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MEASUREMENT OF POLYCHLORINATED BIPHENYLS IN TRANSFOMER OIL: A REVIEW

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ABSTRACT

Given the chemical and physical stability of polychlorinated biphenyls (PCBs), it has been of increasing concern to regulators to monitor and screen samples of various types for PCB contamination. In particular, proposed changes to EU regulations may require all UK Distribution Network Operators (DNOs) to determine if their transformers are contaminated with PCBs. The objective of this study was to explore commercial and non-commercial techniques that could be applied for determining PCB contamination in the oil of ground and pole-mounted transformers. The primary determination technique used for PCBs in air and oil involves gas chromatography with various detectors. Non-chromatographic techniques include infrared (IR) spectrometry, colorimetric assays, immuno-assays, and surface-enhanced Raman scattering. Proton transfer reaction “time of flight” mass spectrometry (PTR-TOF-MS) is a commercially available technique that allows real-time detection of volatile and semi-volatile organic compounds in air without sample preparation. It has yet to be used for sampling PCBs in ambient air, however, it shows promise due to its high sensitivity, low detection limit and that past laboratory-based studies have measured PCBs successfully. This coupled with hot-live rods for sampling the headspace air of the transformers may be the most sensitive and rapid method to screen huge numbers of transformers in the network in a practical timeframe. In order to do this however, PCBs must be present at appropriate concentrations in the headspace of live transformers. In order to achieve this, pre-concentration of the headspace sample or heating of the transformer may be necessary. If neither of these are possible, an engineering solution to sample oil from a live transformer may be the only option to efficiently determine PCB presence and concentrations in live transformers.

1 WP 1.1 LITERATURE REVIEW

1.1 INTRODUCTION

Polychlorinated biphenyls (PCBs) are a group of man-made, aromatic Persistent Organic Pollutant (POP) compounds which were introduced worldwide in the late 1920’s (1). They have a chemical formula of $C_{12}H_{10-n}Cl_n$, where n ranges from 1 to 10. There are 209 different congeners of PCBs, however, only 130 of these have been found in commercial products (2, 3). PCBs are semi-volatile compounds where congeners with a lower degree of chlorination are more volatile than those with a higher degree. When they volatilise, they form vapours which are heavier than air.

In the past PCBs were used widely in industry for a variety of purposes due their physical properties; high flash points making them fire resistant, low electrical conductivity, high thermal conductivity, high dielectric strength, and high resistance to thermal degradation. It is for these reasons that PCBs became popular for use in transformer oil (4). It is also for these reasons that PCBs are non-biodegradable due to their stability and they bioaccumulate in the environment and food chains (4-6). They have potential developmental toxicity and a cancer risk with toxic effects reported in birds, fish and mammals (1, 7). Negative effects of PCBs were discovered in the 1960’s with subsequent production and use banned in the 1970’s in many countries. In the UK, sales of PCBs for open applications were discontinued by 1972 and sales of UK manufactured material ceased in 1977. PCBs still exist in many assets manufactured before this that are still in use today. PCBs were widely used in transformer oil in the last century due to their electrical insulating properties, high thermal stability and non-flammability. Currently, the UK’s guidance allows transformer oil contaminated with PCBs to be used as long as the PCB concentration in the oil is below 500 parts per million (ppm) (0.05% by weight) (8). However, equipment is considered contaminated if it contains more than 50 ppm PCBs or more than five litres of PCB containing material (oil) and must be individually registered on an annual basis with the Environment Agency (EA) or the Scottish Environmental Protection Agency (SEPA) (9). In the UK, the Distribution Network Operators do not know which transformers are currently contaminated and whether contaminated assets are within the 500 ppm limit. Furthermore, proposed changes to European regulations on PCBs have the potential to require all UK distribution network operators to test their old, potentially contaminated transformer assets. There are in excess of 300,000 items with the majority being pole mounted.

