot detect all 209 congeners without significant resources to obtain all 209 quantitative spectra to make this methodology viable.

5.1.2. Key conclusions on cross section data

The availability of quantitative PCB spectroscopic data is extremely limited; in order to enable PCB detection performance assessment, empirical methods have been established to derive semi-quantitative model spectra for a representative range of 12 PCBs in both vapour and liquid phase from the very limited set of quantitative spectroscopic data found in the literature.

The absorption coefficients of model spectra have been generated, which provide the data required to estimate the minimum detectable quantity of PCB in a given sensing scenario.

The positions of congener spectral features have been established, which, together with a knowledge of the spectral characteristics of the mineral oil or its vapour, informs the choice of spectral window for a sensing device.

This would allow a testing device to be developed to detect all 209 PCB congeners, but would rely on the conclusions from section 5.1.1 being available.

5.1.3. Key conclusions on PCBs volatility

The low volatility of PCBs in general limits the concentration of PCB to be expected in a transformer headspace. At room temperature, the headspace above an oil sample containing 50 ppm of the most (monochloro-) and the least (decachloro-) volatile PCBs would show concentrations of ~ 1 ppb and ~ 0.001 ppt respectively.

The gas phase PCB concentration in the transformer headspace increases approximately 10-fold for a temperature increase of 20 °C. Local heating of the transformer is a way to increase vapour phase sensitivity of a detection technique but this is not a viable solution in normal operating conditions.

For a detection technique to have equal sensitivity to all PCB congeners for a given concentration in the liquid, a dynamic range of 6 orders of magnitude would be required.

The conversion factor relating a given concentration of PCB in the vapour to that of the same PCB in the liquid phase varies from $\sim 10^5$ to $\sim 10^{11}$ for the most and least volatile congeners respectively. In consequence, even very low concentration measured in the gas phase implies a concentration between a million and a trillion times larger in the liquid phase.

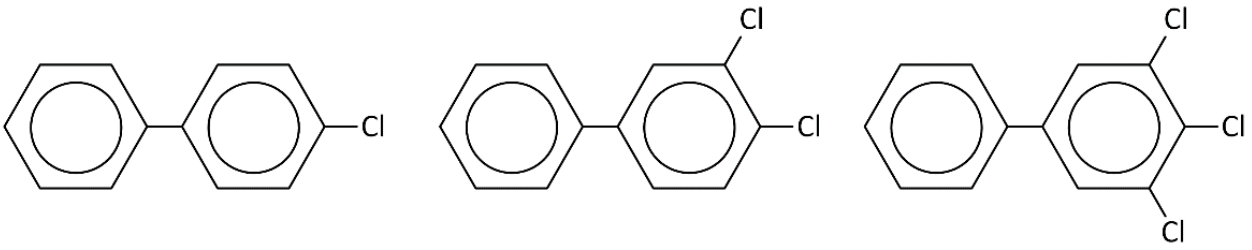
The ability accurately to relate a PCB concentration measured in the gas phase to that in the liquid phase would require knowledge of the temperature of the transformer oil bath to within a few degrees C.

The ability to accurately relate a PCB concentration measured in the gas phase to that in the liquid phase would in addition require knowledge of the enthalpy of vaporisation of each PCB congener, information which is not generally available. Experimental determination of vaporisation enthalpies would be a non-trivial task, especially for the higher homologues.

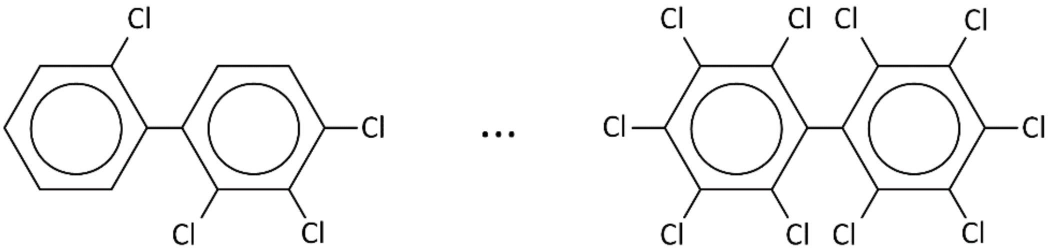
Significant resources would be required in order to obtain knowledge of the enthalpy of vaporisation of each PCB congener, this information is not currently available so the headspace above the oil which contains 50ppm (parts per million) of the least volatile congener (PCB-209) it would be expected to show concentrations of 0.001ppt (parts per trillion) respectively, this would be incredibly difficult to detect whilst the transformer is in situ at the top of a pole and operational.

