

**ESCROW SITE 3
(COMPRESSOR HOUSE)
ANGLESEY ALUMINIUM
HOLYHEAD**

REMEDIATION STRATEGY



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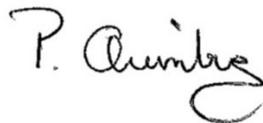
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1 INTRODUCTION

1.1 Background

LK Consult Ltd (LKC) has been commissioned by Orthios to provide a Remediation Strategy for part of the former Anglesey Aluminium Metals (AAM) Works, Penrhos, Holyhead under an escrow agreement.

There are three portions of the former AAM Works site retained by AAM and Orthios under the escrow agreement:

- **Escrow 1 - Compressor House and Boundary (Area 4 of planning application boundary):** This area contains rectifiers, transformers, a control building and a building owned and operated by National Grid. It is understood that a Transformer fire caused a spill of transformer oil into the ground and free product was present.
- **Escrow 2 – Vehicle Refuelling Area (Garage):** This area contained a historical pump island. LKC understand that any tanks in this area have been decommissioned. Diesel impacted water was noted, with free product around the pump island.
- **Escrow 3 – Compressor House:** This area contained pumps and a Compressor House. Free product comprising oil was noted in the only borehole drilled in that area.

This Remediation Strategy details the remediation works to be undertaken in the Compressor House (Escrow site 3) and includes the results of pilot trials already undertaken in the area.

This remediation strategy follows on from further delineation investigation work undertaken by LKC to refine previous outline remediation options. The scope of the investigation works proposed for the escrow sites including preliminary remediation options was provided to the Local Authority, Isle of Anglesey County Council (IOACC), and National Resources Wales (NRW) prior to undertaking the work.

1.1 Site Details

The Compressor House is located in the north of the wider former AAM Works site to the south and west of the A5 at Penrhos, east of Holyhead, Anglesey (approximate National Grid Reference 226610E 381080N). Figure 1 shows the site location and Figure 2 indicates the locations of the three escrow sites within the former AAM Works.

1.2 Previous Reports

The following reports have previously been undertaken by LKC relevant to the Compressor House and should be read in conjunction with this Remediation Strategy:

- Preliminary Risk Assessment (PRA) report (Ref: CL-602-LKC 14 1181-01 R1, dated 8th March 2016).
- Phase 2 Geoenvironmental Investigation and Risk Assessment (Ref: CL-602-LKC 14 1181-02, dated 29th April 2016).
- Delineation Investigation and Risk Assessment Report in the Compressor House area (Ref: CL-602-LKC 14 1181-06, dated June 2017).

1.3 Aims and Objectives

The scope of this Remediation Strategy will be to detail the works required to achieve betterment under the 'As Low as Reasonably Practicable' (ALARP) principle and validation proposals. The report will include the following:

- Summary of previous work including pilot trials.
- Proposed remediation works within the Compressor House area.
- Proposed validation work to confirm betterment of groundwater quality in Compressor House area.

In order to achieve the aims of the Remediation Strategy, the following objectives will be set:

- Ensure that the design meets with current environmental and waste legislation.
- Use of appropriate environmental controls during the remediation and development programme.
- Ensure that the remediation process is transparent and fully involves all stake holders.
- Minimise the impact of the works on adjacent land (wider former AAM Works and adjacent Alpcoco Works).
- Ensure that cost compared to environmental benefit is a driver in developing the final improvement design.
- Remediation works are undertaken using the 'As Low as Reasonably Practicable' (ALARP) principle.

2 SUMMARY OF PREVIOUS WORK

2.1 Delineation Investigation Work

In order to assess the ground conditions and delineate the previously identified lubricating oil contamination, intrusive investigation work was undertaken within the Compressor House area.

The investigation was carried out between 10th October and 16th November 2016 and comprised the following:

- 17no. rotary (open holes and cored) boreholes from 9.0-12.0 mbgl (ref. LKRBH501, LKRBH502, LKRBH504, LKRBH509 to LKRBH516, LKRBH519 to LKRBH524) to assess ground conditions into the underlying schist and install deeper monitoring wells.
- 21no. shallow rotary boreholes from 6.0-7.5 mbgl (ref. LKRBH512a, LKRBH506a, LKRBH514a to LKRBH517a, and LKRBH523a to LKRBH537a) to assess ground conditions in the superficial deposits and install shallower monitoring wells.
- 22no. window sample boreholes drilled from 0.5-5.0 mbgl (ref. WS501 to WS522) including WS504a and WS516a) to delineate previously identified contamination and confirm the absence of other contamination hotspots.
- 3no. trial pits excavated to 1.2-2.5 mbgl (ref. TP501-503) to further delineate contamination identified in other exploratory locations and investigate the presence of below ground structures.

The exploratory locations were initially selected to allow the previously identified lubricating oil contamination to be fully delineated as only one borehole had been undertaken in this area previously.

It should be noted that the scope of the investigation works within the Compressor House area increased significantly as a previously unidentified plume of diesel contamination in groundwater was encountered and so additional delineation locations were required to find the extent of the diesel plume.

Rotary boreholes were used to penetrate the schist bedrock to allow installation of groundwater monitoring wells and rotary coring was undertaken in selected boreholes to assess shallow bedrock weathering and fractures, as well as to provide evidence for the extent of any vertical contamination.

All site investigation locations are shown in Figure 3.

2.2 Ground Conditions

The ground conditions in the Compressor House area generally comprised made ground underlain by superficial deposits of gravelly sandy clay or gravelly clayey sand. The superficial deposits were underlain by weathered schist bedrock and it is likely that the deeper superficial deposits were highly weathered schist recovered as gravelly sandy clay.

The schist bedrock was encountered in the deeper boreholes and was noted to be highly micaceous with the shallow bedrock predominately found to be moderate to highly fractured. The deeper schist bedrock showed a lesser degree of fracturing with predominately sub-horizontal fracturing noted.

The groundwater flow within the bedrock is likely to be predominately within fractures and therefore this will depend on the angle, frequency and interconnectivity of the fractures. Based on the ground conditions encountered, it is likely that hydraulic conductivity is greater in the weathered schist bedrock than the deeper less fractured schist.

This cross section shows that the made ground thicknesses are less (generally <1m) in the west of the area in and around the former Works buildings and greater (>1m) in the east, in the previously undeveloped land used as a materials storage area. In addition, the depth to the underlying more competent schist bedrock and thickness of weathered schist was generally greater in the west of the area (circa 7mbgl).

2.3 Identified Contamination

Visual and olfactory evidence of hydrocarbon contamination, recorded as 'hydrocarbon/chemical odours', was noted by Golders in the made ground and reworked weathered schist between 2.3mbgl and 3.8mbgl. The odour was noted to be very strong between 3.6mbgl and 3.8mbgl. It is now known that the contamination identified in APC02 is lubricating oil.

During LKC's delineation investigation evidence of significant hydrocarbon contamination was also identified in a number of exploratory locations (summarised below). However, it should be noted that the contamination identified in a majority of these locations was related to previously unidentified diesel contamination and only a limited area around APC02 was related to lubricating oil.

- WS501 (0.6-1.35mbgl and 1.6-1.8mbgl) – strong diesel odour in made ground and natural sand. Odour becomes slight from 1.8mbgl.
- WS518 (1.6-3.8mbgl) – moderate diesel odour in natural sand.
- RBH501 (3.5-5.5mbgl) – diesel odour in weathered schist.
- RBH502 (0.0-4.0mbgl) – slight weathered diesel odour in made ground and weathered schist.
- RBH516 (2.5-5.5mbgl) – diesel odour in weathered schist.
- RBH517A (4.5-5.5mbgl) – diesel odour in weathered schist.
- RBH523 (3.5-7.0mbgl) – diesel odour in weathered schist and schist bedrock.
- RBH524 (4.0-6.0mbgl) – diesel odour in weathered schist.
- RBH527A (3.5-5.5mbgl) – diesel odour in weathered schist.
- RBH528A (4.0-5.5mbgl) – slight diesel odour in weathered schist.
- RBH529A (3.5-4.5mbgl and 4.5-6.0mbgl) – slight diesel odours becoming moderate by 4.5mbgl in weathered schist.
- RBH530A (4.0-6.5mbgl) – moderate diesel odour in weathered schist.
- RBH531A (3.5-4.5mbgl) – moderate diesel odour in weathered schist.
- RBH535A (3.5-4.5mbgl) – moderate diesel odour in weathered schist.

Rock cores of the schist bedrock were also assessed for visual or olfactory evidence of hydrocarbon contamination. No evidence of hydrocarbon contamination was noted in any of the cores recovered.

2.4 Delineation Investigation Results Assessment

Key results and findings for soil, superficial groundwater and bedrock groundwater in the Compressor House area following the delineation investigation are summarised below:

2.4.1 Soil

Lubricating Oil Contamination

- Of the seventy three soil samples tested within the Compressor House area, four samples recorded detectable levels of hydrocarbon contamination indicated to be associated with lubricating oil.
- The highest concentration of TPH related to lubricating oil in soils was 4,100mg/kg in WS507 between 0.0-0.2mbgl with the main TPH fraction being aromatic C21-C35.
- TPH concentrations potentially relating to lubricating oil in the other sampling locations were between 63mg/kg and 3,100mg/kg. These were all delineated vertically to within the upper 2m and were present either in made ground or superficial deposits.
- Based on the soil concentrations of TPH relating to lubricating oil, the extent of the contamination previously identified in APC02 is localised and reflects the relative immobility of the contaminant.

Diesel Contamination

- Of the seventy three soil samples tested within the Compressor House area, twelve samples recorded detectable levels of hydrocarbon contamination indicated to be associated with diesel or weathered diesel.
- The highest concentration of diesel related TPH in soil in the Compressor House area was 4,400mg/kg and was identified in WS501 at 3.0-4.0mbgl with the main TPH fractions recorded as aliphatic C12-16 and C16-21.
- The depth of the diesel contamination in soil from laboratory test results and visual or olfactory evidence was generally below 2mbgl, with the exception of WS501/RBH501 and WS502/RBH502 (near surface). The deepest sample with detectable TPH relating to diesel was RBH517a at 4.5mbgl within the weathered schist.
- The vertical distribution of the soil hydrocarbon (diesel) contamination indicates that the contamination is likely to be associated with the shallow groundwater in the more permeable superficial deposits.

2.4.2 Superficial Groundwater

The distribution of hydrocarbon contamination in superficial groundwater before and after delineation is presented in Figure 4.

Lubricating Oil Contamination

- Of twenty seven superficial groundwater samples tested only two recorded detectable levels of hydrocarbons relating to lubricating oil.
- The groundwater samples taken from the existing APC02 and WS508, a newly installed shallow monitoring well adjacent to APC02, recorded TPH concentrations of 0.6mg/l and 2.8mg/l respectively.
- The dissolved phase concentrations of hydrocarbons from this source are considered to be limited by the high viscosity and low diffusion coefficient of the LNAPL.
- Free product identified as lubricating oil was found in APC02 and evidence from previous monitoring by LK suggests that the source of the oil is not exhausted but limited, since after removing the free product recharges relatively slowly once removed.

Diesel Contamination

- Of twenty seven superficial groundwater samples tested only thirteen samples recorded detectable levels of hydrocarbons relating to diesel.
- Diesel contamination in groundwater was previously unidentified in this area based on the limited investigation undertaken.
- The maximum TPH concentration related to diesel or weathered diesel in the shallow groundwater was 710mg/l recorded in RBH527a. Evidence of LNAPL was also noted in this location.
- Four other superficial monitoring wells recorded total TPH in groundwater above 100mg/l with the highest concentrations being to the east of the Compressor House around WS501/RBH501.
- The diesel plume in the superficial groundwater was delineated and covers an area around the Compressor House and extends across North Road to the east.
- The source of the diesel is considered likely to be from mobile diesel powered compressors that, anecdotally, were located immediately to the east of the Compressor House.

2.4.3 Bedrock Groundwater

The distribution of hydrocarbon contamination in bedrock groundwater before and after delineation is presented in Figure 5.

- Seven out of sixteen samples recorded concentrations of petroleum hydrocarbons above detection limits and these concentrations were between 0.1mg/l (RBH502) and 4.6mg/l (RBH519).
- No free product was identified during groundwater monitoring of the monitoring wells installed in the bedrock.
- Generally the bedrock does not appear to be significantly impacted by the hydrocarbon contamination identified in the soil and superficial groundwater as diesel concentrations were only recorded in discrete, localised areas.
- The lateral migration of any contaminated groundwater in the bedrock is limited by less fracturing and the subvertical angle of fracturing.

2.4.4 Conclusions

Based on the results of previous and the current delineation investigation work in the Compressor House area, localised contamination associated with lubricating oil is present in the superficial groundwater as LNAPL around the former borehole APC02.

The source of this contamination has not been proven beyond doubt but it is likely to be associated with the nearby oil-water separator adjacent to the Compressor House. Further investigation following demolition is recommended to confirm this.

Previously unidentified diesel contamination has been encountered during the delineation investigation in superficial groundwater and, to a lesser degree, in some discrete deeper bedrock groundwater.

The diesel plume in the superficial groundwater was delineated and covers an area around the Compressor House and extends across North Road to the east.

The source of the diesel is considered likely to be from mobile diesel powered compressors previously situated to the east of the Compressor House. Given that the

source of the diesel is no longer present (the mobile compressors were removed around 20 years ago) and based on the distribution of the diesel contamination and free product it is considered likely that the diesel is thinly dispersed across the area.

There is evidence from the distribution of diesel in shallow groundwater that local groundwater flows may be influenced by below ground structures/chambers and obstructions relating to the former Works.

Free product or evidence of free product was identified in two locations during the delineation investigation.

Based on the findings of the current delineation investigation, there are two separate sources of groundwater contamination in the Compressor House area. Given the extent of the diesel contamination and presence of free product, LKC recommend that remediation to remove free product and achieve betterment of the groundwater under the ALARP principle is undertaken in the Compressor House area to treat both the oil and diesel contamination.

2.5 Pilot Study

A pilot study was undertaken in December 2016 to trial the proposed remediation techniques in the Compressor House area and this included hydraulic testing and chemical treatability trials.

Copies of the full Remediation Pilot Study report (ref: 17.0626, dated May 2017) and Laboratory Bench Scale Chemical Oxidation Study report (ref: A161201, dated March 2017) are presented in Appendix A and B respectively. The key findings are summarised below:

- Depth profiling of the contamination indicates the peak of the identified impact is located between 3mbgl and 3.85mbgl. The peak impact was noted to be in lower permeability horizons and this likely represents a degree of partitioning of contamination from groundwater.
- More permeable superficial gravels recorded lesser concentrations of hydrocarbons indicating the more gravelly deposits, while allowing a greater flow of groundwater, may not themselves store significant contamination.
- Hydraulic testing in the Compressor House area suggests that there is variable hydraulic conductivity in the superficial deposits in this area. This may be due to bands of less permeable strata or the presence of below ground structures.
- The high permeability in the area around APC02 indicates that a pumped solution as a means of recovering free product and dissolved phase hydrocarbons is considered suitable for this area.
- Chemical oxidation trials have demonstrated that a peroxide based oxidant represents a highly effective means of treating the dissolved phase hydrocarbon impacts in the Compressor House area.

3 PROPOSED REMEDIATION WORKS

The proposed additional investigation, remediation and validation works for Escrow site 3 (Compressor House) are outlined in the following Sections.

The impacts in this area predominantly comprise a large plume of dissolved phased diesel, with a localised hotspot of LNAPL oil contamination, closely associated with an adjacent oil/water separator. The objective of these remediation works is to remove all measurable LNAPL and achieve a significant reduction in residual dissolved phase contaminant concentrations within the groundwater under the ALARP principle.

4.1 Additional Investigation

To confirm the source of lubricating oil, LKC recommend further investigation below the oil/water separator adjacent to APC02 following demolition. Prior to this investigation the oil/water separator should be decommissioned including the removal of any water retained in the sump.

The additional investigation should aim to assess ground conditions below the oil/water separator and confirm the previous assumption that a limited 'pool' of free product is present associated with the oil/water separator. If this is confirmed to be present then the treatment area for remediation may need to be increased.

4.2 Remediation

4.2.1 Proposed Treatment Methodology

Following a review of all available investigation data for the Compressor House area and the results of the pilot study the following remediation methods are considered to be the most effective to achieve betterment in the Compressor House area:

- **Dual Phase Vacuum Extraction (DPVE)** to recover LNAPL and hydrocarbon impacted groundwater in the area around APC02.
- **In-Situ Chemical Oxidation (ISCO)** to treat soil sorbed and groundwater borne dissolved phase contamination (from lubricating oil and diesel).

Other methods such as total fluids pumping, downgradient trench recovery and product skimmers were considered, but experience suggests that these will not achieve the remediation goals within a reasonable timeframe (years rather than months to validate).

4.2.2 System Technology – LNAPL Removal

DPVE provides an intensive method of total fluids recovery, which can achieve maximum permissible rates in low and variable permeability soils. The operating principle involves the application of close to absolute vacuum at the interface between the unsaturated and saturated zones. This is achieved using narrow diameter lances, sealed within designated treatment wells connected to a vacuum pump. The vacuum generated at the lance tip, installed at the groundwater interface, subsequently transmits across the capillary fringe to perform the following functions:

- Any LNAPL present would be drawn towards the abstraction lance(s) under the vacuum pressure gradient. This process is enhanced by the horizontal movement of product within the saturated layer, which reduces the influence of surface tension relative to vertical flow situations.
- Groundwater would be drawn towards the lance tip under the vacuum gradient, exposing the capillary fringe and underlying saturated soils. Maximum groundwater abstraction rates using DPVE are generally 50% greater than those achieved by conventional borehole pumps.
- The DPVE technology also facilitates groundwater depression, where required
- The high vapour flow rates generated through the lance tips would recover released soil gases and volatilise any adsorbed volatile contaminants. This would control vapour migration, effectively confining it within the treatment area.
- The circulation of air through the unsaturated zone also increases the biodegradation potential of organic contaminants. This is stimulated by the replacement of hydrocarbon vapours by oxygenated air, thereby encouraging aerobic respiration by any indigenous bacteria.

The following DPVE equipment may be used on the site and the system will have a capacity to vacuum extract approximately 250m³ per hour from the LNAPL impacted area:

- 1 soundproofed container to house DPVE plant,
- 1 suction-side steel gas/liquid separation hydrocyclone installed with high level cut-off float switches and valves for transfer pump control,
- 1 vacuum pump, fitted with high temperature cut-outs,
- 1 discharge-side gas/liquid separation steel hydrocyclone c/w ultrasonic high level cut-off float switch, float switches & valves for transfer pump control and high pressure cut-out,
- 1 Centrifugal pump for liquid discharge to oil/water separator,
- 1 Centrifugal pump for water transfer from oil/water separator,
- 2 Granular Activated Carbon vessels for liquid-phase adsorption,
- 1 Granular Activated Carbon vessel for gaseous-phase adsorption,
- Bunded Treatment area,
- 1 Product storage quarantine vessel.

Following uplift from the wells via vacuum lances the mixture of liquid and gas is separated via hydrocyclonic knockout pots. The total fluids from the knockout pots are then pumped into an oil/water separator which will remove any phase separated product and allow for silts to settle before being transferred to the GAC units for polishing prior to discharge.

Recovered product would be stored in separate secure barrels or a bunded tank, which would contain overfill protection and be emptied by a suitably licensed waste contractor, in accordance with Duty of Care procedures.

Existing monitoring wells displaying LNAPL will be used as abstraction points, along with additional newly installed abstraction points. It is proposed to install up to an additional ten abstraction wells, installed to the top of the competent schists for this purpose, with spacings and frequency in line with the findings of the Pilot Study.

The extent of the proposed treatment area is indicated on Figure 6.

4.2.3 System Technology Chemical Oxidation

Pilot testing works in the Compressor House area have generally identified a high permeability within the subsurface ensuring that the ground will readily accept injected

oxidants and efficient treatment can be achieved with maximum contact between oxidant and contaminant within the groundwater.

Following the removal of measurable product around APC02, peroxide based chemical oxidation will be used through fixed point injection to generate Fenton's like free-radicals and contaminant oxidation (e.g. hydroxyl radical). In line with the recommendations of the pilot study the treatment zone, as defined on Figure 6, is anticipated to require multiple oxidant applications to achieve the required result.

Although the main contaminant mass in the groundwater is present in the shallower groundwater body, in the area where detectable hydrocarbon concentrations have been identified in the bedrock groundwater, shown on Figure 5, chemical oxidant will be injected into the deeper monitoring wells to treat any dissolved phase hydrocarbons.

Injections would commence on the outside of the plume and concentrically moved inward to ensure that no contaminant is displaced in an uncontrolled manner without being oxidised. This will prevent any migration of untreated contaminants outside of the treatment area.

Oxidant injection will be undertaken using fixed well points, which would comprise newly installed wide diameter, high permeability installations, with robust seals, through the permeable strata overlying the competent schists. It is envisaged that a maximum of thirty new boreholes with installations will be required across the treatment area for oxidant injection. Where suitable and acceptable, some existing wells may be utilised as injection points.

Oxidants will be stored and mixed onsite, in controlled, fenced and bunded areas. At this stage, it is assumed a water and electric supply will be available onsite for this purpose. Oxidant volumes will be injected into the designated wells in suitable volumes to ensure treatment of the entire target pore space in line with the pilot study recommendations.

The oxidant will react very rapidly upon contact with contaminant in the subsurface and would be expected to have become exhausted within a period of seven days post injection. It is expected that to treat all target wells with a single application would take approximately 1-2 weeks (subject to water supply). Repeat injections will be undertaken concurrently to achieve rapid reductions in contaminant concentrations.

4.2.4 Operation Timeframe and Validation

Installation and commissioning of the DPVE system on site is anticipated to take four weeks inclusive of well installation.

It is anticipated that the DPVE system, once fully commissioned would operate for a period of up to 6 months although it is considered likely based on the results of the pilot study that the system may run for a much shorter period.

The ISCO operation would be undertaken over a period of up to two months with validation thereafter. This does not include drilling time, which could be conducted during DPVE works. Chemical oxidation works should not be conducted whilst LNAPL removal works are ongoing.

Validation monitoring following cessation of works would be for a twelve month period with monthly intervals at well locations to be agreed with the regulators. The validation regime will include measuring of phase separated product using an oil/water interface probe and checked with a product bailer and groundwater analysis for contaminants of concern.

4.2.5 Operational Monitoring and Reporting

Once commissioned, the DPVE system will be monitored weekly for the first month to optimise system performance and fortnightly thereafter. A monthly update report will be issued to all stakeholders detailing system progress with monthly laboratory data and product thicknesses, or chemicals oxidation progress, where relevant.

Monitoring will include groundwater sampling and NAPL thickness dips from across the treatment areas to monitoring ongoing performance of the programme as suitable intervals. Additionally, further monitoring may be undertaken as required by the Environmental Permit as detailed below.

4.2.6 Licensing

It is considered that an environmental permit will be required to undertake these works.

A temporary trade effluent discharge licence may also be required during DPVE works, if existing agreements in place at the site cannot be used for the remediation works.

As it is anticipated that the DPVE treatment will take less than 12 months, the abstraction of water should fall outside the licensing regime as it is anticipated the volume will be 20m^3 per day.

4.2.7 Treatment Compound

A treatment compound measuring approximately 20 metres by 20 metres will be required for the DPVE system and any associated welfare. The location of the compound should be agreed with Orthios Eco Parks and will depend on any other operations occurring on the site at the time of the remediation. All vessels used in the remediation works will be fully bunded.

ISCO treatment plant would need to be present during the injection phase only and would occupy a similar footprint to the above.

All compounds will need to be accessible by HIAB mounted low loader trucks for position and removal of plant.

4.2.8 Waste Streams

Waste management operations will be limited to the physical and chemical treatment of contaminated soil and groundwater.

The waste streams generated by the remedial methods proposed are identified as:

- Contaminated groundwater.
- GAC impacted with contaminants.
- Treated wastewater.
- Treated soil vapour.
- NAPL collected in the product storage tank.
- Consumables.

The on-site waste treatment system comprises the following plant.

- Granular activated carbon (GAC) units.

- NAPL/water separators and product storage tank.

During and following treatment, gaseous phase waste will be vented to atmosphere (via GAC filtration if necessary); treated groundwater will be disposed of to sewer. Free product (LNAPL) and spent GAC would be removed off-site for disposal. The disposal would be fully compliant with current Duty of Care requirements.

Granular Activated Carbon Unit

It is anticipated that a minimum of two Granular Activated Carbon vessels would be required for the treatment process.

A liquid phase GAC unit should be used to treat the abstracted groundwater and a gaseous phase GAC unit would be installed and be separate from the other treated waste systems. After treatment, soil vapours will be vented through a stack. A PID shall be used to measure the concentration of contaminants and monitoring of the soil vapour to monitor for breakthrough.

Oil/Water Separator

The separator comprises one tank complete with baffles, weir, product skimmer, high-level cut-off float switch and float switch for transfer pump control. LNAPL floats to form a layer on the surface where it is subsequently skimmed to a product storage tank. The product storage tank/ barrels will be emptied and tankered away for disposal when necessary under duty of care requirements.

4 VALIDATION

Remediation works undertaken on site will need to be validated to ensure the objectives have been met and that betterment has been achieved under the ALARP principle. Validation of any remediation should be undertaken by a competent consultant and should be reported in the Verification Report.

5.1.1 Validation of Groundwater Remediation

The remediation works in the Compressor House area will aim to achieve betterment in accordance with the ALARP principle. The validation of the proposed remediation works are detailed below.

Free Product Recovery

Free product recovery will aim to reduce free phase mass and to achieve asymptotic mass recovery conditions. In the context of demonstrated mass recovery rates it is the point at which the free product recovery curve declines to such a reduced level that will probably be maintained at this level for a considerable length of time without further significant reduction.

This level would be considered to represent a residual concentration that the gross contamination within the source zone would not be cost effective to continue treating and the majority of the mass amenable to extraction would already have been removed by this point.

The quantity of free product recovered will be recorded continuously during the remediation works and recovery will only cease once asymptotic conditions are considered to have been met.

Validation Groundwater Monitoring

Validation monitoring following cessation of works would be for a twelve month period at monthly intervals at existing monitoring well locations within the Compressor House area. The selected remedial techniques were selected to contain remedial works within this area and any impact to groundwater outside this area is considered to be negligible.

Post remediation groundwater analysis will also be used to demonstrate betterment. The groundwater monitoring regime will include measuring of phase separated product using an oil/water interface probe and product balers.

Post remediation groundwater samples will be taken a minimum of 14 days after development of the wells. Prior to sampling of groundwater, monitoring wells will be purged to allow a representative groundwater sample to be taken. Continuous measurement of parameters such as electrical conductivity (EC), pH, temperature and dissolved oxygen will be undertaken during purging to demonstrate equilibrium conditions (as a minimum EC will be tested as per the guidance). Samples will be taken once these parameters have stabilised.

All post remediation groundwater samples will be tested for the following suite of contaminants:

- Banded petroleum hydrocarbons (TPHCWG), BTEX and MTBE.

The proposed groundwater remediation and validation in the Compressor House area will be detailed in a separate Verification Report for approval once betterment is considered to have been achieved.

5 VERIFICATION AND COMPLETION REPORTS

A Verification Report will be provided once the remediation goal of betterment to the ALARP principle has been met in the Compressor House. This will include:

- The summary of groundwater hydrocarbon plume delineation work.
- Results of the pilot studies of proposed remediation techniques.
- Results of additional investigation below the oil/water separator.
- Description of groundwater remediation works in the Compressor House area.
- Volumes of free product recovered from treatment area.
- Details of chemical oxidant injection including volumes and types of oxidant used.
- Results of groundwater validation including dipping records and certificates of analysis.

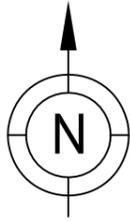
The aim of the Verification Report will be to demonstrate to escrow account stakeholders that the required remediation works in the Compressor House area have been undertaken as per the agreed strategy.

FIGURES

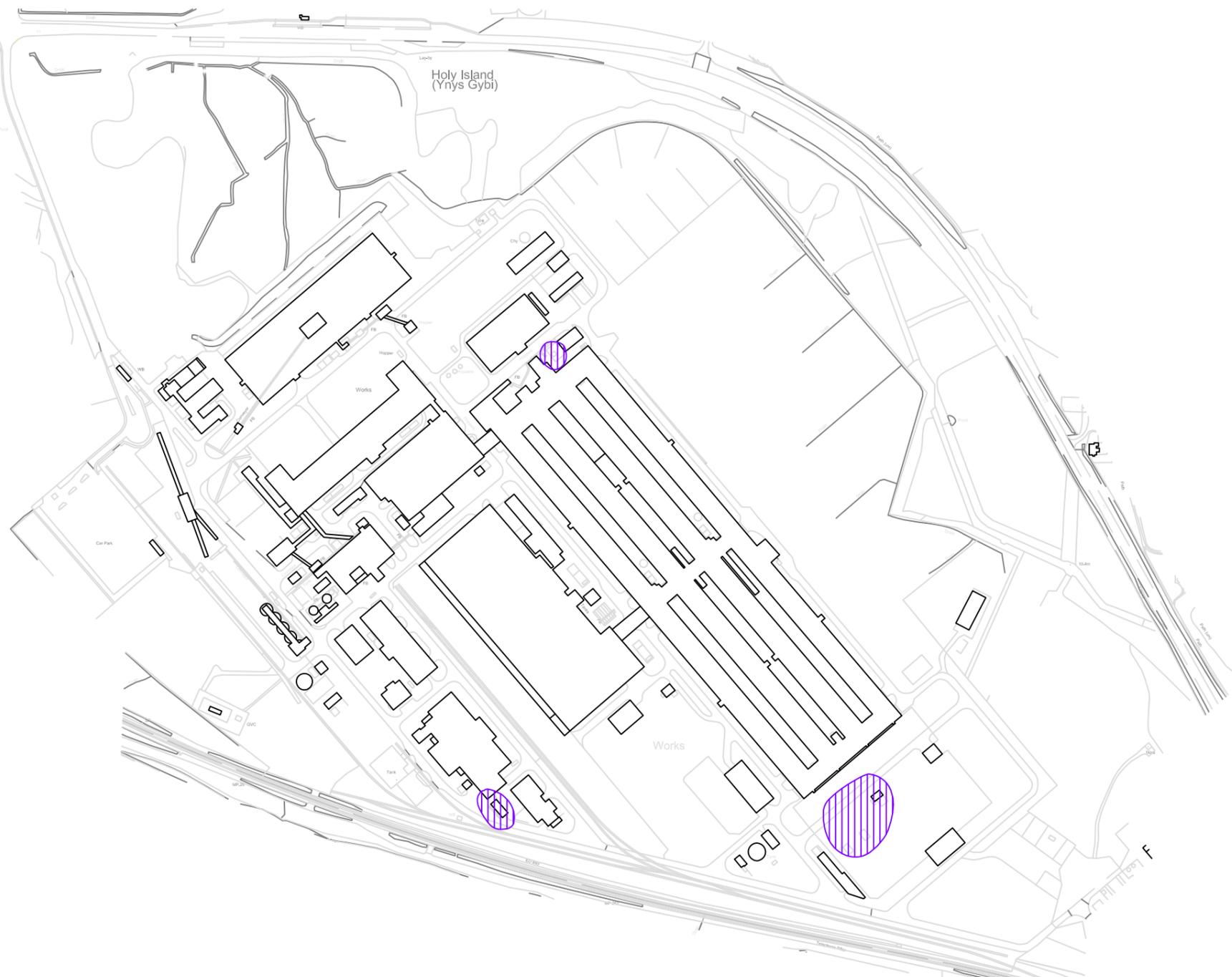


Figure 1: Site Location Plan, Anglesey Aluminium, Holyhead

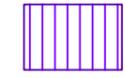
Drawn: June 2017 Scale: 1:25,000 @ A4 (see scale bar)



Holy Island
(Ynys Gybi)



KEY

 Escrow Sites

Sampling Locations and features annotated by LK Consult Ltd are approximate and are based upon observed measurements unless otherwise stated. Do not scale from this drawing and work from marked dimensions only. All dimensions and features should be confirmed on site by the Contractor. Where this drawing includes information provided to LK Consult Ltd by others, LK Consult Ltd gives no warranty, representation or assurance as to the accuracy of such information.



