Asbestos sensing review:

Emerging technologies for asbestos in waste

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Executive Summary

This report was commissioned by the NSW Office of the Chief Scientist and Engineer under their efforts to provide independent advice in relation to the safe and effective management of asbestos in recovered fines and other recovered material for their beneficial reuse.

The purpose of this Expert Paper is to provide an updated perspective on the current and emerging technologies that are relevant to real-time asbestos sensing. The review considered both commercially existing products and results reported in the global academic literature. The use of asbestos containing materials in Australia was gradually phased out in the 1980s, and therefore technologies for their real-time detection in potentially contaminated areas has become a vibrant field of research. Recent work is fuelled by advances in automation, AI/machine learning approaches, and the miniaturisation of sensor technologies.

Current standards for asbestos monitoring are well regulated in most countries. The generally accepted approach involves sampling materials and analysing them in laboratory settings. Optical and electron microscopy methods are often used, with spectroscopic measurements assisting as well. Handheld spectroscopic devices are available on the market, but this Expert Paper has found that there are challenges associated with these in real-world environments. The scientific basis is sound, however when the environment consists of a wide variety of asbestos containing materials and non-asbestos materials, the devices can provide false results. We report on some of the parameters that should be carefully considered when utilising these techniques.

This report's main findings are as follows:

- Real-time asbestos measurements from a single system remains a challenge and should be done in conjunction with approved standard methods.
- **Automated (AI-assisted) asbestos fibre counting methods** on microscope images should be considered be used in parallel to standard procedures. This can assist in the accuracy and speed of analysis. Advances in microscopy also allow for on-site detection and potentially even continuous monitoring.
- **AI-assisted image recognition** for asbestos types is nascent, yet potentially encouraging field of research. Under certain constraints, e.g. environments with a consistently known variety of mixed wastes, this approach could be feasible at low-cost.
- **Near infrared spectroscopy** shows a great deal promise for asbestos detection from a compact device. Care needs to be taken in ensuring the device achieves enough spectral resolution to differentiate asbestos minerals from their non-asbestos counterparts.
- **Hyperspectral imaging** in the short-wave infrared also is an emerging technique that may be able to be part of a mixed waste sorting system. Despite the challenges associated with varying surface conditions, signal processing techniques may allow suitable performances.

In addition to the above, several other promising techniques are covered in this report. This report only considered the techniques from a scientific angle (bottom-up) and has not examined the operating conditions for these sensors. Depending on the exact use-case a more appropriate/simpler solution may be suitable. Future directions for work should include closer inspection of the users/personnel who are at risk so that a suitable solution can be designed.

Glossary of Terms

ACM	Asbestos-containing material
AI	Artificial Intelligence
BRII	Business Research Innovation Initiative
CRI	Commercial Readiness Index
CNN	Convolutional Neural Network
DRIFT	Diffuse Reflectance Infrared Fourier Transform
EU	European Union
f/mL	Fibres/mL
FTIR	Fourier Transform Infrared Spectroscopy
FM	Fluorescence Microscopy
HSE	Health and Safety Executive (of the United Kingdom)
LIDAR	Light Detection and Ranging
LIBS	Laser Induced Breakdown Spectroscopy
NATA	National Association of Testing Authorities
NF	Novel Fluorescence
NIOSH	National Institute for Occupational Safety and Health
NIR	Near Infrared
NSW	New South Wales
OCSE	Office of the Chief Scientist and Engineer
PCM	Phase Contrast Microscopy
PLM	Polarisation Light Microscopy
SEM	Scanning Electron Microscope
STEM(-in-SEM)	Scanning Transmission Electron Microscopy (-in-SEM)
SWIR	Short Wave Infrared
TEM	Transmission Electron Microscope
TRL	Technology Readiness Level
w/w	Weight/weight
XRD	X-ray Diffraction
XRPD	X-ray Power Diffraction

1. Introduction

In December 2022, the Office of the NSW Chief Scientist & Engineer (OCSE) was requested by the previous Minister for Environment, the Hon. James Griffin MP, to provide advice on the management of asbestos in waste and recovered materials intended to be beneficially reused.

The real time and accurate detection of asbestos in waste material is a major challenge faced by the industry. Current industry processes rely on visual inspection of incoming waste materials. This requires a skilled worker to search through loads to identify suspect material. Existing methods require physical samples to be collected and later analysed at a laboratory, delaying the processes involved with waste management. However most times suspect material is not tested and just rejected as non-useable material. To aid this situation, and alleviate the associated health risks to workers, several technologies have emerged on the market for real-time sensing. This is also explored in academic literature where new techniques for identifying and quantifying asbestos in composite materials are often being proposed. To better understand these developments, OCSE has commissioned this report to provide an expert review of existing and emerging technologies to aid future decisions.

The aim of the report is to:

1. **Outline the basic scientific characteristics of asbestos** that are relevant to their detection methods.

2. **Map technologies and equipment** that are commercially available for asbestos detection in Australia (and overseas) and compare their accuracy and efficiency, including in different waste types, as well as training requirements.

3. **Identify new and emerging technological solutions** for real-time and accurate detection of asbestos in waste, particularly when processing waste for beneficial reuse, considering
    a. technology maturity (TRL/CRI level)
    b. estimated time to market
    c. applicability to waste type

2. Definition and molecular structure

Asbestos is a collective term used to describe a set of silicate minerals (chrysotile, amosite, crocidolite, actinolite, tremolite and anthophyllite) that belong to the **serpentine** and **amphibole** groups. Of these, chrysotile is the only serpentine type, and accounts for around 95% of naturally occurring asbestos [1]. Although this report will not dive deep into its chemistry, it is important to cover as it is relevant to how existing technologies uniquely identify them. Chrysotile's chemical composition is $Mg_3Si_2O_5(OH_4)$, and in some cases the magnesium ions can be replaced by iron or nickel via isomorphic substitution [2]. The material forms a layered structure, called 'sheet silicates' as shown in Figure 1, which consists of a magnesium-based octahedral layer and the silicon-based tetrahedral layer. The difference in bonding strengths between the layers causes the structure to prefer to bend and spiral, forming the familiar fibrous material. Of importance here are the two layers of the OH bonds – the interlayer and the inner groups. These bonds absorb light to a specific the vibrational energy, determined by the composition of the material, gives a way to uniquely identify the through spectroscopic means.