5.1.4. Composition of trade PCB formulations

PCBs are composed of 10 homologues, each corresponding to the degree of chlorination from mono- to decachlorobiphenyl, within which physical properties such as melting point an enthalpy of vaporisation are similar. Fig. 2 shows examples of the homologues from mono- to tetrachloro-, and decachlorobiphenyl. Each homologue consists of a range of congeners, varying in number from 1 for decachlorobiphenyl to 46 for pentachlorobiphenyl. Fig. 3 shows the three congener members of the monochloro-PCB homologous set. There are a total of 209 PCB congeners, each having its own IR spectrum. It is not known at this stage the degree to which homologue compounds may share spectral similarities.

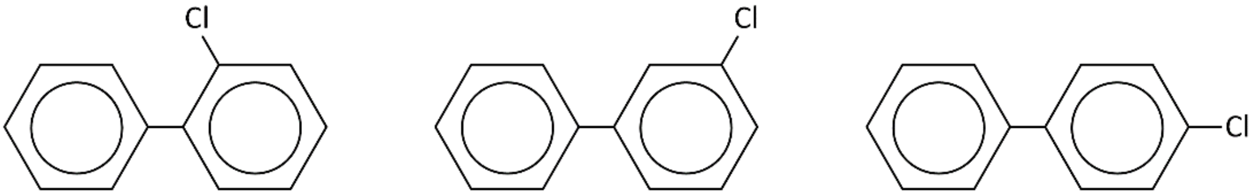


4-chlorobiphenyl 3,4-dichlorobiphenyl 3,4,5-trichlorobiphenyl



4,5,6,2'-tetrachlorobiphenyl Decachlorobiphenyl

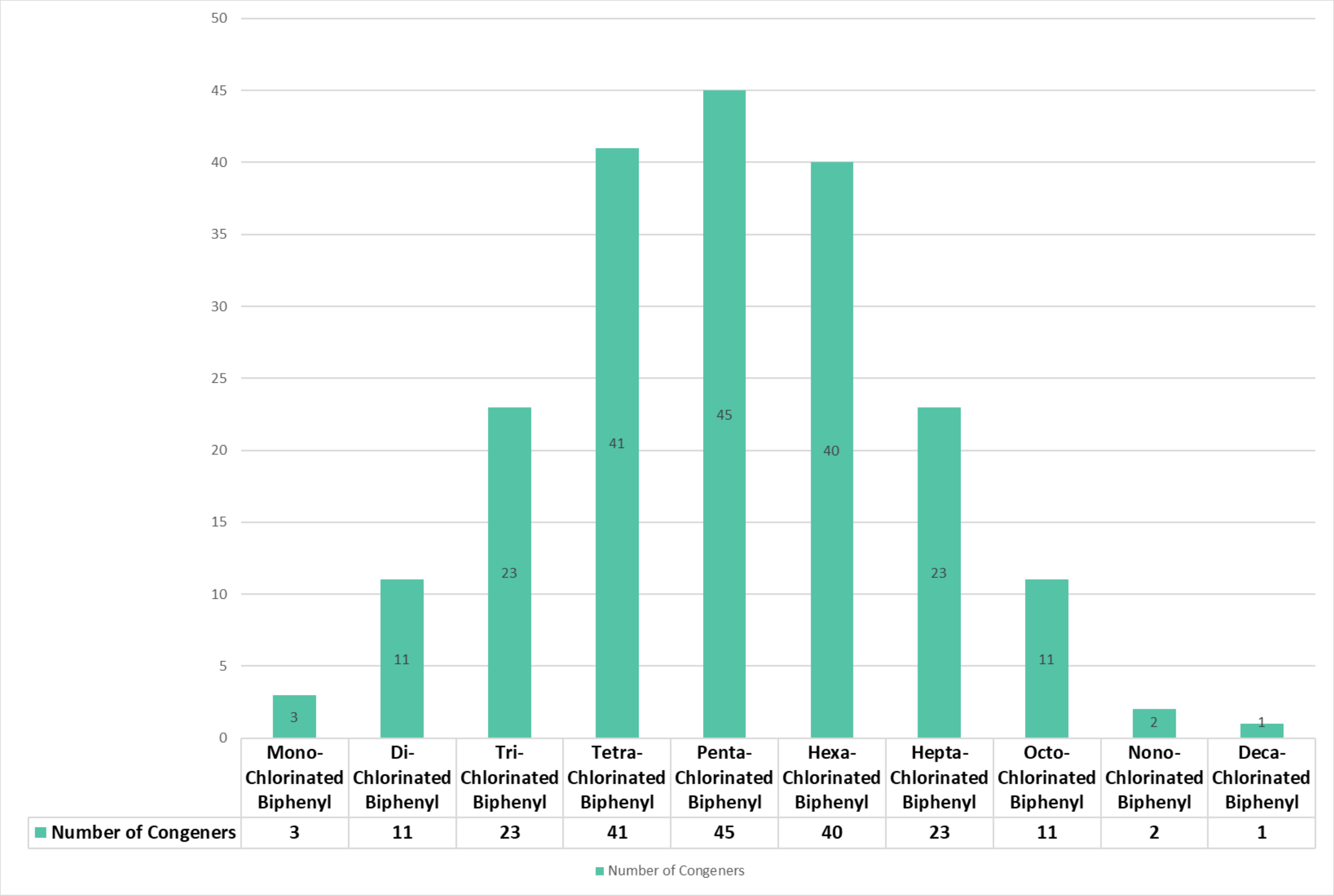
Fig.2: Examples of the first four, and the final, PCB homologues



2-chlorobiphenyl 3-chlorobiphenyl 4-chlorobiphenyl

Fig.3: The three congeners of the monochloro-PCB homologue

There are a total of 209 PCB congeners, each having its own IR spectrum. It is not known at this stage the degree to which homologue compounds may share spectral similarities, Fig.4 represents each PCB homologue and how many PCB congeners sits within each group.



