Inspiring Great British Manufacturing

Report Title: **First-Stage Downselection**

Version Number: 1.0

Project Title: Hyperspectral Imaging for Soils

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Executive Summary

The Environmental Agency (EA) Regulatory Position Statement (RPS) 211 applies to businesses that handle excavated waste from unplanned utilities installation and repair works. Under RPS211, small amounts of spoil from unplanned works can be disposed of or recycled as non-hazardous waste. Electricity North West (ENWL) and fellow utility organisations use this exemption to dispose of or recycle spoil which cannot be reused as backfill for thousands of emergency works activities across the UK each year.

RPS211 is currently under review and will be withdrawn by April 2023 [2]. Withdrawal of this RPS would require companies such as ENWL to classify all of its waste. Without the ability to classify waste on-site, they will be forced to either dispose of all waste as hazardous, or sort and segregate waste at an off-site location. The Energy Innovation Centre has quoted an average disposal cost of £40 for 10 m^3 of non-hazardous spoil, and £1,200 for 10 m^3 of hazardous spoil, with additional costs depending on the type of waste.

ENWL therefore wishes to explore opportunities for technologies which can classify waste on-site. The MTC has offered Hyperspectral Imaging (HSI) as a potential solution and, working collaboratively with ENWL and an independent laboratory (pending advisement from ENWL), is looking to prove the technology as an option to address the problem statement.

The first phase of work aims to demonstrate a proof of concept in a laboratory environment, establishing key contaminants and required sensitivities, and trial selected HSI hardware in a laboratory environment with standardised contaminant samples. The first deliverable of this work detailed inspection requirements [1].

This report constitutes the second deliverable, reviewing commercially available hyperspectral cameras and scoring them against the technical requirements defined in D1, based on manufacturers' specifications and expected performance based on the MTC's expertise. These scores inform selection of systems for practical trials in the third deliverable, and a shortlist of recommended cameras is provided. This report also includes a high-level overview of the practical trials and analysis to be performed in D3.

Contents

1 Introduction

1.1 Background

The Environmental Agency (EA) Regulatory Position Statement 211 (RPS211) applies to businesses that handle excavated waste from unplanned utilities installation and repair works. Under RPS211, small amounts of spoil (≤ 10 m^3, which is approx. 13 tonnes) from unplanned works can be disposed of or recycled as non-hazardous waste. Electricity North West (ENWL) and all fellow utility organisations use this exemption to dispose of or recycle spoil which cannot be reused as backfill for thousands of emergency works activities across the UK each year.

RPS211 is currently under review, and will be withdrawn by April 2023 [2]. Withdrawal of this RPS would require companies such as ENWL to classify all of its waste. Without the ability to classify waste on site, they will be forced to either dispose of all waste as hazardous, or sort and segregate waste at an offsite location. The Energy Innovation Centre has quoted an average disposal cost of £40 for 10 m^3 of non-hazardous spoil, and £1,200 for 10 m^3 of hazardous spoil, with additional costs depending on the type of waste.

ENWL therefore wishes to explore opportunities for technologies with can classify waste on site. The MTC has offered Hyperspectral Imaging (HSI) as a potential solution and, working collaboratively with ENWL and an independent laboratory such as Enviro-Lab (pending advisement from ENWL), is looking to prove the technology as an option to address the problem statement. Spoils should be tested for contaminants in line with *Technical Guidance WM3* [3].

The first phase of work aims to produce a proof of concept, establishing key contaminants, required sensitivities and trialling selected HSI hardware in a laboratory environment with standardised contaminant samples. The first deliverable of this work outlined inspection requirements from both performance (e.g. what contaminants must be detected and at what sensitivity) and practical (e.g. size and cost of hardware) perspectives [1].

This report constitutes the second deliverable, reviewing commercially available hyperspectral cameras and scoring them against the technical requirements defined in D1 based on manufacturers' specifications and expected performance based on the MTC's expertise. These scores are intended to inform selection of systems for practical trials in the third deliverable. This report also includes a high-level overview of the practical trials and analysis to be performed in D3.

1.2 Objectives

Objectives of this report are:

- Provide an overview of commercially available hyperspectral cameras suitable for spoil assessment;
- Identify the most appropriate systems to progress to practical validation trials in D3, by scoring against the technical specification defined in D1;
- Provide a high-level outline of validation trial methodology to be conducted in D3.

2 Downselection Process

The downselection process is used to quantify the suitability of candidate inspection systems for a specific inspection task, scoring each candidate against a number of technical requirements. Figure 1 outlines this process for this project – quantifying the suitability of hyperspectral cameras for detecting contaminants in spoil. This report concerns the third step, first stage downselection. The first two steps were completed in the first deliverable [1], while second stage downselection will be undertaken in the third deliverable.

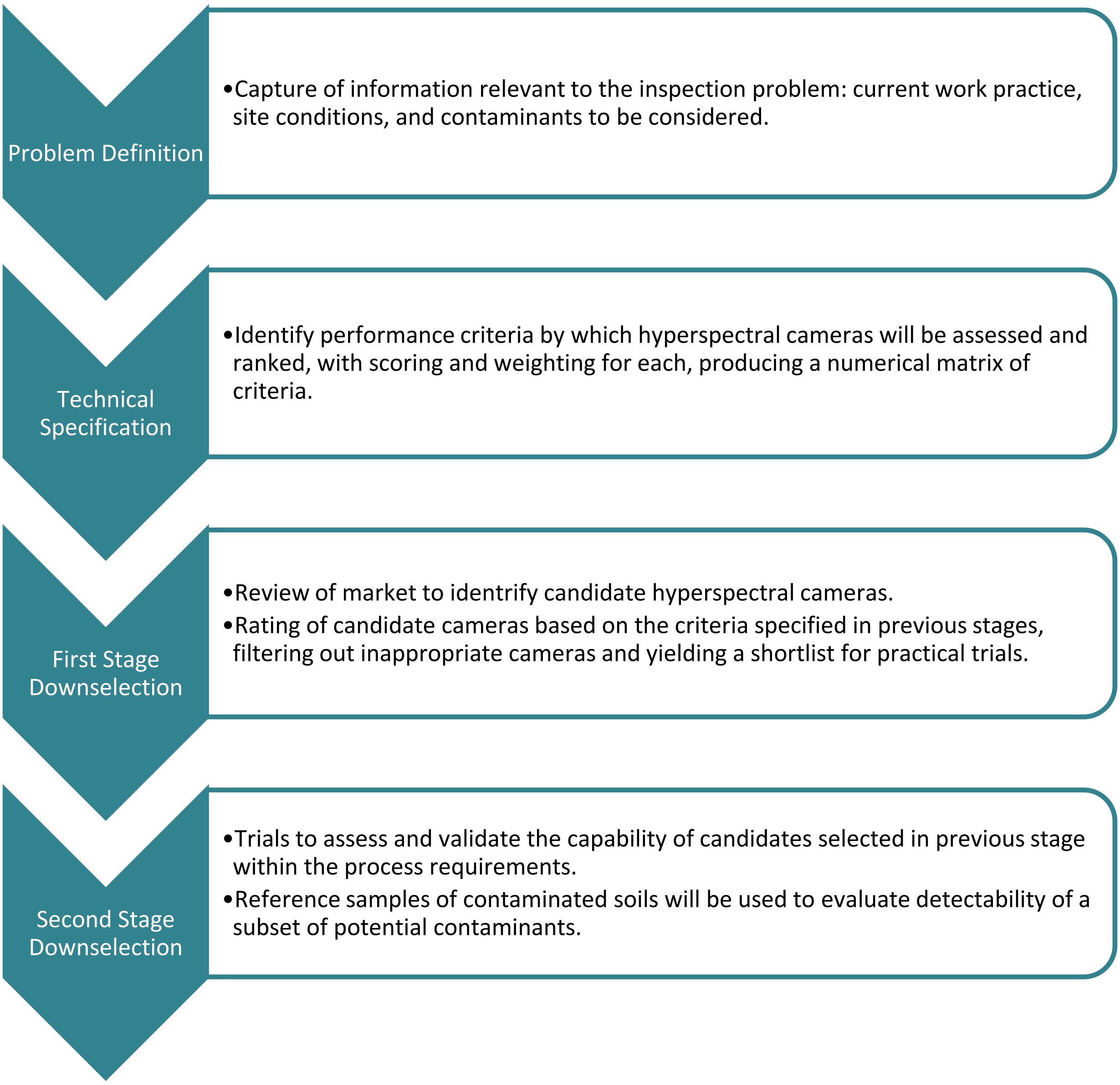

Figure 1. Flowchart showing the downselection process undertaken during this project.

3 Candidate Systems

This section provides an overview of hyperspectral camera hardware identified as candidates for spoil assessment. Besides spectral range, cameras can generally be divided into two categories:

1. **Line-scan** cameras, also known as "push-broom", capture a 1D image with each frame. 2D images are produced from relative motion of camera and imaged object, either linear or rotational. Spatial resolution in one axis is therefore determined by the cameras' optics, while the other is determined by the scanning speed and camera's framerate (lines scanned per second). In this way, spatial resolution in the scanning axis can be varied easily.
2. **Snapshot** (or "non-scanning") cameras capture a 2D image with each frame. This can be achieved either by use of an internal scanning stage (where internal optics change the current field of view while the camera body remains stationary) or through use of a 2D detector array in with filters used to achieve spectral resolution. The latter approach has faster acquisition time than scanning imagers, but generally lower spatial and/or spectral resolution.

While snapshot cameras with an internal scanning stage use the same principles as line-scan cameras, generally they are not comparable in specifications and performance.