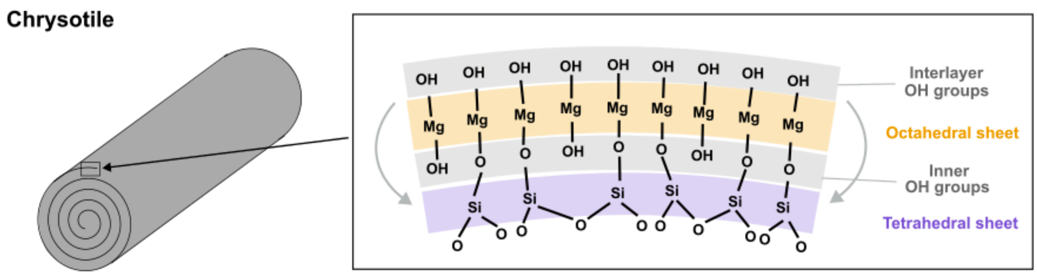


Figure 1: A generic view of a chrysotile fibre, the only serpentine type of asbestos fibre. Its molecular structure consists of Mg-based octahedral and Si-based tetrahedral sheets, which causes the overall structure to 'curl' into spiral structures.

The other category of the amphiboles can have structures with much higher variation. Again, without going into the details, these form 'chain silicates' where the tetrahedra arrange to form a double chain of two rows side by side, Figure 2, resulting in short needle-like structures [3]. Here the general formula is M"SiO_3, (tremolite, for example, is formulated as $Ca_2Mg_5Si_8O_{22}(OH)_2$) and the cations can be replaced with a variety of metals such as Mg, Fe, or Ca, resulting in an extremely wide range of compositions. The OH groups are also of importance here as the strength and length of the bonds are extremely sensitive to their local arrangement of atoms, making it a good indicator for identification.

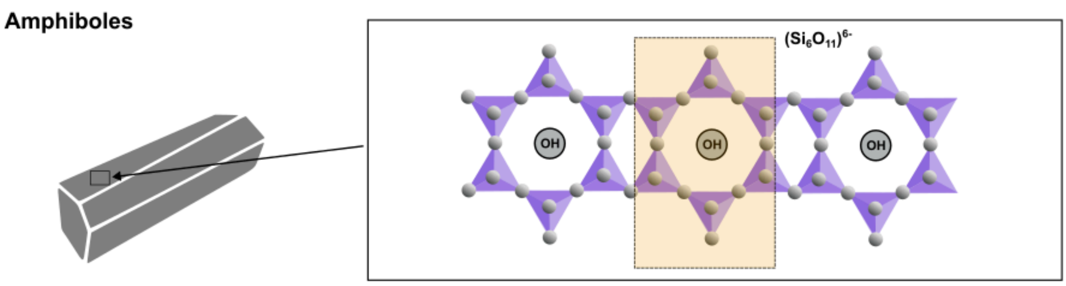


Figure 2: Overall structure of an amphibole fibre – consisting of a double chain of silica tetrahedra.

It is also important to note that even with the same chemical make-up, minerals can form into *non-asbestos* forms which have a different structure. For example, a non-asbestos form of chrysotile is lizardite, which has a sheet-like crystal arrangement that does not form fibrous structures. This prevents it from having the same health risks as chrysotile, but care should be taken to be able to differentiate these non-asbestos forms their asbestos counterparts. There is an extensive literature on the spectral characterisation of asbestos samples available [4, 5]. Section 3 elaborates on the conventional ways asbestos types are identified where many technologies make use of the knowledge built in this literature to develop more portable rapid sensing techniques.

3. Conventional methods for asbestos sensing

There are several existing techniques used to characterise asbestos fibres, see Table 1. Here we cover them at a basic level to establish the starting point before moving to the emerging technologies.

Table 1: A list of conventional methods to identify the existence of asbestos types. These include qualitative and quantitative methods.

Mode	**Technique**	**Reported detection limits**
Optical microscopy	• Phase contrast microscopy • Polarisation light microscopy	0.01f/ml [6] 0.01-0.1%. [7]
Electron microscopy	• Scanning Electron Microscope • Transmission Electron Microscope	<0.1% [8]
X-ray diffraction	• X-ray Powder Diffraction	1-3% [7, 8]
Vibrational spectroscopy	• Fourier transform infared spectroscopy (FTIR) • Diffuse reflectance infrared Fourier transform spectroscopy (DRIFT) • Raman spectroscopy • Near-infrared spectroscopy	2% [9] 10% [10] Not reported 0.1% [11]

Optical microscopy

The primary method used to qualitatively detect the presence of asbestos is through the visual identification under a microscope. **Phase contrast microscopy (PCM)** is one technique that highlights the fibres in the field of view (by using optical interference) so that they can be counted more accurately. Although it is a relatively quick, cost-effective and requires relatively less experience to conduct the analysis, it is not a complete method as it does not differentiate asbestos fibres from other non-asbestos fibres. It is stated by certain experts to be interpreted only as an "*upper limit of the possible airborne asbestos fibre concentration*" and should be part of several analysis techniques [12]. The US Centre for Disease Control provides guidelines under the National Institute for Occupational Safety and Health (NIOSH) for use of PCM in asbestos detection [13], with reports stating that the typical sensitivity of the method is approximately 0.01f/mL – a level that is higher than what is found in non-occupational environments [6].

Polarisation light microscopy (PLM) is another common method which measures the optical properties unique to specific asbestos species. It is still a qualitative method but when done carefully by combining dispersion staining techniques in accordance with AS 4964 it can achieve a 0.01% to 0.10% w/w detection limit [7] (the estimation of the asbestos content is possible, but not NATA accredited). This standard details the procedures required for the identification of amosite, crocidolite and chrysolite in bulk samples. PCM can also be used in combination with PLM to achieve more easily interpretable results.

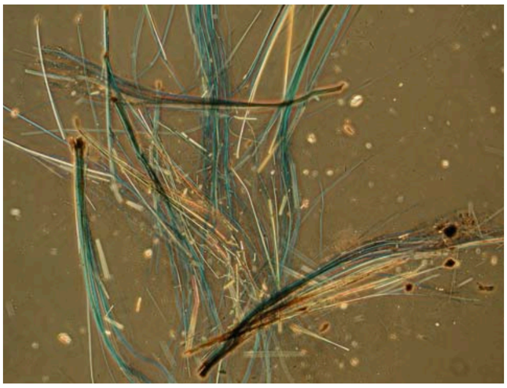


Figure 3: Crocidolite fibres viewed under PLM, showing interference colours (birefringence) and parallel extinction at x125 magnification. Image was sourced from [14].

The majority of these methods are often done on samples collected in accordance with ISO 22262-1:2012 [15] and analysed at a NATA accredited laboratory, requiring adequately skilled personnel. There has been some emerging research in using machine learning approaches to automate this manual inspection procedure. Some emerging technology also explores the use of remote microscopy analysis coupled with automatic image recognition software – which will be detailed in Section 5.