	Mono-Chlorinated Biphenyl	Di-Chlorinated Biphenyl	Tri-Chlorinated Biphenyl	Tetra-Chlorinated Biphenyl	Penta-Chlorinated Biphenyl	Hexa-Chlorinated Biphenyl	Hepta-Chlorinated Biphenyl	Octo-Chlorinated Biphenyl	Nono-Chlorinated Biphenyl	Deca-Chlorinated Biphenyl
🟩 Number of Congeners	3	11	23	41	45	40	23	11	2	1

Fig.4 Total number of PCB congeners within each homologue (group), 10 homologues = 209 Congeners

5.1.5. Key conclusions on PCB mixture composition

For the data limited to specific PCB trade products, the composition at congener level of each formulation is complex, and not entirely reproducible between different batches of the same formulation. We anticipate this situation to be the general case across the industry.

For present purposes it must be assumed that any of all 209 congeners may be present at significant levels in a sample of transformer oil, and would each contribute to the total concentration of 50 ppm in liquid phase.

The requirement for PCB congener spectral reference data is especially acute, given the diversity of composition expected.

Analysis based on gas phase samples would provide information primarily on the less heavily chlorinated, more volatile, PCBs, which, whilst unable to give reliable total PCB quantification, may nevertheless be useful for screening purposes.

Because our assets were cross contaminated, it is not known which PCB composition was being used by specific manufactures and if there may be a mixture of multiple compositions within the oil, therefore not having information on each congener concludes that using Infrared spectral analysis would not sufficiently detect all PCBs within an asset at this time, this could however be successful if the time and effort was put into developing a spectral database of each PCB congener.

5.1.6. Key Conclusions

The regulatory requirement of < 50 ppm of PCB applies to liquid phase samples, irrespective of the actual composition of PCB congeners. Using vapour phase measurements to infer PCB concentrations in the liquid requires an accurate way to relate vapour phase to liquid phase concentrations, which requires an accurate knowledge of temperature of the mixture and the enthalpies of vaporisation of PCB congeners.

The variability in composition of PCB trade formulations and the possibility that the oil in a transformer may have been supplied from a variety of uncontrolled sources means that any detection technique must allow for the presence of the full range of all 209 congeners if the total 50 ppm in liquid phase analysis is required.

The requirements for vapour phase detection and quantification are extremely demanding, especially for the heavier, more chlorinated congeners. The outcome of this study suggests the practical solution should focus on liquid analysis, which has implications for the practical implementation of the solution and particularly on the method of obtaining samples.

Vapour phase solutions are realistic only when applied to volatile monochlorinated PCB congeners. This would allow the development of a screening solution but not a full quantification solution.

Using liquid phase analysis, mid-infrared spectroscopic analysis will fulfil the requirements, based on the partial knowledge we have and the assumptions we made at the time of this study.

The recommendations of this report concludes that the only way to prove the existence or non-existence of PCBs is to use an oil sample rather than analyse the vapour within the headspace of a transformer. Work package two looked to analyse the headspace of a known contaminated asset using a different methodology, this is detailed in section 5.2.

5.2. Work Package 2

This work package consisted of obtaining vapour samples of the headspace of a known contaminated transformer and producing a report on the findings of transformer headspace sampling and analysis for the presence of polychlorinated biphenyls. This was done due to the fact each overhead transformer has a breather tube attached, this is a vent in the side of a transformer, it was theorised that if we can extract air samples through the breather tube and analyse the sample we could detect PCBs within the asset without the need to lose customers supplies and would be a very quick and effective way of testing each asset that could potentially be contaminated (any asset with a manufactures date pre 1987). If the full range of PCBs could be detected through sampling the air within a transformer than a tester would be easily developed to detect PCBs, this section details the testing carried out and the conclusions of the testing.

Transformer Headspace Sampling and Analysis[3]

The aim of the headspace analysis was to ascertain if PCB molecules are present in transformer oil vapour, if so can we detect all PCB congeners that may be present or are there limitations to the detection of particular congeners, mono-chlorinated to deca-chlorinated (PCB01 to PCB209) as found in work package one.