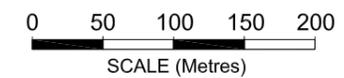
Client: **Orthios**

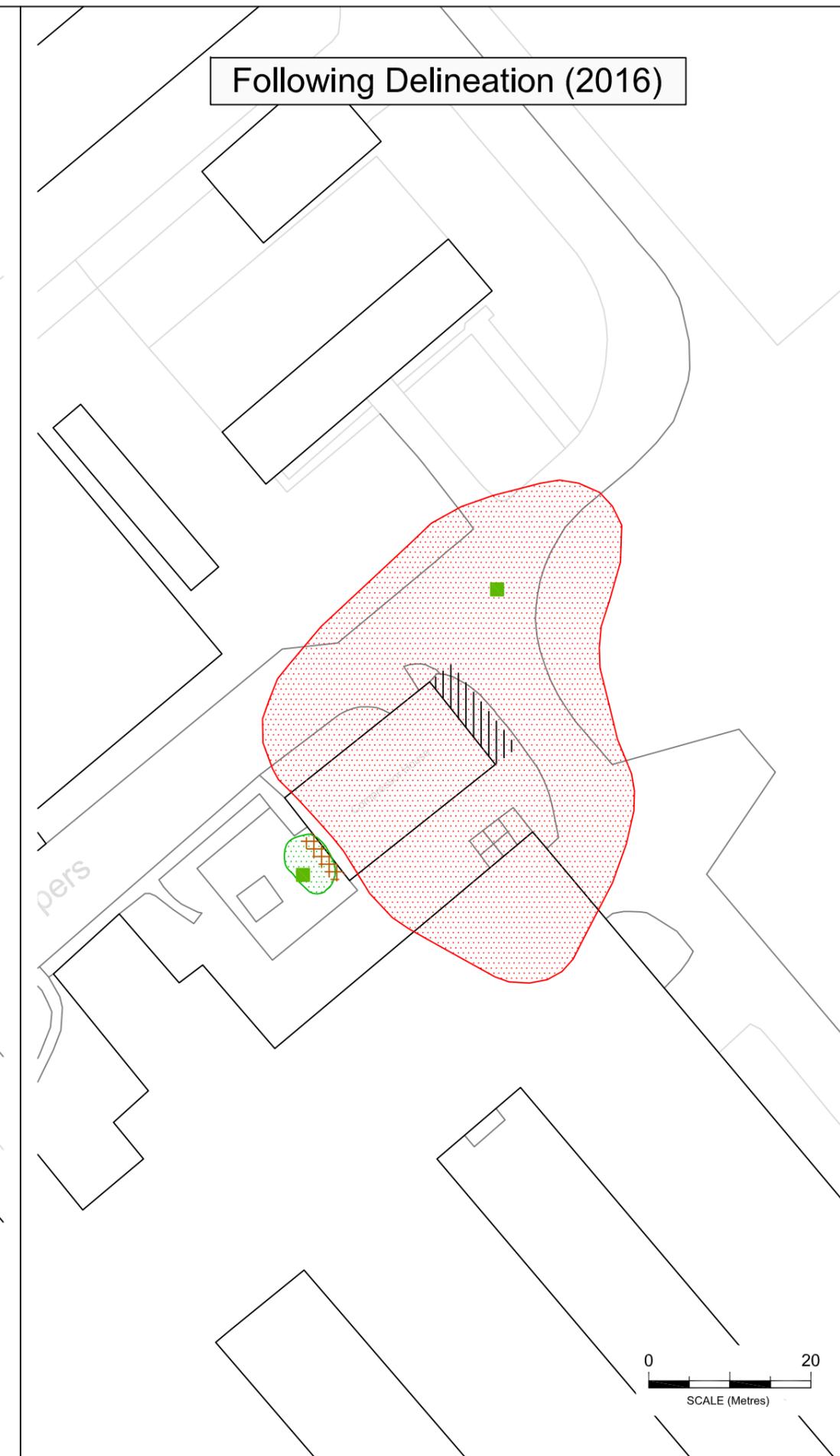
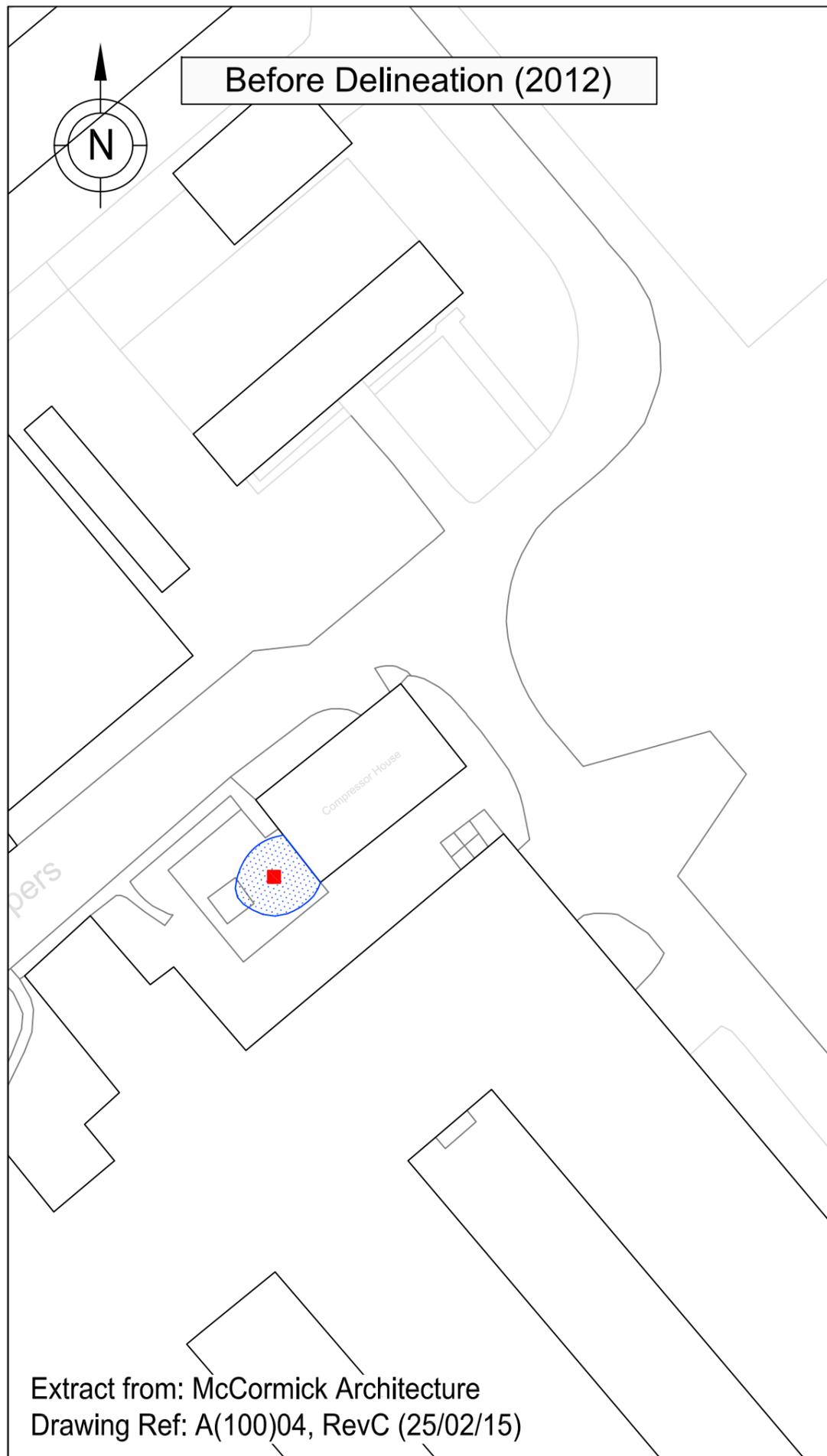
Site: **Anglesey Aluminium**

Title: **Escrow Sites**

Job No.: LKC 14 1181	Scale (See Scale Bar): 1:5000 @ A3	Figure: 2	Revision:
Drawn By: AC	Checked By: PQ	Drawn: May 2016	

Extract from: McCormick Architecture
Drawing Ref: A(100)04, RevC (25/02/15)





KEY

	Diesel Contamination
	Lubricating Oil
	Estimated Plume Extent (Before Delineation)
	Free Product Detected (2012)
	Free Product Detected (2016)
	Assumed Source of Diesel
	Assumed Source of Oil

Sampling Locations and features annotated by LK Consult Ltd are approximate and are based upon observed measurements unless otherwise stated. Do not scale from this drawing and work from marked dimensions only. All dimensions and features should be confirmed on site by the Contractor. Where this drawing includes information provided to LK Consult Ltd by others, LK Consult Ltd gives no warranty, representation or assurance as to the accuracy of such information.



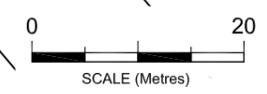
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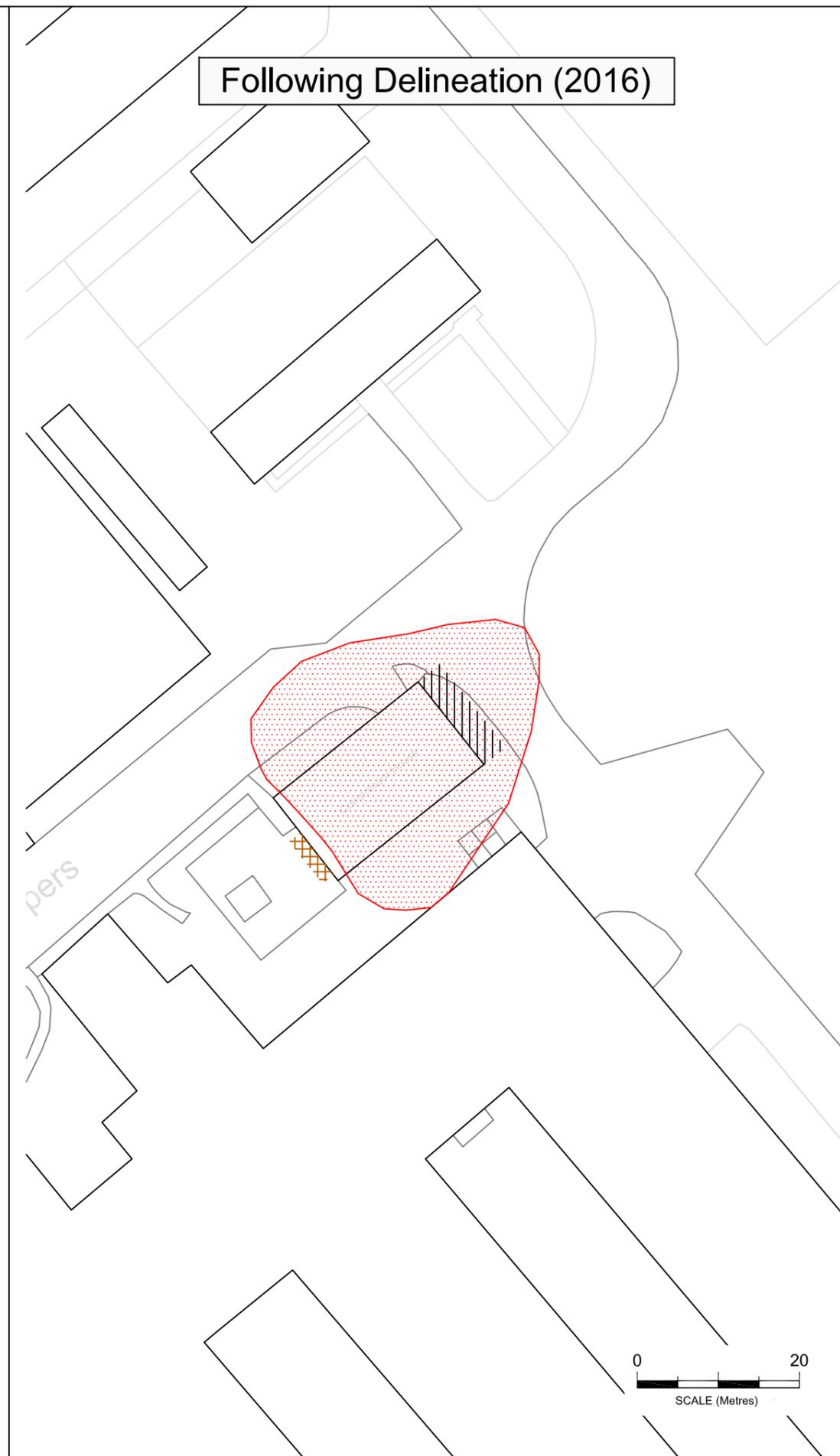
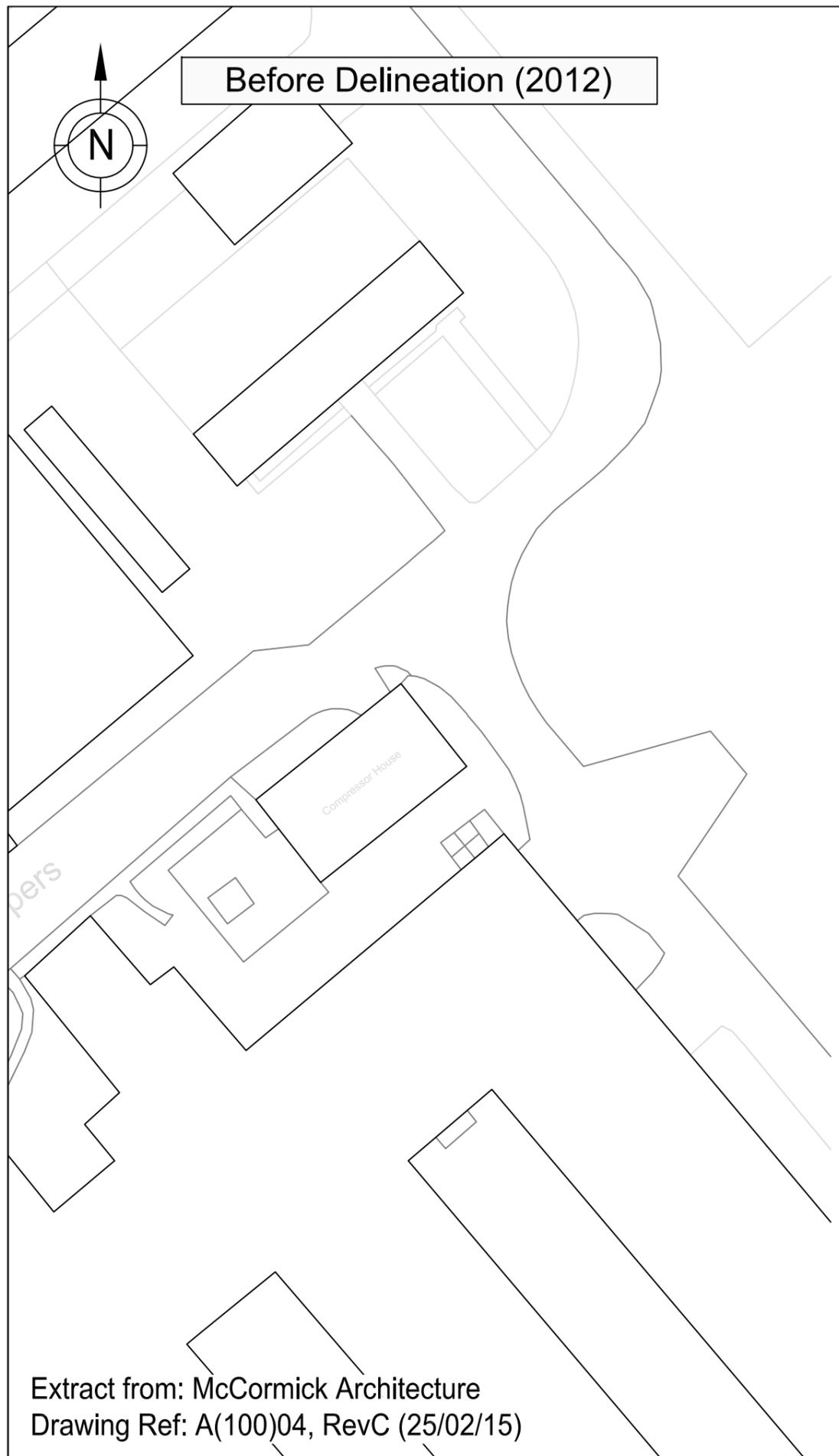
Site: **Anglesey Aluminium, Holyhead**

Title: **Hydrocarbon Distribution in Superficial Groundwater (Compressor House)**

Job No.: LKC 14 1181	Scale (See Scale Bar): See Scale Bar	Figure: 4	Revision:
Drawn By: AC	Checked By: CH	Drawn: Jun 2017	

Extract from: McCormick Architecture
Drawing Ref: A(100)04, RevC (25/02/15)





KEY

-  Diesel Contamination
-  Assumed Source of Diesel
-  Assumed Source of Oil

Sampling Locations and features annotated by LK Consult Ltd are approximate and are based upon observed measurements unless otherwise stated. Do not scale from this drawing and work from marked dimensions only. All dimensions and features should be confirmed on site by the Contractor. Where this drawing includes information provided to LK Consult Ltd by others, LK Consult Ltd gives no warranty, representation or assurance as to the accuracy of such information.



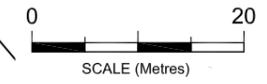
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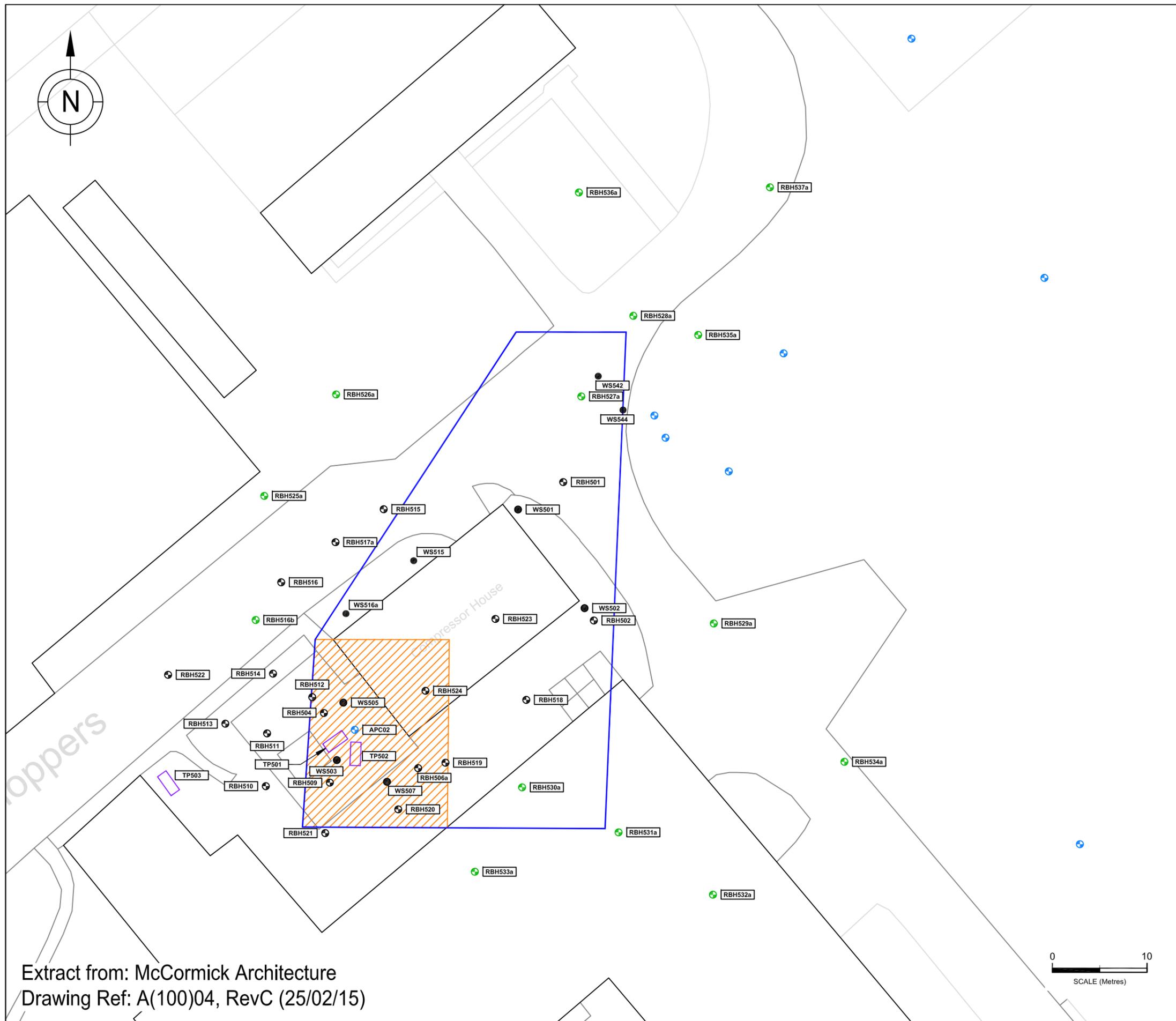
Site: **Anglesey Aluminium, Holyhead**

Title: **Hydrocarbon Distribution in Bedrock (Compressor House)**

Job No.: LKC 14 1181	Scale (See Scale Bar): See Scale Bar	Figure: 5	Revision:
Drawn By: AC	Checked By: CH	Drawn: Jun 2017	

Extract from: McCormick Architecture
Drawing Ref: A(100)04, RevC (25/02/15)





KEY

-  Existing Borehole
-  Proposed Dual Installation (Shallow & Deep)
-  Proposed Window/Cable Borehole
-  Shallow Rotary Borehole
-  Trial Pit (TP)
-  Extent of ISCO Area
-  DPVE Area

Sampling Locations and features annotated by LK Consult Ltd are approximate and are based upon observed measurements unless otherwise stated. Do not scale from this drawing and work from marked dimensions only. All dimensions and features should be confirmed on site by the Contractor. Where this drawing includes information provided to LK Consult Ltd by others, LK Consult Ltd gives no warranty, representation or assurance as to the accuracy of such information.



Client: **Orthios**

Site: **Anglesey Aluminium, Holyhead**

Title: **Proposed Treatment Area**

Job No.: LKC 14 1181	Scale (See Scale Bar): NTS	Figure: 4	Revision:
Drawn By: AC	Checked By: CH	Drawn: Jun 2017	

Extract from: McCormick Architecture
Drawing Ref: A(100)04, RevC (25/02/15)

APPENDIX A

REMEDIATION PILOT STUDY REPORT



**REMEDICATION
PILOT STUDY**

**Escrow Areas:
COMPRESSOR HOUSE
Anglesey Aluminium
Penrhos Works
Holyhead**

For

LK Group

May 2017

17/0626

Geo² Remediation Limited

11, The Mending Rooms, Sunny Bank Mills, Town Street, Farsley, Leeds, LS28 5UJ
Tel 0113 257 5397

LK Group

Remediation Pilot Study

**Escrow Areas:
COMPRESSOR HOUSE
Anglesey Aluminium
Penrhos Works
Holyhead**

May 2017

Report ref no. 17/0626

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- 2.0 Known Contaminant Impacts**
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- 4.0 Pump Testing**
 - 4.1 Slug Tests
 - 4.2 Falling Head Test
 - 4.3 Step Test
 - 4.4 Summary of Hydraulic Conditions
- 5.0 Vacuum Testing**
- 6.0 Treatability Trial**
 - 6.1 Model Development
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- 7.0 Conclusions**
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- Appendix C Photo Appendix**
- Appendix D Hydraulic Testing**
- Appendix E Vacuum Testing**
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LK Group

Remediation Pilot Study

**Escrow Areas:
COMPRESSOR HOUSE
Anglesey Aluminium
Penrhos Works
Holyhead**

April 2017

Report ref no. 17/0626

1.0 Introduction

Geo² Remediation Limited was commissioned by the LK Group to conduct a Remediation Pilot Study of identified contaminated areas that form portion of the Anglesey Aluminium Site. These works targeted three areas, each reported separately. This report details pilot works undertaken in the Compressor House area.

The Anglesey Aluminium site is located on the east side of Holyhead island, as shown on Figure 1 and 2 in Appendix A. The property is currently derelict and undergoing demolition for future reuse as part of Orthios Eco Park.

This testing has been undertaken to aid design and implementation of a suitable remediation programme to ensure maximum environmental improvement can be achieved at this site. The objectives of the remediation are understood to be removal of all Light Non-Aqueous Phase Liquid (LNAPL) and also to undertake remedial works that will achieve maximum betterment following the 'as low as reasonable practicable (ALARP)' principle.

Initial feasibility scoping suggested that the most suitable methods of remediation would include, physical pumped treatment to recover LNAPL coupled with chemical injection as a means of treating the dissolved phase and soil-sorbed impacts.

In order to permit an effective treatment design, this Remediation Pilot Study comprises the following stages:

- Additional intrusive investigation;
- Contaminants Depth Profiling;
- Hydraulic Testing;
- Chemical Treatability Trials.

2.0. Known Contamination Impacts

Significant earlier investigation addressing various portions of the wider aluminium site have been undertaken since 1994 by a number of contractors, mainly URS and Golder Associates. These reports, summarised by the LK Group in a 'Review of Previous Works' identified three key areas potentially requiring treatment.

Additional information from each of the other areas (the 'Garage' and the 'Rectifier Yard') obtained by the LK Group has been reported separately and was used to aid determination of drilling locations and testing schedules.

The following section provides a brief summary of the known impacts in the Compressor house area. Using this information as a baseline further characterisation works have been undertaken, concurrently with additional investigation works by The LK Group, in line with Escrow Sites: Scope of Works document 20.05.2016.

Located in the north area of the aluminium plant site, this area was designated following identification of oils in a single borehole (APC2). Additional investigation undertaken by The LK Group did not indicate a more widespread LNAPL plume (although a potentially distinct LNAPL hotspot was identified in RBHS27A), however a significant dissolved phase hydrocarbon range impact was noted within the groundwater.

Ground conditions in this area comprise clayey sandy gravels, similar to much of the remainder of the site, to a depth of between 5-7mbgl when the underlying schists become competent. Sampling of groundwater in this area is understood to suggest a potential impact within the water body in the underlying schists. This assessment focuses upon the known impact within the shallow deposits.

3.0 Depth Profiling

To characterise the distribution of the contaminant impact vertically within the soils matrix, cores of soil, recovered from the target horizon using dynamic sampling techniques, were sealed and rapidly frozen.

Freezing of cores allows for the preservation of the vadose zone and phreatic zone within the soil structure, which may then later be targeted with forensic scale sampling and analysis. Sampling undertaken subsequently under laboratory conditions allows for recovery of discrete samples collected at frequencies of up to every 100mm. Using this technique ensures that the location of the contaminant impact can be targeted accurately ensuring that any proposed remediation will exactly target the contaminated horizon/s (rather than, for example, simply targeting the groundwater or most permeable horizon).

All samples were submitted for analysis for speciated hydrocarbons (TPH-CWG): the major contaminants of concern. All samples were analysed at a suitably accredited laboratory and full laboratory certification is appended to this report.

Information from earlier works by The LK Group allowed the most contaminated horizons to be targeted for preservation, effectively screening out the less contaminated areas.

Sampling analysis has been plotted onto interactive depth profiling logs appended to this report as excel spreadsheets. Complete borehole logs for locations drilled by Geo² are included in Appendix B.

All logging has been undertaken in line with best practice guidance in BS 5930:2015.

A total of six boreholes (WS538-WS543) were drilled across the area, as shown in Figure 4, in Appendix A. All these locations were targeted across the area considered to be most contaminated as a result of earlier investigation.

Drilling recovered 1m long cores for subsequent laboratory analysis from each of the six boreholes, after screening the quality of recovery, the recovered cores are summarised below on Table 1. Those shaded in grey were not deemed suitable for detailed analysis.

Location	Depth (m)	Geology
WS538	2.0-3.0	SANDS overlying SILTs
WS539	2.0-3.0	No Log reported
WS540	3.0-4.0	Gravelly SILTs
WS541	2.0-3.0	Silty gravelly CLAYs
WS542	-	No Log reported
WS543	4.0-5.0	Silty GRAVELS.

Table 1. Core Sampling from Compressor House

Analysis of cores, demonstrates that the peak of the identified impact is located between 3.00m and 3.85m within the soil cores at maximum concentrations in excess of 2,500mg/kg (WS538). Peak concentrations in WS540 and WS541 were at approximately 1,000mg/kg. Each of these peaks appears to be associated with lower permeability horizons, in the SILT or CLAY deposits. It is likely this represents a degree of partitioning of contamination from the groundwater, present at approximately this depth across this area, into these lower permeability deposits. Analysis from WS543, exhibits a far more permeable, GRAVEL subsurface, where at similar depth maximum recorded concentrations reach a peak value of 800mg/kg, this suggest the gravels themselves, whilst potentially allowing a greater flow of groundwater, may not themselves store significant contamination.

These findings reflect the data obtained by The LK Group which indicates pockets of variability within the plume, with the highest concentrations of contamination associated with the more permeable horizons. The contamination is not principally located within the gravel matrix, however a degree of this impact is held within the lower permeability fractions.

4.0 Pump and Vacuum Testing

A programme of pump testing was scheduled in the Compressor House Area to enable an assessment of the hydraulic setting of each of the contaminated plumes to be made, as this will provide important consideration in determining radius of influence in a future remediation system and the likely volumes of water to be recovered. Vacuum testing was also conducted here to determine air transmissivity through soil pore spaces.

This testing was to comprise, the following:

- Slug tests

In order to determine conductivity, a series of slug tests was undertaken across the area. Slug testing was selected as a rapid means of testing a number of locations and repeatedly, to determine the recharge rate within the aquifer.

- Step Tests

These are undertaken using an electrical pump to abstract from a single pumping borehole at a known speed. Use of pressure transducers in the pumping well and nearby observation points means that the degree of drawdown and radius of influence can be determined. Operation at a set flow rate is conducted until equilibrium is achieved, after which point the rate is increased. This process is repeated at higher flow rates, or steps, until sufficient drawdown is achieved. Data for recovery can be obtained following completion of the step test.

- Falling head tests.

Falling head tests may be undertaken to observe the response of the aquifer to a rapid increase in head level within the target borehole. This provides an alternative means of determining transmissivity.

All testing was undertaken in line with best practice guidance in BS 14686: 2003.

Boreholes selected for pump testing are shown on Figure 4, in Appendix A. These are selected from across the plume to ensure good coverage of the impact and to identify regional variation. Boreholes for which soil bore logs are available, and also which were of a suitable depth, were selected to ensure data collected was representative of the target aquifer.

4.1 Slug Tests

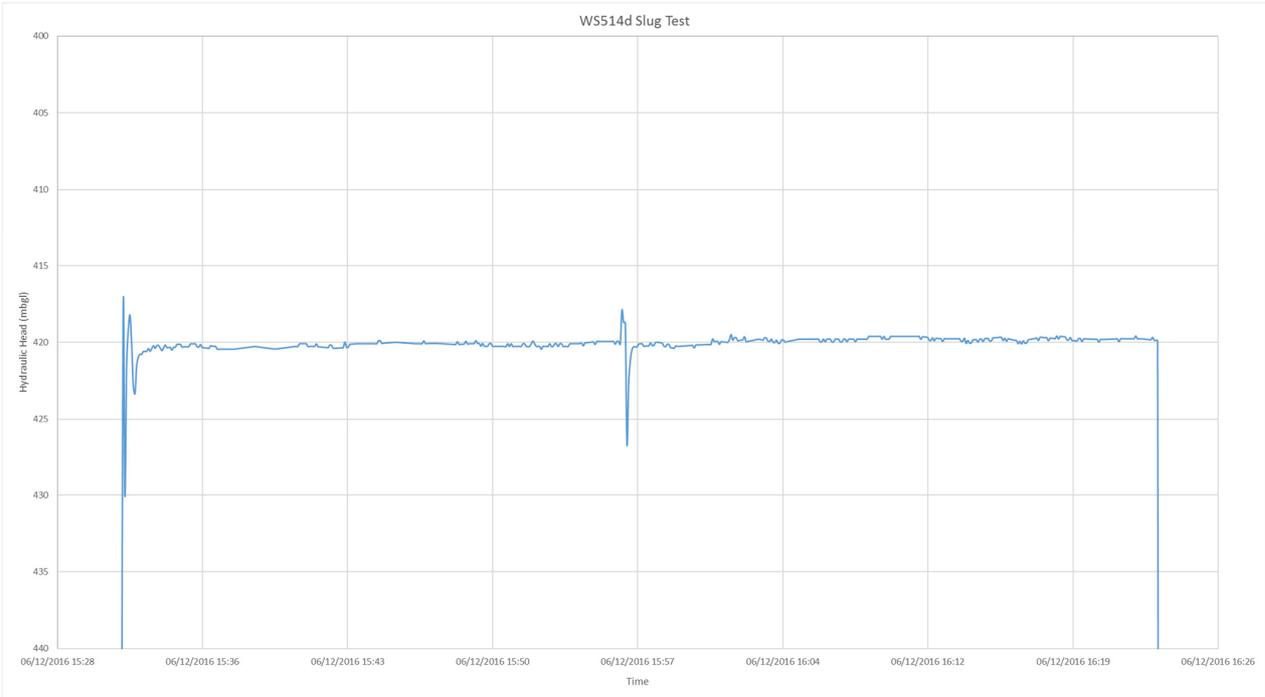
A slug test, where a set volume of water is removed from the column of water in a well before being allowed to recharge, was conducted on a total of three wells in the Compressor House on 06/12/2016. Changes in hydraulic head were monitored during this test using Shlumberger Water Services pressure transducers. These instruments are set at fixed heights in testing wells and measure barometric pressure relative to a fixed surface pressure monitor and subsequently calculate changes in hydraulic head.