The systems described below are listed in alphabetical order, by manufacturer.

3.1 ClydeHSI

Clyde Hyperspectral Imaging and Technology Ltd. (ClydeHSI) are a Scottish company specialising in hyperspectral imaging. Their cameras are line-scan (1D) imagers, cover differing infrared ranges (from visible—very-near-infrared (VNIR) to short-wave infrared (SWIR)) and performance levels. The ClydeHSI systems are advertised as suitable for both industrial and field use. Their systems include:

- **VNIR-S**, described as a "high-performance entry-level hyperspectral camera", though with relatively high resolution (1024 spectral bands and 2560 spatial pixels) [4].
- **VNIR-HR**, with similar specs to the VNIR-S but greater spectral resolution (<2.5 nm vs. 8 nm) [5].
- **NIR-HR** and **NIR-HR+**, imaging in 950—1700 nm [6, 7]. Both have the same spectral resolution but the NIR-HR+ has double the spectral bands and spatial resolution.
- **SWIR-384**, imaging in 900—2500 nm [8].

The NIR-HR+ is shown in Figure 2, though all cameras in the series have similar housing. Despite differences in resolution and performance, the power requirements are similar for the full series. All of the systems support a range of objective lenses (also manufactured by ClydeHSI) with differing focal length and field of view [9]. They use the GigE and Camera Link standards.

ClydeHSI also advertise "turn-key" scanning solutions, with both hardware (e.g. lighting and scanning stage) and software [10], for a range of applications [11].

Figure 2: NIR-HR+ hyperspectral camera, from ClydeHSI.

Figure 3: Transportable scanning system consisting of NIR-HR camera, two lights, and conveyor stage, from ClydeHSI [11].

3.2 Cubert

Cubert GmbH are a German company producing "snapshot" (2D) cameras, including real-time/video functionality, in the visible-VNIR range. Their range consists of four cameras:

- **Ultris 20**, imaging 350–1000 nm at a frame rate of 6 Hz [12]. Has similar resolution to many line-scan cameras, with 164 spectral bands and 410 × 410 pixels.
- **Ultris 20 Plus**, a version of the Ultris 20 with a second "panchromatic" camera with a spatial resolution of 1880 × 1880 pixels (though the resolution of the hyperspectral camera is unchanged) [13].
- **Ultris 5**, imaging 450–850 nm at a frame rate of 15 Hz [14]. This camera is notable for its small size and low weight (126 g), but accordingly has a relatively low spectral and spatial resolution (50 bands and 250 × 250 pixels respectively).
- **FireflEYE 185**, imaging 450—950 nm at 25 Hz [15]. The FireflEYE is marketed for both drone-based imaging and microscopy. Unlike the Ultris series, the FireflEYE supports interchangeable lenses (e.g. macro lenses or microscope mounts).

Cubert's cameras support the GigE standard. They are distributed in the UK by Pro-lite Technology. While the Ultris series is currently available in the visible-VNIR range, SWIR versions are "possible" with different sensors [12].

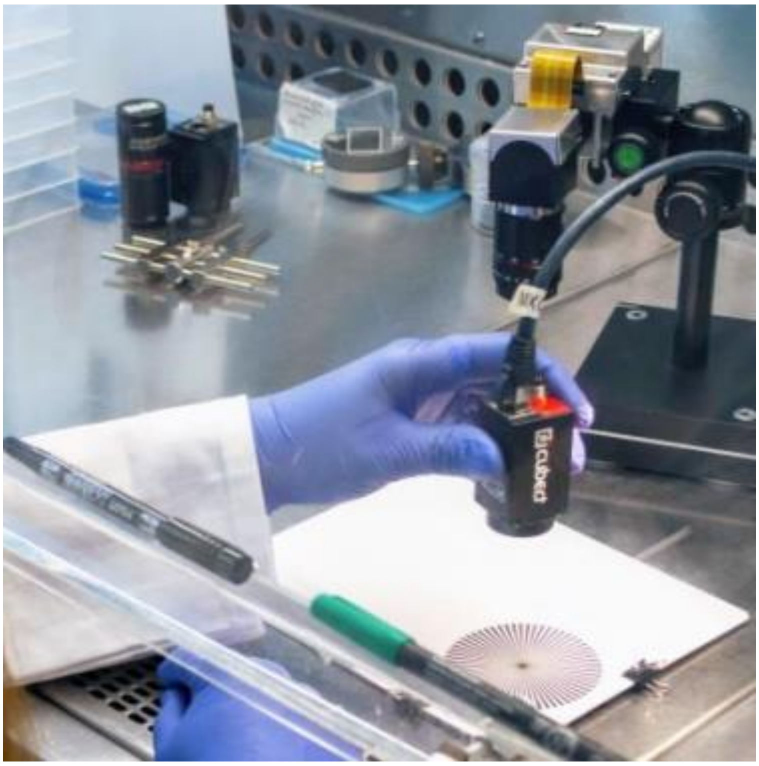

Figure 4: Ultris 5 hyperspectral camera, from Cubert [14].

3.3 Headwall Photonics

Headwall Photonics Inc. are an international company designing and manufacturing a range of spectral imaging sensors, ranging from ultraviolet to short-wave infrared, for remote sensing, biotech, and defence. Their hyperspectral cameras are line-scan (1D) imagers, available for laboratory and field use, and are generally small, light, and with low power requirements. These include:

- **Nano-Hyperspec**, their smallest camera, imaging in VNIR [16].
- **Micro-Hyperspec** series, available in a number of spectral ranges (VNIR, NIR, extended VNIR, and SWIR). The series includes lower- and higher-spec versions for VNIR, NIR, and SWIR [17].
- **Hyperspec Co-Aligned VNIR/SWIR** sensor, shown in Figure 5, which combines independent VNIR and SWIR cameras for an overall spectral range of 400—2500 nm

All three Hyperspec series use the Camera Link interface standard. Headwall Photonics cameras are distributed in the UK by Analytik Ltd.

Figure 5: Hyperspec Co-Aligned VNIR/SWIR Sensor, from Headwall Photonics.

3.4 imec

imec are an international company based in Belgium, providing a range of nano and digital technologies. They manufacture snapshot (2D) cameras with video and real-time imaging capabilities for a range of markets. These cameras include:

- **Snapscan VNIR**, imaging 470—900 nm over 3600 × 2048 pixels and 150 spectral bands [18]. The Snapscan series uses internal scanning mechanisms, with the relatively high spatial resolution.
- **Snapscan SWIR**, imaging 1100—1650 nm over 1200 × 640 pixels and 100 spectral bands [19].
- **Snapshot SWIR**, imaging 1100—1650 nm over 640 × 512 pixels and either 9 or 16 spectral bands. While these spectral bands are not contiguous or uniformly distributed (see Figure 7), more typical of multispectral cameras, the Snapshot SWIR has a high framerate of up to 120 fps and low power consumption of 2 W (at 60 fps).

All imec hyperspectral cameras support a range of lenses and USB 3 for connectivity. The Snapscan and Shapshot series have different proprietary software for acquisition and pre-processing – HSI SNAPSCAN and HSI Mosaic respectively. As well as their off-the-shelf series, imec offer development of cameras for specific use cases.

Figure 6: Snapshot SWIR camera, from imec.

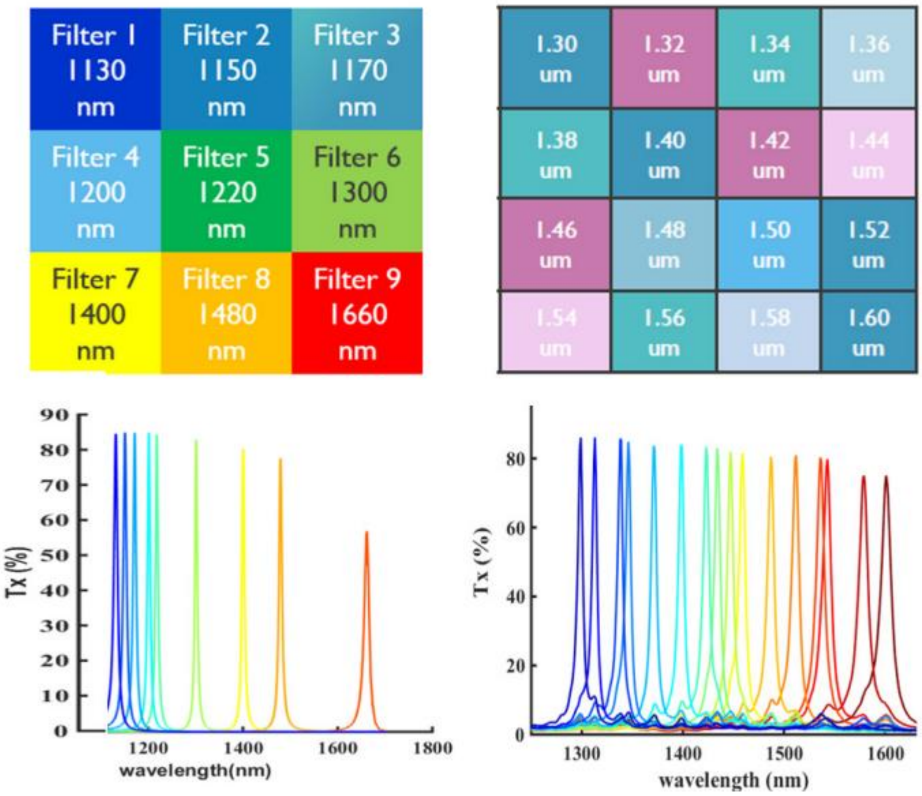

Figure 7: Arrangement of filters in 9-band (top left) and 16-band (top right) Snapshot SWIR detectors, and transmittance of each (bottom left and bottom right). From imec [20].