The analysis found that the higher the temperature of contaminated oil, the higher the vapour pressure of the PCBs in it. The plot of vapour pressure vs temperature shown in Fig.5 suggests that vapour pressure increases by about a factor of 3 or 4 from 25°C to 40°C. Therefore, heating the transformer oil will increase the concentration of PCBs in the

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[3] https://www.westernpower.co.uk/downloads-view-reciteme/367930

headspace. As you can see in Fig.4 even at 55 degrees Celsius, PCB180 is extremely low, therefore it is hard to determine the presence of the less volatile congeners, and as the UK DNOs do not know which PCB congener was accidentally cross contaminated into our assets, this type of testing would not provide sufficient evidence to remove it from the asset register.

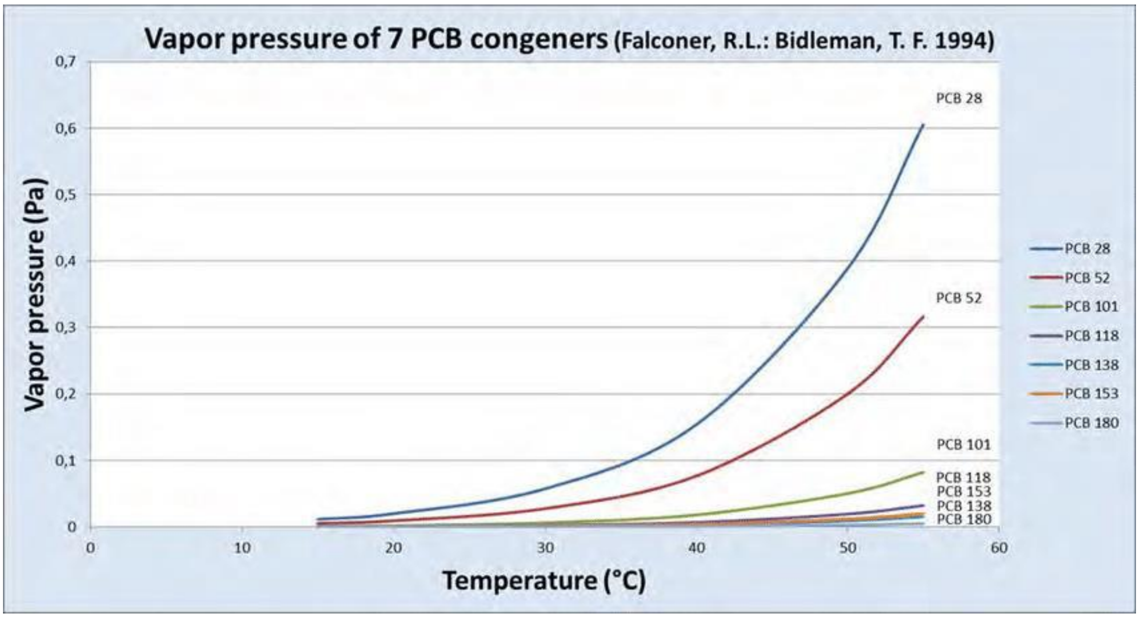


Fig.5: Vapour pressure of the 7 most PCBs most likely to be hazardous to health in environmental applications with respect to temperature.

5.2.1. Materials and Methods

The standard method involves actively sampling the air in the headspace of the transformer through the use of sorbent tubes consisting of Tenax sandwiched between two layers of polyurethane foam (PUF) (SKC 226-124), at 5 l/min for 24 hrs. These tubes have a limit of detection (LoD) of 1 µg. Estimates of the PCB concentration that might be expected in a transformer would suggest that this LoD is not low enough. An alternative sorbent tube, SKC 226-129 (Fig.5), was identified which was designed to meet specifications for high flow sampling of PCBs in ambient air. This tube consists of XAD®-2 sorbent sandwiched between the two PUF layers. This tube combined with High-Resolution Gas Chromatography Mass Spectrometry (HR-GCMS) analysis, has a LoD of 0.5 ng (nanogram) - 1 ng which would provide a better chance of detecting PCBs in the headspace. Though these tubes are high flow tubes and are normally used with flows of around 200 l/min, this flow is not practical for this experiment and lower flows were used. This is not expected to have any impact on the capture efficiency of the tubes. The air was sampled from the breather pipe outlet of the transformer.

Fig.6: SKC 226-129 sorbent tube

5.2.2. Testing Setup

A sampling media holder was designed, and 3D printed for the purpose of this experiment as suitable holders are not readily commercially available for this application, see Fig.7.