Data retrieved yielded response curves, displayed below, that could be then fitted to calculated type curves using Aquifer analysis software. Using these standard curves based on known conditions, estimates can be made from inputted primary data of local hydraulic conductivity.

Where possible, tests were allowed to run to completion with multiple tests run on individual wells to increase reliability. In some instances however, recharge was found to be too slow to allow for multiple tests or even for tests to fully run to completion.

The following tables and graphs detail the findings of the investigation fitted type curves can be found in Appendix D.

WS514d



Graph 1 – Graph displaying changes in hydraulic head in WS514d during performed Slug Tests

Graph 1, above, presents the data for the slug testing in WS14d. Two test runs can be seen here with rapid rebound. Fitting these data points to Bouwer S-type curves in Aquifer yielded a value for hydraulic conductivity displayed in Table 2 below. Graphs displaying these type-curve fittings can be found in Appendix D.

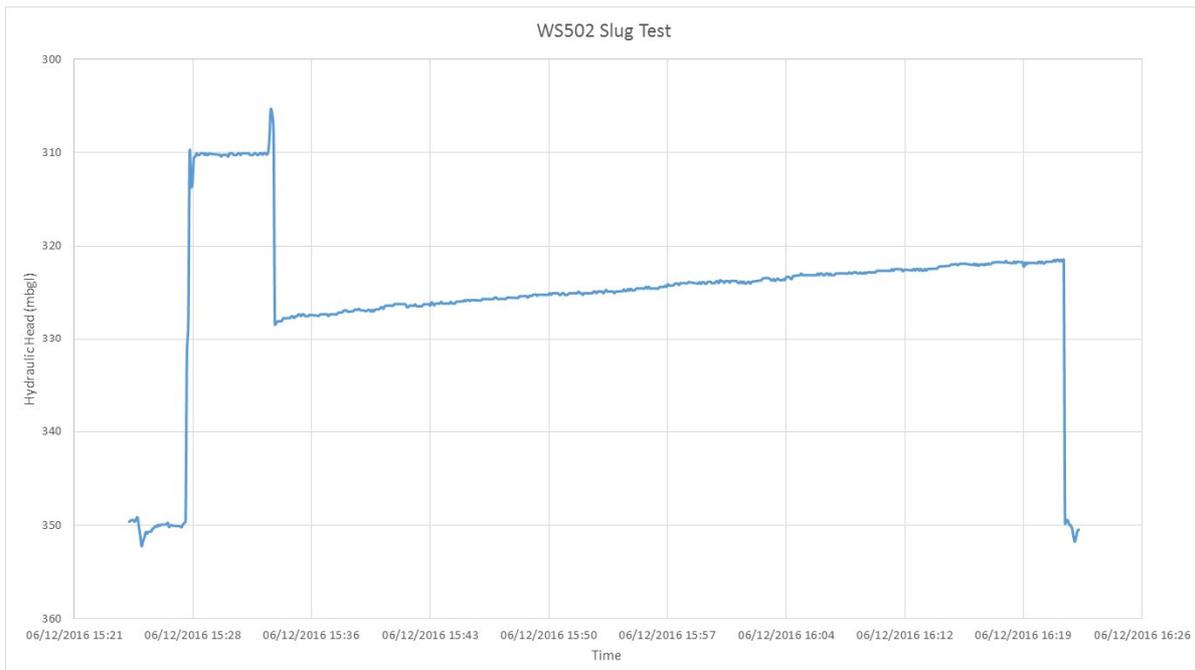
Well	Hydraulic Conductivity (m/d)	Initial Displacement (m)
WS514d	26	0.061

Table 2 - Table calculates hydraulic conductivity and initial displacement calculated from data obtained from Slug Tests conducted on WS514d

The average hydraulic conductivity here was found to be 26m^{-day}. This well was found to have 10m of water head prior to test commencement, as such this sample is considered to be potentially impacted by deeper groundwater bodies.



WS502



Graph 2- Graph displaying changes in hydraulic head in WS502 during performed Slug Tests

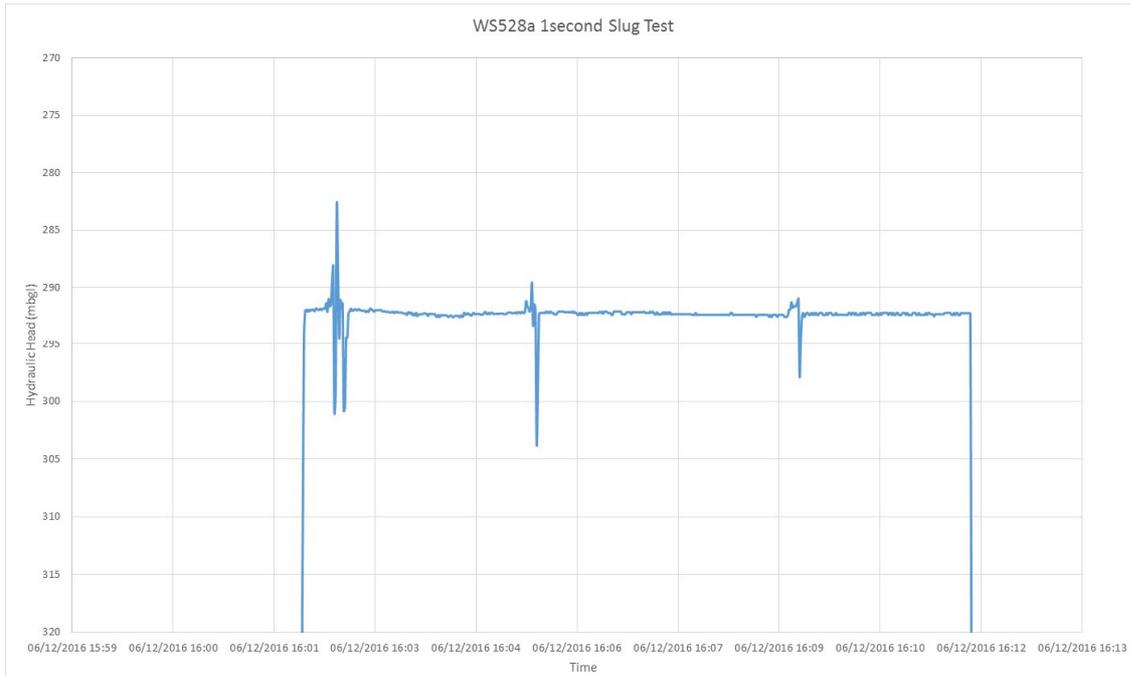
Graph 2, above, presents the data for the slug test in WS502. A single test was conducted due to its slow recharge. Fitting these data points to Bouwer S-type curves in Aquifer yielded a value for hydraulic conductivity displayed in Table 3 below. Graphs displaying these type-curve fittings can be found in Appendix D.

Well	Hydraulic Conductivity (m/d)	Initial Displacement (m)
WS502	0.10	0.007

Table 3 - Table detailing calculated hydraulic conductivity and initial displacement calculated from data obtained from Slug Testing conducted on WS502

One test was carried out on WS502 and, due to its low rate of recharge, testing was discontinued after 50 minutes. The hydraulic conductivity calculated for this location was 0.1m^{day} .

WS528a



Graph 3 - Graph displaying changes in hydraulic head in WS528a during performed Slug Tests

Graph 3, above, presents the data for the slug test performed on WS528a. An initial diver test on a five-second measurement schedule in this well had indicated recharge was extremely rapid. As such, the diver was reset with a one-second measurement schedule in order to obtain useful data. Despite this, recharge was still found to be extremely quick. Three tests can be seen here with rapid rebound. Fitting these data points to Bouwer S-type curves in Aquifer yielded values for hydraulic conductivity displayed in Table 4 below. Graphs displaying these type-curve fittings can be found in Appendix D.

Well	Hydraulic Conductivity WS528a			
	Test 1	Test 2	Test 3	Average
Hydraulic Conductivity (m/d)	134.62	453.58	285.79	291.33
Initial Displacement (m)	0.207	1.459	0.157	0.608

Table 4 - Table detailing calculated hydraulic conductivity and initial displacement calculated from data obtained from Slug Tests conducted on WS528a

The three tests undertaken showed hydraulic conductivity ranging from 134.62m^{-day} to 453m^{-day}. The average for these tests was found to be 291.33m^{-day}. The rapidity of the recharge, in approximately 1-3 seconds leading to few data points, could account for the wide discrepancy in the data.

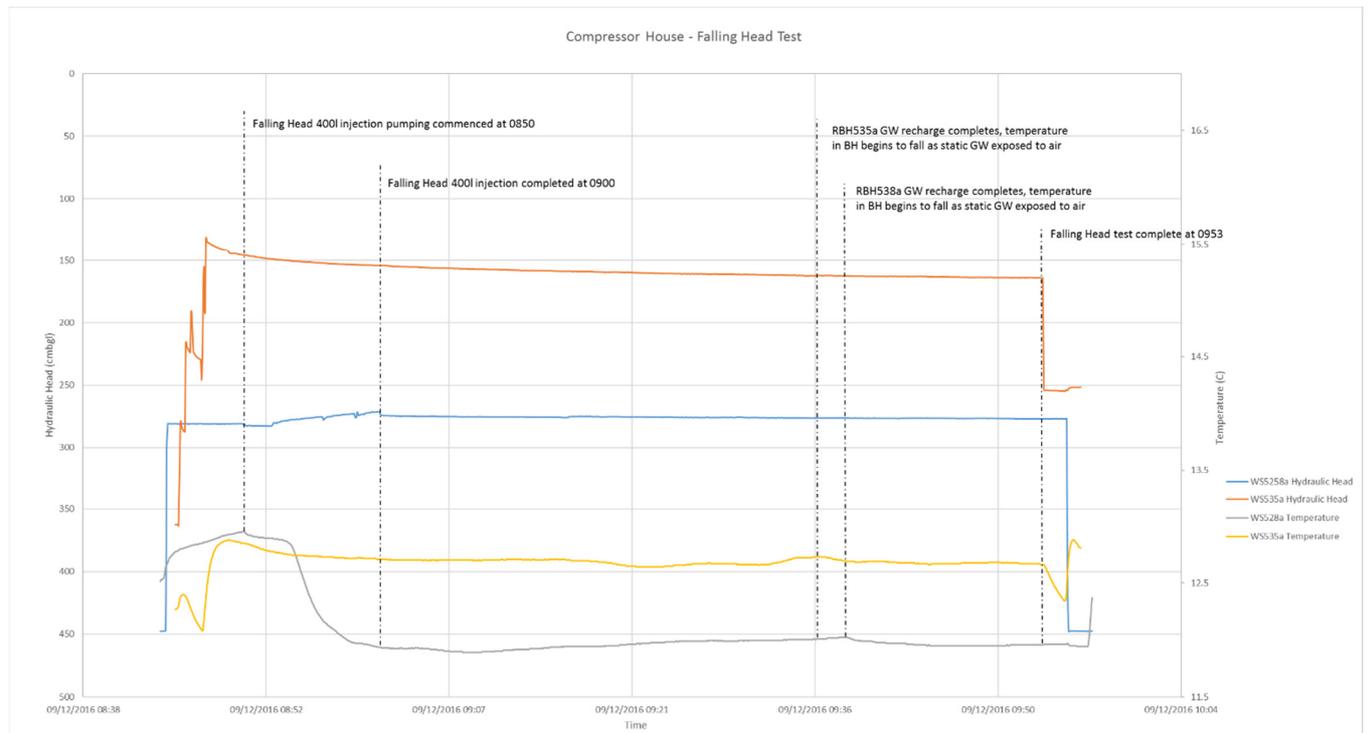
4.2 Falling Head Test

A falling head test was conducted in the Compressor House Area. This test consisted of injecting 400 litres of water into a WS528a at approximately 46l^{-hour}, taking approximately 10 minutes, and allowing the hydraulic head to equilibrate to its previous reading.

Changes in hydraulic head pressure and temperature were monitored during this test using Shlumberger Water Services pressure transducers. Measurements were taken from the injection well and in nearby wells. This test was allowed to run to completion and took approximately 3 hours.

WS528a

Graph 4, below, details the readings taken from divers set in the injection well (WS528a) and a nearby well approximately 10m away (WS535a).



Graph 4 - Graph detailing changes in hydraulic head and water temperature prior to and following the injection of water during a falling head test in the Compressor House area

The transmissivity of the aquifer could be calculated using data that formed the response curve for WS528a shown in the above graph. Using Aquifer, the data and parameters returned the transmissivity and storage coefficient presented in Table 5, overleaf.

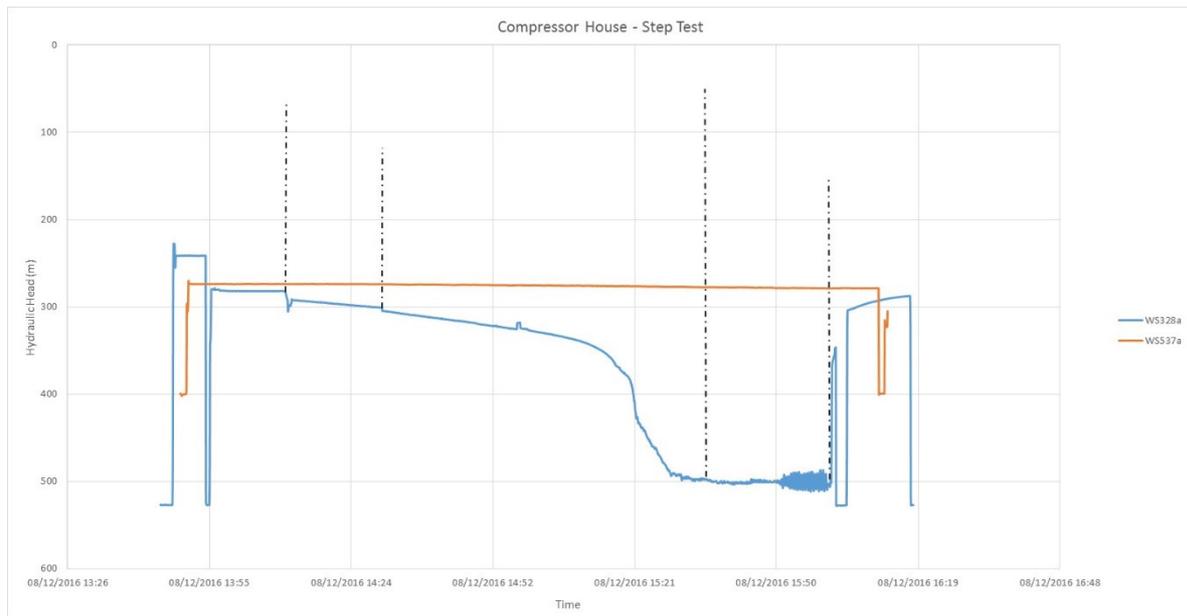
Well	Hydraulic Transmissivity (sq m/d)	Storage Coefficient
WS528a	133.34	1.11x10 ⁻⁷

Table 5 - Hydraulic transmissivity calculated from data obtained from WS528a during the falling head test conducted in the Compressor House area.

Transmissivity was found to be high at 133.34 sq m/d. Water was pumped into the well and found to dissipate into the strata with very little raise in hydraulic head. On completion of pumping, the hydraulic head in WS528a was found to equilibrate within seconds and remained static for the remainder of the test. Hydraulic head was found to decline steadily in WS525a from before the initiation of the test. It is thought that this occurred when the bung was removed from the well. This indicates localised conditions and so no supplementary information from the falling head test was recovered from this well. It should be noted that, due to the rapid transfer of water into the aquifer, the curve generated from the test was not ideal for fitting to the standard Theiss curve. As such the calculated hydraulic transmissivity and storage coefficient may be significantly higher. Although not suitable for use as a direct proxy for aquifer changes, water used for this injection was significantly cooler than the groundwater and as such was registered on the pressure transducers.

4.3 Step Test

A step test was conducted in the compressor house area in WS528a and surrounding wells. The test consists of pumping water at a set rate for a prolonged period until a steady piezometric surface is reached in the pumping well. At this point pumping speed is increased until a new, lower, hydraulic head is reached. This is repeated a final time at a maximum speed to assess the likely limits of the aquifer. During pumping, the piezometric head is measured in the pumping well and also in surrounding wells either with an interface probe or with Shlumberger Water Services pressure transducers. A graph presenting the data collected during the compressor house pump test is displayed overleaf in Graph 5.



Graph 5 - Graph detailing changes in hydraulic head in WS258a and surrounding wells during a step test conducted in the Compressor House area.

Pumping was commenced from WS528a at 25litres^{-min} leading to a quick initial drop in hydraulic head of around ten centimetres. After this a more gradual gradient lowering hydraulic head was observed at 25litres^{-min}. The gradient for a trendline drawn from data from this period was found to be $y = 744.18x - 3E+07$. The rate was increased to 40litres^{-min} at 14:29 as drawdown appeared extremely slow.

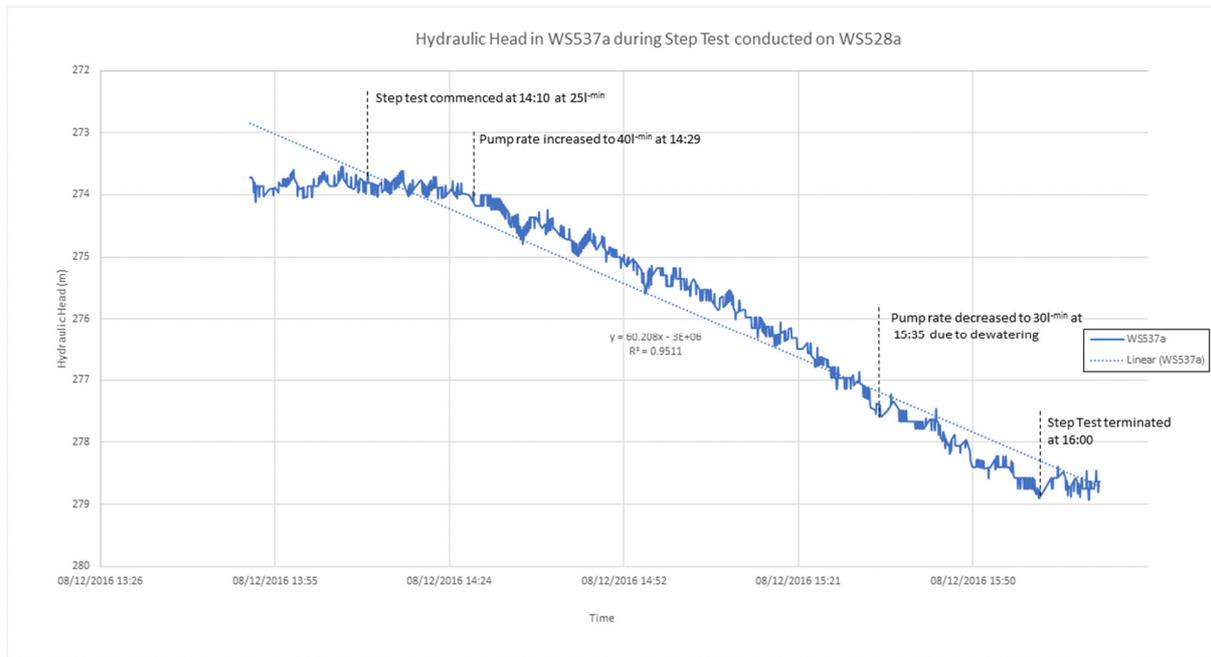
Pumping continued at 40litres^{-min} with relatively low drawdown noted; approximately 40cm over 40 minutes until 15:09. The gradient for a trendline drawn from this data in this period was found to be $y = 1225.5x - 5E+07$.

Rapid drawdown began from 15:09 to 15:22 with the gradient for a trendline drawn being $y = 13934x - 6E+08$. There was no increase in the pumping rate indicating a sudden loss of water from the aquifer. The rate of drawdown decreased slightly from 15:22 to 15:28 with the gradient of a drawn trendline being $y = 12496x - 5E+08$.

The rate of drawdown was relatively static from 15:28 to 15:50 with hydraulic head being kept to around 5mbgl; the level of the pump. Due to well dewatering, the pumping rate was decreased to 30litres^{-min} with no appreciable impact. Pumping was allowed to continue for a time after dewatering was observed in order to monitor drawdown impact on surrounding wells. The gradient of a trendline drawn for this period was $y = 453.58x - 2E+07$.

Due to the pumping well being dewatered, the test was terminated at 16:00. Rebound was noted to be rapid from this point; recovering 140cm of head in approximately two minutes. 220cm of rebound was seen to occur in 17 minutes.

The impact of this test on neighboring wells is shown in in Graph 5, above and shows a slight decline in hydraulic head observed over the monitoring period in well WS537a. Graph 6, overleaf, provides a more useful graphical representation of this, exaggerating the change on the y axis to highlight the trend.

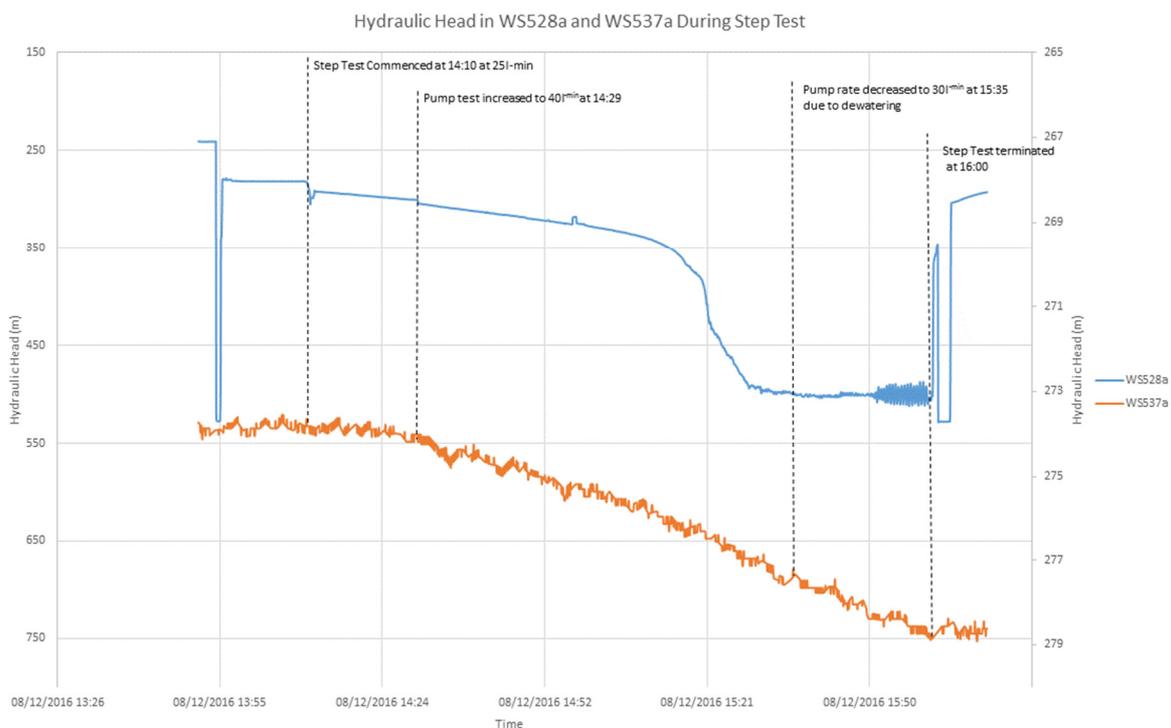


Graph 6 - Graph showing changes in hydraulic head in WS537a and the gradient of a trendline over the test

As can be seen in the graph above, hydraulic head was seen to decline by 0.1cm over 20 minutes with the pump at 25 l^{min}. During the hour period of pumping at 40 l^{min}, hydraulic head was found to drop by 3cm in WS537a. From 15:35 to 16:00 there was no significant change in the rate of decline in WS537a. Graph 7, overleaf, has the series of data obtained from the two wells plotted on separate axes to illustrate when and at what rate pumping from WS528a influenced WS538a. The overall gradient during the test was found to be $y = 68.247x - 3E+06$. Gradients of trendlines drawn for varying stages of the test are presented in Table 6, overleaf.

Well	Pump Rate (litres/sec)	Time From	Time To	Gradient
WS528a	25	14:10	14:29	$y = 744.18x - 3E+07$
WS528a	40	14:29	15:09	$y = 1225.5x - 5E+07$
WS528a	40	15:09	15:22	$y = 13934x - 6E+08$
WS528a	40	15:22	15:28	$y = 12496x - 5E+08$
WS528a	40/30	15:28	15:50	$y = 453.58x - 2E+07$
WS537a	25-40	14:10	1600	$y = 68.247x - 3E+06$
WS537a	25	14:10	14:29	$y = 18.566x - 792706$
WS537a	40	14:29	15:35	$y = 69.393x - 3E+06$
WS537a	40	15:35	16:00	$y = 82.116x - 4E+06$

Table 6 - Table detailing changes in gradient of drawn trendlines to show changes in drawdown rate during separate phases of the step test in WS528a and WS537a



Graph 7 - Graph detailing changes in hydraulic head in WS258a and surrounding wells during a step test conducted in the Compressor House area. Data for each well has been plotted on separate axes due to significant difference in drawdown rate and to effectively illustrate the impact on WS537a.

As can be seen in the Graph 7, above, when plotted on different axes; there is a minor, but clear, impact on WS537a throughout the pumping test. WS537a was located 8.4m distant from the pumping well. This indicates a large volume of water held in the underlying strata. Notably, there is no change in the rate of drawdown in WS538a despite a significant increase in drawdown in WS528a.

The rapid drop off in hydraulic conductivity seen in WS528a illustrated by a sudden drop in water replacement capacity in the well indicates that the well may be installed into schist bedrock or other impermeable strata. When the cone of depression formed by pumping out water deepened sufficiently to have a *potential* cone extending through the rock head, the piezometric head off

dropped rapidly. This is thought to indicate that the hydraulic conditions and rapid drop in head seen in WS528a, were not present or had not yet manifested in WS538a. It is possible that had the test been run over a longer period of time, a similarly rapid dewatering would have also prevailed in WS538a as the drawn down head encountered a shelf of bedrock.

Data was not obtained from all nearby wells during the step test as drawdown was found to be too minor at the distances of these boreholes (between 8.43m and 15.6m).

4.4 Summary of Hydraulic Conditions

Hydraulic conductivity

Table 7 detailing the hydraulic conductivity encountered in the Compressor House area is displayed below.

Slug Test Hydraulic Conductivities Compressor House (m/d)						
Well	Data source	Measuring Device	Test 1	Test 2	Test 3	Average
WS502	Slug Test	Diver	0.106089	N/A	N/A	0.106
WS514d	Slug Test	Diver	25.9827	N/A	N/A	25.982
WS528a	Slug Test	Diver	134.623	453.575	285.789	291.329
Area Average Excluding WS502	179.99					
Average WS514d area	25.98					
Average WS528a area	291.33					

Table 7 - Table detailing overall hydraulic conductivities calculated in the Compressor House area for all tests

Data obtained from WS502 was discarded as it was not considered representative of site conditions. WS514d and WS528a are thought to be representative of their immediate locations and that a broad hydraulic conductivity cannot be applied across the wider compressor house area.

Transmissivity

A table detailing the hydraulic conductivity encountered in the Compressor House area is displayed below in Table 8.

Hydraulic Transmissivity - Compressor House				
Well	Data source	Measuring Device	Transmissivity	Storage Coefficient
WS528a	Falling Head Test	Diver	133.34	1.11x10 ⁻⁷

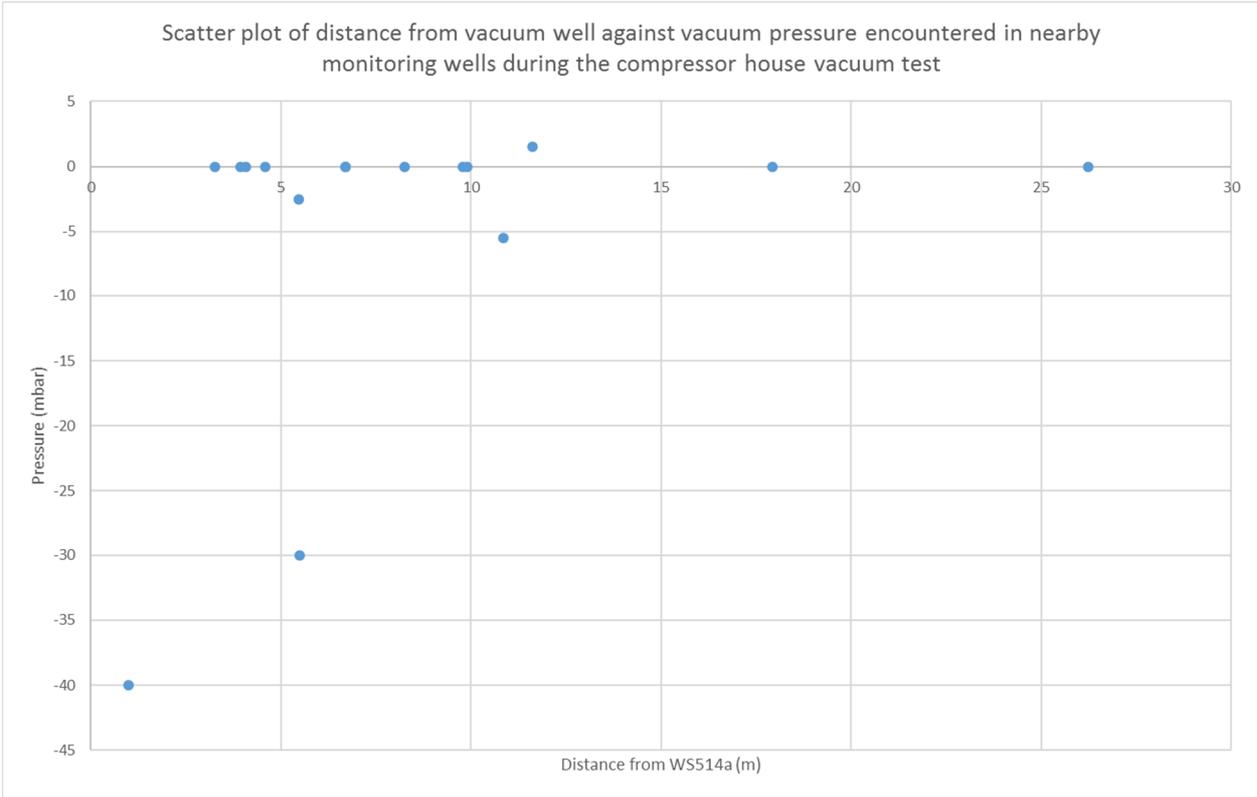
Table 8 - Table detailing calculated hydraulic transmissivity calculated in the Compressor house area during the falling head test

Data obtained from WS528a on hydraulic transmissivity indicated the schist gravel aquifer found underlying the area is capable of absorbing a large quantity of water.

5.0 Vacuum Testing

A vacuum was applied to WS514a, a shallow well, in the compressor house to determine the potential radius of an applied vacuum through the unsaturated soils. Nearby wells both shallow (installed into weathered schist gravels and clays) and deep (installed into schist bedrock) were monitored at varying distances for any induced pressure changes as the vacuum gradient developed in the surrounding soils.

The test overall ran for one hour with -0.4bar of vacuum generated by the tanker. The results of this are displayed on Graph 8, below.



Graph 8- Graph detailing changes in hydraulic head in WS258a and surrounding wells during a step test conducted in the Compressor House area. Data for each well has been plotted on separate axes due to significant difference in drawdown rate and to effectively illustrate the impact on WS537a.