Electron microscopy

Optical microscopy methods are ultimately limited by the resolving power of the microscope, which typically limits detection of only ~0.4-micron wide fibres [16]. Smaller fibres/structures need to move to electron microscopy (resolution of 1-20 nm). Both Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM) are used for the detection of asbestos (NIOSH Method 7402, [17]). Although it comes at the complexity of requiring access to the infrastructure, extensive sample preparation, and skilled staff, it can measure the morphology of the fine fibre structures (Figure 4). The counting accuracy here is difficult to state given the field of view (after ~150,000x magnification) is extremely small. If one assumes homogeneity of the view, estimates can be made to the overall detection limits being 47-170 x 10^{-6} f/g (~ug/g) [18].

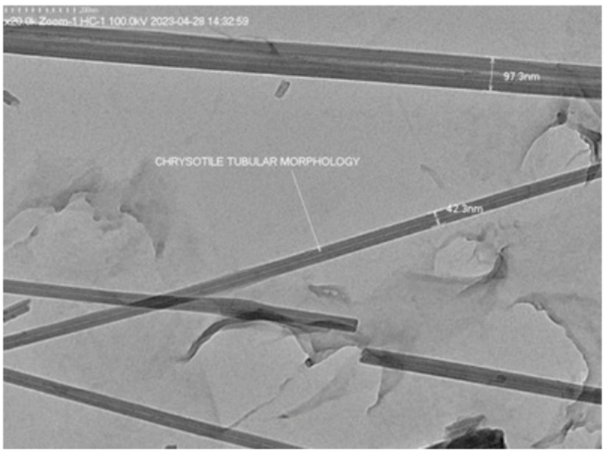


Figure 4: TEM observation of chrysotile asbestos fibre at a display magnification of 150,000x. Image sourced from [76].

X-ray diffraction

SEM/TEM methods can determine surface features, size, shape, structure and chemical composition of asbestos species – however (generally) their accessibility still limits their use for scalable real-time monitoring. X-ray diffraction (XRD) offers a relatively faster and lower cost method – depending upon the amount of measurement rigour. As the name suggests, the method passes X-ray radiation through a sample, often a sample that has been turned into powder, and the diffraction pattern of crystal structures are analysed. The size of the observed diffraction peaks relates to the amount of asbestos material contained inside the sample. It is mentioned in ISO 22262-3 [19] that XRD cannot distinguish the morphological habits of the same mineral – meaning it cannot discriminate between the asbestiform and non-asbestiform analogues of serpentine and amphiboles. Thus, the diffraction peaks detected in this technique are considered as "possible peaks of asbestos". XRD was applied on a perlite board containing chrysotile, and easily quantified its asbestos concentration at 24.1 mass%, and the authors stated the analysis of 0.1 to 1 mass% should be possible [20]. The 0.1 - 1 % w/w limit of detection range seems quite typical for bulk samples when considered solely as a 'present/non-present' detection mode. X-ray powder diffraction (XRPD) is a rapid method of XRD where suspect material is collected, ground into a powder, and collectively analysed with X-rays. XRPD has been successfully applied to detect the distinct crystallographic features of tremolite and chrysotile for samples of 1% and 3% ACMs [21].

These methods can be extended to provide quantitative measurements. The US EPA describes the process for this highly depends on parameters such as particle size distribution, preferred orientation, and matrix absorption affects [22]. Careful sample preparation, such as thin (~10um) samples deposited onto a silver filter alleviates some of these difficulties, and appropriate correction factors need to be applied to account for X-ray absorption and matrix affects (such as fluorescence). This is often achieved using calibration factors, which can result in a 1% chrysotile in talc to be measured with a precision of 12.5% [23]. The same can be done in XRPD. Taylor described a procedure for materials consisting of chrysotile [24]. The process requires careful milling of fibres, removal of carbonates using acetic acid, and adding precise amount of nickel oxide as a control. X-ray analyses are made and the relative peak height difference between the control and chrysotile peaks (e.g. at 7.36-A) are measured. A calibration graph is then used to convert this ratio to a chrysotile concentration percentage (5-80%). There is, however, mention that these calibration lines may be dependent upon the origin of the asbestos samples as they could have differing chemical compositions.

XRD/XRPD methods are reliable and used routinely for material analysis. Modern commercial units can be bench-top sized, Figure *5*, and physically can be placed within a waste recycling centre. Although it may be feasible to serve as a second line of confirmation after visual identification, one of the biggest drawbacks for a real-time monitoring system is the time required for sample preparation, and that it does not determine the fibrous habit of the minerals. This becomes even more so when considering quantified measurements.

Figure 5: A benchtop power XRD device. Although sample preparation is required to perform accurate measurements, the devices themselves have progressed to be able to be located at waste recycling centres. Image sourced from [25].

Vibrational Spectroscopy

Vibrational spectroscopy is of significant interest as it has a strong potential to be performed remotely. These look for the vibrational modes in molecular bonds in the asbestos, which typically lie in the infrared region of the electromagnetic spectrum. This allows for the unique detection of asbestos species [26]. However, it should be noted that the measurements do not resolve individual fibres, are more a collective measurement, and therefore can have influences from other nearby non-asbestos material. Given these are an elemental composition analysis, they do not determine morphology or fibrous habit. Care needs be taken in the interpretation of these results, and often it is used in conjunction with the previously mentioned techniques. These methods are often broken into three main areas of Fourier Transform Infrared Spectroscopy (FTIR), Raman Spectroscopy, and Near Infrared (NIR) spectroscopy.

FTIR techniques for asbestos have drawn attention due to it being non-destructive, cost-effective, and fast (minutes for measurements) [27]. The absorption bands in the infrared region from 800 cm^{-1} to 1100 cm^{-1}, associated with the Si-O stretching vibrations, and around 3650 cm^{-1}, OH stretching vibrations, have shown promise as unique identifiers of asbestos types [27, 28]. With appropriate care being given in the sample preparation and analysis these can yield accuracies in the 2% w/w [9].

Diffuse Reflectance Infrared Fourier Transform (DRIFT) spectroscopy is a particular application of FTIR where the IR light is scattered by a rough surface, collected with optics, and then measured on a detector. As mentioned by Ventura et. al. in [4], "*This technique is helpful when studying cement-asbestos, because the powder to be analyzed can be easily scratched off a wall, a brick, or a roof tile by using an abrasive paper, and subsequently placed onto the DRIFT sample holder without any further preparation*". Studies have shown that a typical device (Figure 6) is able to achieve 10% w/w limit of detection when testing with asbestos bulk samples [10].