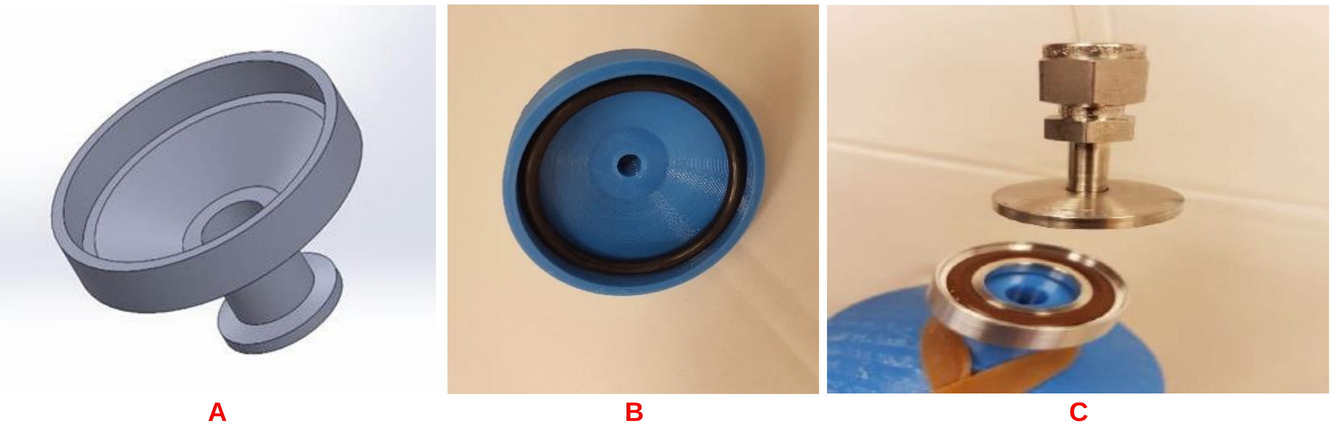


Fig.7: SKC 226-129 sampling holder – A) 3D design, B) 3D printed holder with O-ring, and C) connections from holder to sampling tubing.

The SKC 226-129 tubes were held in place using the 3D printed holders, connecting them to the vacuum pump on one end and the breather tube of a test transformer via tubing on the other. This allowed the sampled headspace air to pass through the sampling tube at a flow controlled by the pump. The test transformer which had a known contamination of ~50 ppm total PCBs. The experimental set up deployed at our site in Exeter is shown in Fig.8.

Fig.8 Experimental setup using a test transformer with ~50 ppm PCB contamination.

5.2.3. Headspace Sampling

Two methods to extract the air from the headspace of the test transformer were performed. The first involved sampling the air close to the end of the breather tube outlet. This had the advantage that it was easy to position the sampling media and a reasonable air flow through it was maintained. The proportion of air from the headspace compared to the surrounding air, however, was expected to be low.

The second method attempted to seal the end of the breather tube so that only air from the headspace was sampled. This had the advantage that most of the air sampled was from the headspace. A perfect seal was not expected nor were the seals around the transformer lid airtight, therefore, air from the surroundings was also extracted.

Both methods 1 and 2 were repeated, however, this time while attempting to heat the oil in the transformer above room temperature. An industrial infrared heat lamp to do this which was positioned approximately 50 cm away from the test transformer for the sampling period. Due to time and equipment constraints, the oil did not reach a steady, controlled temperature. The temperature was recorded at the start and at the end of sampling using a laser thermometer.

Test Plan

Five tests were carried out using the SKC 226-129 tubes. The first test was a background measurement where the air in the room housing the test transformer was actively sampled for 24 hours at approximately 37 l/min. This gave an understanding of the background levels of PCBs present in the room housing the transformer. The second and third tests involved sampling from the breather tube of both the test oil at room temperature and the test oil heated using method 1 mentioned above. The fourth and fifth tests involved sampling from the breather tube of both the test oil at room temperature and the test oil heated using method 2. Table 2 summarises the tests that were carried out.

Table 5-2: Summary of the 5 tests carried out on the test transformer at Exeter

Test	Sampling Time	Temperature (°C)	Flow Rate (l/min)
Background	24 hours	16	37
Unsealed	24 hours	16	41
Unsealed & Heated	24 hours	Between 20 - 40	41
Sealed	24 hours	16	-
Sealed & Heated	24 hours	Between 20 - 40	-

5.2.4. Results & Discussion

Following the sampling of the contaminated transformer, the samples were sent off to Marchwood Scientific Services, a UKAS accredited laboratory.

A summary of the results from Marchwood Scientific is shown in Table 5-3. Table 5-4 shows the concentration of the background and unsealed tests in parts per trillion by volume (pptv) calculated taking the sampling time and flow rate into account. The flow could not be recorded during the sealed tests, however, given that the values in Table 3 are comparable to the background values, the sealed tests appear to give insignificant results.