Evidence of the vacuum being applied to WS14a was detected in five wells during the test at distances of up to 11.62m. The strongest effect was recorded 1m away from the vacuum well in WS514, a deep well. Here 10% of the total vacuum was recorded at the wellhead.

The impact of the vacuum was otherwise found to be variable across the site with many wells between 3.26m-17.93m having no recorded impact. -5.5mbar was recorded at 10.86m distant the vacuum well.

Unexpected results were recorded in APC02 where 1.5mbar of positive pressure was encountered during monitoring. This was attributed to water being dragged toward the vacuum well reducing the column of air in the borehole by rising above the top of the screened pipe.



6.0 Treatability Trials

In order to determine the suitability of a chemical oxidation solution to treat the identified dissolved phase and soil sorbed residual contamination in areas where the LNAPL has been recovered by physical means, or where no LNAPL has been present, a programme of lab scale treatability trials have been undertaken.

A full report from the laboratory is included in Appendix F, this should be read in detail when undertaking any remediation design. What follows is a summary of the works undertaken and findings.

6.1 Model Development

To ensure bench scale trials represented site conditions as accurately as possible samples of materials from the site were recovered including:

- Intact cores of the aquifer material;
- Bulk disturbed samples of the aquifer matrix;
- Bulk samples of the most significantly impacted groundwater, composited from across the plume area.

A conceptual model was devised for each treatment area, based on typical logs, depth to water and rock head (considered impermeable in this assessment) in each area. This model has been advanced using the findings of the depth profiling assessment, sampling of soil and groundwater (source term determination) and matrix oxidant demand testing and derivation of oxidant half-lives based on first order decay.

The findings of these tests were used in contaminant destruction profiling for selected oxidant activator systems also detailing effects of daughter products and rebound potential.

6.2 Technologies Assessed

A series of oxidant and activator designs were tested following an initial screening. The following mixes were trialled in reactor cells based upon the aquifer conditions of each area:

- Persulphate at total oxidant requirement;
- Persulphate at 2 x total oxidant requirement;
- Peroxide activated Persulphate at total oxidant requirement;
- Peroxide activated Persulphate at 2 x total oxidant requirement;
- Peroxide at 2%;
- Peroxide at 5%.

Chemical oxidation reactors were sampled at regular intervals over a period of 672 hours for persulphate based systems and over 96 hours for peroxide based systems (a more rapidly acting oxidant).

Total oxidant requirement is derived from the stoichiometric oxidant demand based on contaminant loading plus the matrix oxidant demand.

6.3 Treatability Results

Based upon the results of the chemical oxidation reactors, peroxide appears to have the greatest level of contaminant destruction. Coupled with the high permeability of the aquifer this also allows efficient delivery of oxidant mass into the subsurface and high groundwater flow zones.

Persulphate based systems showed significantly lower destruction efficiencies at both low and high injection concentrations. Additionally, use of this approach would cause mobilisation of trace metals whereas Peroxide systems do not require subsequent aquifer rehabilitation or pH adjustment in order to prevent mobilisation of trace metals.

Contaminant destruction in both aquifer systems showed similar responses to specific oxidation systems. The similarities in the modelled aquifer parameters for each of the three target areas are such that a single treatment strategy may be applied to all areas.

A 2% oxidant application is considered to be suitable for the site, this will achieve NAPL dissolution from within the matrix in early stages of treatment preventing rebound. The peroxide based oxidant will have completed its treatment by the end of 96 hours after which stepped application of the oxidant is recommended in key areas.

It should be noted that this approach will not treat measurable thicknesses of LNAPL where encountered.

7.0 Conclusions

A remediation pilot study programme was commissioned by The LK Group to aid in design of a remediation system to treat the three known impacts in the Escrow areas of the Anglesey Aluminium Site, Holyhead.

This report details known impacts in the Compressor House, which was targeted with further drilling and depth profiling works to aid vertical delineation of the impact through the soil column. Additionally, hydraulic and vacuum testing was undertaken to assess the hydraulic conductivity and radius of influence of pumped treatment systems within the target formations. Subsequent laboratory scale testing enables the most suitable oxidant system to be determined for use in each of the key areas.

Depth profiling indicates the bulk of the impacts in all areas to be predominantly based within the groundwater within the more permeable gravel fractions. The matrix itself does not typically exhibit high concentrations of sorbed contamination, although some highly-elevated readings were encountered within the Compressor House area. These cores do suggest areas of lower permeability and variability within the Compressor House, with lower permeability areas displaying limited soils impact around the periphery of the main aquifer body.

Hydraulic testing of the Compressor House suggests that all areas have a very high primary permeability within the aquifer, with a significant radius of influence within the aquifer achieved under pumping. Although it should be noted that there is evidence of high variability within the aquifer with low permeability zones present within the subsoils in each of these areas.

This high permeability indicates that a pumped solution as a means of recovering LNAPL and dissolved phase hydrocarbons is considered to be a suitable method for use in the Compressor House area.

Chemical oxidation trials have demonstrated that a peroxide based oxidant represents a highly effective means of treating the dissolved phase hydrocarbon impacts in this area. The high permeability of the subsurface should ensure rapid oxidant transfer and minimal risk of rebound from the soil matrix.

8.0 Limitations

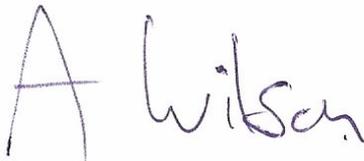
Geo²'s conclusions, recommendations and opinions are based on information gathered at the time of the investigation from a variety of third party sources and from observations made during site reconnaissance and ground conditions encountered during the field work and on the results of laboratory and field tests performed during the investigation. However, there may be conditions at the site that have not been taken into account, such as unpredictable soil strata and water conditions between or below intrusive locations. It should also be noted that groundwater levels may vary due to seasonal or other effects and may at times differ to those measured during the investigation.

A portion of this report is based solely upon information provided by third parties. The information has not been independently verified by Geo². Whilst this report and the opinions given in it are accurate to the best knowledge of Geo², Geo² cannot guarantee the completeness or accuracy of any descriptions, opinions or conclusions based solely upon information that has not been independently verified.

The recommendations contained within this report represent our professional opinions. These opinions were arrived at in accordance with currently accepted industry practices and hydrological and engineering practices at this time. As such they are not a guarantee that the site is free of hazardous materials or conditions.

Geo² prepared this report for our Client; any third parties using this report do so entirely at their risk. Geo² makes no warranty or representation whatsoever, express or implied, with respect to the use by a third party of any information contained in this report or its suitability for any purpose. Geo² assumes no responsibility for any costs, claims, damages or expenses (including any consequential damages) resulting from the use of this report or any information contained in this report by a third party.

This report was prepared by



Adam Wilson

06/04/17
Date

This report was reviewed by



Paul Stapleton

06/04/17
Date

9.0 References

The LK Group

Escrow Sites: Scope of Works. May 2016

Site Condition Report: January 2014

LK Review of Previous Work.

Unpublished laboratory analysis and logs from 2016 works

CE Geochem

ANGLESEY: Lab Bench Scale Oxidation Study. March 2017. A161201

British Standards Institute

BS10175:2011 “Investigation of potentially contaminated land sites – code of practice”

Environment Agency

CLR 11- Model procedures for the management of contaminated land.

Ciria

C552 Contaminated Land Risk Assessment: A guide to good practice.

Appendix A

Figures



Figure 1 - Site Situation

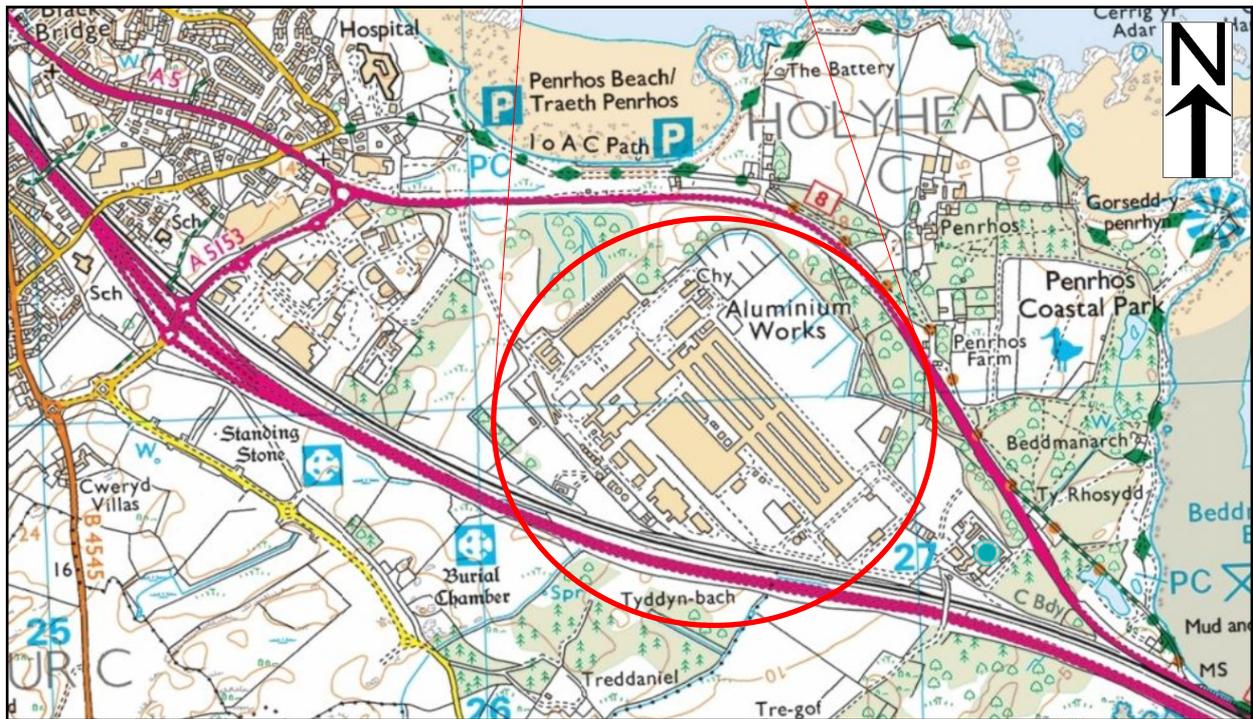


Figure 2 - Site Location

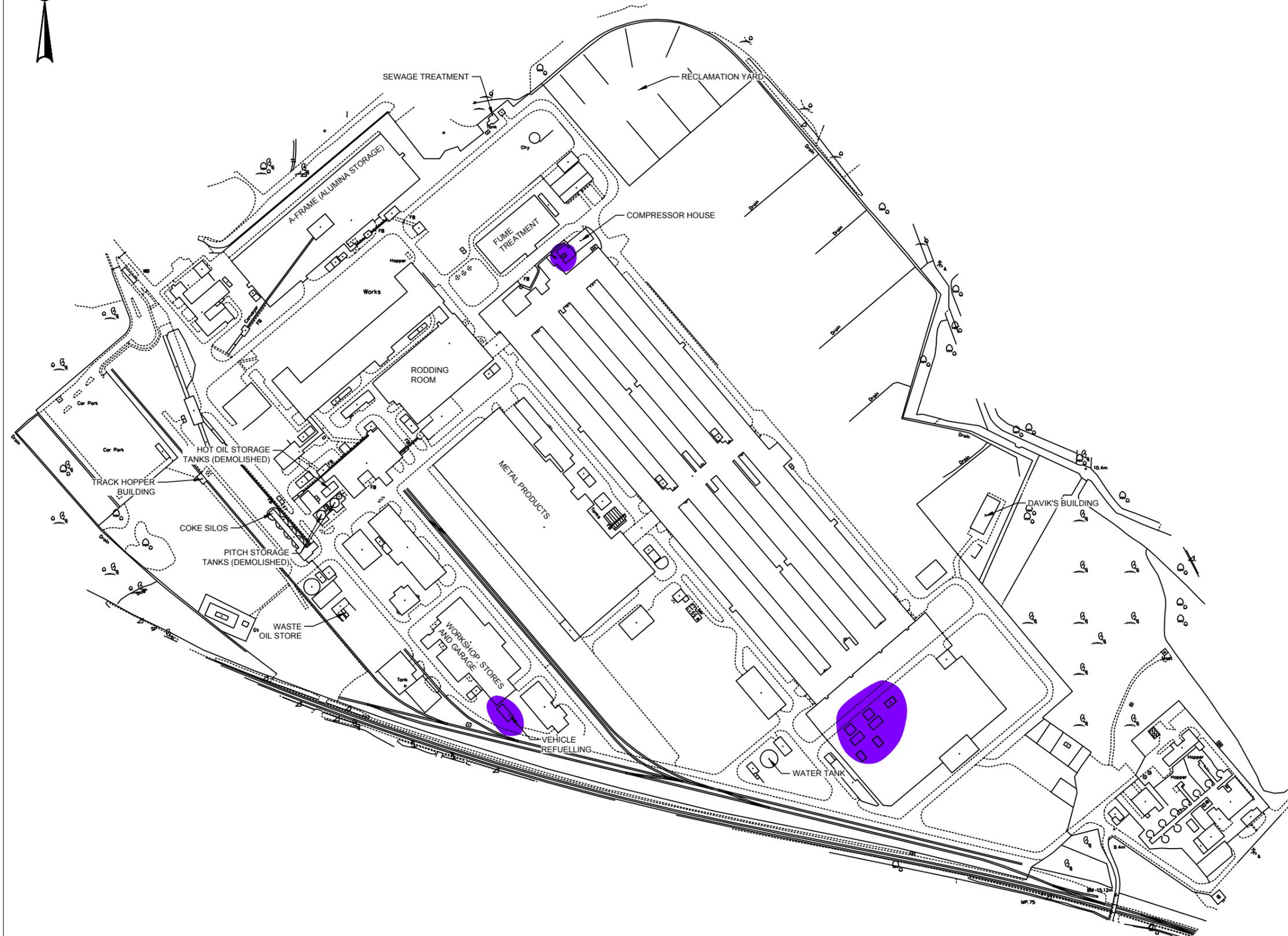
Ref: Envirocheck Report



Figures 1 & 2 Site Situation and Location -
Escrow Areas, Anglesey Aluminium, Penrhos Works, Holyhead

Geo² Remediation Limited, 11 The Mending Rooms, Sunny Bank Mills, Town Street, Farsley, Leeds, LS28 5UJ





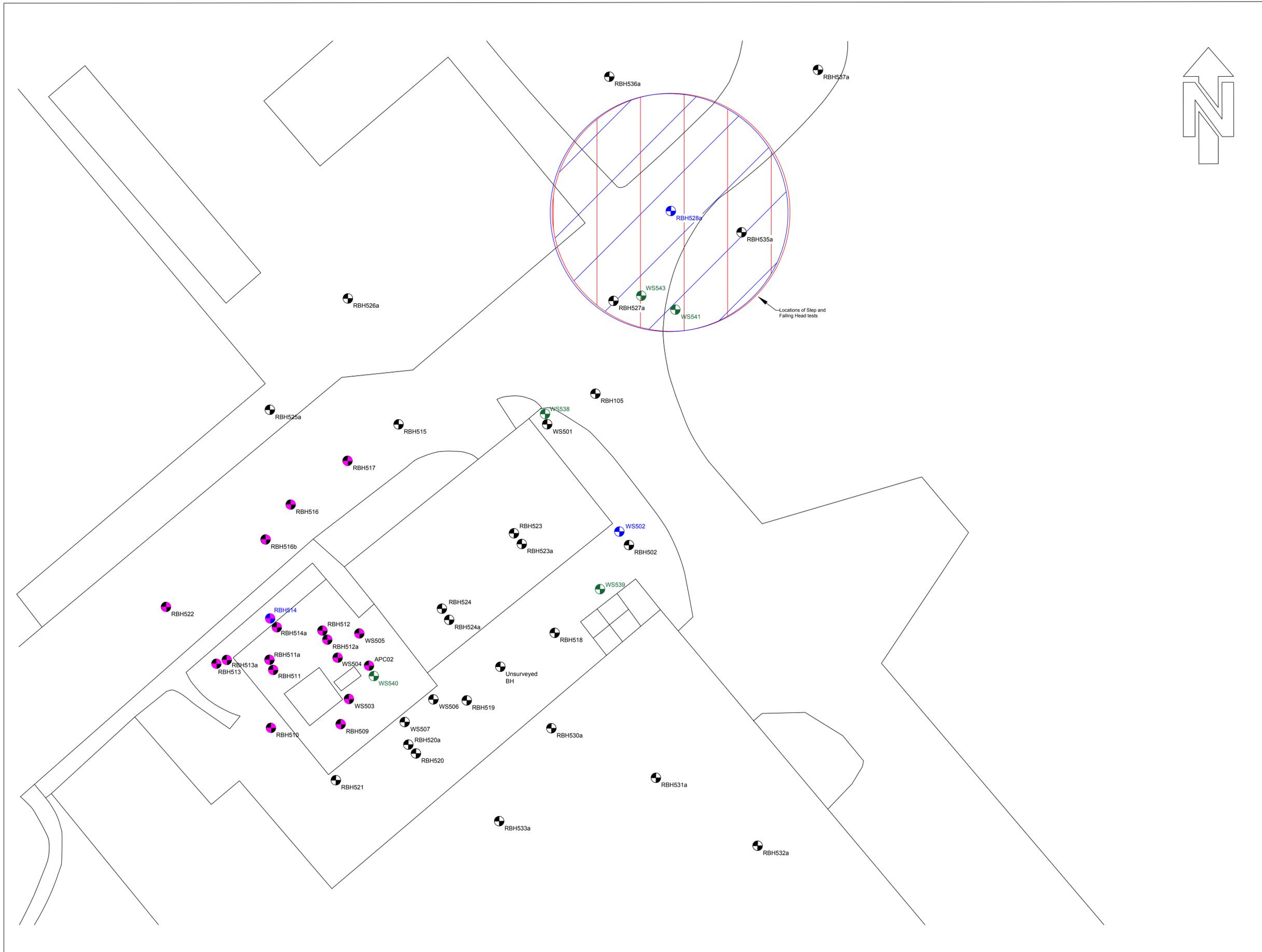
LEGEND
 Area of identified light Non-Aqueous Phase Liquid (LNAPL)

NOTES
 REFERENCES
 DRAWING BASED ON INFORMATION PROVIDED BY: ANGLESEY ALUMINIUM

Rev	Description	PM	Review	Date
Client ANGLESEY ALUMINIUM				
Project SITE SALE				
Title AREAS OF LNAPL				
Created by	Requested by	Proj Manager	Reviewer	Date
AD	HD	HD	HD	14/07/15
File No. 0001-X-0001		Project No. 1419735		
Size A3	Scale 1:4,000	Status REPORT ISSUE		
Drawing No. 1				Rev -




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 GOLDER HOUSE
 TADCASTER ENTERPRISE PARK
 STATION ROAD
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LEGEND

- Borehole
- Borehole used for slug testing
- Borehole constructed for frozen core sampling
- Boreholes monitored during vacuum testing
- Location of Falling Head Test
- Location of Step Test

General Notes:
 Building proportions and borehole locations based on previous survey conducted by LK

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 Tel: 0113 257 5397
 E-Mail: info@geo2.co.uk
 Website: www.geo2.co.uk

Client
LK

Site Location
**Compressor House
 Anglesey Aluminium**

Drawn by	LHD	Approved by	
Revision		Revision	

Appendix B

Borehole Logs



11 The Mending Rooms
Sunny Bank Mills
Town St., Farsley, LS28 5UJ
0113 257 5397

Borehole Log

Borehole No.

WS 538

Sheet 1 of 1

Location Details: Compressor house.

Project Name: Anglesea Aluminium, Anglesea

Project No.
0626

Co-ords:

Hole Type
WS

Location: Anglesea Aluminium - Anglesea

Level:

Scale
1:50

Client: LK

Dates: 06/12/2016

Logged By
L. Hanson Diamond

Well	Water Strikes	Sample and In Situ Testing			Depth (m)	Level (m)	Legend	Stratum Description	
		Depth (m)	Type	Results					
		0.05			0.05		MADE GROUND - Dark grey, schist gravel and sandy fill.		
		0.30	PID	PID=1	0.30		MADE GROUND - Black, concrete gravel crush fill.		
		0.50			0.50		CLAY - Brown, stiff gravelly CLAY. Gravels composed of schist.		
		0.80	PID	PID=1	0.80				
		1.00			1.00		GRAVEL - Schist GRAVELS in a blue, sandy, very clayey matrix.	1	
		1.30	PID	PID=1	1.30				
		1.60			1.60		GRAVEL - Red, small, sandy GRAVEL.		
		1.70	PID	PID=1	1.70		COBBLES - Schist COBBLES.		
		2.00			2.00		Zone of core loss.	2	
		2.10			2.10		SAND - Blue/purple, medium to fine, grey/light brown, gravelly SAND with occasional large, sub-rounded gravel.		
		2.50			2.50		SILT - Blue/grey, graded, gravelly SILT. Slight hydrocarbon odour.		
		3.00			3.00		CLAY - CLAY with schist. Blue from hydrocarbon odour.	3	
		3.30	PID	PID=12	3.30				
		3.80	PID	PID=41	3.80				
		4.00			4.00		POOR RETURNS - very wet, schist sand.	4	
		4.50	PID	PID=59	4.50				
		5.00			5.00		End of Borehole at 5.00m	5	
								6	
								7	
								8	
								9	
								10	

Remarks

Core frozen at 2-3m and logged by third party C E Geochem. Refused at 5.0m in poorly returned sand.



11 The Mending Rooms
Sunny Bank Mills
Town St., Farsley, LS28 5UJ
0113 257 5397

Borehole Log

Borehole No.

WS 540

Sheet 1 of 1

Project Name: Anglesea Aluminium, Anglesea		Project No. 0626	Co-ords:	Location Details: Compressor house.	Hole Type WS
Location: Anglesea Aluminium - Anglesea		Level:		Scale 1:50	
Client: LK		Dates: 06/12/2016		Logged By L. Hanson Diamond	

Well	Water Strikes	Sample and In Situ Testing			Depth (m)	Level (m)	Legend	Stratum Description	
		Depth (m)	Type	Results					
					0.05		 TARMAC - Gravelly tarmac. CLAY - Blue, stiff, dry, friable CLAY with schist gravels. Damp at base.		1
					3.00		 SILT - Blue/grey, slightly gravelly SILT.		3
					3.70		 End of Borehole at 4.00m		4
									5
									6
									7
									8
									9
									10

Remarks
Core frozen at 3-4m and logged by third party C E Geochem. Refused at 4m.



11 The Mending Rooms
Sunny Bank Mills
Town St., Farsley, LS28 5UJ
0113 257 5397

Borehole Log

Borehole No.

WS 541

Sheet 1 of 1

Location Details: Compressor house.

Project Name: Anglesea Aluminium, Anglesea

Project No.
0626

Co-ords:

Hole Type
WS

Location: Anglesea Aluminium - Anglesea

Level:

Scale
1:50

Client: LK

Dates: 07/12/2016

Logged By
Jack Ellis

Well	Water Strikes	Sample and In Situ Testing			Depth (m)	Level (m)	Legend	Stratum Description	
		Depth (m)	Type	Results					
					0.10		GRAVELS - Clayey GRAVEL.		
					0.25		GRAVEL - Dark grey/red, clayey, sandy GRAVEL.		
					0.40		GRAVEL - Grey/brown sandy GRAVEL in a clay matrix. Gravels composed of schist and quartz.		
							GRAVEL - Slightly damp, clayey, sandy, quartz and schist GRAVEL.	1	
					1.25		GRAVEL - Damp, grey, clayey, sandy, schist GRAVEL with a hydrocarbon odour.		
					2.00		CLAY - Light brown, silty, CLAY with occasional green, rounded, medium gravel. Diesel odour.	2	
					2.40		CLAY - Mid to light grey/green, gravelly, sandy CLAY with diesel odour throughout.		
					2.80		CLAY - Light green, silty CLAY with occasional green/brown, fine to medium gravel. Diesel odour throughout.	3	
					3.00		GRAVEL - Schist GRAVEL in a grey clay/sand matrix. Hydrocarbon odour at the top, weakening with depth.		
					4.00		GRAVEL - Schist GRAVEL in a grey sand/clay matrix.	4	
					5.00		End of Borehole at 5.00m	5	
								6	
								7	
								8	
								9	
								10	

Remarks

Core frozen at 2-3m and logged by third party C E Geochem. Ended at 5.0m in gravels.



11 The Mending Rooms
Sunny Bank Mills
Town St., Farsley, LS28 5UJ
0113 257 5397

Borehole Log

Borehole No.

WS 543

Sheet 1 of 1

Project Name: Anglesea Aluminium, Anglesea		Project No. 0626	Co-ords:	Hole Type WS
Location: Anglesea Aluminium - Anglesea		Level:		Scale 1:50
Client: LK		Dates: 07/12/2016		Logged By Jack Ellis

Well	Water Strikes	Sample and In Situ Testing			Depth (m)	Level (m)	Legend	Stratum Description	
		Depth (m)	Type	Results					
					0.25			GRAVEL - Black, clayey, sandy GRAVEL, with rootlets, organic matter and pebble fragments.	
					0.35			GRAVEL - Gravel in a black mud matrix.	
								GRAVEL - Sandy GRAVEL in a brown clay matrix. Gravel composed of schist.	1
					1.10			GRAVEL - Damp, clayey, sandy, schist and quartz GRAVEL.	2
					2.40			GRAVEL - Crumbly, clayey, sandy, schist GRAVEL.	
					2.90			GRAVEL - Damp, quartz and schist GRAVEL in a grey clay matrix with a slight hydrocarbon odour.	3
					3.20			GRAVEL - Dark grey, damp, clayey, schist GRAVEL, with a strong hydrocarbon odour.	
					4.00			GRAVEL - Grey/blue, graded, angular to sub rounded, silty GRAVEL of shale and quartz.	4
					5.00			End of Borehole at 5.00m	5
									6
									7
									8
									9
									10

Remarks
Core frozen at 4-5m and logged by third party C E Geochem. Top 0.5m wet, with hydrocarbon odour. Monitoring well installed. Ended at 5.0m.



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Site
 Anglesey Aluminium REP

Borehole Number
RBH510

Machine :	Casing Diameter	Ground Level (mOD)	Client Orthios Ecoparks (Anglesey) Ltd	Job Number LKC 14 1181
Flush :	Location	Dates 31-10-2016	Engineer LKC	Sheet 1/2
Core Dia: mm				
Method :				

Depth (m)	TCR	SCR	RQD	FI	Field Records	Level (mOD)	Depth (m) (Thickness)	Description	Legend	Water	Instr
0.30-1.30					D1		(0.30)	MADE GROUND: Gravel.			
							0.30	Weathered brown SCHIST.			
							(1.00)				
							1.30	Weathered grey SCHIST.			
							(5.00)				
						Water strike(1) at 6.00m.	6.30	Weathered brown SCHIST.			
							(0.20)	Weathered grey SCHIST.			
							6.50				
							(1.00)				
						7.50	Grey SCHIST.				
						(4.50)					

Remarks	Scale (approx)	Logged By
	1:50	
	Figure No. LKC 14 1181.RBH510	



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Site
 Anglesey Aluminium REP

Borehole Number
RBH510

Machine :	Casing Diameter	Ground Level (mOD)	Client	Job Number
Flush :			Orthios Ecoparks (Anglesey) Ltd	LKC 14 1181
Core Dia: mm	Location	Dates	Engineer	Sheet
Method :		31-10-2016	LKC	2/2

Depth (m)	TCR	SCR	RQD	FI	Field Records	Level (mOD)	Depth (m) (Thickness)	Description	Legend	Water	Instr
							12.00	Complete at 12.00m			

Remarks	Scale (approx)	Logged By
	1:50	
Figure No.		
LKC 14 1181.RBH510		



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Site
 Anglesey Aluminium REP

Borehole Number
RBH511

Machine :	Casing Diameter	Ground Level (mOD)	Client	Job Number
Flush :			Orthios Ecoparks (Anglesey) Ltd	LKC 14 1181
Core Dia: mm	Location	Dates 01-11-2016	Engineer	Sheet
Method :			LKC	1/2

Depth (m)	TCR	SCR	RQD	FI	Field Records	Level (mOD)	Depth (m) (Thickness)	Description	Legend	Water	Instr
0.30-1.30					D1		(0.50)	MADE GROUND: Gravel.			
							0.50	Weathered brown SCHIST.			
							(1.00)				
							1.50	Weathered grey SCHIST.			
						(5.50)					
						7.00	Grey SCHIST.				
						(5.00)					

Remarks	Scale (approx)	Logged By
	1:50	
	Figure No. LKC 14 1181.RBH511	



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Site
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Borehole Number
RBH511

Machine :	Casing Diameter	Ground Level (mOD)	Client	Job Number
Flush :			Orthios Ecoparks (Anglesey) Ltd	LKC 14 1181
Core Dia: mm	Location	Dates	Engineer	Sheet
Method :		01-11-2016	LKC	2/2

Depth (m)	TCR	SCR	RQD	FI	Field Records	Level (mOD)	Depth (m) (Thickness)	Description	Legend	Water	Instr
							12.00	Complete at 12.00m			

Remarks	Scale (approx)	Logged By
	1:50	
Figure No. LKC 14 1181.RBH511		



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Site
 Anglesey Aluminium REP

Borehole Number
RBH512

Machine :	Casing Diameter	Ground Level (mOD)	Client	Job Number LKC 14 1181
Flush :			Orthios Ecoparks (Anglesey) Ltd	
Core Dia: mm	Location	Dates 02-11-2016	Engineer	Sheet 1/2
Method :			LKC	

Depth (m)	TCR	SCR	RQD	I _f	Field Records	Level (mOD)	Depth (m) (Thickness)	Description	Legend	Water	Instr
0.30-1.30					D1		(0.30)	MADE GROUND: Gravel.			
							0.30	Weathered brown SCHIST.			
							(2.70)				
							3.00	Weathered grey brown SCHIST.			
							(4.00)				
							7.00	Grey SCHIST.			
							(0.20)				
							7.20	Brown SCHIST.			
							7.30				
7.50							(0.80)	Weak to medium strength thinly foliated grey green SCHIST with occasional iron staining and rare quartz bands. Several subhorizontal open planar smooth clean fractures, possibly drilling induced from 7.80-8.05m.			
	100	96	25	Av:40 Min:NI Max:260			8.10	Several subhorizontal and subvertical closed stepped fractures from 7.80-10.00m.			
							(0.20)				
							8.30	Weak strength very friable thinly foliated grey green SCHIST with occasional iron staining and rare quartz bands. Subhorizontal open stepped rough clean fracture, possibly drilling induced at 8.15m.			
							8.40				
9.30								Weak to medium strength thinly foliated grey green SCHIST with occasional iron staining and rare quartz bands. 40 degrees open undulating smooth iron stained fracture from 8.30-8.39m.			