There are two methods for determining PCB presence in transformer oil. The first method involves accessing the oil either from an off-line transformer, which is the current method, or by sampling the oil while the transformer is live. The second method involves sampling the headspace with on-line or subsequent gas analysis. This would allow a quick ‘sniffing’ solution for testing live transformers whilst avoiding sampling any oil. There are no current methods developed specifically to do this and it is possible that many different combinations of the 130 PCB congeners found in commercial products may be present. Due to the stability of these congeners, it is likely that only lower mass PCBs such as monochlorobiphenyl, dichlorobiphenyl, trichlorobiphenyl, tetrachlorobiphenyl, and pentachlorobiphenyl will be present in the vapour phase. The main objectives of this literature review are to understand all techniques currently used or which could be used to measure PCBs in air and in transformer oil, and to identify sufficiently sensitive, fast response, mobile techniques that could potentially be adapted to determine PCBs in the headspace of transformers. It is fundamental to consider the PCB concentrations that may be found in the headspace of transformers to identify a suitably sensitive analytical technique. This will depend greatly on the temperature of the transformer. The more chlorine atoms the congener has, the more heat required for vaporisation (10). If transformers are near average ambient UK temperatures of 290 K (17 °C), a 50 ppm PCB concentration in oil will result in a concentration between $5x10^{-4}$ and $5x10^{-9}$ pptv of PCBs in the headspace based on quoted partial pressures for PCBs (11). There are no methods available that can measure concentrations this low. However, if the temperature of the transformer is increased to 450 K (177 C), a concentration between 500 and 0.5 ppt would be expected. If it is not possible to heat the transformers before sniffing, pre-concentrating the samples would need to be explored.

Table 1 summarises the characteristics of different measurement options based on whether the method measures a live or off-line transformer and whether a result is given in real-time or following laboratory analysis. The green box represents the desired method while the red box is the current capability.

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

	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; measures qualitatively 50-ppm or below		Simple sampling and fast analysis; measures qualitatively 50-ppm or below	

1.2 COMMERICAL TECHNIQUES

PCBs are found throughout the environment as a result of spills, improper disposal and storage and leaks from electrical equipment. The widespread distribution of PCBs throughout the world suggests that they are transported in air. The use of certain construction materials has also led to high concentrations of PCBs in indoor air (12, 13). For these reasons, standards were developed in order to measure these POPs.

1.2.1 Standard Methods

The EPA compendium methods TO-10A (14) and TO-4A (15) which incorporate ASTM Method D4861-94, are the standards used for determining PCBs in ambient air. The measurement of PCBs in air following these standards involves active sampling using either low or high-volume polyurethane foam (PUF) sampling followed by solvent extraction and gas chromatographic/Multi-detector detection (GC-MD). Sampling periods are up to 24 hours followed by extraction which can take up to 36 hours. These methods can measure from 0.001 to 50 μg/m^3 of common pesticides and PCBs over 4- to 24-hour sampling periods.

ASTM D4059 is the standard test method for analysis of PCBs in insulating liquids by gas chromatography coupled with an electron capture detector. These standard methods can be labour intensive, and they do not give real-time data. The limits of detection will depend on the length of the sampling period. Furthermore, these methods would be very expensive to undertake for the large number of potentially contaminated transformers across the UK.

1.2.2 Current Techniques Used

Historically and currently, the majority of the ambient and indoor reported measurements of PCBs follow the standard methods using PUF sampling with Soxhlet extraction followed by gas chromatography (GC) coupled with high resolution mass spectrometry (MS) (16-21) or an electron capture detector (ECD) (22). Many of the reported indoor air measurements and environmental studies use passive sampling which does not give fast results and is therefore not suitable for sampling of live transformers (22-25).

One of the quickest and simplest methods used today for testing transformer oil directly for PCBs involves chloride analysis techniques such as colorimetric and electrochemical. All PCBs contain chlorine; therefore, its absence indicates that there are no PCBs present. It is possible however for other sources of chlorine to interfere with these methods although this is rare for transformer oil. Both colorimetric and electrochemical methods work by a reaction of the PCB with a metallic sodium reagent. This removes the chloride from the PCB parent molecule which can then be determined. A Clor-N-Oil test kit is currently the most popular colorimetric kit for testing the presence of PCBs in transformer oil.

This test kit is commercially available, inexpensive and it gives fast results. It gives an indication of whether a sample contains less or greater than 50 ppm of PCBs. It is recommended to use a specific PCB method following a Clor-N-Oil kit if the sample appears to have greater than 50 ppm. A disadvantage of Clor-N-Oil is that an oil sample is required; which currently is difficult when testing pole mounted live transformers, making this approach impractical for rapid screening.