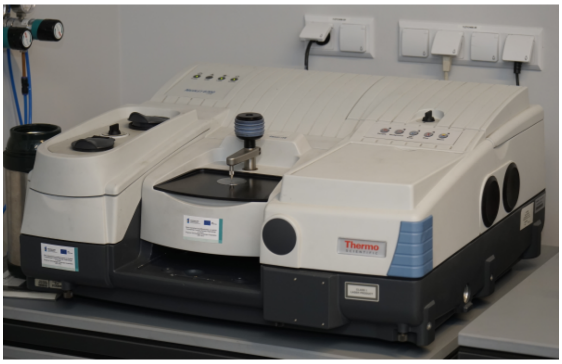


Figure 6: FTIR spectrometer (Nicolet 6700) used for high-quality infrared spectral measurements. This benchtop device allows for relatively simple analysis of asbestos species. Image sourced from [29].

Raman spectroscopy can also be used to measure specific bonds in asbestos species. In a similar way to IR spectroscopy, this is done by monitoring the inelastic scattering of laser light from the sample. Specific peaks in the spectrum correspond to vibration modes and can act as an identifier for asbestos – both for serpentine [30] and amphiboles [31]. When samples are powdered and prepared for benchtop experiments (including liquid N_2 cooled detectors), Raman spectroscopy provides a reliable way to distinguish asbestos from its non-asbestos counterparts [30]. One advantages of this technique is that the optics (light sources, lenses, and detectors) can be simplified to build a portable device. Commercial devices already exist on the market (such as the *RaPort* from Enspectr [32] , Figure 7) where portable measurements can be made from a handheld device. This specific device was tested on various in-situ samples from a mine consisting of asbestos and non-asbestos materials, registering an 80% success rate in terms of spectral quality to identify the mineral phases [33]. It was noted that challenges remained in there being interference from background fluorescence signals from the host material. It was also noted in this study that pointing the laser beam on non-cohesive and irregular surfaces also caused problems, noting that a skilled geologist was operating the device to ensure high quality measurements.

Figure 7: RaPort handheld Raman spectrometer from Enspectr – for in-field diagnostics of minerals. This device uses a green (532 nm) laser to use Raman spectroscopy analyse various minerals, including asbestos. Image was sourced from [34].

A more recent study has found that the use of Raman spectroscopy was not as successful when tested against a wide range of asbestos containing materials (ACM) [11]. This has been attributed to the fact that the Raman spectra of asbestos minerals and their non-asbestos forms (chrysotile and lizardite, amosite and grunerite, crocidolite and riebeckite) are very similar and causes confusion in their correct identification [35, 36].

Near-infrared spectroscopy looks at the 7,300-7,000 cm^{-1} regions corresponding to the overtone of the OH stretching vibrations in the mid-infrared region. Typically, the fundamental absorption lines are the strongest, but recent studies have shown that NIR spectroscopy achieves almost a 10-fold increase in the absorbance of light from ACM. This has been attributed to the fact that the sampling distance depth at these two wavelengths are significantly different (~ 1 mm for NIR, as compared to ~10 um for the mid-IR) [11]. On top of this, the anharmonicity of the OH band position allows for better separation of the absorption lines from different asbestos types – making identification easier. In this study undertaken by Zholobenko [11], it was stated by testing over a range of ACM (including wools, bitumen, cement, plasterboard, floor tile and bricks) the NIR method performed the best when compared to FTIR and Raman spectroscopy. Results indicated that it was comfortably able to achieve a 0.1% w/w detection limit under these conditions.

Furthermore, optical components at the NIR wavelengths are extremely well-developed at low-cost due to the demands in the telecommunications industry. This allows the fundamental components (light sources, detectors, etc.) to be reliable, easily available, and at a small footprint. As such, compact NIR spectrometers have been available in various industries (medical, agricultural) and for asbestos detection. The Thermofisher microPHAZIR [37] has been a prime example of this technique built into a portable device for real-time analysis, Figure 8. One particular application note from Portable Analytical Solutions (PAS) has stated this device performed 48/49 (98%) successful readings on a range of ACMS [38]. It should be noted that this source did not specify details of the samples tested – such as what materials they were, and what concentration of asbestos was contained.

Figure 8: Thermo Fisher Scientific's handheld microPHAZIR AS product – able to identify ACM using NIR spectroscopy. Image sourced from [38].

Foreseen issues with NIR spectroscopy

In 2019 the Queensland Government issued a safety alert for the use of NIR handheld analysers for the identification of asbestos-containing materials [39]:

> *"NIR handheld analysers do not meet the requirements of work health and safety legislation in respect to identifying ACM. The handheld NIR is not an appropriate test method.*
>
> *There is limited peer-reviewed scientific literature, from manufacturers of NIR handheld analysers or others, to validate claims that the NIR handheld analysers are unequivocal in identifying asbestos in a wide range of materials."*

This may have been triggered by inconsistent results achieved by related products on the market. It insists to follow the AS 4964 standards which recommends the usage of PLM with dispersion staining. In response to this statement, the previously mentioned commercial operator PAS had also released statements saying they would investigate issues associated with this particular product through *"…peer-reviewed papers prepared through local University teams"* [40]. No such studies have since been sighted since this announcement.

Meanwhile, the academic literature continued to study and test these techniques and investigated where the limitations arose. To date, Zholobenko's study [11] remains one of the most comprehensive tests conducted for ACMs. In this study one of the key recommendations for accurate NIR spectroscopy was to ensure adequate spectral resolution is achieved. Significant degradation of the technique's ability to differentiate between asbestos types (actinolite, amosite, crocidolite, and chrysotile) was observed as the resolution increased from 6.2 nm to 0.39 nm. Other studies using NIR to measure asbestos have also noted spectral resolution being a key factor [41]. Careful analysis of the measurements using Principal Component Analysis has led to some success, but it is not evident form this study whether the same results can be achieved with bulk ACMs. Zholobenko [11] recommends a high resolution of **0.3-0.5 nm** across the 1370-1430 nm band to ensure good identification. Typical handheld NIR spectrometers do not achieve this level of resolution (a few nanometres and above) due to size limits posed by focal plane arrays and optical layouts required to achieve the dispersion. The microPHAZIR is listed as *"8 nm (pixel resolution) and 12 nm (optical)"* at these sources [42]. Some other sources mentioned specific versions having 1 nm optical resolution [43], although given these are only data sheets, **a recommendation is made to measure the exact resolution from these devices in reality.** Optical spectrum analysers (benchtop devices) can reach sub-picometre resolution, but promising devices are emerging that allow for 50 pm resolution from a show-box sized device [44].