Remarks	Scale (approx)	Logged By
	1:50	
	Figure No. LKC 14 1181.RBH512	



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Site
 Anglesey Aluminium REP
Borehole Number
RBH512

Machine :	Casing Diameter	Ground Level (mOD)	Client	Job Number
Flush :			Orthios Ecoparks (Anglesey) Ltd	LKC 14 1181
Core Dia: mm	Location	Dates	Engineer	Sheet
Method :		02-11-2016	LKC	2/2

Depth (m)	TCR	SCR	RQD	I _f	Field Records	Level (mOD)	Depth (m) (Thickness)	Description	Legend	Water	Instr
10.80	100	93	25	Av:90 Min:NI Max:140			(1.40)	Weak strength very friable thinly foliated grey green SCHIST with occasional iron staining and rare quartz bands.			
							9.30	Weak to medium strength thinly foliated grey green SCHIST with occasional iron staining and rare quartz bands.			
							9.38	60 degrees open stepped rough iron stained fracture from 8.60-8.74m. 20 degrees open planar rough iron stained fracture associated with a quartz band from 8.81-8.83m. Quartz vein with iron staining from 8.83-8.86m. 60 degrees open planar smooth iron stained fracture from 8.93-9.07m. 60 degrees open planar smooth iron stained fracture from 9.18-9.23m, closed to 9.30m. Recovered as GRAVEL. Likely drilling induced. Weak to medium strength thinly foliated grey green SCHIST with occasional iron staining and rare quartz bands. Subhorizontal open planar rough iron stained fracture at 9.51m. 70 degrees open planar rough iron stained fracture from 9.58-9.72m. Subhorizontal open planar smooth iron stained fracture at 9.63m 60 degrees open planar smooth iron stained fracture from 9.67-9.72m. 10 degrees open planar smooth iron stained fracture at 9.74m. Subhorizontal open planar smooth iron stained fracture at 9.76m. 10 degrees open planar smooth iron stained fracture at 9.86m. 50 degrees closed undulating clay infilled fracture from 9.91-9.97m. Subhorizontal open stepped rough iron stained fracture at 10.01m. 60 degrees open planar smooth iron stained fracture from 10.04-10.13m. 60 degrees closed planar smooth clay infilled fracture from 10.06-10.13m. 10 degrees open planar rough iron stained fracture at 10.20m. Subhorizontal open planar rough fracture, possibly drilling induced at 10.34m. 80 degrees closed stepped rough iron stained fracture from 10.43m, open from 10.51-10.58m. Several subhorizontal open stepped rough fractures, possibly drilling induced from 10.60-10.80m.			
							(0.80)	Complete at 10.80m			

Remarks	Scale (approx)	Logged By
	1:50	
	Figure No.	LKC 14 1181.RBH512



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Site
 Anglesey Aluminium REP
Borehole Number
 RBH512A

Machine :	Casing Diameter	Ground Level (mOD)	Client	Job Number
Flush :			Orthios Ecoparks (Anglesey) Ltd	LKC 14 1181
Core Dia: mm	Location	Dates	Engineer	Sheet
Method :		02-11-2016	LKC	1/1

Depth (m)	TCR	SCR	RQD	FI	Field Records	Level (mOD)	Depth (m) (Thickness)	Description	Legend	Water	Instr
0.30-1.30					D1		(1.30)	MADE GROUND: Gravel.			
							1.30	Weathered brown SCHIST.			
							(1.70)				
							3.00	Weathered grey brown SCHIST.			
							(3.00)				
							6.00	Complete at 6.00m			

Remarks	Scale (approx)	Logged By
	1:50	
Figure No. LKC 14 1181.RBH512A		



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 Tel: 0161 763 7200 web: www.thelkgroup.com

Site
 Anglesey Aluminium REP

Borehole Number
RBH513

Machine :		Casing Diameter		Ground Level (mOD)		Client		Job Number	
Flush :						Orthios Ecoparks (Anglesey) Ltd		LKC 14 1181	
Core Dia: mm						Engineer		Sheet	
Method :		Location		Dates		LKC		2/2	
				31-10-2016					

Depth (m)	TCR	SCR	RQD	FI	Field Records	Level (mOD)	Depth (m) (Thickness)	Description	Legend	Water	Instr
							10.30	Complete at 10.30m			

Remarks	Scale (approx)	Logged By
	1:50	
	Figure No. LKC 14 1181.RBH513	



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Site
 Anglesey Aluminium REP
Borehole Number
RBH514

Machine :	Casing Diameter	Ground Level (mOD)	Client Orthios Ecoparks (Anglesey) Ltd	Job Number LKC 14 1181
Flush :	Location	Dates 01-11-2016	Engineer LKC	Sheet 1/2
Core Dia: mm				
Method :				

Depth (m)	TCR	SCR	RQD	FI	Field Records	Level (mOD)	Depth (m) (Thickness)	Description	Legend	Water	Instr
0.30-1.30					D1		(1.30)	MADE GROUND: Gravel.			
							1.30 (0.70)	Weathered brown SCHIST.			
							2.00 (3.00)	Weathered grey SCHIST.			
							5.00 (1.00)	Grey SCHIST with frequent quartz veins.			
							6.00 (6.00)	Grey SCHIST.			

Remarks	Scale (approx) 1:50	Logged By
	Figure No. LKC 14 1181.RBH514	



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Site
 Anglesey Aluminium REP

Borehole Number
RBH514

Machine :	Casing Diameter	Ground Level (mOD)	Client	Job Number
Flush :			Orthios Ecoparks (Anglesey) Ltd	LKC 14 1181
Core Dia: mm	Location	Dates	Engineer	Sheet
Method :		01-11-2016	LKC	2/2

Depth (m)	TCR	SCR	RQD	FI	Field Records	Level (mOD)	Depth (m) (Thickness)	Description	Legend	Water	Instr
							12.00	Complete at 12.00m			

Remarks	Scale (approx)	Logged By
	1:50	
Figure No.		
LKC 14 1181.RBH514		



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Site
 Anglesey Aluminium REP
Borehole Number
 RBH514A

Machine :	Casing Diameter	Ground Level (mOD)	Client	Job Number
Flush :			Orthios Ecoparks (Anglesey) Ltd	LKC 14 1181
Core Dia: mm	Location	Dates 01-11-2016	Engineer	Sheet
Method :			LKC	1/1

Depth (m)	TCR	SCR	RQD	FI	Field Records	Level (mOD)	Depth (m) (Thickness)	Description	Legend	Water	Instr
0.30-1.30					D1		0.30	MADE GROUND: Gravel.			
							0.30	MADE GROUND: Gravel with occasional timber.			
							1.70				
							2.00	Weathered grey SCHIST.			
							4.00				
							6.00	Complete at 6.00m			

Remarks	Scale (approx)	Logged By
	1:50	
Figure No.		
LKC 14 1181.RBH514A		



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Site
 Anglesey Aluminium REP
Borehole Number
RBH515

Machine :	Casing Diameter	Ground Level (mOD)	Client	Job Number LKC 14 1181
Flush :			Orthios Ecoparks (Anglesey) Ltd	
Core Dia: mm	Location	Dates 09-11-2016	Engineer	Sheet 1/2
Method :			LKC	

Depth (m)	TCR	SCR	RQD	I _f	Field Records	Level (mOD)	Depth (m) (Thickness)	Description	Legend	Water	Instr
0.30-1.30					D1		0.20	MADE GROUND: Tarmac.			
							0.20	MADE GROUND Limestone gravel.			
4.00-5.00					D2		0.80				
							1.00	Weathered grey SCHIST.			
6.00-7.00					D3		4.50				
							5.50	Weathered grey SCHIST.			
7.40	100	77	38	Av:200 Min:NI Max:200			1.00				
							6.50	Weak to medium strength thinly foliated grey green SCHIST with occasional iron staining and rare quartz.			
8.80	100	93	55	Av:100 Min:NI Max:150			7.60	Subhorizontal open planar smooth clean, possibly drilling induced at 7.50m.			
							7.90	Subhorizontal open planar smooth clean, possibly drilling induced at 7.56m.			
							8.11	Recovered as GRAVEL.			
							8.18	Weak to medium strength thinly foliated grey green SCHIST with occasional iron staining, several subvertical stepped closed fractures and rare quartz.			
							8.31	Very weak strength thinly foliated orangish grey SCHIST with frequent iron staining and several subvertical stepped closed fractures.			
								Weak to medium strength thinly foliated grey green SCHIST with occasional iron staining, several subvertical stepped closed fractures and rare quartz.			

Remarks	Scale (approx)	Logged By
	1:50	
	Figure No. LKC 14 1181.RBH515	



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Site
 Anglesey Aluminium REP

Borehole Number
RBH515

Machine :		Casing Diameter		Ground Level (mOD)		Client		Job Number	
Flush :						Orthios Ecoparks (Anglesey) Ltd		LKC 14 1181	
Core Dia: mm						Engineer		Sheet	
Method :		Location		Dates 09-11-2016		LKC		2/2	

Depth (m)	TCR	SCR	RQD	I _f	Field Records	Level (mOD)	Depth (m) (Thickness)	Description	Legend	Water	Instr
10.30							8.37	<p>Very weak strength thinly foliated orangish grey SCHIST with frequent iron staining and several subvertical stepped closed fractures.</p> <p>Weak to medium strength thinly foliated grey green SCHIST with occasional iron staining, several subvertical stepped closed fractures and rare quartz.</p> <p>Very weak strength thinly foliated orangish grey SCHIST with frequent iron staining and several subvertical stepped closed fractures. Subhorizontal open planar smooth iron stained at 8.45m. Subvertical open stepped rough iron stained fracture from 8.52-8.64m.</p> <p>Weak to medium strength thinly foliated grey green SCHIST with occasional iron staining, several subvertical stepped closed fractures and rare quartz. Subhorizontal open planar rough clean, possibly drilling induced at 8.74m.</p> <p>Very weak strength thinly foliated orangish grey SCHIST with frequent iron staining and several subvertical stepped closed fractures.</p> <p>Weak to medium strength thinly foliated grey green SCHIST with occasional iron staining, several subvertical stepped closed fractures and rare quartz. Subhorizontal open planar rough iron stained fracture at 8.92m. Subhorizontal open planar rough iron stained fracture at 9.01m. Subhorizontal to 30 degrees closed stepped rough iron stained fracture from 9.15-9.30m. Subhorizontal open planar smooth clean, possibly drilling induced at 9.43m. Subhorizontal open planar smooth clean, possibly drilling induced at 9.59m. Subhorizontal open stepped rough iron stained fracture at 9.69m. Several subhorizontal fractures with two 60 degrees planar smooth iron stained fractures from 9.80-10.10m. Subhorizontal open planar smooth iron stained at 9.80m. Subhorizontal open planar rough iron stained fracture at 10.03m. Subhorizontal open planar rough iron stained fracture at 10.14m.</p>			
							8.45				
							8.70				
							8.80				
							8.92				
							10.30				
							(0.25)				
							(1.38)				
								Complete at 10.30m			

Remarks	Scale (approx)	Logged By
	1:50	
Figure No.		
LKC 14 1181.RBH515		



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Site
 Anglesey Aluminium REP
Borehole Number
 RBH515A

Machine :	Casing Diameter	Ground Level (mOD)	Client Orthios Ecoparks (Anglesey) Ltd	Job Number LKC 14 1181
Flush :			Engineer LKC	Sheet 1/1
Core Dia: mm	Location	Dates 09-11-2016		
Method :				

Depth (m)	TCR	SCR	RQD	FI	Field Records	Level (mOD)	Depth (m) (Thickness)	Description	Legend	Water	Instr
0.30-1.30					D1		0.10 (0.90) 1.00	MADE GROUND: Tarmac. MADE GROUND: Limestone gravel.			
							(3.00)	Weathered brown SCHIST.			
4.50-5.50					D2		4.00 (2.00) 6.00	Weathered grey SCHIST. Diesel odour from 4.50-6.00mbgl.			
								Complete at 6.00m			

Remarks	Scale (approx) 1:50	Logged By
	Figure No. LKC 14 1181.RBH515A	



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Site
 Anglesey Aluminium REP
Borehole Number
RBH516

Machine :	Casing Diameter	Ground Level (mOD)	Client	Job Number
Flush :			Orthios Ecoparks (Anglesey) Ltd	LKC 14 1181
Core Dia: mm	Location	Dates	Engineer	Sheet
Method :		03-11-2016	LKC	1/2

Depth (m)	TCR	SCR	RQD	FI	Field Records	Level (mOD)	Depth (m) (Thickness)	Description	Legend	Water	Instr
0.30-1.30					D1		0.10 (0.90)	MADE GROUND: Tarmac. MADE GROUND: Gravel.			
							1.00 (1.50)	MADE GROUND: Limestone gravel.			
2.50-2.80					D2		2.50	Weathered grey SCHIST. Diesel odour from 2.50-5.50mbgl.		∇1	
4.00-4.30					D3		(4.70)				
					Water strike(1) at 3.00m.						
6.00-6.50					D4		7.20 (0.30)	Weathered brown SCHIST.			
					Water strike(2) at 6.00m.		7.50 (4.50)	Grey SCHIST.		∇2	

Remarks	Scale (approx)	Logged By
	1:50	
	Figure No. LKC 14 1181.RBH516	



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Site
 Anglesey Aluminium REP

Borehole Number
RBH516

Machine :	Casing Diameter	Ground Level (mOD)	Client	Job Number
Flush :			Orthios Ecoparks (Anglesey) Ltd	LKC 14 1181
Core Dia: mm	Location	Dates	Engineer	Sheet
Method :		03-11-2016	LKC	2/2

Depth (m)	TCR	SCR	RQD	FI	Field Records	Level (mOD)	Depth (m) (Thickness)	Description	Legend	Water	Instr
							12.00	Complete at 12.00m			

Remarks	Scale (approx)	Logged By
	1:50	
Figure No.		
LKC 14 1181.RBH516		



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Site
 Anglesey Aluminium REP
Borehole Number
 RBH516B

Machine :	Casing Diameter	Ground Level (mOD)	Client Orthios Ecoparks (Anglesey) Ltd	Job Number LKC 14 1181
Flush :	Location	Dates 09-11-2016	Engineer LKC	Sheet 1/1
Core Dia: mm				
Method :				

Depth (m)	TCR	SCR	RQD	FI	Field Records	Level (mOD)	Depth (m) (Thickness)	Description	Legend	Water	Instr
0.30-1.30					D1		0.10 (0.90) 1.00	MADE GROUND: Tarmac. MADE GROUND. Limestone gravel.			
							(4.50)	Weathered brown SCHIST.			
5.00-6.00					D2		5.50 (0.50) 6.00	Weathered grey SCHIST.			
								Complete at 6.00m			

Remarks	Scale (approx) 1:50	Logged By
	Figure No. LKC 14 1181.RBH516B	



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Site
 Anglesey Aluminium REP

Borehole Number
RBH520

Machine :	Casing Diameter	Ground Level (mOD)	Client	Job Number
Flush :			Orthios Ecoparks (Anglesey) Ltd	LKC 14 1181
Core Dia: mm	Location	Dates	Engineer	Sheet
Method :		07-11-2016	LKC	1/2

Depth (m)	TCR	SCR	RQD	I _f	Field Records	Level (mOD)	Depth (m) (Thickness)	Description	Legend	Water	Instr
0.30-1.30					D1		0.20 0.20	MADE GROUND: Gravel. Weathered brown SCHIST.			
							(1.30)				
							1.50	Weathered grey SCHIST.			
							(4.00)				
							5.50	Weathered grey brown SCHIST.			
					Water strike(1) at 6.00m.		(1.00)			∇1	
7.50	100	100	70	Av:120 Min:30 Max:320			6.50	Medium strength thinly foliated grey green SCHIST with occasional quartz banding.			
							(4.10)	Subvertical to 80 degrees open planar rough slight iron stained fracture from 7.55-7.77m. Subhorizontal open planar rough clean, possibly drilling induced at 7.55m. Subhorizontal open planar smooth fracture, possibly drilling induced at 7.83m. 70 degrees closed planar clean fracture from 7.90-8.05m 50 degrees open planar rough slight iron stained fracture from 8.02-8.10m. 70 degrees open planar rough slight iron stained fracture from 8.10-8.30m. Subhorizontal open planar smooth clean fracture, possibly drilling induced at 8.15m. Subhorizontal open planar smooth clean fracture, possibly drilling induced at 8.23m. Subhorizontal open planar smooth clean fracture, possibly drilling induced at 8.37m. Subhorizontal open planar rough clean			
9.10	100	100	51	Av:130	Min:30,Max:150						

Remarks	Scale (approx)	Logged By
	1:50	
	Figure No. LKC 14 1181.RBH520	



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Site
 Anglesey Aluminium REP

Borehole Number
RBH520

Machine :	Casing Diameter	Ground Level (mOD)	Client	Job Number
Flush :			Orthios Ecoparks (Anglesey) Ltd	LKC 14 1181
Core Dia: mm	Location	Dates	Engineer	Sheet
Method :		07-11-2016	LKC	2/2

Depth (m)	TCR	SCR	RQD	I _f	Field Records	Level (mOD)	Depth (m) (Thickness)	Description	Legend	Water	Instr
10.60							10.60	fracture, possibly drilling induced at 8.60m. Subvertical open stepped rough iron stained fracture from 8.89-9.00m. Subhorizontal open planar rough clean fracture, possibly drilling induced at 9.00m. Subhorizontal open planar rough clean fracture, possibly drilling induced at 9.05m. Subhorizontal open planar rough clean fracture, possibly drilling induced at 9.08m. Subhorizontal open planar rough clean fracture, possibly drilling induced at 9.11m. Subvertical closed stepped iron stained fracture from 9.21-9.75m. Subhorizontal open planar rough clean fracture, possibly drilling induced at 9.30m. Subvertical closed stepped iron stained fracture from 9.39-9.47m. Subhorizontal open planar rough clean fracture, possibly drilling induced at 9.54m. Several subvertical closed stepped fractures from 9.60-10.27m. Subvertical open planar smooth iron stained fracture from 9.76-10.24m. 50 degrees open planar smooth iron stained fracture from 9.87-9.97m. Subhorizontal open planar smooth clean fracture, possibly drilling induced at 10.04m. 60 degrees open planar rough iron stained fracture from 10.12-10.28m. Subhorizontal open planar smooth clean, possibly drilling induced from 10.36-10.40m. Subhorizontal open planar rough iron stained fracture at 10.44m.			
								Complete at 10.60m			

Remarks	Scale (approx)	Logged By
	1:50	
Figure No.		
LKC 14 1181.RBH520		



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Site
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Borehole Number
 RBH528A

Machine :	Casing Diameter	Ground Level (mOD)	Client	Job Number
Flush :			Orthios Ecoparks (Anglesey) Ltd	LKC 14 1181
Core Dia: mm	Location	Dates 15-11-2016	Engineer	Sheet
Method :			LKC	1/1

Depth (m)	TCR	SCR	RQD	FI	Field Records	Level (mOD)	Depth (m) (Thickness)	Description	Legend	Water	Instr
0.30-1.30					D1		0.20 0.20	MADE GROUND: Tarmac.			
							0.80	MADE GROUND: Limestone gravel.			
							1.00	Weatherd brown SCHIST.			
3.50-4.50					D2		(5.00)	Slight diesel odour from 4.00-5.50mbgl.		∇1	
					Water strike(1) at 4.50m.		6.00	Complete at 6.00m			

Remarks	Scale (approx)	Logged By
	1:50	
Figure No. LKC 14 1181.RBH528A		



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Site
 Anglesey Aluminium REP

Borehole Number
RBH530A

Machine :	Casing Diameter	Ground Level (mOD)	Client	Job Number
Flush :			Orthios Ecoparks (Anglesey) Ltd	LKC 14 1181
Core Dia: mm	Location	Dates 16-11-2016	Engineer	Sheet
Method :			LKC	1/1

Depth (m)	TCR	SCR	RQD	FI	Field Records	Level (mOD)	Depth (m) (Thickness)	Description	Legend	Water	Instr
0.30-1.30					D1		(0.30)	CONCRETE.			
							0.30	Weathered brown SCHIST.			
							(1.00)				
4.00-4.50					D2		1.30	Weatherd brown grey SCHIST.			
							(1.20)				
							2.50	Weathered grey SCHIST.			
6.50-7.50					D3		(2.50)	Moderate diesel odour from 4.00-6.50mbgl.			
							5.00	Weathered brown SCHIST.			
							(1.50)				
							6.50	Grey SCHIST.			
							(1.00)				
							7.50	Complete at 7.50m			

Remarks	Scale (approx)	Logged By
	1:50	
	Figure No. LKC 14 1181.RBH530A	

Appendix C

Photographic Appendix

Photo Survey



Figure 1 - Compressor house building and area of frozen core collection. Percussive drilling rig used to obtain core samples is visible in the midground here.



Figure 2 - Cores selected for freezing were sealed at the base using a plastic cap before further sealing with plastic film and tape to prevent water loss

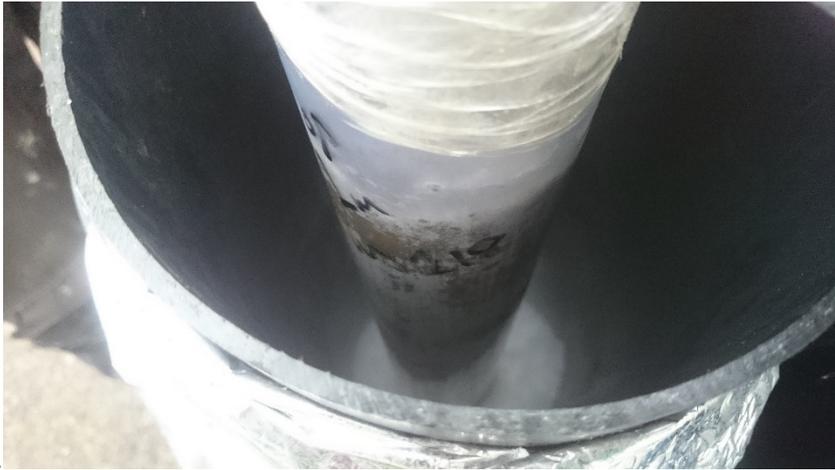


Figure 3 - Cores were subsequently placed into insulated HDPE rapid preservation tubes before being surrounded with frozen pellets of CO². Once processed, these tubes were removed for longer-term storage in prepared insulated caskets.



Figure 4- Insulated caskets prepared for the storage of dry ice were also used to store frozen cores.

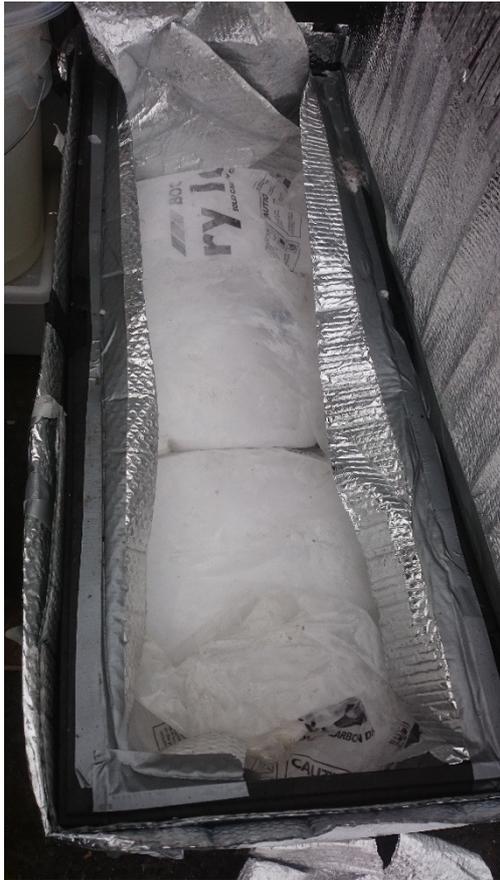


Figure 5- Storage of dry ice in insulated caskets.

Hydraulic Testing



Figure 6 – Ideal locations for hydraulic testing were identified prior to arrival onsite, monitoring using an interface probe was undertaken during the works to confirm these locations or to select alternative areas for study. The wells in the above photograph were located in the Compressor House area.



Figure 7 - Hydraulic testing was undertaken on selected boreholes to determine aquifer properties. Here, a step test is in progress in the Compressor House area drawing from RBH528a. Pressure transducers have been placed in the extraction well and in wells in the surrounding area to monitor changes in hydraulic head.



Figure 8 - Hydraulic testing was undertaken on selected boreholes to determine aquifer properties. Here, a step test is in progress in the Compressor House area drawing from RBH528a. Pressure transducers have been placed in the extraction well and in wells in the surrounding area to monitor changes in hydraulic head. Some restrictions were placed on hydraulic works at the time of the investigation due to other ongoing works.

Vacuum Testing



Figure 9 - Vacuum testing being carried out in the Compressor House area using a vacuum tanker. Here, RBH514a is being drawn from at 4bar. Changes in pressure in surrounding wells are being monitored using pressure gauges visible in the foreground of the above photograph.

Appendix D

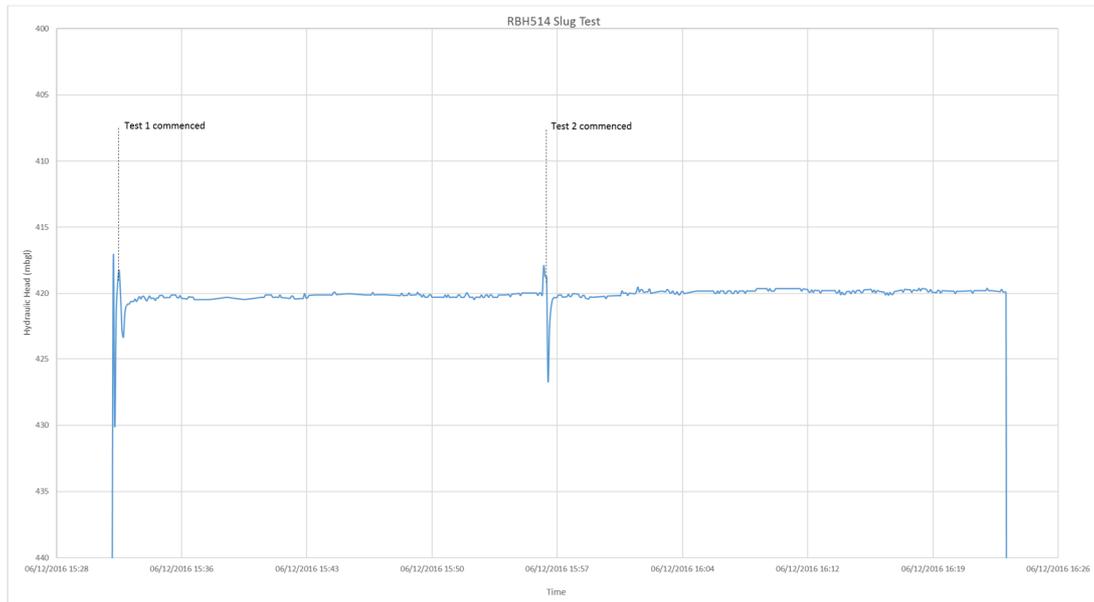
Hydraulic Testing

Hydraulic Testing Supplementary Graphs

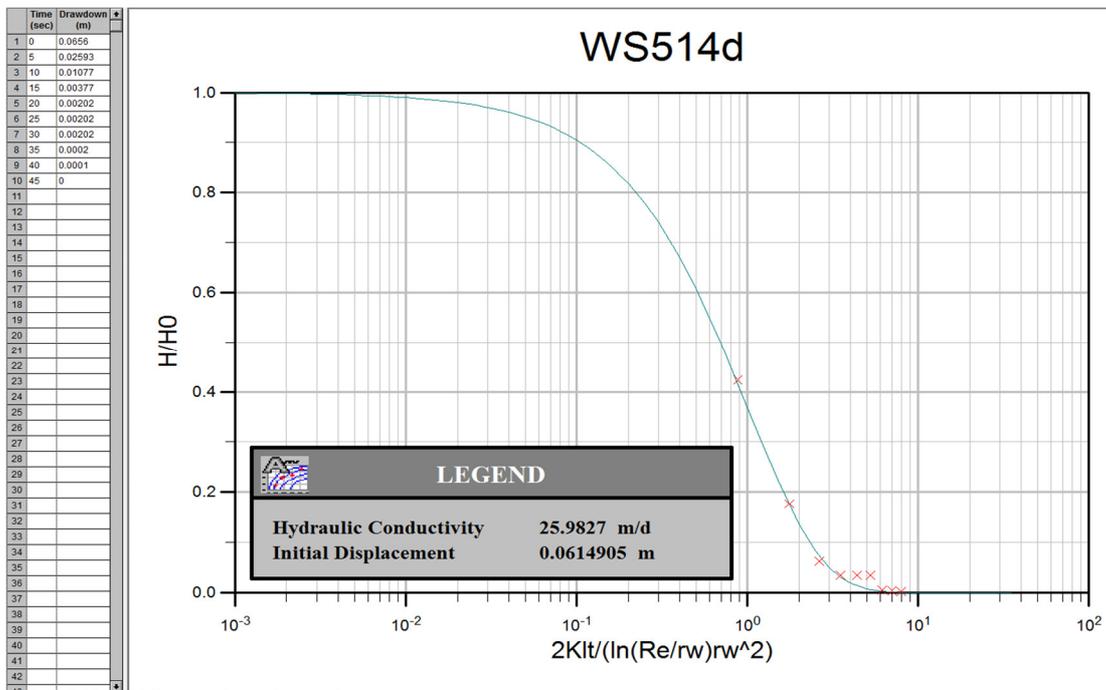
Compressor House

Slug Tests

RBH514

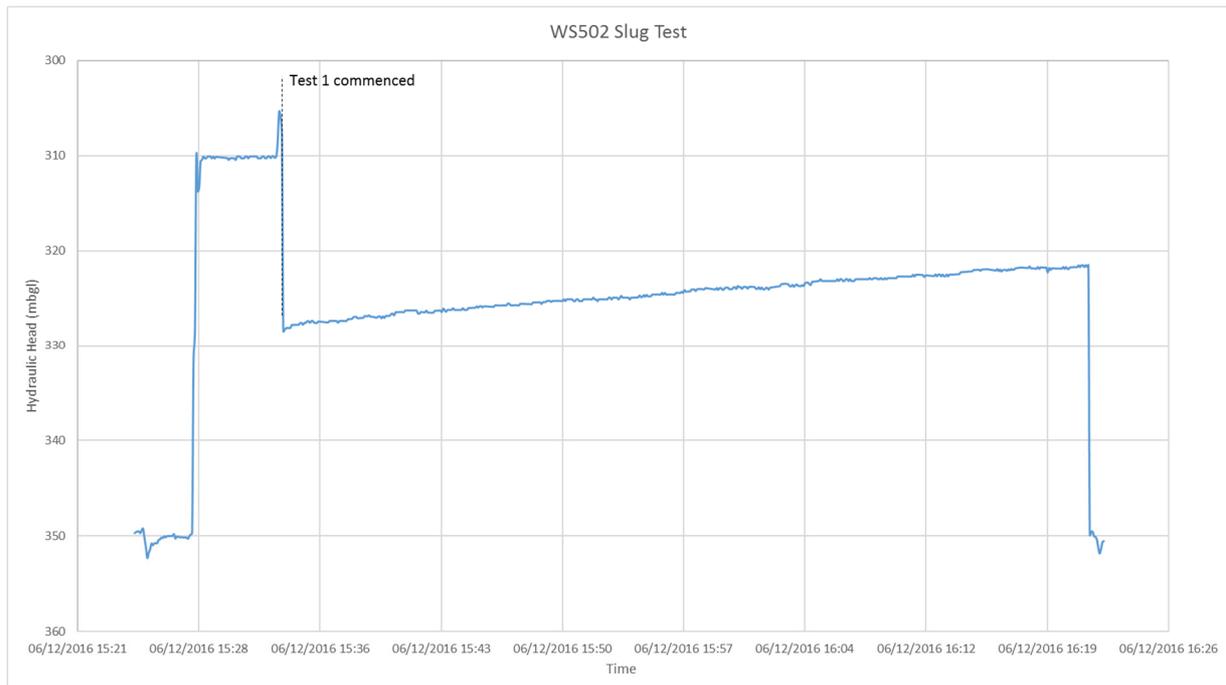


Graph 1 - Contextual graph detailing changes in hydraulic head in RBH514 during Slug testing

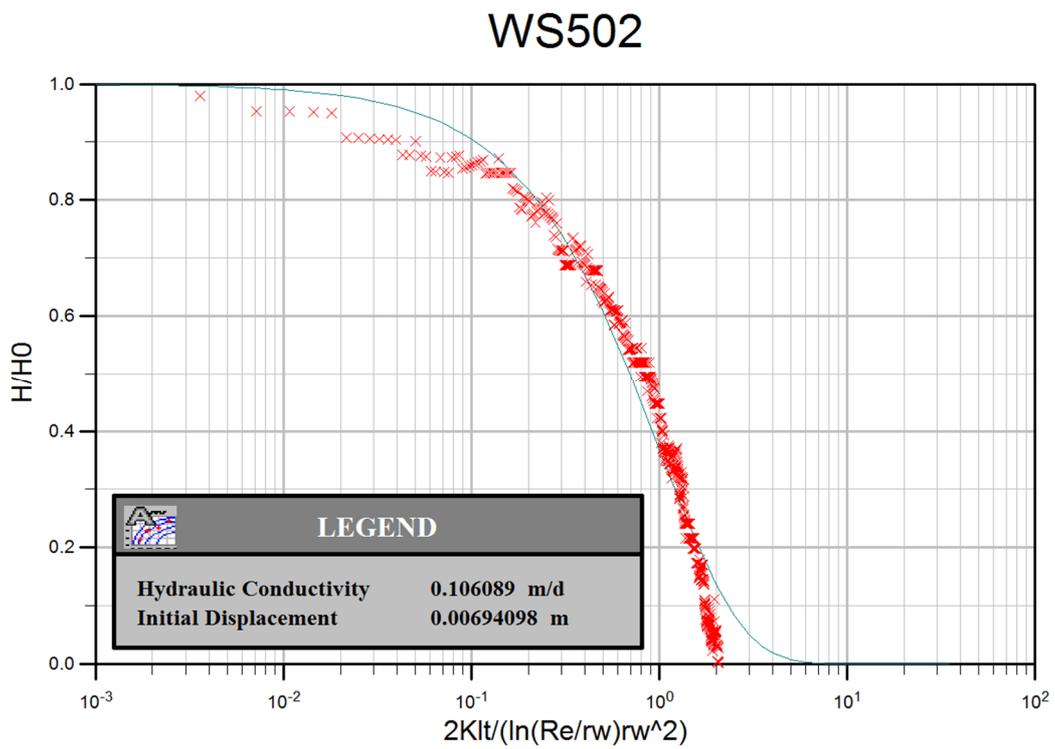


Graph 2 - Hydraulic conductivity type-fit curve for a Slug Test undertaken on RBH514