As the standard methods are time consuming and labour intensive, and as it is impractical to extract the oil in live transformers in order to use a simple Clor-N-Oil test, NPL has investigated the use of other potential techniques, both commercial and non-commercial, that are sensitive enough to detect/sniff PCBs in the headspace of transformer oil. As PCB volatility depends on their level of chlorination, techniques should be capable of measuring lower mass PCBs such as monochlorobiphenyl, dichlorobiphenyl, trichlorobiphenyl, tetrachlorobiphenyl, and pentachlorobiphenyl.

1.2.3 Potential Commercial techniques

A technique called proton transfer reaction “time of flight” mass spectrometry (PTR-TOF-MS) is a commercially available technique that allows real-time detection without sample preparation, it has high sensitivity and a low detection limit. For these reasons, it is an ideal candidate for detecting trace hazardous compounds in industry and pollution monitoring. In this technique gas-phase molecules are ionised by the transfer of a proton from $H3O^+$ where the resulting ions produced are detected by a mass analyser. PTR-TOF has been deployed previously by Aerodyne Research in a mobile laboratory (26) and PTR-MS has been used on-board aircraft, therefore has proven suitable for use on a mobile platform. This system has yet to be used for measuring ambient PCBs however, a PTR-TOF 8000 system has been calibrated for an individual PCB (PCB 77; 3,3’,4,4’-tetrachlorobiphenyl) showing a limit of detection of 0.16 ppbv (27). Furthermore, Agarwal et al., (28) used a PTR-TOF 8000 to measure the vapour phase of both low-mass and high-mass PCBs in the headspace of a PCB sample. The low-mass PCBs were measured at room temperature and the high-mass PCBs were heated due to their low vapour pressures. The calculated and measured isotopic ratios/relative abundances values agreed very well with an estimated statistical error of 3-5% for the low-mass PCBs, and approximately 15% for the high-mass PCBs. This study has shown the potential of using PTR-TOF for rapidly detecting PCBs via headspace sampling. A more sensitive PTR-TOF than the 8000 is commercially available, the PTR-TOF 4000, whose specifications indicate a detection limit of < 5 pptv (parts per trillion volume) for trace VOC’s (volatile organic compounds). If a PTR-TOF is to be used to sample from live transformers, a well-designed heated sampling line is required to sample the air directly from the breather tube.

Another commercially available and leading technology which has the ability to measure ultra-trace levels of volatile organic compounds at the pptv level and in real-time is Selected Ion Flow Tube Mass Spectrometry (SIFT-MS). This technique eliminates sample preparation, preconcentration and chromatography. However, this method has not been used for measuring PCBs and as it uses quadrupole mass selection, it is limited to compounds with a molecular mass of 400 g/mol or less (i.e. PCBs with 7 or less chlorine atoms).

Fourier Transform Infrared Spectroscopy (FTIR) is a well-established, high resolution spectroscopic technique which can distinguish between different PCB congeners due to their distinctly different in the mid-infrared wavelength region. (29). The spectra that have been obtained using FTIR, however, were observed with a gas chromatograph linked via a light pipe with an FTIR spectrometer. There is no evidence that FTIR has yet been used to measure PCBs in air in real-time and it is expected that the quantification limits of this would be in the 10 – 100 ppb range. If a laboratory FTIR were used to measure PCBs, it would require a preconcentrated sample, therefore real-time results would not be achievable.

1.3 NON-COMMERICAL TECHNIQUES

A literature search was carried out for the detection and quantification methods (optical, fluorescence, microfluidic etc.) which are currently not commercially available but are or have been in the early stages of research or development.

Further optical techniques were explored as they have many advantages over the conventional chromatography methods; lower cost, non-destructive sampling and fast results. Many studies have adapted or enhanced surface-enhanced Raman scattering (SERS) for the detection of PCBs (30, 31). For example, Zhu et al., (32) studied the rapid detection of PCB-77 using Ag nanoplate-assembled films as SERS substrates. SERS technique is commonly employed to detect many substances including drugs and explosives, but substrates do not appear to be commercially available for the detection of PCBs.