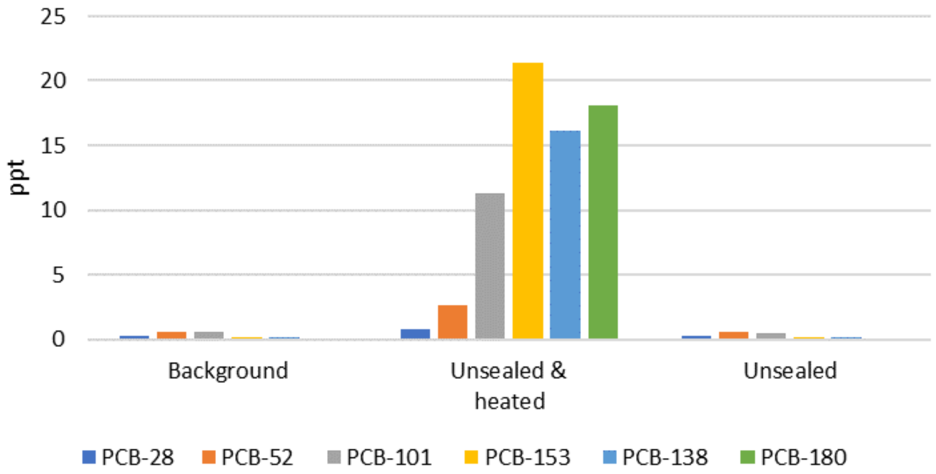
Table 5-3: Results of concentrations in ng / sample for each of the five sampling tests

Test	PCB-28	PCB-52	PCB-101	PCB-153	PCB-138	PCB-180
Background	15	29.8	28.1	7.1	5.85	0.748
Sealed	12.7	15.7	8.87	5.61	2.93	3.33
Unsealed	16.6	34	27.8	10.9	6.36	4.14
Unsealed & heated	48.6	158	664	1262	953	1066
Sealed & heated	9.72	17.2	13.8	10.7	5.46	5.81

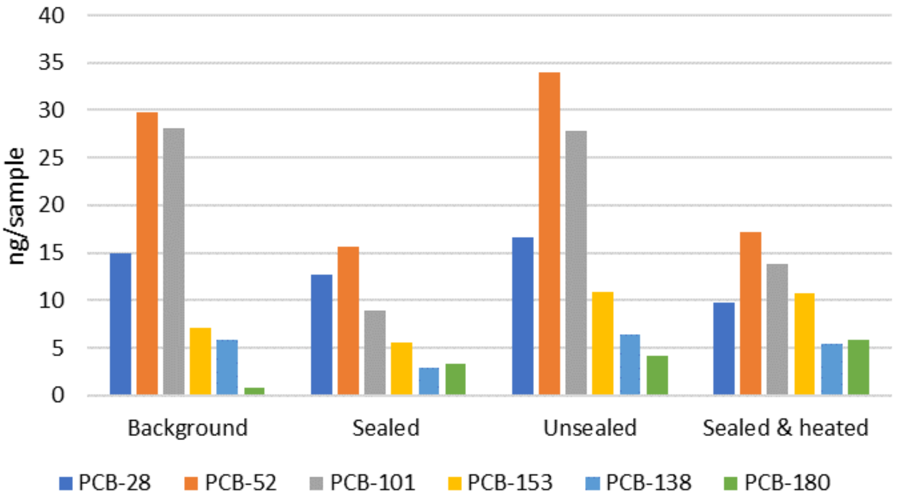
Table 5-4: Results of concentrations in ppt for each of the five sampling tests

Test	PCB-28	PCB-52	PCB-101	PCB-153	PCB-138	PCB-180
Background	0.282	0.559	0.527	0.133	0.110	0.014
Unsealed & heated	0.823	2.676	11.247	21.375	16.142	18.056
Unsealed	0.281	0.576	0.471	0.185	0.108	0.070

From plotting the results from Table 5-4, it is clear that PCBs have only been detected above background during the unsealed & heated test with PCB-153 being the largest component shown. However, if we compare the results from the other four tests in ng/sample, we can see that the three lightest PCBs are the dominant congeners in the vapour phase in background air and transformer headspace. This indicates that the ratio of the different congeners is different for the heated headspace when compared to background air samples. This shows that all PCBs must be heated to be detectable in the vapour phase above background, in particular, the heavier PCBs in the vapour phase increase upon heating.



Comparison of the background, unsealed & heated, and unsealed results in pptv.



Comparison of the results excluding the unsealed & heated in ng/sample.

Given these results, it can be concluded that the transformer oil must be heated to approximately 60°C in order for PCBs in the vapour phase to measure above background using this method. However, even with heating, it would appear that a contaminated transformer with a concentration of approximately 50 ppm, contains 22 pptv or less PCBs in the vapour phase.

5.2.5. Headspace Analysis Conclusions

The results from the testing carried out supported by the information from the feasibility study in work package one has shown that PCBs are not present at detectable levels in the headspace of transformers unless the oil in the transformer is excessively heated. Even if the transformer is approximately at a temperature between 20°C and 60°C, PCBs may only be present in the low ppt levels, with the transformer containing at least 50 ppm of PCBs overall. The technique identified in Work Package 1, PTR-TOF-MS may have the ability to measure PCBs at this ppt level, however, this instrument has yet to be used to sample, detect and quantify PCBs in practice and has only shown its ability to measure standard PCB mixes in a laboratory setting.