4. Mapping existing technologies

As covered in Section 3, there are emerging products on the market to conduct real-time asbestos identification. It is not possible within this report to comment on the quality of the measurements across different ACMs but we provide a list of relevant technologies and some commentary around its usage. Table 2 provides the list of these products.

Product name	Technique	Features	Comments	Ref.
microPHAZIR	NIR spectroscopy	• Handheld/portable • ~seconds per measurement	Optical resolution typically low, may face issues differentiating bulk samples.	[37]
RaPORT	Raman spectroscopy	• Handheld/portable	May face difficulty with background fluorescence.	[32]
Asbestoprobe	NIR spectroscopy	• Handheld/portable • ~seconds per measurement	Developed in partnership with Keele University. Optical resolution questionable.	[45]
ALERT Pro	Light scattering	• Airborne asbestos detection using laser scattering	Original parent company discontinued the product, but research on the technique is on-going	[46]
HySpex	Hyperspectral	• Real-time monitoring of mixed waste • High throughput	Operates on industrial conveyer belt setting, exact performance yet to be verified,	[47]

The microPHAZIR and RaPORT were mentioned in the previous section, and in addition we discuss the following products.

Asbestoprobe – developed by Greenwall is a handheld NIR asbestos sensor, Figure 9. It allows measurements to be made within ~10 seconds on suspected ACM, covering all six forms of the material. However, there are no details available on the product's performance, specifications, and any relevant field tests. The company claims to be collaborating with Keele University's Chemistry Department (Vladimir Zholobenko) who has a track record of rigorous testing of ACM identification as shown in Ref. [11]. The literature claims that sub-nanometre resolution is required for NIR spectroscopy to be accurate, and given the size of this device, it remains questionable whether this device can achieve this. NIR spectrometers typically require substantial optics that is housed within a tissue-box sized volume (such as the *Dwarf-Star* spectrometer at approximately 13 x 8 x 6 cm from StellarNet Inc [48]) which achieves 1 nm resolution over 900-1700 nm. It indeed could be feasible that for a smaller spectral window (e.g. 1300-1500 nm) is being monitored at high resolution from the Asbestoprobe, but without further evidence it is difficult to confirm. Presently this product should be taken with a level of optimistic caution in terms of its performance.

Figure 9: The handheld Asbestoprobe commercialised by Greenwall, which utilises the power of micro near infrared spectroscopy combined with artificial intelligent software. Image sourced from [45].

ALERT Pro 1000 was developed from research in the 1990s by the University of Hertfordshire, that explored a way to count asbestos fibres through a light-scattering technique. Although it was initially developed for airborne monitoring, the technology is worth mentioning as they could be strategically placed in conjunction with other sensing devices to best understand ACM contamination. Direct scattering of light from airborne fibres, in the right conditions, allows for a method to estimate the length and diameter. Baron [49] provides an extensive review of these approaches – many of them finding difficulties in replicating the set up and attempts for commercialisation being discontinued. It should be mentioned that the parent company Alert Technology Ltd are in liquidation, but a significant amount of research and development was conducted [46]. The product detects airborne asbestos by pumping air through the device and passing the fibres through a magnetic field. Due to the magnetic susceptibility of asbestos the fibres then orient in a specific direction, allowing them to pass through a laser beam in a controlled fashion. The scattering patterns are then analysed as the fibres rotate to identify whether they were asbestos. The technique claims to respond to both amphiboles and chrysotile fibres, but does not have the ability to distinguish between them. Details are available in European Patent EP 14705390.4.

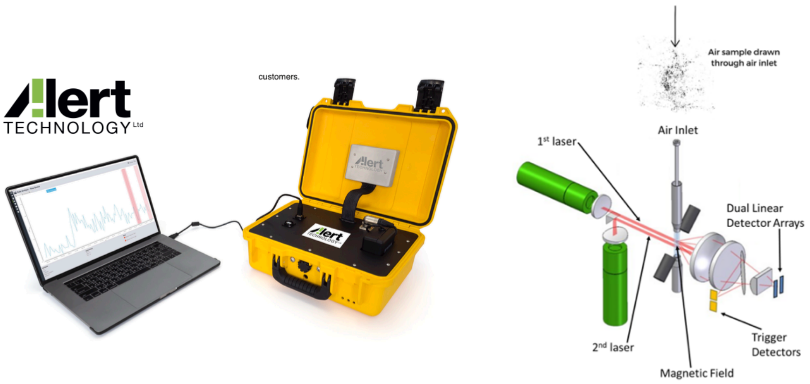


Figure 10: (Left) Alert Technology's ALERT Pro 1000, which uses light scattering from oriented fibres to detect airborne asbestos. (Right) The operating principle of the technology – using magnetic fields to align flowing fibres as they interact with laser light.

The ALERT technology completed an EU Horizon 2020 project in 2013, which reported that the prototypes was tested under a variety of locations including industrial, commercial, retail and domestic buildings where asbestos removal or remediation work was underway. It reported that “In each case, the prototypes successfully identified the presence or absence of asbestos to a 99% confidence level” [50]. No further information is publicly available to comment further on this technique.

Subsequently in 2022 the same technology was explored in the Business Research Innovation Initiative (BRII) administered by the Australian Government through the Department of Industry, Science and Resources. Under this program, Alemir International Pty Ltd undertook a feasibility study “*for ALERT, for a real-time monitoring and warning device for airborne asbestos*” [51], but no further details are available on the outcomes of this project.

HySpex – utilises an optical imaging technique known as hyperspectral imaging. This works by dividing up images into discrete spectral bands (typically across the visible to near-infrared wavelengths) either by splitting the light using a dispersive element, or simply through filters at specific bands. Since materials exhibit different characteristics under different wavelengths, each of these spectral images could provide information that associates to the material composition. These systems have been used to detect ACM in a mixture of construction and demolition waste. Spectral measurements are made using the HySpex Baldur S-382 N camera (930-2500 nm) with a spectral resolution of 5.45 nm [52]. The intention is for this real-time system to identify ACM on a conveyer belt, to work in conjunction with third-party sorting solutions (Figure 11). Despite with these spatial and spectral resolutions, where spectral features may not be clear between ACM and non-ACMS, it is claimed that identification is possible through robust classification models. No specifics are provided here on what type of asbestos samples were tested.