3.5 Resonon

Resonon Inc. are an American manufacture of hyperspectral cameras, scanning systems, and software. Their Pika series of cameras are line-scan (1D) imagers in either visible-VNIR (400—1000 nm) and NIR (900—1700 nm) ranges. These include:

- **Pika L**, a compact VNIR imager marketed for airborne applications [21].
- **Pika XC2**, a VNIR imager marketed for laboratory, outdoor, and airborne applications, with greater spectral and spatial resolution than the Pika L [22].
- **Pika IR** and **IR+**, NIR imagers marketed for machine vision and laboratory applications [23, 24].
- **Pika IR-L** and **IR-L+**, compact equivalents to the IR and IR+ with greater spectral resolution (albeit reduced range of 925—1700 nm), but lower framerate [25, 26].

Pika cameras support either USB 3 (Pika L and XC2) or GigE (IR, IR+, IR-L, and IR-L+) connection. Resonon also offer "fully-integrated, plug-and-play" scanning systems, including one for outdoor field imaging, shown in Figure 8 [27]. They are distributed in the UK by Photon Lines Ltd.

Figure 8: Outdoor scanning system with Pika camera, rotational scanning stage, and ruggedized laptop, from Resonon [27].

3.6 Specim

Specim are an international supplier of hyperspectral cameras, imaging systems, and software based in Finland. Their hyperspectral cameras include both line-scan and snapshot imagers:

- The FX series of line-scan imagers for industrial and laboratory use, including the **FX10** (400—1000 nm) and **FX17** (900—1700 nm) [28, 29]. The FX series has relatively fine spectral resolution and high frame rate, with the option to increase frame rate by recording only a subset of wavebands. These recorded bands need not be contiguous, and hence may include only wavelengths used in processing.
- The **Specim IQ**, shown in Figure 9, a snapshot VNIR (400—1000 nm) imager with internal scanning mechanism. The IQ may be operated standalone, with a touch-screen interface similar to conventional DSLR cameras, or via a connected PC.

Specim FX cameras support GigE and Camera Link connections.

Figure 9: Specim IQ camera.

4 First-Stage Downselection

Systems are scored against criteria defined in the first deliverable report, *Problem Definition* [1]. The criteria are split into two categories: detection (concerning the ability to resolve characteristic features for materials in spoil) and practical (concerning suitability for conducting on-site assessments of spoil). Scores for each section are totalled separately.

In first-stage downselection, candidates are scored according to manufacturer's materials (e.g. technical specifications) and expected performance based on the MTC's expertise. These reflect what each is capable of detecting in ideal conditions (based on reference spectra and literature), but do not confirm that the contaminant is detectable within spoil, nor evaluate the sensitivity of such detection. Concentration and distribution of the contaminant, along with other materials in the sample, will affect practical performance. A number of these factors will be evaluated in laboratory trials during Deliverable 3.

The criteria and their scoring conditions are listed in Appendix A – *Downselection Criteria*. General observations arising from the first-stage scoring of cameras are discussed in the subsection below, followed by a summary of each camera's scoring for detection and practical criteria. Full scoring matrices are provided in Appendix B – *Downselection Matrix*.

4.1 General Observations

4.1.1 Detection

While not the only factor, the most significant factor in whether a camera can detect a given material is its spectral range. This in turn is predominantly determined by the detector type, with cameras imaging in visible-VNIR, NIR, or SWIR ranges, with limited overlap. This is due to the sensitivity of the respective detectors varying by wavelength, typical examples of which for VNIR and NIR are shown in Figure 10.

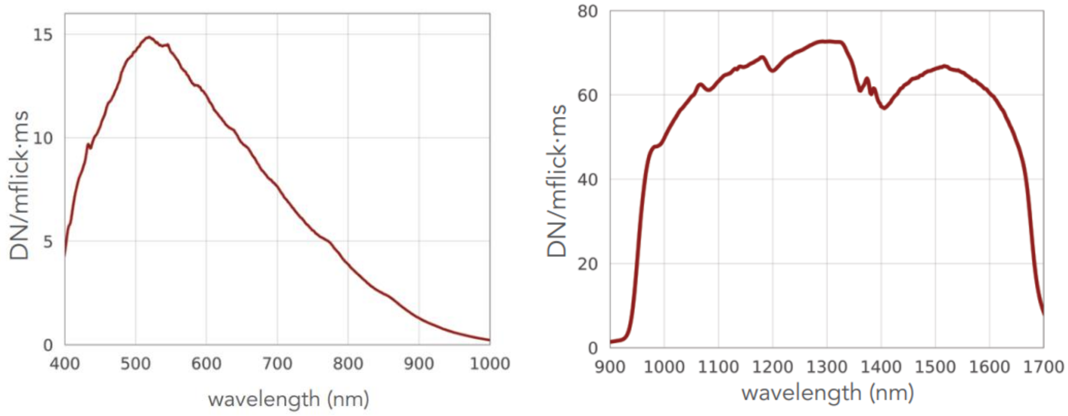

Figure 10: Spectral response curves for Resonon Pika XC2 (left) and Pika IR+ (right). From [22] and [24].

At this stage, detection scores are based on cameras' spectral ranges and what characteristic features have been identified in literature. These do not take into account factors such as camera sensitivity, or the effect of other chemicals' spectra. Detection may be possible from spectral features that have not been identified in literature, or not practically possible from those that have.

While it was not scored directly, a camera with finer spectral resolution and more spectral bands (all else being equal) will be more sensitive to key spectral features. This has been incorporated into scoring on the assumption that it limits what spectral features may be resolved.

4.1.2 Cost

All candidate cameras are well above the target maximum price of £3,000 defined in Deliverable 1, with the cheapest camera (the Cubert Ultris 5) costing £12,000. In order to provide meaningful input for downselection, the scoring for this criterion has been rescaled to the extreme costs amongst cameras considered.

Generally, SWIR cameras are more expensive than VNIR and NIR cameras, but this should be considered alongside the (predicted) difference in detection performance.

4.1.3 Ease of Use

Systems are generally hard to distinguish in terms of ease of use. The majority of systems have similar requirements for set-up and use, with respect to both hardware and software. The majority of the HSI cameras identified require a connection to a laptop for data acquisition and processing. However, some, such as the Specim IQ and those intended for drone-based imaging, support independent data acquisition, this is unlikely to present any benefit in this use case. While manufacturers typically provide proprietary software for data acquisition and pre-processing, processing may be carried out with a variety of software, exploiting standard hyperspectral data formats and APIs. Appropriate software may be selected (or developed, if necessary) independent of the choice of camera.

The most significant factor for a camera’s ease of use is likely to be whether it is line-scan or snapshot, with line-scan cameras generally requiring more care to set up correctly with respect to field of view and focus. With work conditions, amount of spoil etc. varying from site to site, the set-up of hardware may not be the same for all sites. If the camera must be repositioned multiple times on a given site, the advantage of snapshot cameras may be compounded.

4.2 Overall Scores

Overall first-stage scoring, in both detection and practical criteria, is listed for each candidate camera in Table 1. Please note that scores for detection and practical criteria should be considered independently; they do not necessarily have the same ‘ideal’ score nor range of scores. Table 1 also includes a combined score, which is the sum of detection and practical scores normalised to a range of 0—100 in each category. This combined score gives equal weight to both categories.

Table 1: Overall scores for each camera in detection and practical categories and normalised combined score.

Manufacturer	Camera	Detection	Practical	Combined
ClydeHSI	VNIR-S	171	205	64
	VNIR-HR	171	211	72
	NIR-HR	270	180	97
	NIR-HR+	270	183	101
	SWIR-384	279	183	107
Cubert	Ultris X20	171	236	104
	Ultris X20 Plus	171	222	86
	Ultris 5	147	256	113
	FireflEYE	171	237	105
Headwall	Nano-Hyperspec	171	220	83
	Micro-Hyperspec VNIR A-series	171	204	63
	Micro-Hyperspec VNIR E-series	171	213	74
	Micro-Hyperspec NIR 640	243	193	96
	Micro-Hyperspec NIR 320	243	203	109
	Micro-Hyperspec Extended VNIR	279	200	129
	Micro-Hyperspec SWIR 384	243	194	97
	Micro-Hyperspec SWIR 640	279	191	117
	Hyperspec Co-Aligned VNIR-SWIR	279	177	100
imec	Snapscan VNIR	171	228	93
	Snapscan SWIR	234	203	103
	Snapshot SWIR	126	214	46
Resonon	Pika L	171	238	106
	Pika XC2	171	235	102
	Pika IR	225	210	106
	Pika IR+	270	204	128
	Pika IR-L	270	204	128
	Pika IR-L+	270	201	124
Specim	FX10	171	243	112
	FX17	270	222	151
	IQ	171	249	120

5 Trial Outline

Experimental trials for selected cameras can be divided into three stages:

1. Measurement of each soil reference material (see §5.1 – *Soil Samples*) with each camera. In order to establish variability in spectra arising from inhomogeneity in spoil, repeat measurements will be taken following agitation of samples to bring new material to the surface. Repeat measurements will also be taken to establish variability in measurements from each camera alone. (See §5.2 – *Assessing Variation within Materials* for more detail.)
2. Spectra from each reference material will be compared to others with different soil texture or with different contaminant to establish spectral variation associated with different textures and contaminants. These will be compared to spectral features identified in literature in order to identify and validate which correspond to specific chemicals.
3. Spectral features identified from previous stages will be compared in spectra measured by different cameras in order to evaluate relative sensitivity.