In recent years, the search for a rapid, low-cost method for the measurement of PCBs has been a priority due to the high number of contaminated transformers in service. Immunoassays have been a popular technique (33); however, these methods can be complex, may give false readings and require an oil sample. Immunoassay tests work by detecting specific chemicals by measuring the chemicals' response to certain antibodies. Kim et al., describe a combined sample preparation and PCB-specific immunoassay method for measuring transformer oils with a PCB concentration >35 ppm (34). This study showed a significant advance in the development of immunoassays for laboratory or field-based operations. Ohmura et al., (35) developed a simple and rapid procedure using an immunoassay implemented on a handheld battery-powered instrument where the results suggest that this can be used as an alternative to GC-ECD for screening transformer oil for PCBs. More recently, Fan et al., (36) developed a method using electrochemical aptasensors to detect PCBs based on nickel hexacyanoferrate nanoparticles (NiHCF NPs) or reduced graphene oxides (rGO) hybrids. PCBs are electrochemically inert, meaning they are difficult to determine directly by electrochemical oxidation and therefore electrochemical immunosensors have been developed for their detection. Biosensors using antibodies or aptamers as recognition elements are a novel concept that may be key in the development of devices that could be used in the design of improved commercial PCB-kits (37). In biosensors a recognition element such as an antibody or aptamer is selected that specifically reacts with the intended target, and there are options available for PCB specific elements. Fan et al. (36) used the nature of some aptamers to bond specifically with certain PCBs to develop an electrochemical aptasensor for detecting PCBs. The authors claim that this is a much simpler and shorter process than conventional instrumental analyses.

Liu et.al., 2016 (38) have examined the use of hexagonal lattices of triangular periodic nanoparticle arrays as a sensor for a PCB-77 solution using extinction efficiency. From this study they concluded that it is possible to develop a highly efficient chemo-sensing technique which will allow the detection of PCBs by directly using the periodic nanoparticle arrays. In 2011, Aota et al., (39) developed a low-cost, rapid screening technique where PCBs in oil are extracted and enriched into dimethyl sulfoxide confined in the microrecesses (compartments off the main channel of a microchip) under the oil flow condition of a microfluidic device. This method can serve as a powerful tool for the pre-treatment of contaminated oil during on-site analysis without using centrifugation for phase separation. There are a lot of methods with great potential for PCB measurement, however, most are still in very early stages and not yet suitable for real world application.

1.4 PATENT SEARCH

A patent search was conducted to further investigate any potential techniques that may not appear in literature searches. US Patent 5,318,751 (40) is a technique published in the nineties using luminescence. The presence of PCBs in a sample is determined by treating the sample with a photo-activator and then exposing the treated sample to a UV light source. This produces a complex which is excited using UV light to cause luminescence which in turn is detected. The luminescence spectra are used to detect and quantify the presence of chlorine compounds.

US Patent 5,538,852 (41) discusses qualitative and quantitative detection of PCBs by adding a known quantity of anti-bodies in a competitive immunoassay technique. This patent was first published in 1994 and although there has been a lot of research activity to develop this technique, it has not become a commercially available method.

More recently patent WO2015189262A1 (42) discloses a method for the chemical modification and analysis of a suspected PCB field sample along with the corresponding equipment for improved affinity towards noble metal surfaces. This method enhances the aforementioned SERS technique.

1.5 SAMPLING OPTIONS

Accurate sampling of PCBs from building surfaces has been a focus of past research. A high precision and sensitive passive sampling technique using the partition coefficients of PCB congeners between indoor air and silicone has been recently developed (23). It is potentially much easier than active sampling techniques, using inexpensive materials, however, it still requires a 1 to 2-week period of exposure. More research is required before its use outdoors as outside the silicone has variable and inconsistent sorption behaviour, implying more factors are important than just temperature and air flow. An inexpensive and portable emission test cell was developed by Lyng et al., (12) for measuring off gassing of PCBs from building surfaces. The test cell consists of a 50 cm x 30cm x 10cm chamber where the open side sits on the surface to be measured. A clean air stream is supplied to allow an air exchange with the test cell. The pumps were connected to sampling tubes from which subsequent GC-MS analysis is carried out. However, these sampling methods would not be suitable in their current development stage for sampling air from breather tubes of pole mounted transformers.