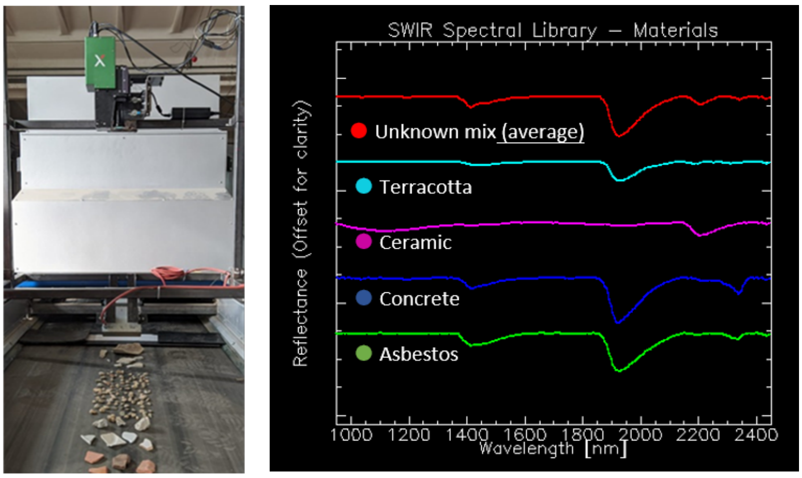


Figure 11: (Left) HySpex Baldur S-384N camera working at ~1 metre working distance to conduct real-time NIR imaging of asbestos samples. (Right) Average SWIR reflectance spectra of five different building materials.

Recent academic literature has also investigated the use of hyperspectral imaging [53]. Here, samples containing amosite, chrysotile, and crocidolite fibres were tested. Typical samples included concrete and plasterboard mixtures which were selected to be representative of the construction industry. Upon application of principle component analysis and an ensemble classification approach, the technique was confirmed to be suitable. The advantage of this method provides rapid identification of ACMs that is a level higher than visual identification. There are no reports on the limits of detection, however perhaps that may not be necessary if this technique is intended to be a course detection, working in conjunction with more precise methods. **This remains an emerging technology with strong potential should it continue to deliver promising results for other kinds of ACMs.**

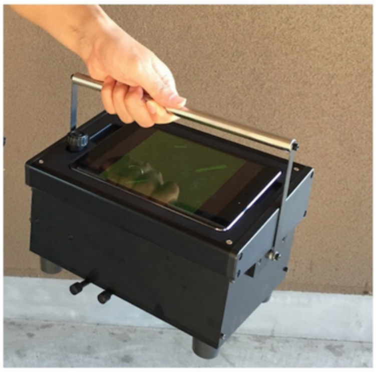
5. Emerging technologies for asbestos detection

In this final section we look toward new technologies that are currently in development which show promise for real-time detection of asbestos. The accuracy of the technique may not fully be realised yet, but we will attempt to map their technology readiness level and eventual impact.

Advances in microscopy methods

As PCM remains the standard approach for airborne fibre analysis, recent innovation has focused on how to automate this procedure or make this labor-intensive process easier. Automating the fibre counting process under a microscope, using the recent advances in deep-learning algorithms has been an area of interest.

Early works from Inou et. al. [54] in 2007 used PCM image analysis techniques (not deep-learning) to extract fibre features and automate the counting for airborne respirable fibre analysis. It has been commented that the process of extracting fibre parameters at times resulted from connecting seemingly disjointed/separate fibres - which contributed to errors [55]. Around the same time a new approach was proposed by Kuroda [56] and Ishida [57] where asbestos fibres are selectively stained using a fluorescent dye (fluorescein) bound to an asbestos-binding protein. These are available commercially and have shown successful results (see Figure 12) – highlighting asbestos from their non-asbestos backgrounds. Subsequently a deep learning convolutional neural network (CNN) algorithm was applied to these fluorescence microscopy images, resulting in a 96% mean average precision rate when compared with NIOSH fibre counting Method 7400 [58].



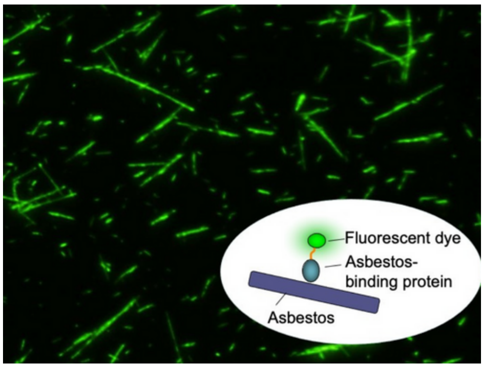


Figure 12: Shining the light on asbestos – Hiroshima University's developments for a robust and portable fluorescence microscope for on-site asbestos detection. Image adapted from [59].

Instead of the accurate counting of fibres, the vision of the technology has shifted to rapid onsite asbestos analysis [59]. As such, a portable prototype has been developed for increased accessibility of the technology (Figure *12*). It should also be noted that the fluorescence microscopy (FM) process has been independently tested by the UK HSE in 2023 [60], and the scientists "*were unable to replicate the findings of the Japanese developers of the FM method and concluded that our results did not at this point, support the use of the FM method for evaluation of airborne asbestos fibres on filter or lung samples*". This being the case, the technique continues to be successfully demonstrated in different ACM such as in talc mixtures [61]. In addition to FM staining, there also has been other reports of staining asbestos with dyes to enhance their visibility - avoiding the need to pulverize potentially hazardous materials [62]. **There is considerable room for further testing on how much fibre identification methods can be improved with these techniques.**

Similarly, promising results have been observed applying deep learning to asbestos-containing SEM images – 87.9% of fibres with a diameter of 0.06-3 µm, being successfully detected [63]. It was commented that this is equivalent to skilled analyst, and 20 times faster than a PCM analyst. It should also be noted that only 25 out of 108 SEM images were used for training the algorithm, leaving plenty of room for further development. Given SEM/TEM still involves a high level of sample preparation and cannot be done in real-time, we will not consider them further for this section of the report. More generally, deep learning algorithms on microscopy images continue to develop and deliver promising results. Rabiee et. al [55], provides an example of deep learning algorithm used on standard microscope images, with the best trained models provides a total precision of 0.84. These results are well within the accepted values of the PCM method.

Recommendation:

Automated counting using AI/machine learning based methods holds strong promise for accurate asbestos counting. Portable microscopes are accessible technologies for on-site usage, and with the assistance of fluorescence staining, these could be conducted in real-time in future. Remote microscopy analysis is also an emerging technology - *Bioscout* is an Australian company that provides a platform that conducts microscopy, to be analysed using machine learning algorithms on the cloud [64]. Although this technology is originally designed to be used for pathogen detection in the agricultural sector, there is certainly a possibility of combining this hardware with the above-mentioned technologies to achieve real-time and asbestos counting.

Figure 13: Bioscout's remotely operated microscopy sensor for automated agricultural disease detection. Platforms such as these could potentially enable remote and real-time microscopy analysis of asbestos fibres. Image sourced from [64].