WS502



Graph 3 - Contextual graph detailing changes in hydraulic head in WS502 during Slug testing



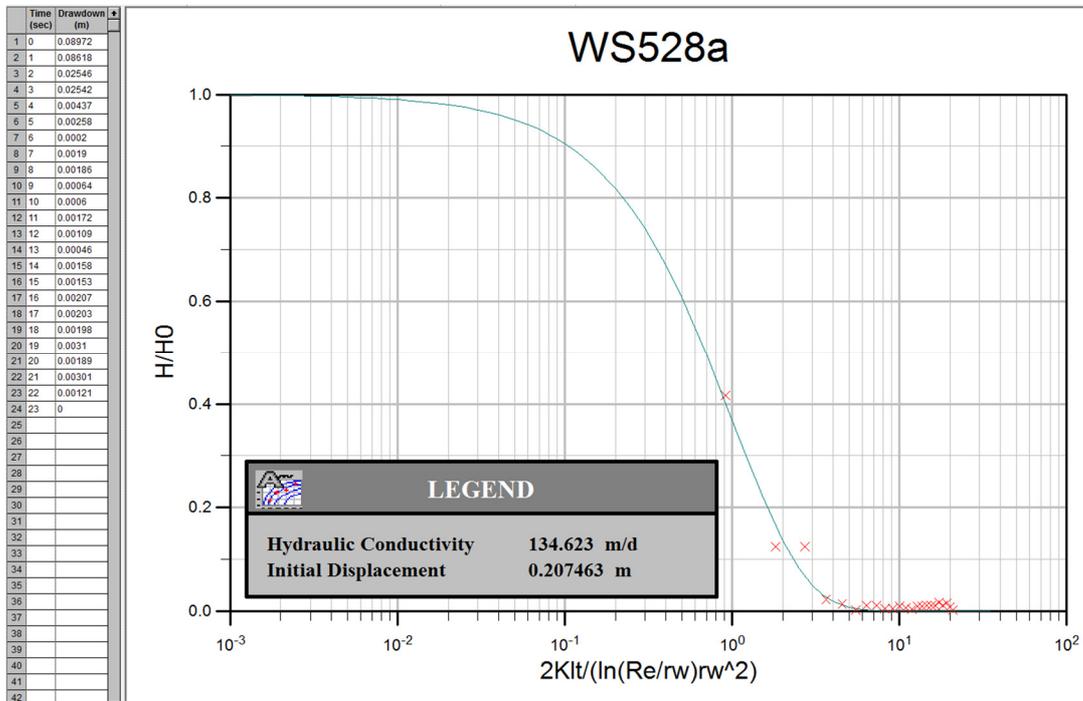
Graph 4 - Hydraulic conductivity type fit curve for a Slug Test undertaken on WS502

RBH528a



Graph 5 – Contextual graph detailing changes in hydraulic head in RBH528a during Slug testing

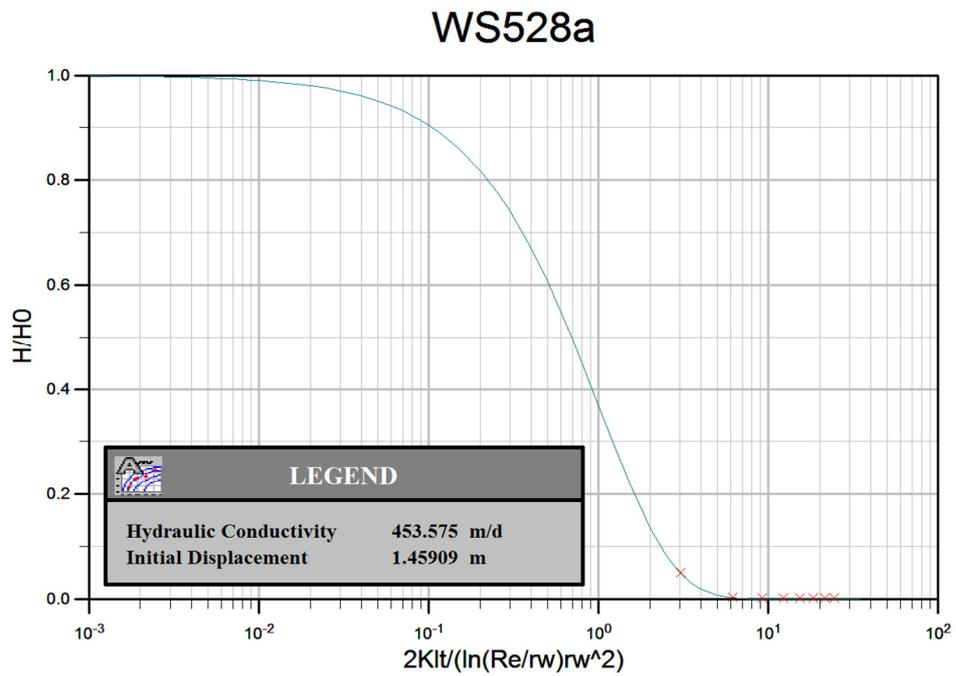
Test 1



Graph 6 Hydraulic conductivity type-fit curve for Slug Test 1 of 3 in RBH528a

Test 2

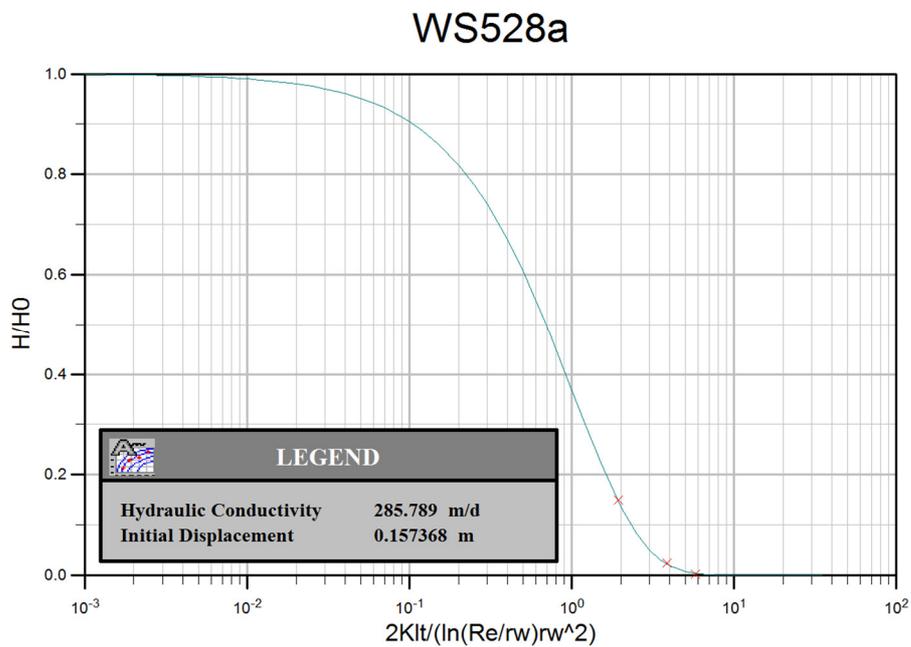
Time (sec)	Drawdown (m)
1	0
2	0.11491
3	0.07116
4	0.00291
5	0.00116
6	0.00116
7	0.00116
8	0.00116
9	0
10	
11	
12	
13	
14	
15	
16	
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Graph 7-Hydraulic conductivity type-fit curve for Slug Test 2 of 3 in RBH528a

Test 3

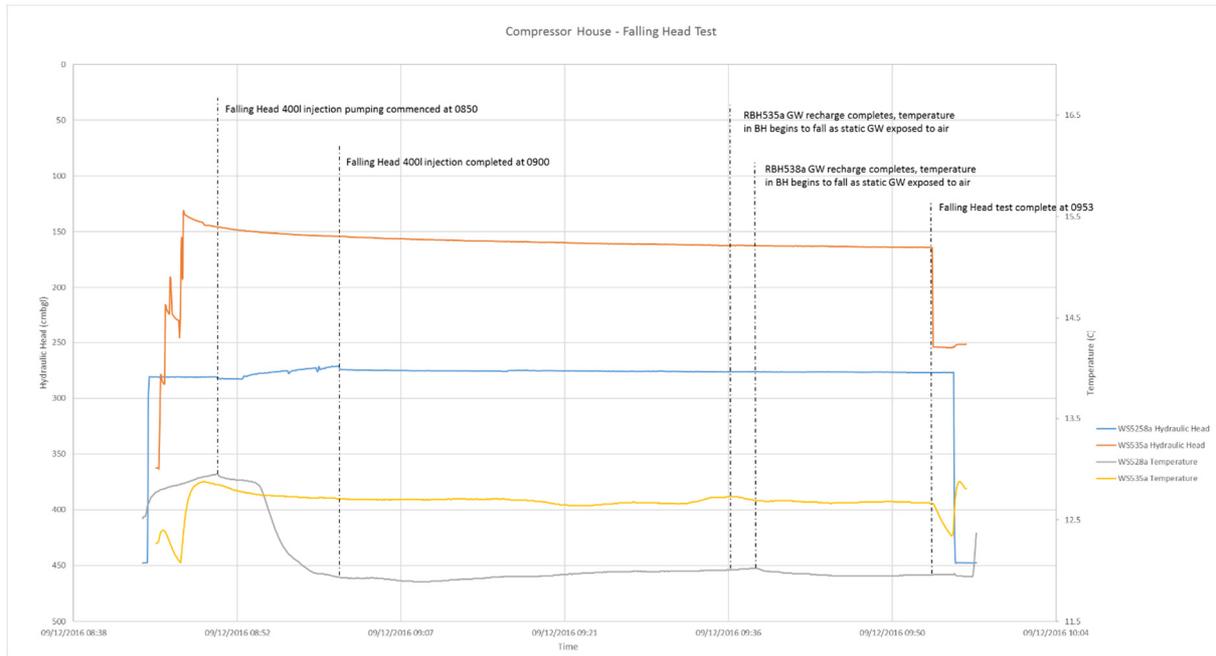
Time (sec)	Drawdown (m)
1	0
2	0.056
3	0.02334
4	0.0035
5	0
6	
7	
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9	
10	
11	
12	
13	
14	
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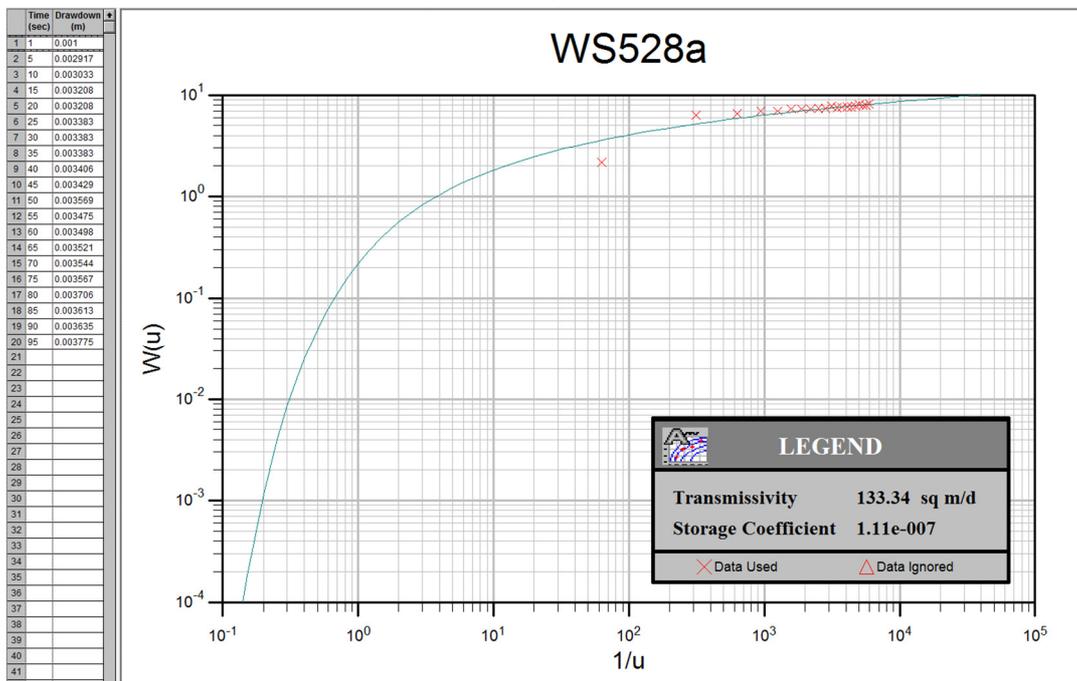
Graph 8 - Hydraulic conductivity type-fit curve for Slug Test 3 of 3 in RBH528a

Falling Head Test

WS528a



Graph 9 - Contextual graph detailing changes in hydraulic head during the Falling Head Test in RBH528a and RBH537a



Graph 10 - Hydraulic transmissivity type-fit curve for RBH528a using data taken from the Falling Head test.

Appendix E

Vacuum Testing

Compressor house

08/12/2016

Pulled from WS514a

Commenced 0906 @0.4bar
Terminated @ 11.10

Well	Distance from WS514a	Pressure (mbar)
WS514	1	-40
WS513a	5.5	-30
WS513	4.07	0
WS511a	4.58	0
WS511	5.47	-2.5
WS512a	3.26	0
WS512	3.94	0
WS516a	10.86	-5.5
WS516	9.9	0
WS504a	6.7	0
WS504	6.7	0
WS510a	9.78	0
WS510	8.25	0
APC02 Oily Well	11.62	1.5
WS520	17.93	0
WS515	26.25	0

Rectifier Yard

08/12/2016

Vacuum too strong for relatively high water table and incompatible geology. As soon as vacuum applied, water raised above pipe level resulting in drawing of groundwater. After attempting to lower pressure and move locations, test abandoned.

Appendix F

Treatability Trial

Interactive logs detailing chemical testing results and logging Cores retrieved for the Treatability Trial are available in digital spreadsheet form.

APPENDIX B

CHEMICAL OXIDANT LABORATORY TRIALS REPORT

Anglesey

Laboratory Bench Scale Chemical Oxidation Study

Report A161201
March 2017



Prepared for



Revision Schedule

March 2017

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1 Executive Summary

CE Geochem have been commissioned by Geo2 to undertake a laboratory study and prepare an interpretive laboratory report for bench scale treatability trials to assess the feasibility of, and optimise where possible, the deployment of In Situ Chemical Oxidation (ISCO) groundwater treatment technology for an undisclosed site on Anglesey, Wales, UK.

3 No. candidate oxidant-activator systems were assessed for 2 No. different aquifer matrices. Candidate oxidants included persulphate, both with and without peroxide as an activator, and hydrogen peroxide alone as a single oxidant system.

Kinetic studies were used to derive pseudo-first order rate constants for oxidant utilisation in the presence of the target aquifer matrix under a suite of potential oxidant loading concentrations and during treatability trials. Site specific half-lives for oxidant decomposition were computed from the experimentally derived rate constants. The relatively high groundwater travel velocities present within the target aquifers favour the application of high energy oxidants demonstrating rapid decomposition kinetics. The use of peroxide based chemical oxidation techniques will ensure source zones are not bypassed due to the low residence times that may be encountered.

6 No. candidate oxidant systems were investigated for contaminant destruction profiling in order to assess the extent of target contaminant destruction. Persulphate was added at the respective Total Oxidant Requirement (TOR) with, and without peroxide as an activator and also at 2 x TOR, with and without peroxide as an activator. In addition, peroxide trialled at application rates of 2% and 5%. Chemical oxidation systems were investigated for 2 No. aquifer matrices; composited Garage and Compressor samples (GC) and also an aquifer matrix composed of the Rectifier (R) area.

Treatability study datasets showed that greatest oxidant efficacy was achieved for peroxide systems. Both low (2%) and high-range (5%) peroxide systems demonstrated similar destruction efficacies across the full range of TPH fractions present. Dissolved phase contaminant destruction profiles suggest that peroxide systems may enhance the dissolution of free phase NAPL components where present at the subject site, enable contaminant mass mineralisation in the dissolved phase. No rebound was observed for peroxide system, a feature that was encountered over extended time, for both of the trialled persulphate oxidant systems.

In contrast to peroxide activated persulphate, single oxidant peroxide applications provided circum-neutral reaction conditions, effectively limiting any trace metal release that may be associated with low pH ISCO technologies such as the dual oxidant, peroxide activated persulphate system investigated in this study.

Based on available datasets, and in particular the predicted rapid sub-surface reactivity of peroxide, CE Geochem recommend that 2% peroxide be considered the optimum oxidant system for the subject site.

Because peroxide is relatively short-lived in the sub-surface, multiple injections may be administered, based on the residual TPH concentrations following oxidant consumption (circa. 96 hours after injection). This approach should enable specific areas of elevated source mass to be treated sequentially without significant impact on the proposed site works injection programme.

2 Introduction

2.1 Project Appreciation

2.1.1 Geo2 have commissioned CE Geochem to undertake a bench-scale chemical oxidation study to assess the feasibility of deploying optimised oxidant-activator systems for achieving remedial betterment at the subject site (undisclosed). This chemical oxidation study has been completed in order to develop a detailed design for the treatment of groundwater contaminants.

2.2 Geochemical Test Work Programme

2.2.1 The geochemical test work programme has included the following core components;

- Groundwater and aquifer characterisation
 - Depth profiling study to assess subsurface contaminant distribution and identify target aquifer compartments for this study
 - Matrix Oxidant Demand (MOD) testing and the derivation of oxidant half-lives from pseudo-first order rate laws
 - Contaminant destruction profiling for selected oxidant-activator systems with assessment of transition products, daughter products and rebound potential
- 2.2.2 Persulphate decomposition / utilisation rates under hydrogen peroxide activated and native (unactivated) conditions, in addition to peroxide decomposition / utilisation rates, were assessed through initial MOD investigations.
- 2.2.3 The two aquifer matrices investigated, were designated as GC, which comprised representative aquifer matrix and groundwater samples from both the Garage and Compressor area, and R, which relates to the Rectifier area.
- 2.2.4 Test work samples used in this study may be regarded as; weathered schist comprising horizons of gravel, sand and silt.
- 2.2.5 The selection of trial oxidant-activator stoichiometries was based on providing appropriate oxidant mass to destroy the source contaminant mass, persulphate based oxidant chemistries selected to promote greater oxidant longevity if required in lower permeability strata. The chemical oxidation studies were replicated for the both GC and R materials.

I. Persulphate at TOR

II. Persulphate at 2 x TOR

III. Peroxide activated Persulphate at TOR

IV. Peroxide activated Persulphate at 2 x TOR

V.Peroxide at 2%

VI.Peroxide at 5%

2.3 Nominated Third-Party Analytical Laboratory Accreditation and Quality Assurance

- 2.3.1 Chemtest is accredited to the ISO17025 International Standard *General Requirements for the Competence of Testing and Calibration Laboratories* (Lab Ref. 2183), for those tests that are so identified and listed on our current UKAS schedule. ISO17025 accreditation also demonstrates that our Quality Management System operates in accordance with the principles of ISO9001.
- 2.3.2 In addition to ISO17025, the laboratory is accredited to the EA MCERTS *Performance Standard for Laboratories Undertaking Chemical Testing of Soil* and MCERTS *Performance Standard for Organisations Undertaking Sampling and Chemical Testing of Water*. MCERTS accredited tests are also detailed on our UKAS schedule, available from the UKAS website.
- 2.3.3 Quality Control in the laboratory is ensured by a comprehensive system of internal and external QC measures. This includes the use of Certified Reference Materials (CRMs) in method validation and routine Analytical Quality Control (AQC) by means of in-house QC samples, independent AQC standards and blanks, as appropriate to the method and to satisfy the requirements of the accreditation held.
- 2.3.4 Inter-laboratory Proficiency Testing (PT) studies, notably the LGC CONTEST, LGC Aquacheck and DEFRA LEAP schemes, are participated in for a wide range of determinands and the resulting proficiency scores scrutinised by means of internal quality system procedures, in order to affirm fitness for purpose of the relevant tests.
- 2.3.5 Analytical results are controlled by means of AQC data subject to statistically derived limits and plotted on Shewhart control charts. These charts are reviewed regularly to monitor on-going method performance and are, where applicable, subject to the QC limits for bias and precision specified by the MCERTS standard.

3 Conceptual Technology Design Model

- 3.1.1 For the purpose of assessing the potential deployment of In Situ Chemical Oxidation (ISCO) techniques at the subject site, CE Geochem have conceptualised the hydrogeological system as an unconfined superficial aquifer, composed primarily of drift deposits.
- 3.1.2 The underlying geology schist, a medium grained metamorphic bedrock, overlain by variable thicknesses of unconsolidated superficial deposits.
- 3.1.3 The conceptual design model considers rockhead will act as the impermeable base of the superficial aquifer systems to be targeted for treatment. Hydrogeological site investigations undertaken by Geo2 during 2016, have characterised the unconsolidated drift deposits as relatively high permeability groundwater systems, which may be locally variable.
- 3.1.4 The saturate thickness of superficial deposits is taken as defining the mixing zone depth of site injection protocols. Table 3.1 provides information used to determine the saturated zone thickness for relevant areas of the subject site.
- 3.1.5 The main hydrogeological compartments are presented in Table 3.1 below.

Hydrogeological Unit	Depth to groundwater (m)	Depth to rockhead (m)
Rectifier Area	1.7-1.8	2-2.5
Compressor Area	2.8-3.3	2.3-5.8

Table 3.1 Data used for computation of mixing zone depths.

- 3.1.6 It is important to note that the underlying schists have been identified as a physical barrier to the vertical component of contaminant migration, with an assumed low vertical permeability. This defines the only treatment zone as the overlying drift.
- 3.1.7 Based on the maximum saturated thickness above rockhead we calculate mix zone depths of 0.8m in the Rectifier area and 3.0m in the Compressor area.
- 3.1.8 Average hydraulic conductivities for the compressor area were determined to be 180m/day (n=3 locations), whilst the average for the Rectifier area was determined to be 10m/day (n=5 locations).
- 3.1.9 Due to the relatively high groundwater travel velocity in the target aquifer, the selection of short-lived, high energy peroxygenic compounds may be favoured as an ISCO groundwater treatment technique at the subject site.
- 3.1.10 Please see Appendix B for interactive depth profiling logs which provide litho-geochemical details for sub-surface contaminant mass distribution.

4 Experimental Methodology

4.1 Sample Selection, Characterisation and Preparation

- 4.1.1 All samples used in this study were provided by Geo2. An initial test work composite was formed from the Garage, Compressor, and Rectifier area for Matrix Oxidant Demand studies. Separate homogenised test work composites were produced for the Garage and Compressor (GC) areas, and the Rectifier (R) area, for use in Treatability Trials.
- 4.1.2 3 No. discrete 20L Groundwater samples from the Garage, Compressor and Rectifier areas, respectively, were received from Geo2 and composites of Garage and Compressor samples were prepared for GC Treatability Trials. GW samples from the Rectifier area were used exclusively for R treatability trials.
- 4.1.3 Source characterisation studies were undertaken on frozen intact cores, sampled at 100mm depth intervals throughout the full depth of recovered cores. All core samples were stored at -20°C prior to sectioning, logging and sampling. Source term characterisation certificates of analysis are presented in Appendix A with Interactive Depth Profiling Logs provided in Appendix B.
- 4.1.4 Soil source characterisation was undertaken on the homogenised composite test work sample produced from the Garage and Compressor areas, and the discrete sample from the Rectifier area. Certificates of Analysis are presented in Appendix A.
- 4.1.5 Groundwater characterisation datasets were undertaken on unfiltered groundwater samples from all three areas. Certificates of analysis are presented in Appendix A.
- 4.1.6 Mineralogical and major elemental composition determined by X-Ray Diffraction (XRD) and X-Ray Fluorescence Spectrometry (XRF), respectively. Analyses were carried out on a dried and ground sub-sample recovered from the composited GC test work sample. Results are presented in Appendix C. This sample was selected to represent geological materials of greatest interest to this study in terms of the host mineralogy likely to be provide subsurface reactivity within the aquifer matrix.

4.2 Matrix Oxidant Demand & Chemical Oxidation Kinetics

- 4.2.1 Aquifer Matrix Oxidant Demand (MOD) curves were generated using a derivative method of ASTM D7262-07 at slurry densities of 50 w/w % for oxidant loadings of 0, 5, 10, 20, 35 and 50 g/l in deionised water (ASTM Type II – 15 MΩ),
- 4.2.2 Oxidant demand testing was conducted under ambient temperature and pressure with continual agitation on a Gyro-rocker platform at 40 rpm. All MOD testing was performed in 250 ml glass erlenmyeyer flasks with supernatant recovery by centrifugation for sub-samples collected at time (t) = 24, 96, 168, 240, & 336 hours for persulphate oxidant systems and (t) = 6, 24, 48 hours for peroxide oxidant systems. Residual oxidant concentrations were determined using the iodometric spectrophotometric method of Liang, 2008.

- 4.2.3 pH, Eh, and EC were also determined for each time point.
- 4.2.4 The experimental matrix employed is shown in Table 4.1.
- 4.2.5 Datasets were used to derive first order rate constants and absolute MOD in g/kg and mol/kg. MOD datasets are presented in Appendix B

Oxidant – Activator System	Activator	Oxidant Mass (g/l)				
<i>Persulphate</i>	-	5	10	20	35	50
<i>Peroxide Activated Persulphate</i>	5g/L Peroxide	5	10	20	35	50
<i>Peroxide</i>		5	10	20	35	50

Table 4.1 MOD and oxidant kinetics experimental matrix

4.3 Treatability Trials

- 4.3.1 Chemical Oxidation (Chemox) treatability trials were conducted in continuous batch mode at room temperature under sealed headspace conditions. All chemox investigations employed a 20 w/w % aquifer matrix slurry density.
- 4.3.2 Chemox experiments were conducted for each of the identified hydrogeological systems (GC or R), employing 2000 ml glass reactors for assessing the destruction of 8-band TPH. Residual dissolved phase metals were analysed in each reactor system at the final time point. All reactors were hermetically sealed using PTFE bound threads to prevent gaseous exchange with atmosphere.
- 4.3.3 Residual oxidant concentrations, pH, Eh and EC were also monitored at each sampling point.
- 4.3.4 Residual aquifer matrices were recovered by centrifugation at time (t) = 672 hours for persulphate oxidant systems and (t) = 96 hours for peroxide oxidant systems, to allow residual source mass determination.
- 4.3.5 The chemox experimental matrix is shown in Table 4.2.

Chemox System	Chemox Reactor	Oxidant (g/l)	Activator Chemistry
<i>Control</i>	1(9)		
<i>Duplicate Persulphate TOR</i>	2(10)	3.81	
<i>Persulphate TOR</i>	3(11)	3.81 (12.63)	
<i>Persulphate 2 x TOR</i>	4(12)	7.62 (25.26)	
<i>Persulphate TOR / Peroxide</i>	5(13)	17.41 (26.23)	5g/L H ₂ O ₂
<i>Persulphate 2 x TOR/ Peroxide</i>	6(14)	34.82 (52.46)	5g/L H ₂ O ₂
<i>Peroxide 2%</i>	7(15)	20	
<i>Peroxide 5%</i>	8(16)	50	

Table 4.2 Chemox Experimental Matrix. Chemox Reactors and Oxidants in ()'s relate to Rectifier matrix and groundwater whereas non-bracketed reactor ID's relate to the Garage/Compressor composite matrix and groundwater.

- 4.3.6 Oxidant masses employed were calculated as Total Oxidant Requirements (TOR) based on the Stoichiometric Oxidant Demand (SOD) for dissolved phase & sorbed phase TPH + Matrix Oxidant Demand (MOD) from MOD determinations.
- 4.3.7 Chemox reactors were sampled at time (t) = 0, 24, 96, 168, 336 & 672 hours for persulphate oxidant systems, and (t) = 0, 6, 24, 48 & 96 hours for peroxide oxidant systems.
- 4.3.8 Sub samples were collected from below the aqueous phase surface, to ensure analytical datasets relate exclusively to dissolved phase concentrations. TPH extractions were undertaken immediately following sampling using a 40:1 liquid-liquid pentane extraction technique to immediately quench chemical oxidation samples. All certificates of analysis are presented in Appendix A.

5 Preliminary Investigations

5.1 Groundwater Characterisation & Aquifer Depth Profiling Studies

5.1.1 Source term characterisation was conducted on bulk samples recovered by Geo2 from intrusive locations representative of the Garage, Compressor and Rectifier areas. Source characterisation data for the Garage and Compressor area relate to the homogenised composite test work sample. Datasets for the composited Garage & Compressor (GC) and Rectifier (R) are presented in Table 5.1. No VOC components were detected in either test work sample.

5.1.2 Depth profiling investigations are presented in Appendix B as interactive Excel™ files.

Determinand	Units	LOD	GC	R
Moisture	%	0.020	11	8.9
Acid Neutralisation Capacity	mol/kg	0.0020	0.071	0.069
Calcium	mg/l	20	2300	1500
Sodium	mg/l	2.0	70	31
Iron (Total)	mg/kg	100	20000	21000
Arsenic	mg/kg	1.0	5.6	4.0
Cadmium	mg/kg	0.10	< 0.10	< 0.10
Chromium	mg/kg	1.0	26	22
Copper	mg/kg	0.50	35	160
Mercury	mg/kg	0.10	< 0.10	< 0.10
Manganese	mg/kg	5.0	710	640
Nickel	mg/kg	0.50	34	31
Lead	mg/kg	0.50	6.9	5.7
Selenium	mg/kg	0.20	< 0.20	< 0.20
Vanadium	mg/kg	5.0	23	19
Zinc	mg/kg	0.50	71	67
Total Organic Carbon	%	0.20	0.46	0.22
TPH >C5-C6	mg/kg	1.0	< 1.0	< 1.0
TPH >C6-C7	mg/kg	1.0	< 1.0	< 1.0
TPH >C7-C8	mg/kg	1.0	< 1.0	< 1.0
TPH >C8-C10	mg/kg	1.0	< 1.0	< 1.0
TPH >C10-C12	mg/kg	1.0	< 1.0	< 1.0
TPH >C12-C16	mg/kg	1.0	< 1.0	25
TPH >C16-C21	mg/kg	1.0	< 1.0	280
TPH >C21-C35	mg/kg	1.0	< 1.0	150
Total TPH >C5-C35	mg/kg	10	< 10	450

Table 5.1. Source term concentrations for target contaminants identified within the test work sample composites. All data presented to 2 significant figures. VOC data not presented.

5.1.3 As can be seen by inspection of Table 5.1, target contaminants are identified as TPH in the area R only. The inorganic composition of both test work matrices was fairly consistent,

with circa. 2 wt.% Fe and an ANC of circa. 0.07 mol/kg. Due to the similarity between both areas, MOD testing was undertaken on a composite test work sample formed from the Garage, Rectifier and Compressor bulk samples.

- 5.1.4 TPH source term mass in the R test work matrix was predominately composed of large chain hydrocarbons spanning C12-C35, with a Total TPH concentration of 450 mg/kg. No TPH was detected in the GC composite test work matrix.
- 5.1.5 Groundwater source characterisation datasets for the 3 No. areas under investigation are presented in Table 5.2 below.
- 5.1.6 Dissolved phase TPH, predominately C12-C21 is present within G and R groundwaters, however TPH was below analytical detection limits for Area C. Low levels of benzene and toluene were detected in area G. Due to the limited dissolved phase source term mass of VOCs, these compounds were excluded from treatability studies.
- 5.1.7 Ground water test work composites were formed by compositing G and C samples at 50:50 ratio, whereas trials conducted on area R were taken from the homogenised groundwater bulk sample as received.