5.1 Soil Samples

The reference samples procured for trials in Deliverable 3 are listed in Table 2, with their full composition specified in the referenced safety data sheets (SDS).

Table 2: List of reference materials for validation trials.

Contaminant Type	Reference Material		SDS
Total Petroleum Hydrocarbons (TPH)	CRM353	TPH – Sandy Loam 3	[30]
	CRM359	TPH – Clay Loam 1	[31]
Coal Tar	CRM141	PAHs – Loamy Clay 1	[32]
	CRM170	PAHs – Clay Soil	[33]
Heavy Metals	CRM043	Trace Metals – Sandy Loam 6	[34]
	CRM052	Trace Metals – Loamy Clay 1	[35]
	SQC001	Metals in Soil	[36]
	PB3000	Lead - Soil	[37]
Uncontaminated Soil	CLNSOIL2	Clean Clay Loam	[38]
	CLNSOIL5	Clean Clay #5	[39]

With the exception of SQC001 and PB3000, for each of these reference materials there is another with the same soil texture (but different contaminant) and another with the same contaminant type (but different texture); these correspondences are shown in Table 3. In principle, comparison of the spectra of (e.g.) CRM353 and CRM359 enables the spectral differences of sandy and clay loam to be identified, and CLNSOIL2 and CRM259 the spectral difference of TPH contamination.

Table 3: Reference materials by soil texture and contaminant type.

↓Soil Contaminant→	TPH	Coal Tar	Heavy Metals	Uncontaminated
Sandy Loam	CRM353		CRM043	
Clay Loam	CRM359			CLNSOIL2
Loamy Clay		CRM141	CRM052	
Clay Soil		CRM170		CLNSOIL5

However, there may be variations between reference materials that are not accounted for in their nominal composition. For example, while the heavy metal compounds in CRM043 and CRM052 are nominally identical [34, 35], the concentration of each contaminant falls within a range, e.g. 0.025 – 0.01%. Likewise, there may be differences in the soil matrix of each material even for the same soil texture.

The spectral differences suspected to belong to a given contaminant or soil type will be compared to reference spectra from literature. If characteristic features identified in literature (belonging to specific contaminants) correspond to those identified from experimental measurements, this will suggest that the presence of contaminants is being captured.

5.2 Assessing Variation within Materials

Soils are generally inhomogeneous, with local variations in composition (e.g. distribution of organic matter, stones, moisture etc.). Likewise, contaminants may be distributed unevenly within spoil. Both must be accounted for in order to characterise spoil reliably. Contaminants must be distinguished from “benign” variations in spoil composition (and corresponding variations in spectra), and the distribution of contaminant concentration must be measured to calculate overall concentration correctly.

Figure 11 shows an RGB photograph of soil captured with a Specim IQ hyperspectral camera in bright sunlight. The texture of this soil is unknown, but contains stones/gravel and vegetation. Figure 12 shows the reflectance spectra of two stones, a plant, and soil (see annotations in Figure 11). The spectra for each differ significantly, though the difference between the two stones’ spectra may be accounted for by difference in illumination and can be mitigated by normalising the spectra, Figure 13.

Figure 14 shows normalised spectra for four arbitrary patches of soil, each 8 × 8 pixels in size. While have similar characteristics (especially in comparison to stone and plant spectra), the spectra differ in relative reflectance of shorter and longer wavelengths. This is consistent with differing moisture levels.

Averaging spectra over multiple pixels can lessen the impact of local inhomogeneity on spectra, but with a loss of spatial resolution, affecting detection sensitivity. Pixel-by-pixel variation is also dependent on camera properties such as detector noise.

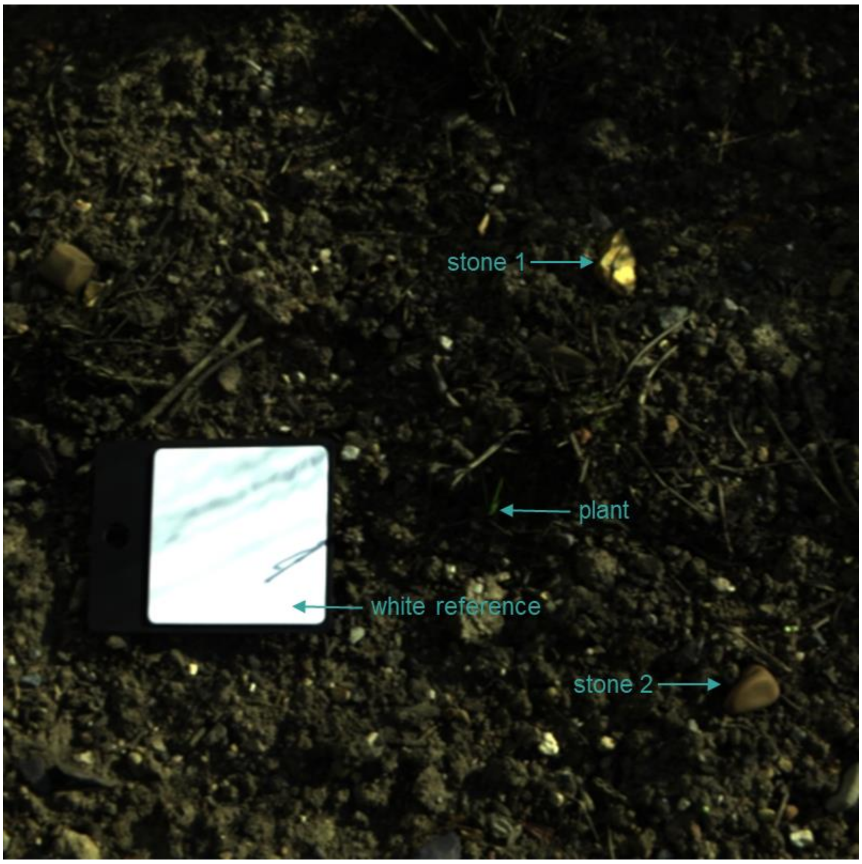

Figure 11: RGB image of soil, captured by Specim IQ hyperspectral camera. Two stones, a plant (in shadow), and the white reference plate are annotated.

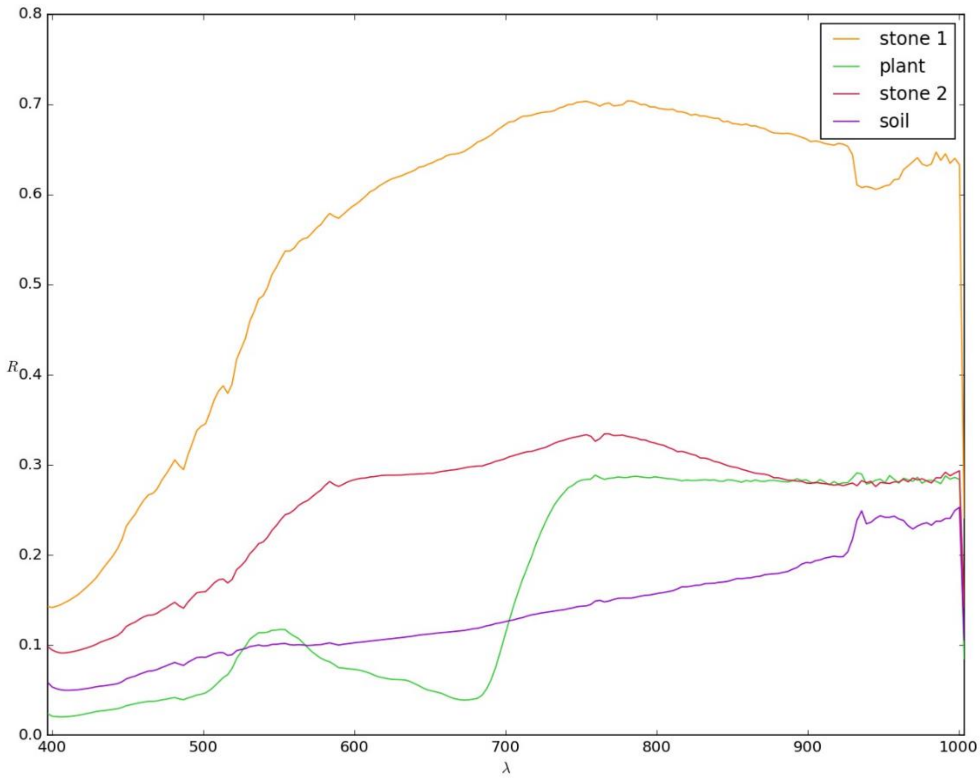

Figure 12: Plot of reflectance spectra, *R*, over the visible and very-near infrared spectrum ($400 \leq \lambda \leq 1000$ nm) of two stones, a plant, and soil from Specim IQ image (Figure 11).