6. Performance Compared to Original Aims, Objectives and Success Criteria

The project achieved the following in fulfilment of the originally stated objectives:

Objectives	Status
Solution to identify PCBs in network assets	Complete - Multiple solutions have been discovered to identify PCB molecules within mineral oil, all solutions identified had to utilise physical oil samples.
Develop a central database of known contaminated assets	Ongoing – the creation of a central database of potentially contaminated assets was led by the ENA and their working groups in collaboration with all UK DNOs, this was not a specific output of this project.
Share the potential learning	Complete - Throughout the project all learning has been shared with the ENA working and Cohort groups and the learning from each report has also been shared, this has led to a development of another DNO lead project to develop an alternative non-intrusive testing methodology.

The project achieved the following in fulfilment of the originally stated success criteria:

Success Criteria	Status
Demonstrating a potential solution to the wide scale replacement of assets is achievable	Complete - Although this project demonstrated that PCBs can be detected accurately and quantified in either a liquid or vapour phase, the barrier to wide scale adoption of this testing methodology is access to the assets and its contents
Demonstrating to the wider community that us and the industry are actively investigating solutions to this issue	Complete - Registering this project would have demonstrated to the wider community and the industry that all DNOs and the ENA are actively investigating solutions to this particular issue, the communication between all DNOs and the EA has been very important and the knowledge sharing has been a significant factor to the removal of thousands of assets that were on the database

7. Required Modifications to the Planned Approach during the Course of the Project

Following the impact of COVID 19 lockdown the access to site to carry out the tests and the laboratories were closed to non-essential works, therefore the project was delayed by a number of months until such a time it was deemed safe to return to finish analysing the samples.

8. Project Costs

Table 8.1 summarises the details of the final costs that have been made with respect to the project budget.

Table 8.1: Project Costs

Spend Area	Budget (£k)	Expected Spend to Date (£k)	Actual Spend to Date (£k)	Variance to expected (£k)	Variance to expected %
WPD Project Management	£8,000.00[4]	£8,000.00	£7,683.00	£317	-3.9%*
Contractor Project Costs	£98,600.00[5]	£98,600.00	£98,600.00	£0	0%
Contingency	£3,000[6]	£0	£0	£0	0%
TOTAL	**£109,600.00**	**£106,600.00**	**£106,283.00**	£317.00	-0.3%

WPD Project Management – actual spend is lower than expected due to less time required to manage the project, increased in efficiencies of our internal processes meant that some management activities were less intensive than anticipated.

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[4] WPD Funding
[5] NIA Funding
[6] WPD Funding

9. Lessons Learnt for Future Projects

Multiple solutions have been discovered to identify PCB molecules within mineral oil, this was completed as part of a literature review carried out by National Physical Laboratory (NPL) and RAL Space. The solutions discovered by the literature review in Work Package 1, required physical samples of oil, but as a result the tests are able to determine the quantification of PCBs. This is important as there is an allowed threshold of 50ppm so a test that quantified results is far better than a positive/negative one. The only downside is to accurately quantify levels of PCBs in mineral oil, we require a physical oil sample which would require system outages and a safe method of extraction at height.

Ultraviolet (UV) and infrared (IR) absorption spectroscopy are the two methods that are able to accurately quantify PCB molecules in a gaseous state, this is key when analysing the vapour within the headspace of an asset, but the limitations of this method is there is insufficient data available for the full range of PCB congeners. There are known methods of detection for physical oil samples such as the tests that are currently being used such as 'Chlor n Ol' tests, the issue with these is they do not quantify PCBs and can provide false positive results.

Headspace sampling showed real promise as a testing solution due to ease of access and the ability to test an asset in situ and operational. The limitations here is that in order to detect the full range of congeners the asset would need to be externally heated to beyond safe operating temperatures and therefore rendering this technique unsafe and not a viable detection method for PCBs.

9.1.1. Key conclusions on spectroscopic data

Spectroscopic data currently available is limited and therefore this methodology cannot detect all 209 congeners without significant resources to obtain all 209 quantitative spectra to make this methodology viable.
The UV (Ultra-Violet) absorption method has poor congener selectivity and so is not considered further.

9.1.2. Key conclusions on cross section data

A testing device could be developed to detect all 209 PCB congeners, but would rely on a laboratory measurement campaign to obtain quantitative spectra of ideally all 209 PCB congeners.

9.1.3. Key conclusions on PCBs volatility

Significant resources would be required in order to obtain knowledge of the enthalpy of vaporisation of each PCB congener, this information is not currently available so the headspace above the oil which contains 50ppm (parts per million) of the least volatile congener (PCB-209) it would be expected to show concentrations of 0.001ppt (parts per trillion) respectively, this would be incredibly difficult to detect whilst the transformer is in situ at the top of a pole and operational.