Macroscopic imaging (including hyperspectral)

It is also worth noting the developments in image identification at a macroscopic level – looking at extracting features from ACM. Although this may seem difficult given the varying types of surfaces involved, a good amount of progress has been seen.

Deep learning methods applied on smartphone images of an ACM has been explored [65]. This study used a 30x magnification clip-on microscope to a smartphone to capture images. Using 7328 images collected over 1,000 samples of cement sheet, the distinctiveness of asbestos was detected in 90% of cases. This suggests that such simple solutions could be quite effective if the observation conditions for the samples are relatively uniform. Caution should be employed as images only capture the exposed surfaces and only a rough examination of material type can be conducted which is only likely to lead to detection when the asbestos is in high concentrations. This technique is not suitable for trace detection of asbestos types in various homogeneous and non homogeneous sample matrices. Future tests will need to be conducted to better understand how the technique varies as environmental conditions change and what range of ACMs the models are effective.

As mentioned in Section 4, hyperspectral imaging in the NIR (1000-2400 nm) combined with appropriate signal processing allows for a promising differentiating mechanism for asbestos. HySpex provides an internal note on how this technology is being used to separate demolition and renovation materials [47]. In this case the TRL is very high, commercial products already in existence, and the research and development needed is to better understand what range of surface types and depths this is applicable for. More details are available in Reference [53] and is another emerging area worth monitoring.

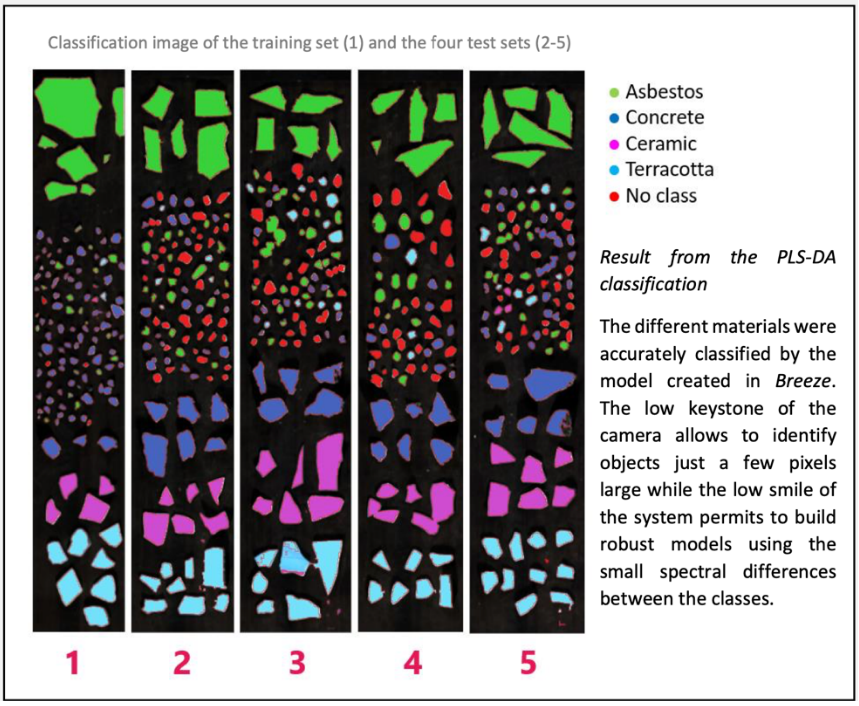


Figure 14: NIR image classification performed on a variety of building materials – identifying whether some of the objects contained asbestos. Image adapted from [52].

Light detection and ranging (LIDAR)

Lidar is a remote sensing method that uses light pulses, often from a laser, to illuminate objects and analyses the reflected components. The time taken for the light to return is used to determine the range to that target and has found significant uses in the autonomous vehicle industry. Typically, for industrial applications, these technologies utilise light sources in the near-infrared spectrum (1,550 nm) and the light emitter and receiver are packaged together. The light beam can be steered mechanically, opto-mechanically using MEMs arrays, or through more advanced non-moving techniques such as spectral or phased-array steering. LIDAR was initially developed to probe the upper atmosphere, and careful analysis of the returning light, such as changes in its spectral characteristics, revealed composition information of the air.

Figure 15: Baraja's LiDAR system initially used in the autonomous vehicle industry. The unit consists of a near-IR laser emitter and detector to produce a point cloud of its surrounding. Image sourced from [66].

In a recent study it was noted that the polarisation property of light is affected upon reflection by the physical structure of the target [67]. This method was improved upon by performing LIDAR measurements with a random modulated continuous wave (RMCW) ranging. This enabled instantaneous measurements that, with the aid of a well-designed photonic architecture, could be rapidly scanned at a range of 10 metres. Basic material classification using this set up yielded promising results differentiating coated aluminium, concrete, black plastic, and engineered wood at an accuracy of 85.4%. Most relevant to this review, subsequent research was conducted by Baraja to examine ACMs with this technique with an overall accuracy of 95% [68]. A variety of representative materials such as roofing, piping, and cement samples containing asbestos were detected at ranges of ~10 m. Although no details were provided on the concentrations in these samples, this shows promise as a macro-scale method prior to more detailed tests.

Other emerging technologies

- **SEM technology development** - It is also worth noting the developments in SEM technologies over the last few decades. Traditionally TEM measurements were favoured over SEM due to its higher resolution and penetration ability to conduct detailed structural and elemental analysis. However, driven by the need for more readily accessible material analyses (particularly in the semiconductor industry) tabletop/benchtop sized SEMs have emerged on the market. A recent study has shown that SEM imaging can be used to identify the diffraction patterns of asbestos types (chrysotile, amosite, and crocidolite) without difficulty [69]. They also note more advanced techniques such as 4D Scanning Transmission Electron Microscopy in an SEM (STEM-in-SEM) may enable automated data collection and analyses over large area [70]. By automating these processes there exists a pathway towards a more efficient, cost-effective asbestos fibre identification.

- **Laser induced breakdown spectroscopy (LIBS)** is a technique also explored for asbestos detection. Here a high energy laser pulse is delivered to the sample, causing a plasma to be generated which emits characteristic wavelengths of light based on the original materials composition. Studies have applied the technique to asbestos samples noting that satisfactory elemental composition measurements were made, with an accuracy comparable to SEM data [71]. Subsequent research has shown this technique can be used to identify the 6 types of asbestos, from an overall process that is faster than PLM and yet simpler than traditional SEM [72]. Though this remains an alternative method for asbestos identification (elemental analysis only and no fibre identification), the complexity of the equipment still should be recognised, and the laser-induced breakdown of material may be itself a source of asbestos fibres/particles being released into the air.