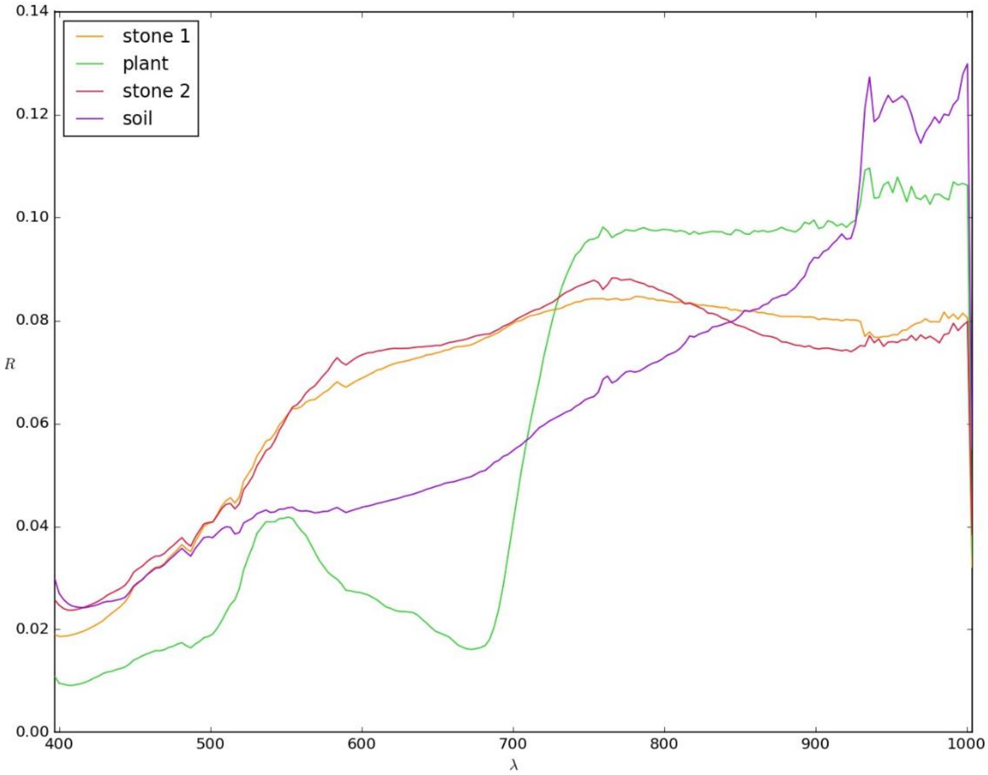

Figure 13: Plot of normalised reflectance spectra, *R*, over the visible and very-near infrared spectrum ($400 \leq \lambda \leq 1000$ nm) of two stones, a plant, and soil from Specim IQ image (Figure 11).

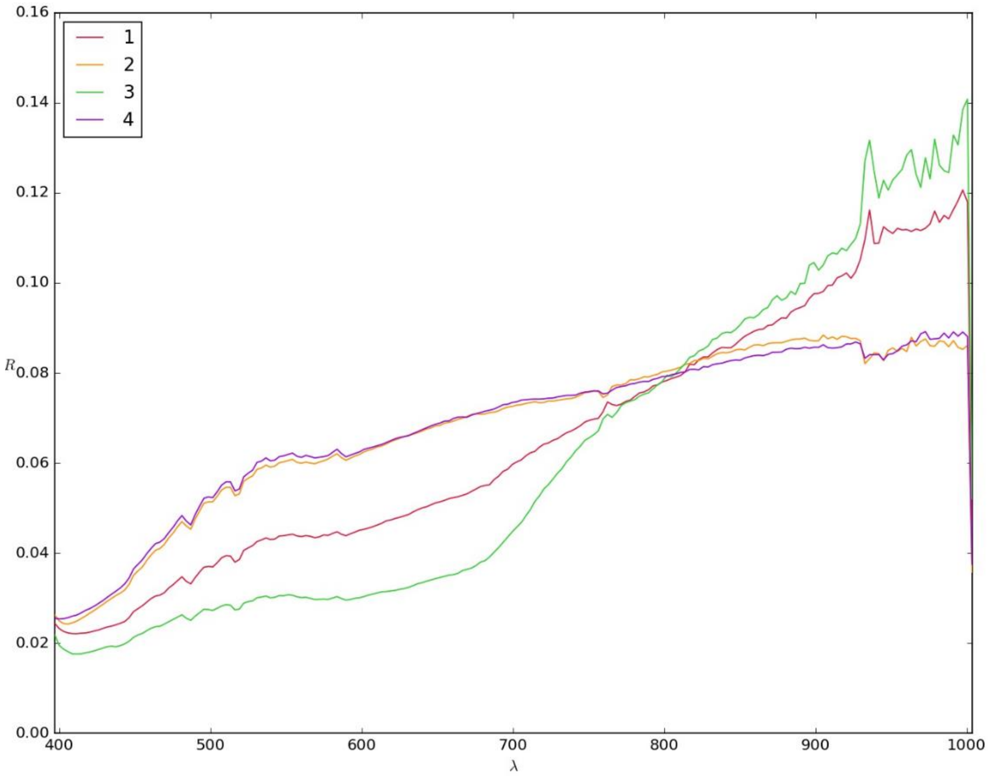

Figure 14: Plot of normalised reflectance spectra, *R*, over the visible and very-near infrared spectrum ($400 \leq \lambda \leq 1000$ nm) of four arbitrary 8 × 8 px regions of soil in Specim IQ image (Figure 11).

5.3 Comparing Camera Performance

Multiple captures of the same reference material (without altering the surface visible to the camera) will be used to characterise repeatability of measurements with each camera, e.g. the influence of noise. With the possibility of highly variable spectra for most of the reference materials (due to large number of contaminants in small concentrations, which may be unevenly distributed throughout the sample), comparing sensitivity may be challenging.

Reference materials that are likely to be used for this comparison are PB3000 and SQC001.

PB3000 is contaminated solely with lead (II) nitrate, and with relatively high nominal concentration among individual contaminants (0.1—1%). SQC001 has multiple contaminants, but also the highest nominal concentration of a single contaminant (calcium carbonate and vitreous silica, both at 1—10%). PB3000 presents a "best case" for detection in terms of fewest confounding features from multiple sources, while SQC001 likely presents a more "realistic" case.

6 Recommendations

A moderate, negative correlation may be observed between detection and practical scores (see 4.2 – *Overall Scores,* pg. 14); cameras that are (in principle) better suited to detection of contaminants are less suited to practical concerns. A large part of this relationship is in the differences between VNIR and NIR/SWIR cameras. VNIR cameras tend to be smaller and higher-resolution, but many spectral features of interest are found within the NIR—SWIR range.

Given the minimal overlap between VNIR and NIR/SWIR cameras' spectral ranges, we recommend considering these separately as candidates for trials in Deliverable 3. While fewer spectral features of interest have been identified within the visible—NIR range, this may (at least to an extent) be a limitation of current work.

In considering cameras of like spectral ranges, the most significant differences are within spatial resolution, spectral resolution, and frame rate. Spectral resolution affects detection sensitivity, while spatial resolution and frame rate affect throughput. Given the cost of hyperspectral cameras, effective deployment of them for spoil inspection will likely require a compromise between these factors.

The ten highest-combined-scoring cameras are listed in Table 4. Of these, seven operate in NIR or SWIR, while three (italicised) operate in vis—VNIR. The former score highest in detection, and the latter in practical criteria.

Table 4: Detection, practical, and combined scores of ten highest-combined-scoring cameras. Italicised cameras

Manufacturer	Camera	Detection	Practical	Combined
Specim	FX17	270	222	151
Headwall	Micro-Hyperspec Extended VNIR	279	200	129
Resonon	Pika IR+	270	204	128
Resonon	Pika IR-L	270	204	128
Resonon	Pika IR-L+	270	201	124
Specim	*IQ*	*171*	*249*	*120*
Headwall	Micro-Hyperspec SWIR 640	279	191	117
Cubert	*Ultris 5*	*147*	*256*	*113*
Specim	*FX10*	*171*	*243*	*112*
Headwall	Micro-Hyperspec NIR 320	243	203	109

Of these, we recommend trialling the Specim IQ (snapshot; vis—VNIR) and at least two of:

- Specim FX17,
- Headwall Micro-Hyperspec Extended VNIR or SWIR 640,
- Resonon Pika IR+ or IR-L+.

These are all line-scan imagers with similar spatial resolution. The Specim FX17 offers the greatest frame rate, while the Pika IR-L+ offers the most spectral bands and finest spectral resolution. As such, these two offer the most contrast between (expected) sensitivity to contaminants and throughput.

If feasible, we also recommend trialling the Cubert Ultris 5. While this has a very low detection score, it has the highest practical score due to its extremely small form factor, high frame rate (for a snapshot camera) and relatively low expense. If it is sufficient for detection, this may be the easiest to deploy by a large margin.

7 References

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Appendix A – Downselection Criteria

The following appendix is a summary of downselection criteria definition given in Deliverable 1, *Problem Definition* [1].

A.1 Detection

Detection criteria concern the (nominal) suitability of the camera to detect and distinguish potential contaminants, other foreign bodies, and soil type. These are listed in Table 5. The scoring is identical for each criterion, on the principle that each material (or group of materials) will be identifiable from one or more spectral features in the visible–infrared range. To identify these materials, these spectral features must lie within the range that the hyperspectral camera is sensitive to.

Multiple, resolvable, characteristic features within a camera's range are preferable for greater sensitivity and confidence in classification, and cameras will be scored higher where this is a case. Generally, cameras are less sensitive to wavelengths at the extremes of their range, in which case they will be scored lower for a given material.

Which features are resolvable (in ideal conditions) depends on the camera's spectral resolution. While a camera with (for example) 300 channels in the spectral range of 400–1000 nm may have a spectral sampling of 2 nm per channel, channels typically have some sensitivity to wavelengths outside of their nominal width, e.g. a spectral resolution of 4 nm. Finer resolution is preferable, but is not included as a separate criterion. Generally, cameras have greater spectral sampling and resolution at longer wavelengths. Spectral sampling and resolution will be considered in whether cameras are able to resolve characteristic features for each contaminant.

A.1.1 Total Petroleum Hydrocarbons

Spectral features corresponding to petroleum hydrocarbons have been identified in the range of 1200—2400 nm [40], in particular 1415, 1712, 1758, 1914, 2200, and 2207 nm [41].