It may be possible to sample the latter via live-line working using operating rods. Slot together, hollow rods are available which could potentially be adapted to draw air from transformer headspace using a pump and subsequently connected to an analyser. These hollow, hot-line operating rods are available commercially, however, may not be completely air-tight. They have a simple spring mechanism that connects up to eight 1.22 metre rods together. These rods may need to be modified to provide an airtight sampling technique if used for sampling air from pole mounted transformers. Five metre telescopic type insulated poles are also commercially available which could be used to carry suitable air sampling tubing up to the breather tubes on pole mounted transformers.

The option of sampling oil directly from the breather tube should also be considered as this is the only way to accurately quantify the level of PCBs present in the oil.

US patent 5,131,283 (43) discusses a tool for sampling oil from transformers by piercing the tank to obtain a sample to avoid the need to de-energise it. The sampling method involves inserting a pin into a lug nut shaft attached to the tank to pierce the surface by tightening the fitting using a spanner. A threaded nut is used to seal the hole following sampling. This strategy has been tainted by past industry practices resulting in corrosion and premature failure of the transformer (44).

1.6 LITERATURE REVIEW CONCLUSIONS

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. 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 appears promising, however, this method may damage the transformer, it is time consuming and the technique would have to be modified for individual transformers.

The SERS 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 vent, is PTR-TOF-MS. This method has been used in a laboratory setting to measure PCBs in the vapour phase. SIFT-MS 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 must be present in the headspace. Current and potential commercially available techniques are summarised in Table 2, 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.

Part of this project includes a laboratory study to understand what PCBs are in the vapour phase of the headspace of a live transformer and the sensitivity requirement of measuring these. Both are fundamental to understanding whether a current technique can be used to determine if oil in live transformers are contaminated with PCBs by measuring the headspace alone. It is possible, that even if using a very highly sensitive technique, a zero response does not indicate that no PCBs are present in the transformer oil. There may still be the stable, more chlorinated compounds in the oil that do not enter the vapour phase. Testing will be carried out as per the standard technique using SKC 226-129 PUF/XAD-2/PUF sorbent tubes followed by high resolution GC-MS. Active sampling of a test transformer contaminated with PCBs will be carried out for 24 hours and sent to an external laboratory for analysis. Test reports of the contaminated test transformer oil provided by Western Power Distribution (WPD) should be supplied in order to understand which congeners present in the oil are present in the vapour phase.

If the results of the headspace analysis show that PCBs are present in the vapour phase of live transformers (may require heating) and if PTR-TOF-MS is chosen as the technique to take forward for this application, further testing will be required to understand the partition function of different PCB congeners and a correlation curve will need to be generated using different concentrations of PCBs in different oil samples. This correlation between the levels of PCBs in the gas phase to the concentration of PCBs in the oil is required in order to provide discrimination near to the 500 ppm limit value, to avoid either too many false positives or false negatives.

Table 2: Commercially available options for determining PCBs in the oil of live, pole-mounted transformers and off-line transformers.

	Live Transformer		Off-Line Transformer	
	Real-Time	**Laboratory**	**Real-Time**	**Laboratory**
Headspace / gas	PTR-TOF-MS	PUF with GC-MS	N/A	PUF with GC-MS
	SIFT-MS			
Oil	Drill and seal with Clor-N-Oil	Syphon through breather tube with GC FTIR or GC-MS/ECD	Clor-N-Oil	GC-MS/ECD
	Syphon through breather tube with Clor-N-Oil			

2 WP 1.2 COST-BENEFIT ANALYSIS

Current techniques used to determine if a transformer contains oil contaminated with PCBs involves taking the transformer off-line to safely access the oil, followed by a simple Clor-N-Oil colorimetric test. While Clor-N-Oil test kits are inexpensive, the cost of taking 300,000 potentially contaminated transformers offline both in terms of time and loss of profit, would be huge and is considered a last resort. With 300,000 potentially contaminated live transformers, there is a requirement for a technique that can determine in real-time the presence of PCBs from pole-mounted, live transformers. In order for this technique to be cost-effective, both the sampling and analysis time must be fast, effective and have the ability to be made mobile to travel to 300,000 different transformers.