Determinand	Units	LOD	C	G	R
pH		N/A	8.4	8.4	7.8
Electrical Conductivity	µS/cm	1.0	640	630	450
Chemical Oxygen Demand	mg O2/l	10	29	78	180
Alkalinity (Total)	mg CaCO3/l	10	210	290	190
Chloride	mg/l	1.0	44	34	27
Sulphate	mg/l	1.0	46	24	7.8
Calcium	mg/l	5.0	28	50	72
Sodium	mg/l	0.50	100	49	14
Arsenic (Dissolved)	µg/l	1.0	1.0	1.9	< 1.0
Cadmium (Dissolved)	µg/l	0.080	< 0.080	0.082	< 0.080
Chromium (Dissolved)	µg/l	1.0	< 1.0	< 1.0	< 1.0
Copper (Dissolved)	µg/l	1.0	11	4.4	< 1.0
Iron (Dissolved)	µg/l	20	83	160	230
Mercury (Dissolved)	µg/l	0.50	< 0.50	< 0.50	< 0.50
Manganese (Dissolved)	µg/l	1.0	49	1600	3500
Nickel (Dissolved)	µg/l	1.0	1.0	2.5	< 1.0
Lead (Dissolved)	µg/l	1.0	< 1.0	< 1.0	< 1.0
Selenium (Dissolved)	µg/l	1.0	1.3	2.2	< 1.0
Vanadium (Dissolved)	µg/l	1.0	< 1.0	< 1.0	< 1.0
Zinc (Dissolved)	µg/l	1.0	3.6	4.0	8.0
Manganese [II]	µg/l	1.0	62	1400	4200
Iron [II]	µg/l	20	< 20	< 20	310
Dissolved Organic Carbon	mg/l	2.0	11	23	68
TPH >C5-C6	µg/l	0.10	< 0.10	< 0.10	< 0.10
TPH >C6-C7	µg/l	0.10	< 0.10	< 0.10	< 0.10
TPH >C7-C8	µg/l	0.10	< 0.10	< 0.10	< 0.10
TPH >C8-C10	µg/l	0.10	< 0.10	10	2.8
TPH >C10-C12	µg/l	0.10	< 0.10	140	33

Determinand	Units	LOD	C	G	R
TPH >C12-C16	µg/l	0.10	< 0.10	870	280
TPH >C16-C21	µg/l	0.10	< 0.10	940	660
TPH >C21-C35	µg/l	0.10	< 0.10	190	320
Total TPH >C5-C35	µg/l	10	< 10	2100	1300
Benzene	µg/l	1.0	< 1.0	13	< 1.0
Toluene	µg/l	1.0	< 1.0	52	< 1.0

Table 5.2. Groundwater characterisation data for areas G, C and R. All VOC compounds with the exception of benzene and toluene were reported below LOD and are not presented.

- 5.1.8 As presented in Table 5.2, groundwater's are circum-neutral with a a relatively low COD, consistent with the low DOC levels reported. Elevated concentrations of dissolved divalent iron and manganese, likely generated through dissolution of iron and manganese aquifer minerals may provide the basis for in situ activation chemistries in G and R areas. Corresponding dissolved phase trace metal concentrations are relatively low, all within expected natural background geochemical baseline concentrations.
- 5.1.9 X-Ray Diffraction (XRD) data revealed that the aquifer matrix is predominantly composed of quartz and ferroan clinocllore with minor components of albite muscovite. We assume that Fe groundwater concentrations are linked to the dissolution of ferroan clinocllore.
- 5.1.10 X-Ray Fluorescence (XRF) data confirms the predominance of silicon and aluminosilicate-iron based phases. XRF data is presented for both major and trace elements in Appendix A.
- 5.1.11 Based on the available data presented above we would generally not anticipate that matrix derived rebound effects from sorbed phase contaminant mass would liberate significant dissolved phase mass.
- 5.1.12 Transient rebound during field applications may however occur when oxidants and/or groundwater pH profiles directly influence the mobilisation of contaminant mass. This may give rise to elevated aqueous phase concentrations both during the onset of ISCO treatment, particularly where peroxide chemistries are used, that provide a potential for gas induced liberation (scrubbing) of TPH from the matrix through decomposition to molecular oxygen. Any dissolved phase rebound is considered to be short-lived due to the low sorbed phase TPH mass present within the target aquifer.

6 Oxidant Kinetics & Subsurface Travel

- 6.1.1 CE Geochem believe the most appropriate treatment of oxidant kinetics is through the derivation of pseudo-first order rate constants to allow the estimation of half-lives that can subsequently be used for analytical fate and transport simulations. This approach provides a consistent framework for comparing different oxidant travel times and provides an insight into the likely local oxidation potential provided at distance from the injection well, assuming a homogeneous isotropic aquifer model.
- 6.1.2 The use of single value Matrix Oxidant Demand (MOD) parameters, although convenient, is limited to only providing a single point estimate of oxidant utilisation over a known time period. These empirical values cannot easily or robustly be extrapolated and provide no basis for assessing oxidant utilisation v travel velocities. The use of the MOD approach is typically best suited to kinetically slow oxidants such as persulphate. Peroxide systems undergo complete decomposition, hence the total oxidant mass utilised needs to be reconciled with kinetic rates in order to provide a benchmark for assessing matrix oxidant demand across multiple oxidant systems.

6.2 Derivation of Oxidant Kinetics

- 6.2.1 A summary of rate constants and half-lives derived from MOD tests are provided in Table 6.1 below.
- 6.2.2 Half-lives have been generated from pseudo-first order rate constants from linearization of $\ln(A)$ over t plots, where A is residual oxidant mass.
- 6.2.3 Both persulphate and peroxide activated persulphate datasets demonstrate reasonable regression statistics for the aforementioned kinetic rate laws. Both systems demonstrated initial oxidant concentration dependence on the experimentally derived rate constant, as can be seen from inspection of Table 6.1. It is noteworthy that persulphate in the absence of activation showed a plateau in oxidant utilisation rates after time (t) = 96 hours.
- 6.2.4 Persulphate utilisation in peroxide activated systems is significantly faster than persulphate alone, particularly at low persulphate loading where the peroxide : persulphate ratio is higher. All peroxide activated persulphate systems exhibit a persulphate dependant pH reduction which appears to recover to circum-neutral conditions following the complete consumption of persulphate as shown by 10g/l persulphate systems. Higher persulphate loadings do also show a general recovery of pH over extended time, however all systems with Co persulphate concentrations >10 g/l remained net acidic.
- 6.2.5 Peroxide MOD test systems showed no acidification. Oxidant consumption rates provide an excellent fit to pseudo-first order reaction kinetics, which are both rapid and complete within 96 hours. Typical half-lives are estimated to range from 4.7-5.8 hours.
- 6.2.6 MOD datasets with pseudo-first order kinetic plots are presented in Appendix B.

	Persulphate				
	5g/l	10g/l	20g/l	35g/l	50g/l
Matrix Oxidant Demand (g/kg)	3.8	5	8.5	14	17.65
Matrix Oxidant Demand (mol/kg)	0.0160	0.0210	0.0357	0.0588	0.0742
1st Order Rate Constant (k)	4.09E-04	3.09E-04	2.35E-04	1.95E-04	1.63E-04
Regression Stat for k (R2)	0.877	0.870	0.835	0.706	0.716
Persulphate Half-life (hours)	1693.8	2243.2	2944.1	3558.5	4251.6
Persulphate Half-life (days)	70.6	93.5	122.7	148.3	177.1
	Peroxide				
	5g/l	10g/l	20g/l	35g/l	50g/l
Matrix Oxidant Demand (g/kg)	25	50	100	175	250
Matrix Oxidant Demand (mol/kg)	0.1050	0.2101	0.4202	0.7353	1.0504
1st Order Rate Constant (k)	N.A.	1.49E-01	1.19E-01	1.25E-01	1.56E-01
Regression Stat for k (R2)	N.A.	0.999	0.994	0.999	0.991
Peroxide Half-life (hours)	N.A.	4.7	5.8	5.5	4.4
Peroxide Half-life (days)	N.A.	0.2	0.2	0.2	0.2
	Peroxide activated Persulphate				
	5g/l	10g/l	20g/l	35g/l	50g/l
Matrix Oxidant Demand (g/kg)	25	50	85.65	121.5	119.7
Matrix Oxidant Demand (mol/kg)	0.1050	0.2101	0.3599	0.5105	0.5029
1st Order Rate Constant (k)	2.20E-02	3.17E-02	1.81E-03	7.61E-04	5.50E-04
Regression Stat for k (R2)	1.000	0.760	0.625	0.920	0.855
Persulphate Half-life (hours)	31.5	21.8	383.2	911.1	1260.2
Persulphate Half-life (days)	1.3	0.9	16.0	38.0	52.5

Table 6.1. Derived Oxidant half-lives for persulphate, peroxide and peroxide activated persulphate decomposition using a mixed G,C and R aquifer matrix..

- 6.2.7 The derivation of oxidant-activator-matrix specific rate constants has enabled scoping calculations for estimating the Radius of Influence (RoI) for different candidate oxidant systems. This approach allows visualisation of sub surface oxidant distribution for specific oxidant application rates.
- 6.2.8 It should be recognised that MOD testing is undertaken using a deionised water matrix rather than groundwater. This approach is employed to specifically investigate matrix mediated oxidant decomposition rates. Due to the elevated dissolved Fe(II) load in native groundwater at the subject site, kinetic rates may be higher than those reported here.
- 6.2.9 Due to the high permeability of the target aquifer, the favoured oxidant systems should ideally undergo relatively rapid decomposition kinetics in order that the oxidant delivers treatment within the affected source zone. Slower decomposition rates for oxidants such as persulphate, may lead to the oxidant by-passing the target aquifer compartment as residence times may be unsuitable.
- 6.2.10 Trial oxidant selection is based on the observed lithological characteristics of the target aquifer compartment, which showed little evidence of sorbed phase contaminant mass. This suggests that the majority of mass destruction should be possible through aqueous phase reactions and that the slower long term diffusion of oxidants into low permeability lithologies is not required or desirable at the subject site.
- 6.2.11 Optimum oxidant systems for the subject site are considered to be those displaying higher energy rapid kinetics, specifically peroxide or peroxide activated persulphate. Peroxide is considered for immediate source mass destruction through the delivery of high energy oxidation potentials. The high oxidation potentials created by peroxide will influence direct redox coupling and contaminant mineralisation, whilst also delivering relatively short lived free radical attack species in close proximity to the injection wells. This approach also includes peroxide activated persulphate as a dual oxidant system (Caros acid type) which, by reference to Table 6.1, demonstrated accelerated oxidant kinetics relative to persulphate alone.

6.3 2D Oxidant Travel and Decay Simulations

- 6.3.1 2D oxidant travel and decomposition has been modelled using the following analytical governing equation to visualise the radius of influence for peroxide and persulphate under the assumption of an isotropic aquifer system. These simulations assume 10 % dispersivity along the primary flow axis (α_x) and 1% dispersivity perpendicular to primary flow (α_y).
- 6.3.2 Simulations for the Rectifier and Compressor areas are based on site specific hydraulic conductivity data provided by Geo2 of 10 m/day and 180 m/day respectively. Modelling is based on the assumptions of an isotropic aquifer system comprising porous media with 40 % effective porosity. The simulations are based on an instantaneous mass injection as a line source at the injection well. Please note that these simulations have been undertaken to model absolute mass injections required to produce oxidant concentrations at distance (x,y), after (t) hours following injection.

6.3.3 For comparative purposes we present visualisation of oxidant travel at time (t) = 1, 6, 12, 24 for the Rectifier and, 1, 3, 6, 9 hours for the compressor area.

6.3.4 Rectifier area simulations are based on delivering a total oxidant mass equivalent to 1 pore volume of 5% peroxide or 5% persulphate over a 10 m Rol which equates to 160 kg.

$$c_s(x, y, t) = \frac{\Delta M}{4\pi n_e m \sqrt{\alpha_x \alpha_y} t} \exp\left(-\frac{(x - \bar{v}t/R)^2}{4\alpha_x \bar{v}t/R} - \frac{y^2}{4\alpha_y \bar{v}t/R}\right) \exp(-\lambda t)$$

Equation 1. Governing equation for 2D simulations.

6.3.5 Mixing zone depths are assumed to be constrained by rock head and hence provide a barrier preventing the vertical migration of groundwater contaminants. Under this site model we characterise drift deposits as the target aquifer with a maximum saturated thickness of 0.8m in the Rectifier area and 3.0m in the Compressor area.

6.3.6 Figures 6.1 & 6.2 presents Rol simulations for peroxide and peroxide activated persulphate injections in the Rectifier area, assuming an absolute mass injection of 160kg to achieve one pore volume of 5% oxidant, considering a target 10m Rol at 40% effective porosity(n_e).

6.3.7 These simulations are repeated for the higher groundwater conductance zone in the Compressor area, whilst maintaining all other parameters consistent with the Rectifier area simulations; $n_e = 0.4$, $\alpha_x = 2.5m$, $\alpha_y = 0.25m$, $R=1$ (no retardation) and Oxidant Mass =160 Kg. Although 1 pore volume at 5% would require 600 Kg of oxidant for the 3m mixing zone in this area. Preliminary simulations demonstrated that the higher injection mass is unlikely to be beneficial, as the target oxidant concentrations are achieved within the treatment zone by utilising a 160 kg injection. Note the influence of dispersion perpendicular to the flow pathway, which limits the extent of oxidant destruction in the y-axis.

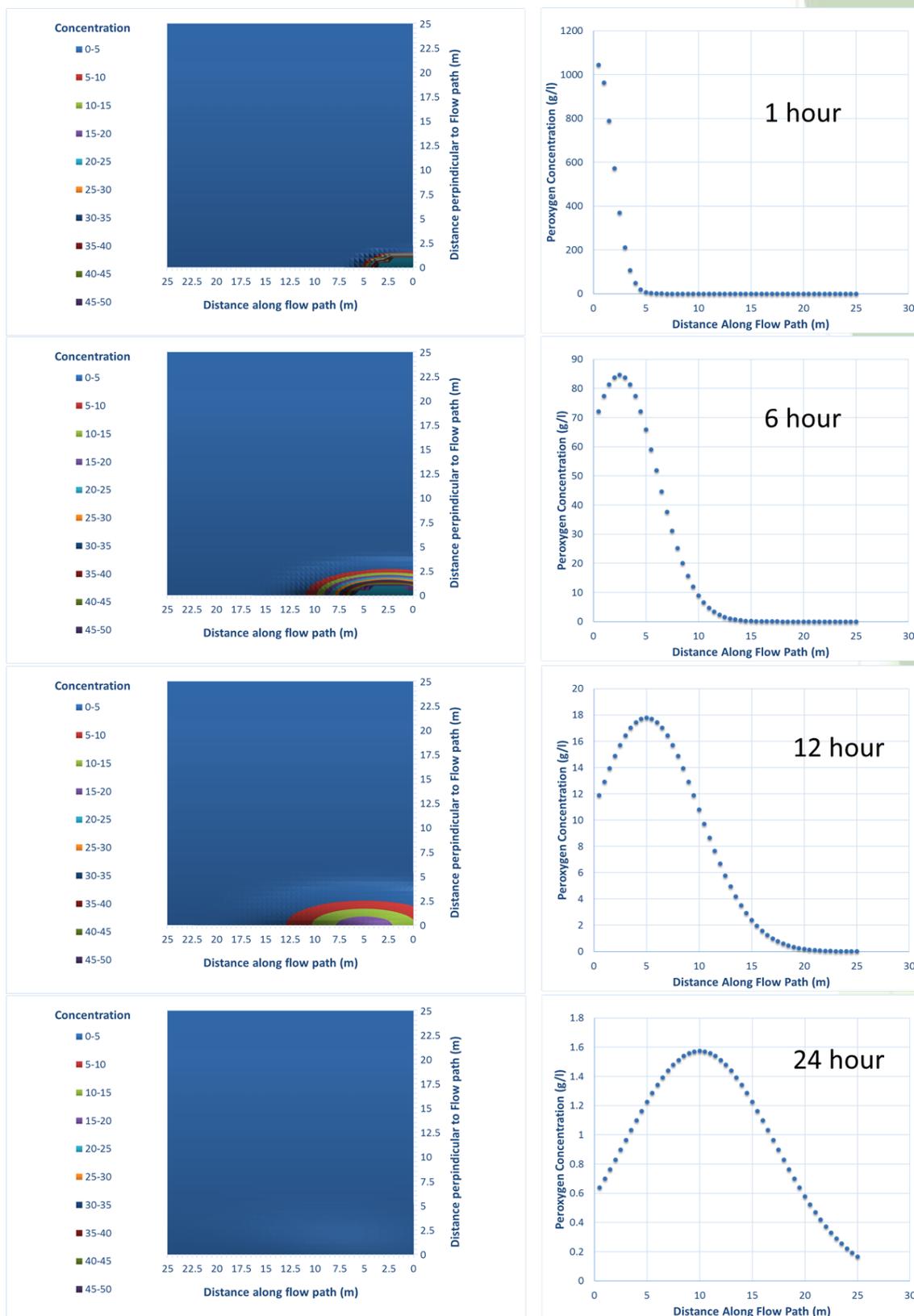


Figure 6.1 Radius of influence for peroxide injections (without activator) within the Rectifier area ($\lambda = 0.2$).

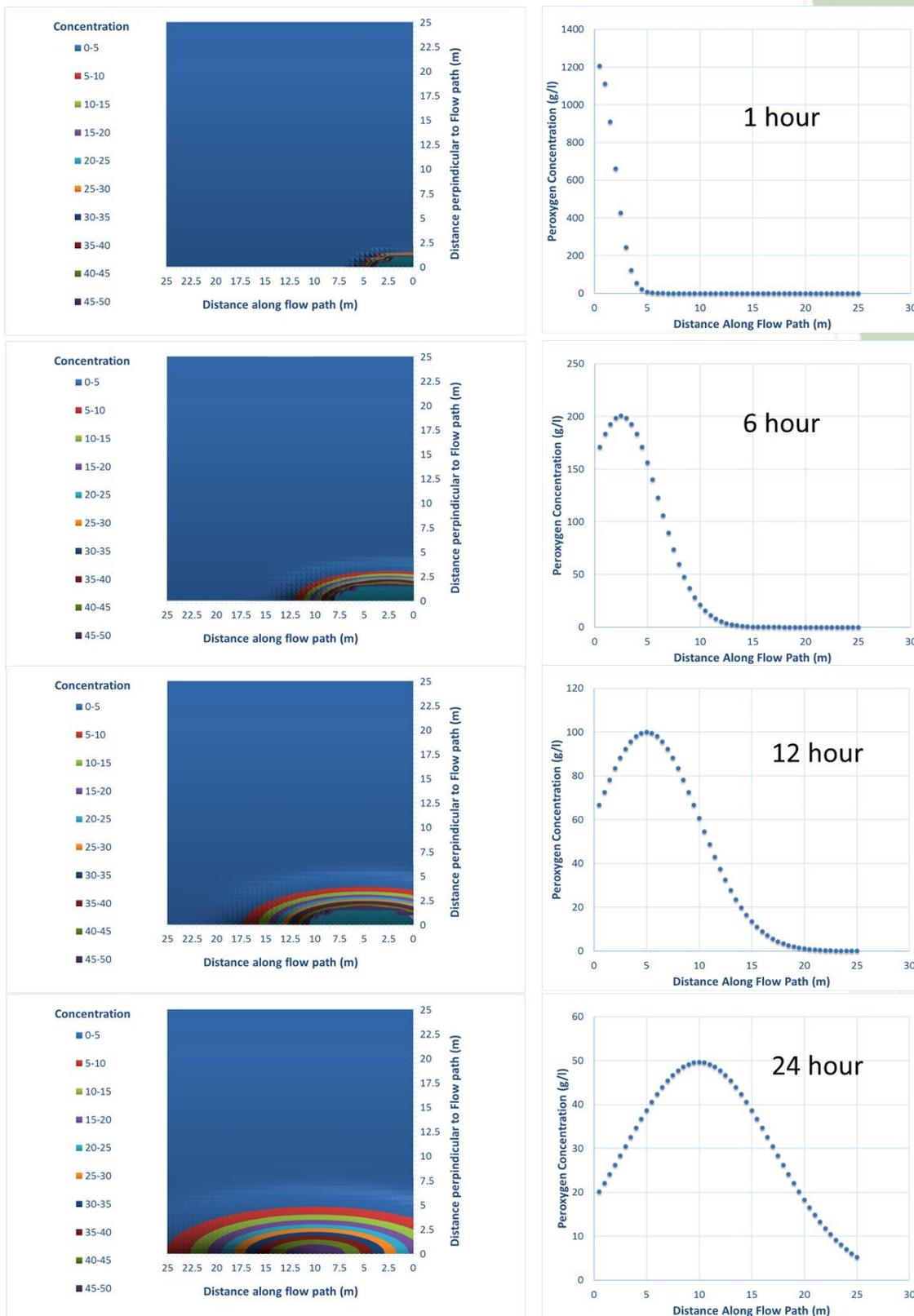


Figure 6.2 Radius of influence for peroxide activated persulphate injections within the Rectifier area ($\lambda = 52.5$).

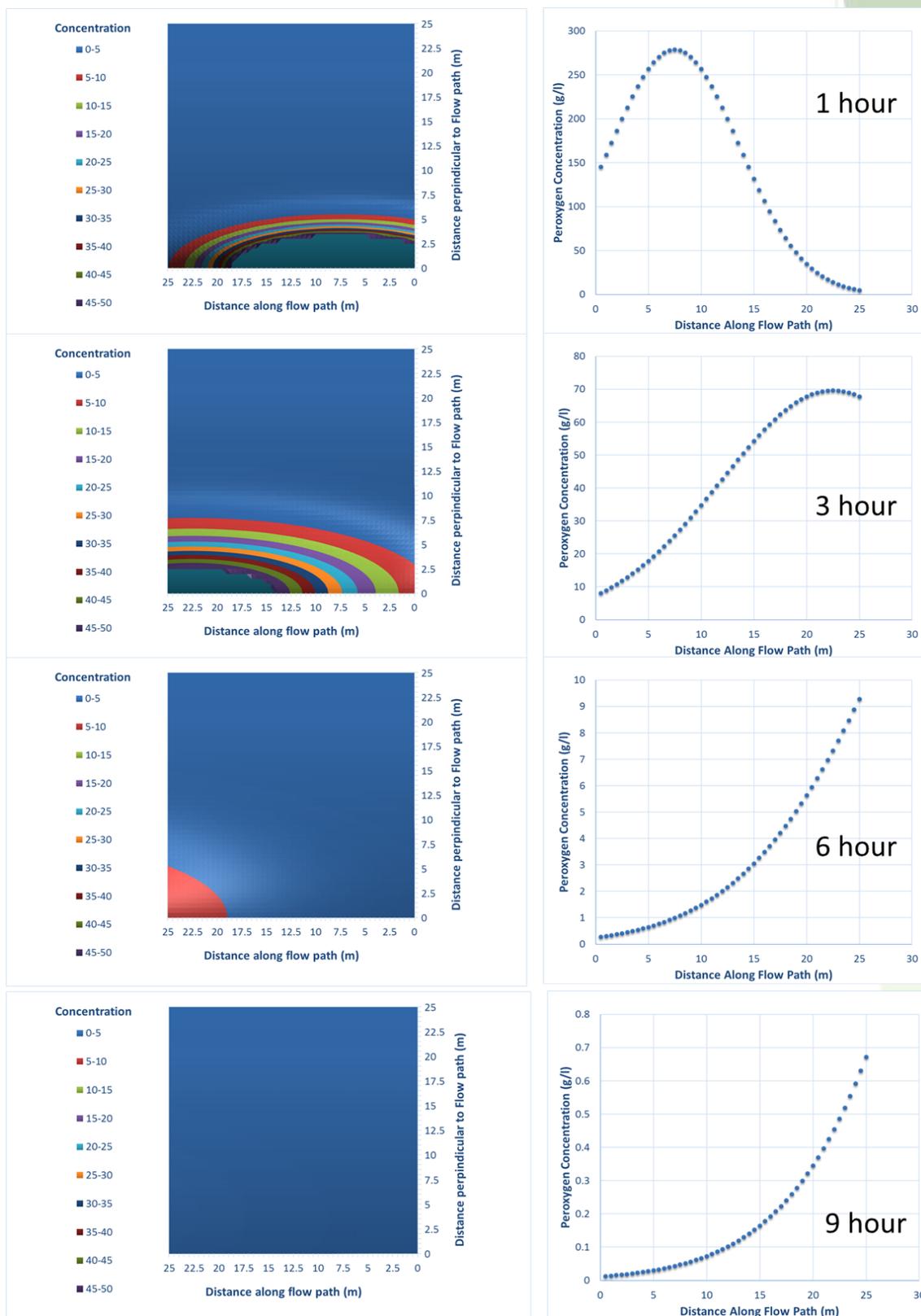


Figure 6.3 Radius of influence for peroxide injections (without activator) within the Compressor area ($\lambda = 0.2$).

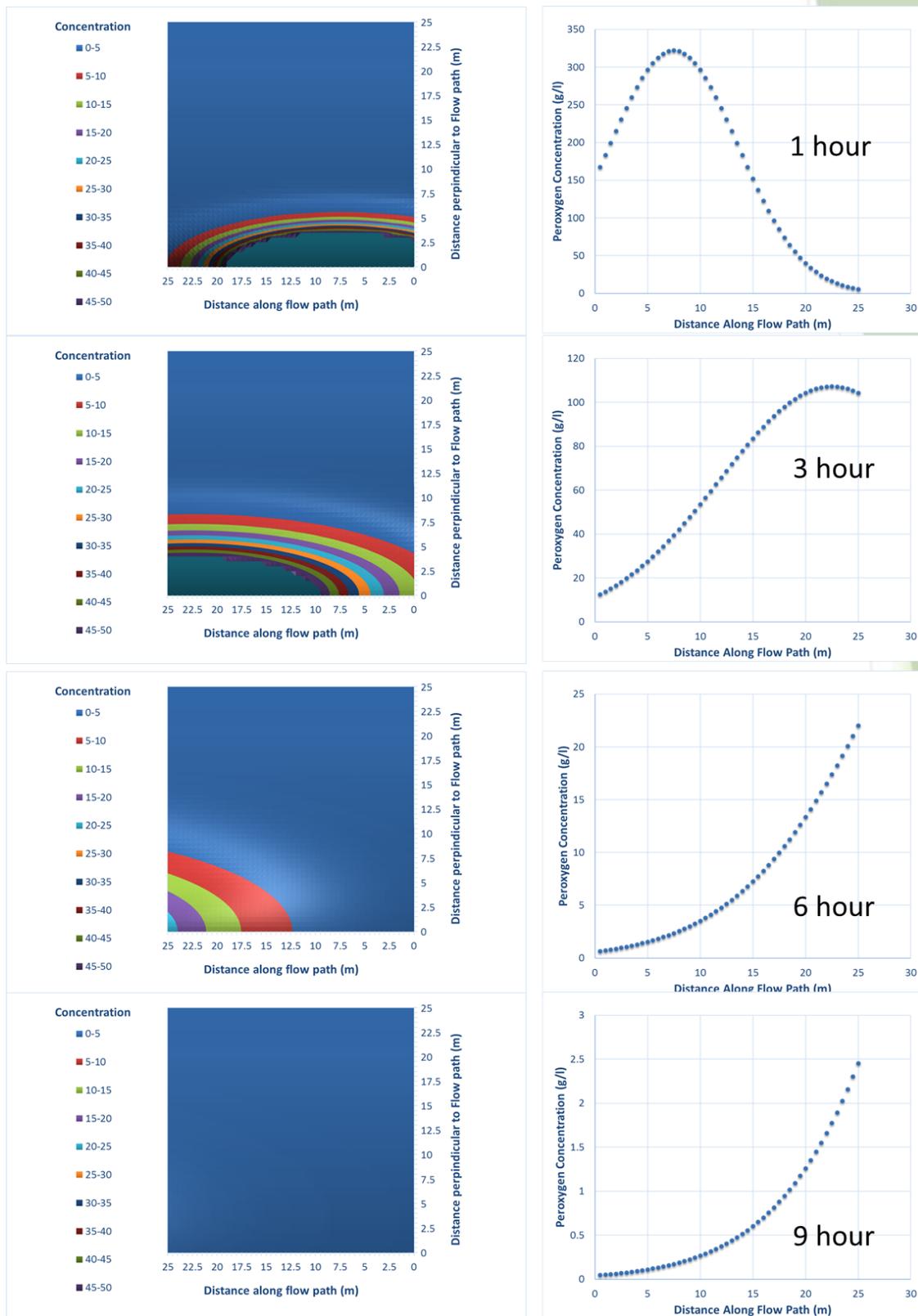


Figure 6.4 Radius of influence for peroxide activated persulphate injections within the Compressor area. ($\lambda = 52.5$).

- 6.3.8 As can be seen from comparison of simulated time slices, based on the experimentally derived half-lives, oxidant systems are expected to remain active within the target groundwater treatment zone of the Rectifier for up to 24 hours, with residence times dictated by decomposition rates rather than groundwater velocity.
- 6.3.9 Peroxyen residence times within the Compressor area however are likely to be dictated by groundwater flow velocity, allow up to circa. 6 hours contact time.
- 6.3.10 It is of interest to note that the radius of influence achieved by peroxide may be up to 45m at 6 hours following injection, whilst still achieving slightly in excess of 2% (22.52 g/l) groundwater peroxide concentrations.

7 Treatability Assessment

- 7.1.1 Treatability investigations are discussed below for the main contaminants of concern; 8-band TPH.
- 7.1.2 Please note that section 8 is dedicated to the interpretation of trace element mobility post chemical oxidation.
- 7.1.3 Details of chemox reactor systems are presented in Table 4.2
- 7.1.4 All experimental chemox reactor systems have been operated to provide bench marking, optimisation and validation for the trialled oxidant system's performance at the subject site. Chemox Reactors 2, 3, 4, 5, 6, 7 and 8 were trialled for persulphate, peroxide activated persulphate and peroxide chemistries on Garage/Compressor composite systems. Reactors 10, 11, 12, 13, 14, 15 and 16 were trialled for persulphate, peroxide activated persulphate and peroxide chemistries for Rectifier systems. Reactor 2 is a duplicate system of chemox reactor 3 and Reactor 10 is a duplicate system of chemox reactor 11. Reactors 1 and 9 act as controls for the Garage /Compressor and for the Rectifier areas respectively.

7.2 Contaminant Destruction

- 7.2.1 An interactive Excel™ workbook presenting contaminant destruction profiles is provided in Appendix B. Only data for the key contaminants previously identified in section 5 are discussed within this section.
- 7.2.2 Please note that dissolved phase sampling was undertaken by inserting a Teflon sampling tube below the surface to avoid any inadvertent inclusion of free phase TPH that may be present within the source groundwater.
- 7.2.3 Although no visual identification of a discrete free phase NAPL was identified during these investigations, a hydrophobic coating of the sampling tube was noted during removal of samples, indicating some NAPL may be present within the groundwater / aquifer slurry matrix.
- 7.2.4 Results are discussed below for each TPH fraction, with an assessment of performance for each of the candidate chemical oxidation systems under investigation for each of the target aquifer types. It should be noted that contaminant destruction in both aquifer systems showed similar responses to specific oxidation systems. We conclude that for the purpose of future ISCO design, both aquifer groundwater systems may be considered under a single groundwater treatment strategy with respect to the selected oxidant.
- 7.2.5 As with the interpretation of any time-variant geochemical process, it must be recognised that analytical datasets from chemical oxidation studies represent a “snap-shot” of transient system conditions at a single point in time. In particular, the influence of chemical oxidation reagents may encourage desorption of target compounds from the test matrix, including the diffusion controlled release of organic contaminants from high surface area substrates such as clays or, particularly in this case, may influence free phase dissolution kinetics.

- 7.2.6 Dissolved phase rebound can occur during chemical oxidation treatment, especially in high surface area (high sorbed mass) matrices or where components occur as a free phase product. This is due to the competing effects of mass transfer (desorption / dissolution) and chemical destruction in the dissolved phase. These processes are most conveniently conceptualised as forward and reverse kinetic reactions. At low oxidant mass, rebound is observed when the forward reaction controlling contaminant destruction in the dissolved phase (chemical oxidation), is exceeded by the rate of production from desorption or dissolution (increasing dissolved mass).
- 7.2.7 Where contaminant mass is present in the sorbed phase, these competing processes are often observed as an initial reduction in dissolved phase mass whilst peroxygen concentrations within the system exceed the required activation energy for target contaminant mass destruction. As reaction times proceed however, peroxygen concentrations become depleted through both direct redox coupling and natural decomposition reactions, and the chemical oxidation potential of the systems declines. Rebound is hence observed as the effects of cumulative contaminant mass transfer into the dissolved phase overcome the systems chemical oxidation capacity (system run-down) over extended time frames.
- 7.2.8 Where contaminants may be present as in a separate non-aqueous phase liquid (NAPL), the influence on dissolved phase mass will be a function of dissolution kinetics, whereby a reduction in dissolved phase mass would only be observed when the rate of contaminant destruction exceeds the rate of NAPL dissolution. A sustained plateau in dissolved phase mass following complete oxidant utilisation would tend to indicate complete dissolution of free phase mass.
- 7.2.9 The Total Oxidant Requirement (TOR) for Chemox Reactors (CR) was calculated from the Matrix Oxidant Demand (MOD) discussed in section 6, plus the Stoichiometric Oxidant Demand (SOD) calculated from redox coupling equations for complete mineralisation of Diesel Range Organics (DRO) based on a stoichiometric co-factor of 50.015 for persulphate. It must be noted that oxidant mass is based on observed dissolved and sorbed phase mass only, as NAPL was not quantified during the source term characterisation.
- 7.2.10 As per Table 4.2, reactors for all persulphate trials were operated at TOR or TOR x2, whilst peroxide reactors were operated at 2% and 5%.