A.1.2 Coal Tar

Polycyclic aromatic hydrocarbons (PAHs), such as those found in coal tar, have various spectral features in the vis—NIR range. In particular, benzo[a]pyrene has strong features around 1100 and 1650 nm [42].

A.1.3 Asbestos

Spectral features for asbestos depend on specific formula and morphology. Chrysotile and amphibole asbestoses have characteristic features at 1383 nm and 1393 nm respectively [43]. Features may also be found around 2350 nm [44, 45].

A.1.4 Heavy Metals

Heavy metals' spectral features vary by element and compound, though common features have been found in the SWIR range [46]. Some work has found useful wavelengths in the visible-NIR range, though these do not appear as significant [47, 48].

Table 5: Summary of detection downselection criteria.

Criterion	Summary	Scoring	Weight
TPH	Ability to detect total petroleum hydrocarbons (TPH).	5 – Multiple characteristic spectral features resolvable in camera's spectral range. 4 – As (5), but one or more in less-sensitive range. 3 – Single resolvable characteristic feature in range. 2 – As (3), but feature in less-sensitive range. 0 – No resolvable characteristic features in range.	9
Coal Tar	Ability to detect coal tar.		9
Asbestos	Ability to detect asbestos.		9
Arsenic	For each heavy metal: ability to detect heavy metal and/or its compounds.		1
Cadmium			1
Chromium			1
Copper			1
Lead			1
Mercury			1
Nickel			1
Selenium			1
Zinc			1
Asphalt	Ability to detect asphalt.		3
Litter	Ability to detect litter (e.g. plastics).		3
Water	Ability to infer water content, if it may affect contaminant detection.		6
Soil Types	Ability to distinguish soil textures (proportion of sand, clay, loam).		9

A.2 Practical

Practical criteria are summarised in Table 6. These criteria are those not directly related to the hyperspectral camera's sensitivity to various materials but relate to practicality of the camera system for inspection at ENWL's work sites. These criteria are described in more detail in *Problem Definition* [1].

Table 6: Summary of practical downselection criteria.

Criterion	Summary	Scoring	Weight
Cost	Cost to acquire camera (not including peripheral hardware).	Relative to least/most expensive among candidates. [1]	5
Bulk	Size and weight of camera (with respect to portability and handling).	5 - Smaller than work light. 4 - Similar size to light. 3 - Larger, but can be carrier by one person. 2 - Requires two people to carry. 1 - Requires entire van to transport. 0 - Exceeds van's capacity.	7
Weatherproofing	Protection from elements (i.e. dust and rain).	5 - Camera has rating of IP55 or higher. 4 - Optional housing, rated IP55 or higher. 2 - Bespoke housing required. 1 - Unsuited to outdoor use.	7
Durability	Protection from physical impact (e.g. from system being dropped.	5 - Can withstand drops of ≥2 m. 4 - Durable housing available. 3 - Can withstand drops of 1–2 m. 2 - Bespoke housing required. 1 - No protection.	7
Power	Power supply required to operate camera. Van *may* be on site with 240 V supply, generators not on site as standard.	5 - Battery, single required for full shift, 50% duty cycle.	7

[1] This has been changed since Deliverable 1.

		4 - Battery, multiple required for shift. 2 - 240 V supply from van. 0 - 240 V supply insufficient.	
Frame Rate	Higher frame rates allow greater throughput/faster inspection and/or greater spatial resolution in one axis (for 1D cameras).	Relative to best/worst among candidates.	3
Angular Resolution	Spatial resolution in second axis dependent on angular resolution, field of view, and standoff distance. May be specified in one or two axes, depending on camera type.	Relative to best/worst among candidates.	3
Ease of Use (Software)	Ease of use of system by operator, including set up, from perspective of inspection system software (data acquisition, processing, and interpretation).	5 - Intuitive interface. 3 - Some background knowledge required. 1 - Specialist knowledge/training required.	7
Ease of Use (Hardware)	Ease of use of system by operator, including set up, from perspective of hardware (e.g. manual handling), and considering PPE (e.g. gloves).	5 - Requires single operator, no hindrance from PPE. 3 - Requires multiple operators OR difficult with PPE. 1 - Multiple operators AND difficult with PPE.	7
Time for Set-Up	Time required to set up system on site before use, and time to take down after. Potentially includes time to reposition.	5 - <15 minutes 3 - < 1 hour 0 - > 1 day	5
Lighting	Whether camera requires specialist lighting, or may be used with sunlight and/or standard work lights.	5 - Suitable for standard work lights. 3 - Specialist lighting OR sunlight. 0 - Specialist lighting only.	7
Spectral Range	Range of wavelengths detected. Most relevant to detectability of various contaminants, and so reflected in scoring of those criteria.	n/a - Reflected in scoring of Detection criteria.	0
Number of Bands /Spectral Spacing	Number of bands (channels) within spectral range, and resultant spectral spacing.		

Spectral Resolution	Range of wavelengths each band is sensitive to. This is typically defined as the full-width-half-maximum.		

Appendix B – Downselection Matrix

This appendix includes downselection matrixes (Pugh matrixes) for candidate cameras, listed by manufacturer in alphabetical order. Colour-highlighted cells and italics represent scores that have been inferred due to information not being available from the manufacturer.

ClydeHSI cameras are scored in Table 7 and Table 8, pp. 33—34.

Cubert cameras are scored in Table 9 and Table 10, pp. 35—36.

Headwall cameras are scored in Table 11, Table 12, and Table 13, pp. 37—39.

imec cameras are scored in Table 14, pg. 40.

Resonon cameras are scored in Table 15 and Table 16, pp. 41—42.

Specim cameras are scored in Table 17, pg. 43.

Table 7: Downselection scores for ClydeHSI VNIR-S, VNIR-HR, and NIR-HR cameras.

System		VNIR-S		VNIR-HR		NIR-HR	
Total Weighted Scores for each Category:		**Detection:**	171	**Detection:**	171	**Detection:**	270
		Practical:	205	**Practical:**	211	**Practical:**	180
Criterion		**Value**		**Value**		**Value**	
TPH			1		1		4
Coal Tar			5		5		5
Asbestos			1		1		5
Heavy Metals	Arsenic		3		3		5
	Cadmium		3		3		5
	Chromium		3		3		5
	Copper		3		3		5
	Lead		3		3		5
	Mercury		3		3		5
	Nickel		3		3		5
	Selenium		3		3		5
	Zinc		3		3		5
Asphalt			1		1		3
Litter			1		1		5
Water			5		5		5
Soil Types			5		5		5
Cost			*3*		*3*		*2*
Bulk			3		3		3
Weatherproofing			2		2		2
Durability			3		3		3
Power		24 V	3	24 V	3	24 V	3
Frame Rate		< 420 Hz	4	< 420 Hz	4	< 344 Hz	3
Angular Resolution		1024 px 13.7 - 38.9 deg	3	2560 px 13.7 - 38.9 deg	5	320 px 9.8 - 24.6 deg	2
Ease of Use			3		3		3
			3		3		3
Time for Set-Up			3		3		3
Lighting			5		5		3
Spectral Range		400 - 1000 nm		400 - 1000 nm		950 - 1700 nm	
Number of Bands/ Spectral Spacing		1024		1024		256	
Spectral Resolution		8 nm		< 2.5 nm		< 5 nm	

Table 8: Downselection scores for ClydeHSI NIR-HR+ and SWIR-384 cameras.

	System	NIR-HR+		SWIR-384	
	Total Weighted Scores for each Category:	**Detection:**	270	**Detection:**	279
		Practical:	183	**Practical:**	183
	Criterion	**Value**		**Value**	
	TPH		4		5
	Coal Tar		5		5
	Asbestos		5		5
Heavy Metals	Arsenic		5		5
	Cadmium		5		5
	Chromium		5		5
	Copper		5		5
	Lead		5		5
	Mercury		5		5
	Nickel		5		5
	Selenium		5		5
	Zinc		5		5
	Asphalt		3		3
	Litter		5		5
	Water		5		5
	Soil Types		5		5
	Cost		*2*		*2*
	Bulk		3		3
	Weatherproofing		2		2
	Durability		3		3
	Power	24 V	3	24 V	3
	Frame Rate	300 Hz	3	< 450 Hz	4
	Angular Resolution	640 px 9.8 - 24.6 deg	3	384 px 9.8 - 24.6 deg	2
	Ease of Use		3		3
			3		3
	Time for Set-Up		3		3
	Lighting		3		3
	Spectral Range	950 - 1700 nm		1000 - 2500 nm	
	Number of Bands/ Spectral Spacing	512		288	
	Spectral Resolution	< 5 nm		< 12 nm	

Table 9: Downselection scores of Cubert Ultris X20, X20 plus, and 5 cameras.