10. The Outcomes of the Project

Three papers have been produced as part of the project, these are;

Draft Measurement of PCBs in Transformer Oil - NPL (National Physical Laboratory)

The objective of the literature review was to understand the techniques available, both commercially and non-commercially, for measuring PCBs in the oil of pole-mounted transformers by either safely accessing the oil itself from a live transformer, or by measuring PCBs in the headspace of the transformer from the breather tubes. From extensive internet, literature and patent searches, it was found that a high number of the techniques that may give rapid results and that may be suitable for this application are in the developmental phase and not yet at a stage where they could be deployed for the work under consideration.

Literature Review and Headspace Analysis report - NPL (National Physical Laboratory)

This feasibility study has shown that PCBs are not present at detectable levels in the headspace of transformers unless the oil in the transformer is heated. Even if the transformer is approximately at a temperature between 20°C and 60°C, PCBs may only be present in the low ppt levels, with the transformer containing at least 50 ppm of PCBs overall.

Report on spectroscopic detection - RAL Space

The study focuses on optical spectroscopic detection techniques, with emphasis on the mid-infrared (mid-IR) wavelengths.

11. Data Access Details

The project reports and papers have been circulated with the ENA PCB Cohort group and shared internally between all; UK DNOs, this was done throughout the project to aid in the removal of potentially contaminated assets from UK DNO networks.

All reports and findings of this project are within this report and within its appendices, this can also be accessed via a request to wpdinnovation@westernpower.co.uk

Additional project information including the reports can be found by visiting www.westernpower.co.uk/innovation

12. Foreground IPR

The table below presents a complete list of all IPR generated within the project from all project partners.

Title	Description	Ownership	Access Location
Literature Review: Measurement of PCBs in Transformer Oil	Relevant Foreground	NPL (National Physical Laboratory)	https://www.westernpower.co.uk/downloads-view-reciteme/367933
Transformer Headspace Sampling and Analysis report	Relevant Foreground	NPL (National Physical Laboratory)	https://www.westernpower.co.uk/downloads-view-reciteme/367930
Report on spectroscopic detection of PCB	Relevant Foreground	RAL Space	https://www.westernpower.co.uk/downloads-view-reciteme/367936

13. Planned Implementation

Although there are methods for detection of PCBs in oil that are currently available which are being utilised by all DNOs, the main barrier is that we require a physical oil sample in order to do so. Currently this is only done when a transformer is removed from service and scrapped as per our maintenance and replacement programme, this information is stored centrally and a database is kept on all positive tests on each scrapped asset. The main issue is how we would retrieve the samples from network assets which are pole mounted and vary in construction type, but also in good working order and not due to be replaced any time soon. DNOs want to maintain customers' supplies and it is not feasible to replace every potentially contaminated asset across the UK distribution networks. This would be in excess of 300,000 pole mounted and ground mounted items across the UK, of which around 94,000 are owned by us. While the ground mounted items could be tested in situ without considerable cost and inconvenience, the vast majority of the 300,000 items are pole mounted and essentially inaccessible. Information from this project has informed all UK DNOs and the ENA working groups on the best direction to meet this requirement.

This project concluded there is no safe method of extracting oil from an overhead asset whilst it remains operational, it has also concluded that not all PCB congeners are present within the headspace of an asset under normal operating conditions so therefore headspace analysis isn't an accurate testing method for the detection of PCBs. Either a new innovative non-intrusive testing method needs to be developed, or the development of a safe method of obtaining an oil sample from an operational transformer is needed. It has also concluded there is insufficient spectroscopic data for all 209 PCB congeners to be able to use this method of detection, this would require a significant laboratory based task. There is a deadline of 2025 to remove all potentially contaminated assets and this task would not be feasible within those timescales.

14. Contact

Further details on replicating the project can be made available from the following points of contact:

Innovation Team
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Herald Way,
Castle Donnington,
Derbyshire
DE74 2TU
Email: wpdinnovation@westernpower.co.uk

15. Appendices

There are no appendices in this report, all supporting information and reports are detailed in section 12 of this report.

16. Glossary

Abbreviation	Term
WPD	Western Power Distribution
DNO	Distribution Network Operator
PCB	Polychlorinated Biphenyl
GB	Great Britain
IR	Infrared
UV	Ultra Violet
ppm	Parts per million
ppb	Parts per billion
pptv	Parts per trillion volume
ENA	Electricity Networks Association
SERS	Surface-Enhanced Raman Scattering
PTR-TOF-MS	Proton Transfer – ''Time of Flight'' Mass Spectrometry
SIFT-MS	Selected Iron Flow Tube – Mass Spectrometry
HR-GCMS	High Resolution – Gas Chromatography – Mass Spectrometry
QCL	Quantum Cascade Lasers
PuF	Polyurethane Foam
LoD	Limit of Detection
NPL	National Physical Laboratory
RAL	Rutherford Appleton Laboratory
IPR	Intellectual Property Rights
COVID-19	Coronavirus Disease 2019

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