Novel Fluorescence

In 2023 the BRII scheme provided $1 million in funding to the team to Flawless Photonics Pty Ltd to explore "*a breakthrough hand-held real-time asbestos sensor device using novel fluorescence technology*" [51]. A new approach has recently been taken by the University of Adelaide looking at unique fluorescence signatures from ACMs [73]. Here, samples of ACM are imaged under various bands of UV, violet, and blue filters and run through a machine learning algorithm to detect unique features. In essence, this is an adaptation on traditional microscopy image recognition by observing them under fluorescence conditions. It was reported that by adding spectral information alongside with the images, when fed into a machine learning algorithm, an improvement in the accuracy of detection was observed from 78% to 86% [74]. However, there are no previous reports of fluorescence in (unaltered) asbestos or its use in fluorescence-based detection. More research needs to be conducted to understand how the algorithm improved its accuracy, and whether the spectral data had indeed contributed significantly to this increase.

The technology is made to be portable, and the future designs of the product are intending the system to be a hand-held sensor to be used on site. The authors acknowledged that it is not for sensitive detection of ACMS but a secondary method to provide additional data where manual inspection of samples is uncertain. Rather than excluding materials from re-use, when they may not have been non-asbestos, this is imagined to provide a next layer of detection as a preliminary screening technique.

6. Conclusion and comments on TRL

Considering a wide range of sensing technologies for detecting ACMs in bulk materials, it is valuable to consider the broader process of recycled construction materials. Beyond standard asbestos detection asbestos, emerging technologies present various use-cases. Some technologies, acknowledging limited specificity for asbestos types, are put forward as 'early warning' systems, or as secondary options when visible observation is inconclusive.

We break down the process as in Figure 16, consisting of four main sections: demolition site / tipping yard, the point of waste receiving and sorting, physical recycling process, and post-process material analysis. At each stage, there could be risk of contamination where specific sensors could be beneficial. Based on the evidence collected in this Report, we also place a technology readiness level (TRL), in accordance with the definition by the NSW Government [75]. These TRLs, however, are only indicative based on the author of this report and still need to go through a more rigorous process. As previously mentioned, each technology has different advantages and disadvantages, and some can be used in conjunction with one another, therefore it is difficult to state an exact TRL for each method.

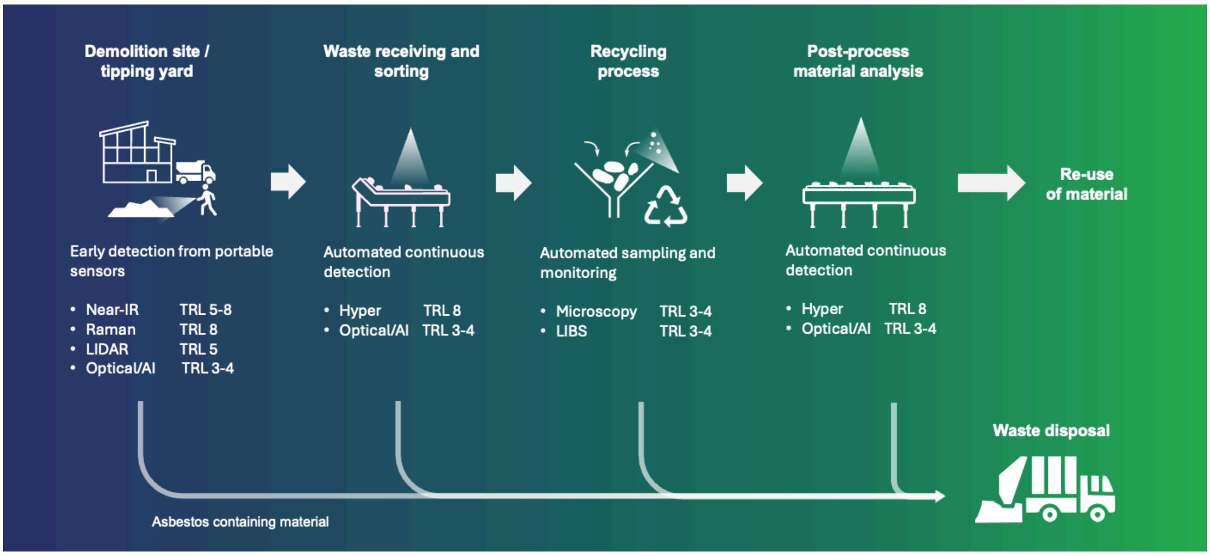


Figure 16: Summary of relevant emerging sensing technologies for asbestos detection, across various points in the recycling process.

1. **Demolition site / tipping yard**

   The site where raw materials are collected may have the highest volume of ACMs . Given the remote environment, access to technologies like microscope analysis, XRD, and SEM/TEM imaging is limited. Low-cost handheld devices could provide valuable information at this early stage. Near-IR sensing has seen commercial adoption (TRL 8), but due to issues with spectral resolution, the most effective devices are still at TRL 5. Raman sensors have been demonstrated at multiple locations and are estimated at TRL 7, though challenges with asbestos type specificity remain. LIDAR approaches are also emerging as a promising technology, having been demonstrated in relevant environments, though more testing is needed (TRL 5). Finally, the optical/camera-based approaches combined with machine learning may also play a role, though they are still in early stages, with recent academic proof-ofconcepts advancing to simple prototypes (TRL 3-4). This includes the fluorescence imaging works mentioned earlier.

2. **Waste receiving and sorting**

   Once the material is received at a processing facility, the volume of material to be examined is high, making automated systems valuable. Techniques such as hyperspectral imaging (currently commercial, TRL 8) have strong potential here. Optical methods also show promise for continuous use across large volumes, though noting their TRL is currently estimated at 3-4.

3. **Recycling process**

   Here, we refer to the physical processing and breakdown of material into a reusable form. Although this may be out of the main scope, sensing techniques could still be relevant. Collecting material samples and analysing them via microscopy methods (such as the dyes) could help mitigate the risk of asbestos contamination. LIBS methods could also be used on well-mixed materials. Both methods are estimated to be at TRL 3-4, with prototypes in development, though further testing is needed to validate these techniques in representative environments.

4. **Post-process material analysis**

   Once the reusable material is ready for dispatch, a final detection step could confirm that no contamination has occurred. Hyperspectral and optical methods are suitable here, as they are automated and capable of high throughput

These suggestions are made solely from a technical standpoint and do not consider the associated costs, infrastructure, or required labour and skills. Accurate early detection would be key to reducing downstream costs and avoiding potential downtimes at recycling facilities. Future work in this area should also include a thorough review of what is operationally feasible for the industry.

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