System		Ultris X20		Ultris X20 Plus		Ultris 5	
Total Weighted Scores for each Category:		**Detection:**	171	**Detection:**	171	**Detection:**	147
		Practical:	236	**Practical:**	222	**Practical:**	256
Criterion		**Value**		**Value**		**Value**	
TPH			1		1		1
Coal Tar			5		5		4
Asbestos			1		1		1
Heavy Metals	Arsenic		3		3		3
	Cadmium		3		3		3
	Chromium		3		3		3
	Copper		3		3		3
	Lead		3		3		3
	Mercury		3		3		3
	Nickel		3		3		3
	Selenium		3		3		3
	Zinc		3		3		3
Asphalt			1		1		1
Litter			1		1		1
Water			5		5		4
Soil Types			5		5		4
Cost		£45,000	3	*>£45,000*	3	£12,000	5
Bulk		350 g 60 x 60 x 57 mm	5	630 g 60 x 107 x 95 mm	5	120 g 30 x 30 x 50 mm	5
Weatherproofing		IP65 or IP68 housing.	4	*IP40*	*3*	IP40 IP66 housing	4
Durability			3		3		3
Power		8 W	4	8 W	4	3.1 W	5
Frame Rate		8 Hz	2	8 Hz	2	15 Hz	3
Angular Resolution		410 x 410 px 35 deg	2	410 x 410 px 35 deg	2	250 x 250 px 15 deg	2
Ease of Use			3	Secondary camera adds extra pre-processing.	2		3
			3		3		3
Time for Set-Up			4		4		4
Lighting			5		5		5
Spectral Range		350 - 1000 nm		350 - 1000 nm		450 - 850 nm	
Number of Bands/ Spectral Spacing		164		164		50	
Spectral Resolution		10 nm		10 nm		26 nm @ 532 nm	

Table 10: Downselection scores of Cubert FireflEYE camera.

System		FireflEYE	
Total Weighted Scores for each Category:		**Detection:**	171
		Practical:	237
Criterion		**Value**	
TPH			1
Coal Tar			5
Asbestos			1
Heavy Metals	Arsenic		3
	Cadmium		3
	Chromium		3
	Copper		3
	Lead		3
	Mercury		3
	Nickel?		3
	Selenium		3
	Zinc		3
Asphalt			1
Litter			1
Water			5
Soil Types			5
Cost		*>£45,000*	3
Bulk		490 g 200 x 67 x 60 mm	4
Weatherproofing		*IP40*	*3*
Durability			3
Power		7 W	4
Frame Rate		25 Hz	5
Angular Resolution		1000 x 1000 px 7 - 30 deg	4
Ease of Use			3
			3
Time for Set-Up			4
Lighting			5
Spectral Range		450 - 950 nm	
Number of Bands/ Spectral Spacing		125	
Spectral Resolution		8 nm @ 532 nm	

Table 11: Downselection scores for Headwall Nano-Hyperspec and Micro-Hyperspec VNIR cameras.

System		Nano-Hyperspec		Micro-Hyperspec VNIR A-series		Micro-Hyperspec VNIR E-series	
Total Weighted Scores for each Category:		**Detection:**	171	**Detection:**	171	**Detection:**	171
		Practical:	220	**Practical:**	204	**Practical:**	213
Criterion		**Value**		**Value**		**Value**	
TPH			1		1		1
Coal Tar			5		5		5
Asbestos			1		1		1
Heavy Metals	Arsenic		3		3		3
	Cadmium		3		3		3
	Chromium		3		3		3
	Copper		3		3		3
	Lead		3		3		3
	Mercury		3		3		3
	Nickel		3		3		3
	Selenium		3		3		3
	Zinc		3		3		3
Asphalt			1		1		1
Litter			1		1		1
Water			5		5		5
Soil Types			5		5		5
Cost			*1*		*1*		*1*
Bulk		500 g	5	700 g	4	1100 g	4
Weatherproofing			3		3		3
Durability			3		3		3
Power		13 W req.	4	6.6 W	4	13.2 W	4
Frame Rate		350 Hz	3	90 Hz	0	250 Hz	2
Angular Resolution		640 px	3	1004 px	3	1600 px	4
Ease of Use			3		3		3
			3		3		3
Time for Set-Up			3		3		3
Lighting			5		5		5
Spectral Range		400-1000 nm		400 - 100 nm		400 - 1000 nm	
Number of Bands/ Spectral Spacing		270		324		369	
Spectral Resolution		6		5.8		5.8	

Table 12: Downselection scores for Headwall Micro-Hyperspec NIR and Extended VNIR cameras.

	System	Micro-Hyperspec NIR 640		Micro-Hyperspec NIR 320		Micro-Hyperspec Extended VNIR	
Total Weighted Scores for each Category:		**Detection:**	243	**Detection:**	243	**Detection:**	279
		Practical:	193	**Practical:**	203	**Practical:**	200
Criterion		**Value**		**Value**		**Value**	
TPH			4		4		5
Coal Tar			4		4		5
Asbestos			4		4		5
Heavy Metals	Arsenic		4		4		5
	Cadmium		4		4		5
	Chromium		4		4		5
	Copper		4		4		5
	Lead		4		4		5
	Mercury		4		4		5
	Nickel?		4		4		5
	Selenium		4		4		5
	Zinc		4		4		5
Asphalt			3		3		3
Litter			5		5		5
Water			5		5		5
Soil Types			5		5		5
Cost			*1*		*1*		*1*
Bulk		900 g	4	900 g	4	900 g	4
Weatherproofing			3		3		3
Durability			3		3		3
Power		2.5 W	4	4 W	5	4 W	5
Frame Rate		120 Hz	1	346 Hz	3	120 Hz	1
Angular Resolution		640 px	3	320 px	2	640 px	3
Ease of Use			3		3		3
			3		3		3
Time for Set-Up			3		3		3
Lighting			3		3		3
Spectral Range		900 - 1700 nm		900 - 1700 nm		600 - 1700 nm	
Number of Bands/ Spectral Spacing		134		67		267	
Spectral Resolution		10		10		5.5	

Table 13: Downselection scores for Headwall Micro-Hyperspec SWIR and Hyperspec Co-Aligned VNIR-SWIR cameras.

System		Micro-Hyperspec SWIR 384		Micro-Hyperspec SWIR 640		Co-Aligned VNIR-SWIR	
Total Weighted Scores for each Category:		**Detection:**	243	**Detection:**	279	**Detection:**	279
		Practical:	194	**Practical:**	191	**Practical:**	177
Criterion		**Value**		**Value**		**Value**	
TPH			4		5		5
Coal Tar			4		5		5
Asbestos			4		5		5
Heavy Metals	Arsenic		4		5		5
	Cadmium		4		5		5
	Chromium		4		5		5
	Copper		4		5		5
	Lead		4		5		5
	Mercury		4		5		5
	Nickel		4		5		5
	Selenium		4		5		5
	Zinc		4		5		5
Asphalt			3		3		3
Litter			5		5		5
Water			5		5		5
Soil Types			5		5		5
Cost			*0*	£160,000 (full system)	0		*0*
Bulk		2000 g	4	1600 g	4	3520 g	3
Weatherproofing			3		3		3
Durability			3		3		3
Power		14.4 W	4	14 W	4	26 W (max. 30)	3
Frame Rate		450 Hz	4	>200 Hz	2	350 Hz (VNIR) 200 Hz (SWIR)	2
Angular Resolution		384 px	2	640 px	3	640 px	3
Ease of Use			3		3		3
			3		3		3
Time for Set-Up			3		3		3
Lighting			3		3	Limited by SWIR.	3
Spectral Range		900 - 2500 nm		900 - 2500 nm		400 - 1000 nm 900 - 2500 nm	
Number of Bands/ Spectral Spacing		166		267		270 (VNIR) 267 (SWIR)	
Spectral Resolution		10 nm		8 nm		6 nm (VNIR) 10 nm (SWIR)	

Table 14: Downselection scores of imec Snapscan VNIR and SWIR and Spapshot SWIR cameras.

	System	Snapscan VNIR		Snapscan SWIR		Snapshot SWIR	
	Total Weighted Scores for each Category:	**Detection:**	171	**Detection:**	234	**Detection:**	126
		Practical:	228	**Practical:**	203	**Practical:**	214
	Criterion	**Value**		**Value**		**Value**	
	TPH		1		4		3
	Coal Tar		5		4		1
	Asbestos		1		4		1
Heavy Metals	Arsenic		3		4		3
	Cadmium		3		4		3
	Chromium		3		4		3
	Copper		3		4		3
	Lead		3		4		3
	Mercury		3		4		3
	Nickel		3		4		3
	Selenium		3		4		3
	Zinc		3		4		3
	Asphalt		1		3		1
	Litter		1		4		2
	Water		5		4		3
	Soil Types		5		5		3
	Cost		*3*		*2*		*2*
	Bulk	580 g (w/out optics) 100 x 70 x 65 mm	5	895 g (w/out optics) 90 x 90 x 150 mm	5	260 g (w/out optics) 65 x 65 x 130 mm	5
	Weatherproofing		3		3		3
	Durability		3		3		3
	Power		*3*		*3*	2 W @ 60 Hz	5
	Frame Rate	2 - 20 s	1	2 - 10 s	1	120 Hz	1
	Angular Resolution	3600 x 2048 px 20-50 mm focal	5	1200 x 640 px 16-50 mm focal	3	640 x 512 px 16-50 mm focal	2
	Ease of Use		3		3		3
			3		3		3
	Time for Set-Up		4		4		4
	Lighting		5		3		3
	Spectral Range	470 - 900 nm		1100-1650 nm		1100-1650 nm	
	Number of Bands/ Spectral Spacing	150		100		9 or 16	
	Spectral Resolution	10-15 nm		10-15 nm		variable	

Table 15: Downselection scores of Resonon Pika L, XC2, and IR cameras.