7.3 C5-C8 TPH

- 7.3.1 Only a single detection was reported within the C7-C8 band for CR13 at 672 hours (48 µg/l). It is noteworthy that this reactor showed complete consumption of oxidant (peroxide activated persulphate at TOR) following 24 hours, hence we tentatively ascribe the appearance of C7-C8 TPH over extended time points to free phase dissolution / matrix desorption phenomena in the absence of adequate oxidant mass that may have otherwise maintained TPH mass below the analytical limits of detection.

7.4 C8-C10 TPH

- 7.4.1 All reactors show an initial spiking in dissolved phase C8-C10 TPH. This may relate to the production of lower molecular weight hydrocarbons from the cleavage of larger TPH molecules, or may be as a result of free phase dissolution. Both of these processes are indistinguishable, when interpretations are based on macroscopic observations relating to changes in dissolved phase concentrations.
- 7.4.2 As can be seen from inspection of Figure 7.1, peroxide systems demonstrate rapid and complete destruction of C8-C10 TPH compounds in the Rectifier area (R), whereas the initial increase in dissolved phase mass for Garage / Compressor (GC) peroxide systems was not observed. We assume this may be due to the complete destruction of this determinand prior to the first 3 hour sampling point, or limited non-aqueous phase source.
- 7.4.3 Later stage rebounding of dissolved phase concentrations is observed at time (t) = 672 hours for both persulphate and peroxide activated persulphate systems trialled for the GC area, which based on the initial source characterisation datasets contained no sorbed phase contamination. This later stage increase in dissolved phase C8-C10 is considered likely to be due to dissolution of free phase NAPL acting as a TPH pool, becoming evident over time as the dissolved phase concentration exceeds the oxidant activity. From the available peroxide treatability datasets, it is assumed that peroxide has effectively removed any free phase source.
- 7.4.4 Area R shows no evidence of dissolved phase rebound for C8-10.
- 7.4.5 Peroxide activated persulphate and peroxide ISCO formulations are observed to provide the greatest treatment efficacy against dissolved phase C8-C10 TPH.

7.5 C10-C12 TPH

- 7.5.1 All candidate ISCO systems demonstrated satisfactory performance over the time course of this chemical oxidation study for Area R, which showed the anticipated trend in destruction kinetics from fastest to slowest: peroxide>peroxide activated persulphate>>persulphate.
- 7.5.2 Duplicate reactors CR10 and CR11 show good agreement in dissolved contaminant concentrations, suggesting reasonable reproducibility. In addition, as may be expected, contaminant destruction profiles show oxidant mass dependant rates for C10-C12 TPH mineralisation.
- 7.5.3 As with C8-C10 fractions, no rebound in dissolved phase contaminant mass was identified for Area R.
- 7.5.4 Contaminant destruction profiles for Area GC suggest near complete mineralisation of C10-C12 for peroxide systems, again supporting the notion of oxidant concentration dependant rates of treatments. Again, there is strong evidence for peroxide induced NAPL dissolution with a notable spiking in dissolved phase concentrations at t=6 hours.

- 7.5.5 Both persulphate based oxidant systems show evidence for possible groundwater dissolved phase rebound over extended time periods, particularly at the lower TOR application rate.
- 7.5.6 Peroxide based oxidant systems are identified as providing superior performance over persulphate systems for both source areas, with evidence from CR7, 8, 15 and 16 providing indirect evidence for enhanced NAPL dissolution and subsequent C10-12 TPH destruction in the aqueous phase.

7.6 C12-C16 TPH

- 7.6.1 Significant liberation of C12-C16 mass was observed in Area GC peroxide reactors, generating 5,800 µg/l dissolved phase concentrations for the 5% peroxide treatment. As previously discussed, we infer from the matrix characterisation datasets that aqueous TPH concentrations are generated through NAPL dissolution rather than matrix desorption. There was no observable increase in dissolved phase C12-C16 TPH from Area R peroxide reactors.
- 7.6.2 Peroxide activated persulphate systems were seen to out-perform persulphate only treatments, with no rebounding effects identified for Area R in either system. Good reproducibility was seen again between duplicates, with ISCO chemistries again showing an oxidant concentration dependant response in residual dissolved phase contaminant mass over time.
- 7.6.3 Both Area GC persulphate based chemox systems demonstrated later stage rebound in dissolved phase C12-C16 components, consistent with observations from C10-C12 and C8-C10 TPH analysis.
- 7.6.4 Both peroxide activated persulphate and peroxide treatments produced similar treatment efficacies for C12-C16, out-performing systems that employed just persulphate for Area R, however peroxide provided superior performance in Area GC reactors.

7.7 C16-C21 & C21-C35 TPH

- 7.7.1 Changes in dissolved phase C16-C21 and C21-C35 fractions are discussed together given their similar response to oxidants over the time course of the chemox study discussed herein.
- 7.7.2 As can be observed from inspection of Figures 7.4 and 7.5, persulphate systems for Area R and GC show an initial drop in dissolved phases TPH concentrations for the C16-C35 band, followed by a plateauing or gradual increase.

A similar response is seen for peroxide activate persulphate systems, however the magnitude of dissolved phase rebound is notably higher for Area GC.

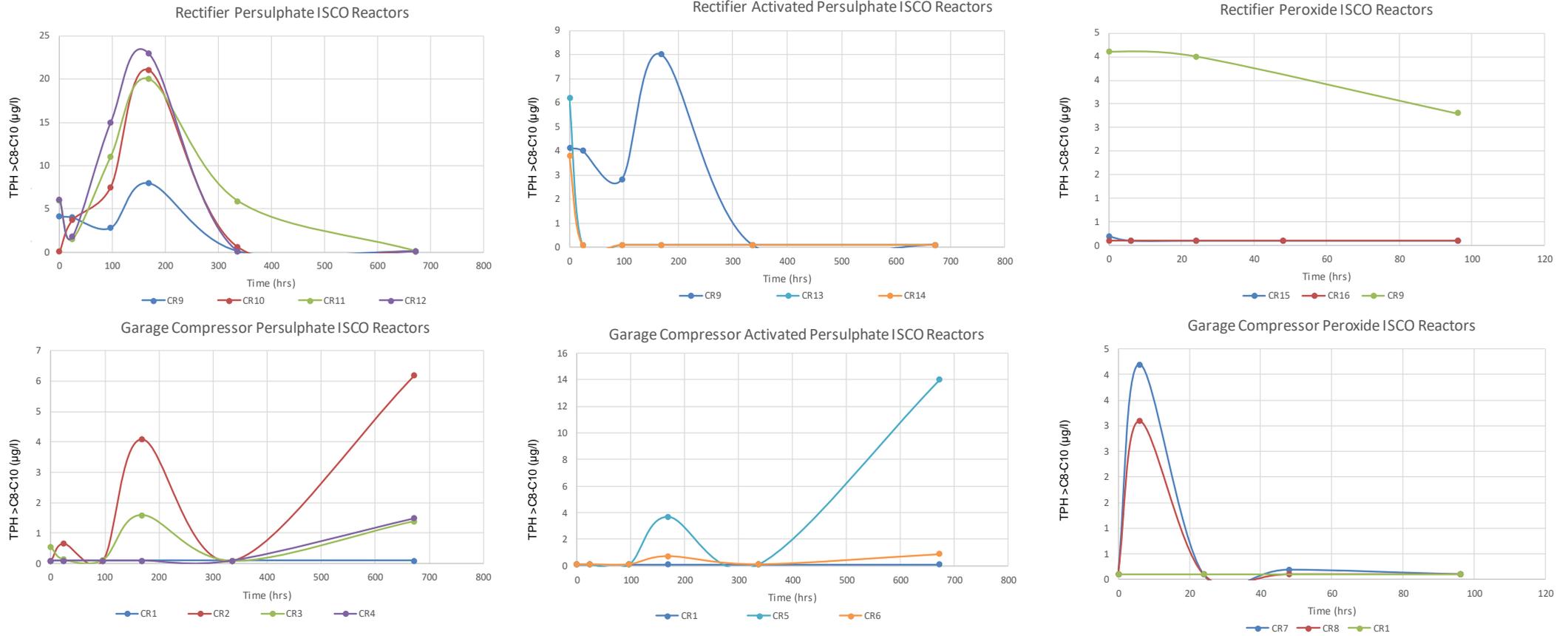


Figure 7.1 C8-C10 TPH dissolved phase concentrations during chemical oxidation studies. Note different sampling times employed for peroxide and persulphate systems.

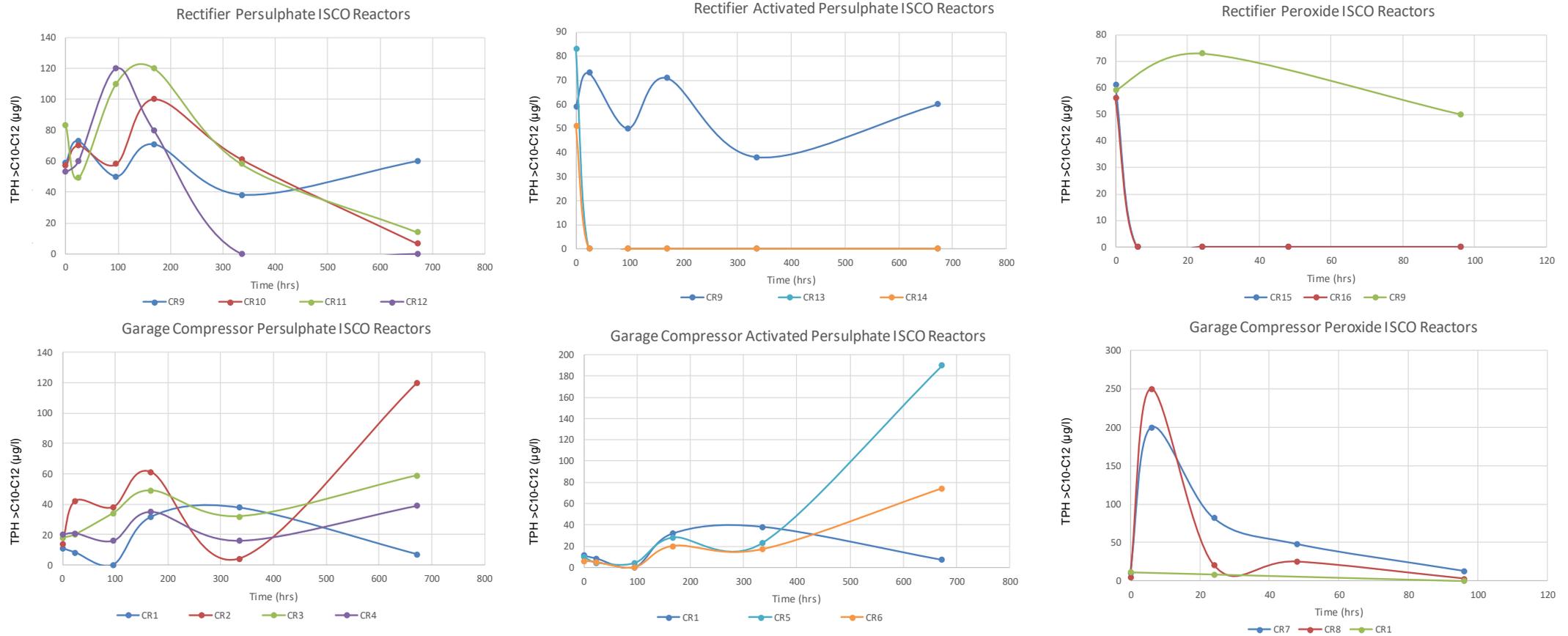


Figure 7.2 C10-C12 TPH dissolved phase concentrations during chemical oxidation studies. Note different sampling times employed for peroxide and persulphate systems.

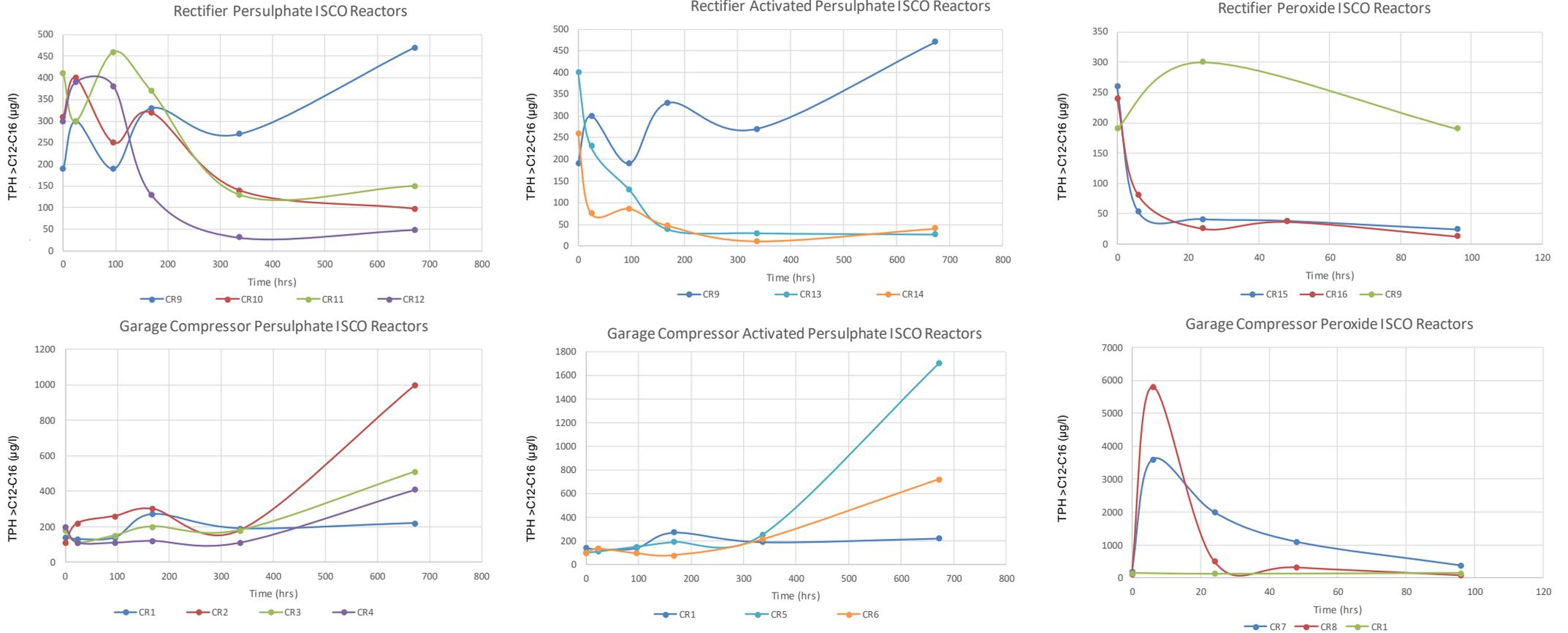


Figure 7.3 C12-C16 TPH dissolved phase concentrations during chemical oxidation studies. Note different sampling times employed for peroxide and persulphate systems.

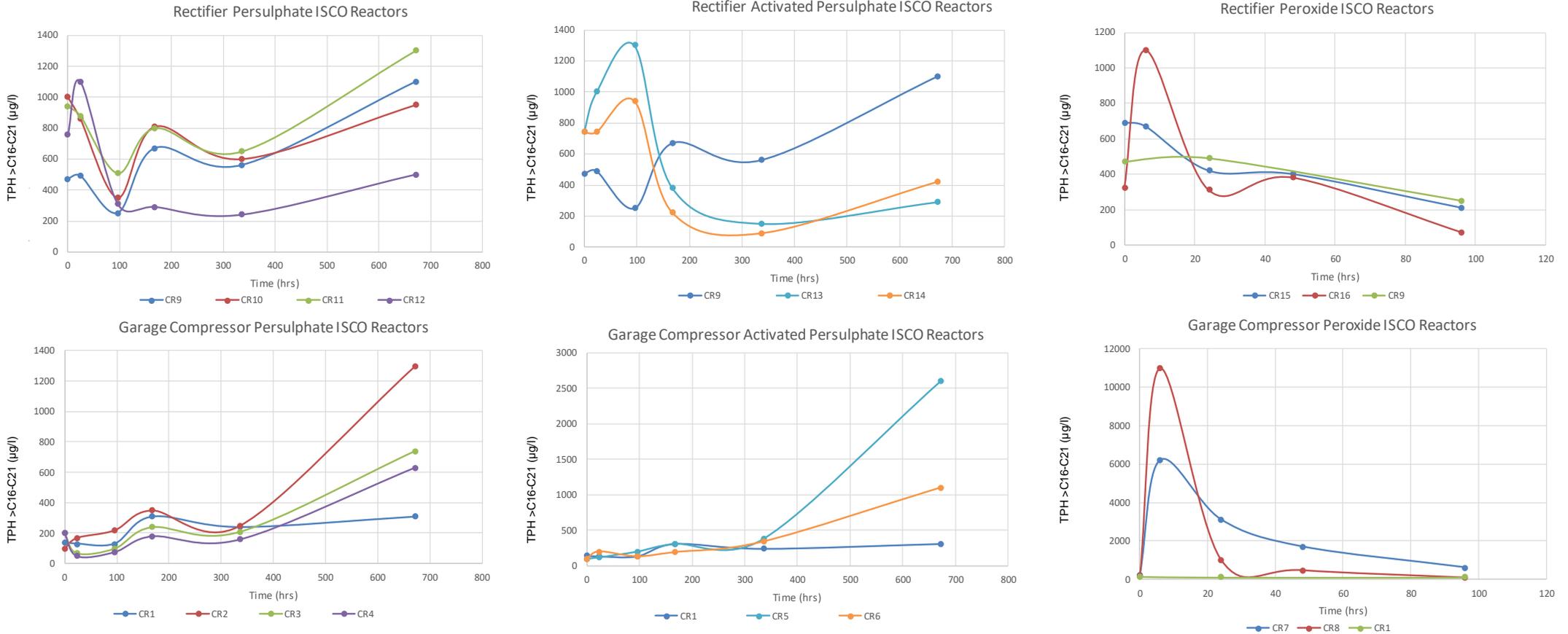


Figure 7.4 C16-C21 TPH dissolved phase concentrations during chemical oxidation studies. Note different sampling times employed for peroxide and persulphate systems

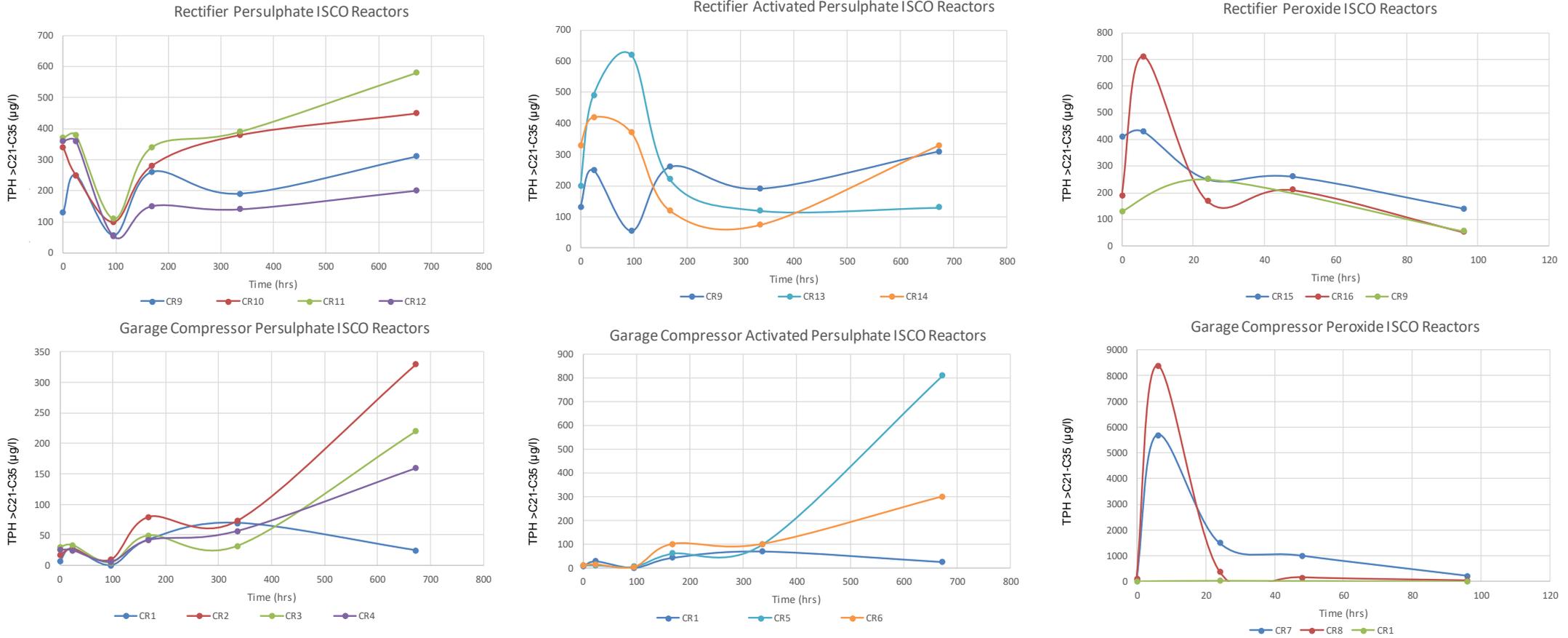


Figure 7.5 C21-C35 TPH dissolved phase concentrations during chemical oxidation studies. Note different sampling times employed for peroxide and persulphate systems.

- 7.7.3 Peroxide systems show the previously described early increase in dissolved phase C16-C35 TPH, which is possibly associated with oxidant mediated NAPL dissolution in Area GC, followed by a sustained reduction in aqueous concentrations. Peroxide systems demonstrate good remedial efficacy over the initial 24 hours, consistent with the high decomposition kinetics of peroxide, followed by lower rates of TPH destruction and oxidant mass becomes depleted.
- 7.7.4 Based on the available datasets generated from this chemical oxidation study, peroxide appears to provide the greatest treatment efficacy for C16-C35 TPH compounds, suggesting this oxidant may also be actively enhancing free phase dissolution, enabling destruction to proceed via direct redox coupling and / or free radical attack in the dissolved phase.

7.8 Residual Sorbed Phase Mass

- 7.8.1 Certificates of analysis for residual sorbed phase mass are presented in Appendix A.
- 7.8.2 Initial source characterisation datasets revealed that test work aquifer matrix composites for the Garage / Compressor (GC) area contained no detectable levels of TPH, whereas the Rectifier (R) area matrix contained only C12-C35 fractions, with a total TPH concentration of 450 mg/kg.
- 7.8.3 Consistent with initial source characterisation datasets, no TPH compounds were detected above analytical detection limits in any of the matrix samples recovered from chemox reactors at the final time point for any of the GC systems investigated.
- 7.8.4 Low residual TPH source mass (C12-C35) was detected in all persulphate based chemox reactors except CR12 (persulphate @ 2 x TOR). No residual TPH was detected in any of the peroxide treatment systems for area G.

7.9 Chemical Oxidation Performance Summary

- 7.9.1 Due to the observed influence of candidate peroxygenic compounds on desorption / dissolution of sorbed or free phase TPH mass, direct quantification of performance ranking has not been possible for this study.
- 7.9.2 Qualitatively, if we consider the trajectories for dissolved phase TPH fractions, peroxide based systems clearly demonstrate the highest rate of contaminant mass destruction.
- 7.9.3 In addition, the strongest oxidant studied in these investigations, peroxide, also appears to have facilitated rapid and complete NAPL dissolution with no evidence for dissolved phase rebound. The action of peroxide, leads to an initial rise in dissolved phase TPH, followed by sustained degradation in the dissolved phase.
- 7.9.4 All persulphate based systems appear to result in slower dissolution / desorption of TPH in the systems tested, leading to increasing dissolved phase TPH over time as the oxidant pool becomes depleted. This phenomena suggests that if deployed at the subject site,

persulphate based ISCO strategies may lead to longer term rebounding of groundwater TPH concentrations

8 Trace Element Leaching Assessment

- 8.1.1 The potential for trace metal mobilisation following ISCO applications has been assessed through the analysis of residual groundwater samples for persulphate chemox systems at t=672 hours and peroxide chemox systems at t=96 under final equilibrium Eh and pH conditions.
- 8.1.2 As would typically be anticipated, trace metals (Cu, Cd, Cr, Ni and Zn) show enhanced solubility at low pH. We would generally ascribe this trace metal solubility in acidic conditions to be related to dissolution and desorption from the aquifer matrix materials. This particularly effects peroxide activated persulphate systems, which produce extremely acidic groundwater conditions, as low as pH 1.4 in the rectifier area reactors at 2 x TOR.
- 8.1.3 Neither peroxide or persulphate single oxidant systems produced significant changes to the native pH. Complete decomposition of peroxide leads to the generation of water and molecular oxygen as terminal end products, whereas persulphate results in significantly elevated levels of residual dissolved sulphate. This is apparent from EC data which shows peroxide treatments remained circum-neutral with EC of circa 600-700 μS , not dissimilar to pre-treatment conditions.
- 8.1.4 Elevated Fe and Mn concentrations are also reported for all peroxide activated persulphate reactors trialled. The increase in Fe and Mn solubility observed for both aquifer matrices in contact with low and high persulphate loadings is likely due to the associated reduction in pH causing matrix dissolution of Mn (and Fe) from accessory aquifer mineral phases.
- 8.1.5 Trace metal datasets are presented in Tables 8.1 for area R and area GC chemox reactor systems.
- 8.1.6 As discussed above, high residual sulphate loadings are to be anticipated for all persulphate systems under investigation.
- 8.1.7 We strongly recommend that should peroxide ISCO systems should be considered optimum for deployment at the subject site. From the datasets generated in this study, peroxide based ISCO should not require any post treatment rehabilitation of groundwater to re-adjust pH or amend high sulphate loading.

Determinand	Units	LOD	Garage Compressor								Rectifier							
			Control	PS@TOR	PS@TOR	PS@2xTOR	APS@TOR	APS@2xTOR	2% PO	5% PO	Control	PS@TOR	PS@TOR	PS@2xTOR	APS@TOR	APS@2xTOR	2% PO	5% PO
			CR1	CR2	CR3	CR4	CR5	CR6	CR7	CR8	CR9	CR10	CR11	CR12	CR13	CR14	CR15	CR16
pH			7.41	7.309	7.325	7.173	2.879	1.809	7.398	7.534	7.132	6.09	6.15	3.865	1.71	1.44	6.977	7.23
Eh	mV		281.8	486.4	514.6	522.2	370.7	658.9	215.2	209.3	304.9	566.7	559.8	661.1	381.7	812.9	232.5	217.5
EC	mS		0.7	4.499	4.468	7.909	15.87	35.56	0.64	0.64	0.64	12.15	12.26	22.22	32.41	58.9	0.57	0.55
Oxidant	g/l	0.01	0	3.78	3.77	7.83	0.01	1.08	0.637	0.325	0.01	13	13.2	27.3	0.17	18.44	0.802	1.254
Calcium	mg/l	5.0	76	180	170	250	520	610	110	74	95	290	310	390	500	630	110	110
Sodium	mg/l	0.50	54	800	770	1600	3400	8600	130	75	53	2700	2700	4800	5800	100000	15	15
Arsenic (Dissolved)	µg/l	1.0	910	28	8.1	10	17	220	3	2.9	12	2.9	130	1.2	150	240	1.8	1.8
Boron (Dissolved)	µg/l	20	170	120	120	120	150	1400	110	99	53	45	3500	23	23	27	42	37
Cadmium (Dissolved)	µg/l	0.080	0.08	0.08	0.08	0.08	8.4	42	0.08	0.08	0.77	0.14	5.9	0.72	9.9	7.3	0.28	0.2
Chromium (Dissolved)	µg/l	1.0	1.3	12	10	17	320	1100	40	51	35	9.9	760	1.3	830	1100	18	31
Copper (Dissolved)	µg/l	1.0	2	11	14	24	2300	4100	32	27	110	77	4500	260	4700	5600	120	77
Mercury (Dissolved)	µg/l	0.50	0.5	0.5	0.55	0.99	0.66	31	0.58	0.5	0.5	2.9	72	7.1	2.8	1.2	0.5	0.5
Manganese (Dissolved)	µg/l	1.0	1100	26	3	1.5	36000	42000	1100	670	4200	140	690	200	34000	38000	4000	3000
Molybdenum (Dissolved)	µg/l	1.0	13	6.6	6.7	6.9	1	68	13	12	6.9	1.4	90	1	1.4	4.7	11	14
Nickel (Dissolved)	µg/l	1.0	2.3	1.6	1.2	1.6	420	1400	4.3	2.8	56	5.4	220	14	1100	1400	12	8.3
Lead (Dissolved)	µg/l	1.0	1	1	1	1	57	270	1	1	6.2	7	2.5	1	370	310	1	1
Selenium (Dissolved)	µg/l	1.0	4.6	5.3	5.3	7	26	150	7.7	7.5	5	21	1500	22	15	1	16	16
Vanadium (Dissolved)	µg/l	1.0	3.5	3.1	3.1	3.2	210	440	98	100	16	1.4	140	1	780	590	91	100
Zinc (Dissolved)	µg/l	1.0	9.8	55	63	110	2200	4200	5.6	4.1	130	240	19000	570	4000	4200	14	5.4
Iron (Total)	µg/l	20	310	530	520	760	190000	910000	200	180	13000	740	69000	320	6000000	770000	300	280

Table 8.1 Trace element mobilisation in chemox reactors at t= 672 hours for persulphate reactors and t=96 hours for peroxide reactors.

9 Conclusions & Recommendations

- 9.1.1 The information and interpretations presented in this report are provided to support the assessment of In Situ Chemical Oxidation (ISCO) as a viable groundwater treatment technology for the destruction of target contaminants discussed in section 7.
- 9.1.2 The candidate chemical oxidation systems trialled have allowed assessment of oxidant kinetics, derivation of half-lives and the estimation of Matrix Oxidant Demand (MOD). In addition, treatability level investigations have been used to establish the efficacy of treatment systems for contaminant destruction.
- 9.1.3 Through the assessment of target contaminant destruction profiles and oxidant depletion rates, CE Geochem conclude that peroxide based chemox systems provide the greatest level of contaminant destruction, and are expected to exhibit efficient delivery of reactive oxidant mass into the high groundwater flow velocity source zone.
- 9.1.4 Persulphate chemistries showed relatively poor treatment efficacies in general at both low and high-range application rates. We ascribe this to the milder oxidising potential of the persulphate ion relative to the peroxy species. The generation of acidic groundwater conditions by peroxide activate persulphate would also limit the applicability of this technique at the subject site due to the observed magnitude of trace metal release.
- 9.1.5 Taking into consideration the relatively high hydraulic conductivities of superficial drift deposits at the subject site, and the nature of the key remedial drivers, considered to be TPH, we recommend that 2% peroxide be considered as an optimum solution (cost v performance) for ISCO at the subject site. As observed in treatability trials, oxidant induced NAPL dissolution is likely to be observed in the target aquifer during early stages of treatment, however treatability datasets support significant mass reduction of dissolved phase TPH over the time course of 96 hours.
- 9.1.6 CE Geochem strongly recommend that the ISCO injection strategy is based on step-wise applications to achieve 2% peroxide within the target groundwater compartment. The use of sequential injection protocols should allow oxidant delivery to be optimised for the most heavily impacted aquifer compartment through monitoring of residual dissolved phase TPH. Based on the results of this study, peroxide is considered capable of treating residual NAPL sources through enhanced dissolution followed by dissolved phase destruction.
- 9.1.7 Field injection trials should be undertaken prior to full scale injection works to confirm that equivalent subsurface peroxygen travel and reactivity can be achieved as demonstrated during these trials.

Appendix A *Certificates of Analysis*

Appendix B *Data Interpretations*

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