The most crucial element in attempting to measure PCBs in the headspace of transformer oil is the concentration of PCBs in the vapour phase. Currently, the existing analytical techniques are likely not sensitive enough to measure PCBs directly from live transformers at typical operating oil temperatures and therefore either sample pre-concentration or chemical conversion to a measurable compound may be required. To implement either of these would require further research and development. With this in mind, following a detailed literature, patent and internet search, we have concluded that there are very limited options for measuring PCBs from the breather tubes of transformers or for accessing the oil of live transformers with subsequent measurement. In terms of the commercial availability, a PTR-TOF 4000 coupled with EVR (extended volatility range) from Ionicon Analytik, coupled with hot-line rods for sampling from air from the transformer breather tubes may have potential for this application. Past literature has investigated the use of the PTR-TOF 8000 for measuring PCBs in the vapour phase, however, this model is not manufactured anymore. PTR-TOF 4000, although has a slightly lower mass resolution (> 4500) compared to the 8000 (>5000) (its ability to distinguish two peaks of slightly different mass-to-charge ratios), it has a higher sensitivity. It is the smallest and lightest high-resolution PTR-TOFMS real-time trace VOC analyser. It has the capability of measuring PCBs in real-time with a detection limit of < 5 pptv (transformer would need to have a temperature of approximately 450 K). Coupling this with EVR allows the use of a specially coated drift tube rather than a standard stainless-steel drift tube. This allows the measurement of sticky compounds and reduces the response time significantly. The estimated cost of this instrument coupled with the EVR drift tube is EUR 320.000. This excludes VAT, taxes, import taxes and duties and, shipping. There is an approximate lead time of 35 weeks from ordering to allow this instrument to be manufactured whilst delivery times from the manufacturer to the UK will take approximately 5 working days.

There is a possibility of leasing this instrument. For a basic configuration for 3 months (the minimum rental period) the cost, including shipping, 2 days installation, training and insurance is in the range of EUR 45.000. If you rent such an instrument including the “option to buy”, 80% of the rental fee (excluding shipping, training, installation, insurance) will be deducted from the purchasing price of the rented instrument.

Tofwerk offer a similar instrument, Vocus PTR-TOF, which according to the manufacturers, can measure PCBs with an estimated detection limit in the range of single digit pptv’s. A Vocus PTR-TOF has been installed previously into an Aerodyne mobile laboratory indicating this instrument is suitable for mobile measurements (26).

Hot-line rods are commercially available in the UK, with many supplier options. On average, they are costed at approximately £35 per 1.22 metres excluding VAT and delivery costs.

Table 3 summarises the costs, benefits and drawbacks of PTR-TOF-MS, accessing the oil of a live transformer via drilling with subsequent analysis, and current de-energising practices followed by Clor-N-Oil testing. A Canadian company, Powertech, provide tools for sampling oil from live transformers. Further discussions with both WPD and Powertech are necessary to understand the costs and benefits of choosing this technique. Furthermore, discussions with WPD are required to provide an estimate of both staff costs for carrying out the different measurement options, and the cost of de-energising a transformer.

Table 3: Cost of PTR-TOF with hot-line rods for sampling versus the cost of de-energizing the transformers to obtain an oil sample.

	PTR-TOF-MS with Hot-Line Working		**Drill and Seal via Hot-Line Working**		**De-Energising Transformers**	
Capital Cost	Analyser plus EVR	€320,000.00 (~£280,000)	Live-Line Tools	Canadian company £?	Taking transformers offline	£?
	Hot-Line Rods	£175.00	Clor-N-Oil Test / sample	£22	Oil Access	£?
	Mobile Installation	Suitable transit type van			Clor-N-Oil Test / sample	£22
Staff Cost	~30 minutes / transformer with 2 staff members	£?	2 or 3 transformers / day with 2 staff members	£?	1 day / transformer with ? staff members	£?
Advantages	Fast and sensitive measurements of heated live transformers		Access to oil while transformer is live followed by cheap analysis		If inexpensive to take offline and access the oil directly, Clor-N-Oil is a cheap detection technique	
Disadvantages	Further laboratory testing required before this can be deployed; PCBs possibly not in headspace		Further laboratory testing required before this can be deployed, potentially time consuming, and further expensive analysis may be required		Time consuming. Loss of profits from offline transformer, and further expensive analysis may be required	
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