	System	Pika L		Pika XC2		Pika IR	
Total Weighted Scores for each Category:		**Detection:**	171	**Detection:**	171	**Detection:**	225
		Practical:	238	**Practical:**	235	**Practical:**	210
Criterion		**Value**		**Value**		**Value**	
TPH			1		1		4
Coal Tar			5		5		4
Asbestos			1		1		4
Heavy Metals	Arsenic		3		3		4
	Cadmium		3		3		4
	Chromium		3		3		4
	Copper		3		3		4
	Lead		3		3		4
	Mercury		3		3		4
	Nickel		3		3		4
	Selenium		3		3		4
	Zinc		3		3		4
Asphalt			1		1		3
Litter			1		1		4
Water			5		5		4
Soil Types			5		5		4
Cost		£30,000	4	*~£30,000*	4	*~£30,000*	4
Bulk		640 g (w/out lens) 115 x 104 x 66 mm	4	2,510 g 265 x 106 x 75 mm	4	2,960 g 264 x 115 x 88 mm	4
Weatherproofing			3		3		3
Durability			3		3		3
Power		3.4 W USB	5	3.4 W USB	5	10.8 - 30.0 V	3
Frame Rate		249 Hz	2	165 Hz	1	521 Hz	5
Angular Resolution		900 px 4 - 47 deg	5	1600 px 8 - 76 deg	5	320 px 5 - 77 deg	2
Ease of Use			3		3		3
			3		3		3
Time for Set-Up			3		3		3
Lighting			5		5		3
Spectral Range		400 - 1000 nm		400 - 1000 nm		900 - 1700 nm	
Number of Bands/ Spectral Spacing		281		447		164	
Spectral Resolution		3.3 nm		1.9 nm		8.8 nm	

Table 16: Downselection scores for Resonon Pika IR+, IR-L, and IR-L+ cameras.

	System	Pika IR+		Pika IR-L		Pika IR-L+	
Total Weighted Scores for each Category:		**Detection:**	270	**Detection:**	270	**Detection:**	270
		Practical:	204	**Practical:**	204	**Practical:**	201
Criterion		**Value**		**Value**		**Value**	
TPH			4		4		4
Coal Tar			5		5		5
Asbestos			5		5		5
Heavy Metals	Arsenic		5		5		5
	Cadmium		5		5		5
	Chromium		5		5		5
	Copper		5		5		5
	Lead		5		5		5
	Mercury		5		5		5
	Nickel		5		5		5
	Selenium		5		5		5
	Zinc		5		5		5
Asphalt			3		3		3
Litter			5		5		5
Water			5		5		5
Soil Types			5		5		5
Cost		*~£30,000*	4	*~£30,000*	4	*~£30,000*	4
Bulk		2,960 g 264 x 115 x 88 mm	4	1,010 g 210 x 68 x 63 mm	4	1,010 g 210 x 68 x 63 mm	4
Weatherproofing			3		3		3
Durability			3		3		3
Power		10.8 - 30.0 V	3	10.8 - 30.0 V	3	10.8 - 30.0 V	3
Frame Rate		250 Hz	2	364 Hz	3	176 Hz	1
Angular Resolution		640 px 5 - 77 deg	3	320 px 5 - 77 deg	2	640 px 5 - 77 deg	3
Ease of Use			3		3		3
			3		3		3
Time for Set-Up			3		3		3
Lighting			3		3		3
Spectral Range		900 - 1700 nm		925 - 1700 nm		925 - 1700 nm	
Number of Bands/ Spectral Spacing		328		236		470	
Spectral Resolution		5.6 nm		5.9 nm		3.8 nm	

Table 17: Downselection scores of Specim FX10, FX17, and IQ cameras.

System		FX10		FX17		Specim IQ	
Total Weighted Scores for each Category:		**Detection:**	171	**Detection:**	270	**Detection:**	171
		Practical:	243	**Practical:**	222	**Practical:**	249
Criterion		**Value**		**Value**		**Value**	
TPH			1		4		1
Coal Tar			5		5		5
Asbestos			1		5		1
Heavy Metals	Arsenic		3		5		3
	Cadmium		3		5		3
	Chromium		3		5		3
	Copper		3		5		3
	Lead		3		5		3
	Mercury		3		5		3
	Nickel		3		5		3
	Selenium		3		5		3
	Zinc		3		5		3
Asphalt			1		3		1
Litter			1		5		1
Water			5		5		5
Soil Types			5		5		5
Cost		£14-18,000	5	£40-45,000	3	£20-25,000	4
Bulk		1,300 g 150 x 85 x 71 mm	4	1,560 g 150 x 75 x 85 mm	4	1,300 g 207 x 91 x 126 mm	4
Weatherproofing		IP52	4	IP52	4	IP5x	4
Durability			3		3		3
Power		12 V	4	max. 24 W	4	internal battery	4
Frame Rate		327 Hz full range	3	670 Hz GigE 527 Hz C' Link	5	variable	3
Angular Resolution		1024 px 12 - 83 deg	4	640 px 12 - 92 deg	3	512 x 512 px 31 deg	2
Ease of Use			3		3		4
			3		3	Touchscreen on camera.	3
Time for Set-Up			3		3	DSLR-like viewfinder	5
Lighting			5		3		5
Spectral Range		400 - 1000 nm		900 - 1700 nm		400 - 1000 nm	
Number of Bands/ Spectral Spacing		224		224		204	
Spectral Resolution		5.5 nm mean		8 nm mean		7 nm	

Appendix C – Reference Materials

C.1 – Total Petroleum Hydrocarbons (TPH)

The reference materials selected to represent TPH-contaminated spoil are CRM353 – TPH – Sandy Loam 3 and CRM359 – TPH – Clay Loam 1 [30, 31]. The contaminants in each are nominally identical, and listed in Table 18.

Table 18: Contaminants in reference materials CRM353 and CRM359.

Contaminant	Concentration
Baseoil	0.1 – 1%
Fuel oil no. 2	0.1 – 1%

C.2 – Coal Tar

The reference materials selected to represent coal-tar-contaminated spoil are CRM141 – PAHs – Loamy Clay 1 and CRM170 – PAHs – Clay Soil [32, 33]. Rather than coal tar itself, these are contaminated with polycyclic aromatic hydrocarbons (PAHs) found in coal tar, and which may be used as "marker" chemicals for identifying the presence of coal tar. Of particular importance is benzo[a]pyrene, which has its own concentration limit. The contaminants in both CRM141 and CRM170 are nominally identical, and listed in Table 19.

Table 19: Contaminants in reference materials CRM141 and CRM170.

Contaminant	Concentration
2,2,2,o,p'-Pentachloroethylidenebisbenzene	0.025 – 0.1%
2,2,o,p'-Tetrachlorobinylidenebisbenzene	0.025 – 0.1%
Heptachlor	0.025 – 0.1%
Heptachlor endo-epoxide isomer	0.025 – 0.1%
Endrin	0.025 – 0.1%
Hexachlorobenzene	0.025 – 0.1%
Benz[a]anthracene	0.025 – 0.1%
Acenaphthene	0.025 – 0.1%
Benzo[ghi]perylene	0.025 – 0.1%
Anthracene	0.025 – 0.1%
Benzo[jk]fluorene	0.025 – 0.1%
Benzo[k]fluoranthene	0.025 – 0.1%
Chrysene	0.025 – 0.1%
Benz[e]acephenanthrylene	0.025 – 0.1%
2,2-bis(4-Chlorophenyl)-1,1-dichloro-ethane	0.025 – 0.1%
Dieldrin	0.025 – 0.1%
Aldrin	0.025 – 0.1%
1,1,1-Trichloro-2,2-bis(4-chlorophenyl)ethane	0.025 – 0.1%
2,2-bis(p-Chlorophenyl)-1,1-dichloroethylene	0.025 – 0.1%
2,2',5,5'-Tetrachlorobiphenyl	0.025 – 0.1%
2,4,4'-Trichlorobiphenyl	0.025 - 0.1%
2,2',4,5,5'-Pentachlorobiphenyl	0.025 – 0.1%
2,2',3,4,4',5,5'-Heptachlorobiphenyl	0.025 – 0.1%
2,2',3,4,4',5'-Hexachlorobiphenyl	0.025 – 0.1%
2,2',4,4',5,5'-Hexachlorobiphenyl,	0.025 – 0.1%
Dibenz[a,h]anthracene,	0.025 – 0.1%

Benzo[a]pyrene,	0.025 – 0.1%

C.3 – Heavy Metals

The reference materials selected to represent heavy-metal-contaminated soil are CRM043 – Trace Metals – Sandy Loam 6, CRM052 – Trace Metals – Loamy Clay 1, SQC001 – Metals in Soil, and PB3000 – Lead – Soil [34, 35, 36, 37]. The contaminants for CRM043 and CRM052 are nominally identical and are listed in , while the contaminants for SQC001 and PB3000 are listed in and respectively.

Table 20: Contaminants in reference materials CRM043 and CRM052.

Contaminant	Concentration
Nickel (II) nitrate	0.025 – 0.1%
Cadmium nitrate	0.025 – 0.1%
Cobalt (II) nitrate	0.025 – 0.1%
Ammonium dichromate	0.025 – 0.1%
Silver nitrate	0.025 – 0.1%
Lead (II) nitrate	0.025 – 0.1%
Selenious acid	0.025 – 0.1%
Mercury (II) nitrate	0.025 – 0.1%
Arsenic trioxide	0.025 – 0.1%
Tin (II) chloride	0.025 – 0.1%

Table 21: Contaminants in reference material SQC001.

Contaminant	Concentration
Calcium chloride	1 – 10%
Vitreous silica	1 – 10%
Barium nitrate	0.1 – 1%
Nickel dinitrate hexahydrate	0.025 – 0.1%
Cobalt dichloride hexahydrate	0.025 – 0.1%
Lead (II) nitrate	0.025 – 0.1%
Cadmium chloride	0.025 – 0.1%
Arsenic	0.025 – 0.1%
Selenium dioxide	0.025 – 0.1%
Silver (II) nitrate	0.0025 – 0.25%

Table 22: Contaminant in reference material PB3000.

Contaminant	Concentration
Lead (II) nitrate	0.5 – 1%