# Appendix M: Chapter 7 Supporting Information

## M.1 Remediation Option Treatment Design

*Monitored Natural Attenuation (MNA)*

No additional site infrastructure planning is required to start the MNA option as it is already in place. The treatment design requires agreement on the frequency of sampling in the first year and subsequent years (four and one respectively). The treatment duration range is specified in consultant reports and is dependent on the degradation rates of MtBE within the channel sands and chalk aquifer.

*Electrokinetic Bioremediation (EK-BIO)*

The main assumptions of the electron balance model include:

* Contaminants and the relevant actively degrading microorganisms are distributed uniformly through the model domain and at their highest observed concentrations.
* The electromigration of nitrate and values for power consumption are derived using equations from the literature (Table M.2). Nitrate will migrate into the sediment from the cathode chamber.
* The model domain is designed to represent the physical heterogeneity observed within the channel sands, i.e. clay lenses interspersed within high-K host material. It consists of three layers of high-, low- and high-K material (Figure M.1). The surface area is assumed to be rectangular to simplify the model.
* Upon addition of nitrate (electron acceptor) the reaction with the organic contaminants (electron donors) is assumed to be instantaneous, hence, the effect of bioavailability is not considered in this model.
* The total dissolved contaminant mass targeted for remediation is based on the maximum observed concentration and is equivalent to a mass of 630 kg which is consistent with site reports.
* EK-BIO treatment will be split into 3 phases to better manage logistics (Figure M.1). The total number of electrode wells that need to be drilled is 35, with 24 monitoring wells located between the different rows or electrodes.
* pH changes at the electrodes are controlled by anolyte and catholyte fluid recirculation and managed by continuous operation of 3 pumps, simultaneously supplying amendment and mixing electrode fluids (Figure M.2).
* The voltage gradient between electrodes is 50 V m-1 and assumed to drop 60% to 20 V m-1 at the cathode/sediment interface. This phenomena will prolong the influx of amendment into the sediment and is noted by different authors (Gill et al., 2015; Wu et al., 2012)
* The reservoir tank is topped up weekly with the amendment, sodium nitrate, to maintain a nitrate flux into the sediment. The reservoir tank dosing interval is weekly to coincide with the site visit.
* Overall treatment time is the time required to add sufficient mass of electron acceptors and time required for the amendment to migrate between the electrodes.
* Both the AS/SVE and PT treatments include a contamination rebound event to prolonged treatment, resulting from contaminant back-diffusion out of the low hydraulic conductivity zones. This is not included in the EK treatment because the principle mechanisms target these zones and thus prevent a rebound above acceptable levels.

The duration range for the EK-BIO treatment is represented by the uncertainty associated with subsurface material electromigration properties. Specifically, the low-hydraulic conductivity material will be the rate limiting material for nitrate migration because transport is generally lower compared to high-K materials due to the effect of electroosmosis and potentially, reduced effective ionic mobility values. A range of electromigration properties for low-K materials with different hydraulic conductivities, presented in Gill et al. (2015), have been applied to the electron balance model (Table M.3).

|  |
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|  |
| Figure M.1. Electron balance model domain showing EK-BIO treatment area. Light colour indicates high-K and dark colour indicates low-K aquifer material. |

|  |
| --- |
|  |
| Figure M.2. Schematic diagram of the recirculation system used in the EK-BIO treatment. |

Table M.1 Redox half reactions used to calculate electron balance model.

|  |
| --- |
| **Electron donating reactions**  Benzene:  Toluene:  Ethylbenzene:  Xylene:  MtBE: |
| **Electron accepting reactions**  Dissolved oxygen:  Dissolved nitrate:  Dissolved sulphate: |

Table M.2. Equations used in EK-BIO electron balance model.

|  |  |  |
| --- | --- | --- |
| **Equation** | **Inputs / outputs** | **Reference and notes** |
| One dimensional solute mass flux (kg/m2/s): | Ji = One dimensional solute mass flux (kg/m2/s)  Ci = concentration of solute, I (kg/m3)  ui\* = effective ionic mobility (m2/V/s)  ke = electroosmotic permeability (m2/V/s)  dE = change in voltage (V)  dx= change in distance (m) | Acar and Alshawabkeh (1993).  Used to calculate the mass flux of nitrate and sodium into the sediment. |
| Effective electrical conductivity | σ\*= effective electrical conductivity (S/m)  F = Faraday constant (C/mol)  z = ion valence | Alshawabkeh and Acar (1996).  Used to calculate σ\*as a function of ions migrated into the sediment |
| Current density | I = current density (A/m2) | Ohms law  Used to calculate I as a function of changing σ\* |
| Energy expenditure | W = energy expenditure (J/m3)  I = current density (A/m2)  t = time (s)  L = distance between electrodes (m) | Alshawabkeh et al. (1999).  Used to calculate energy expenditure over certain duration |
| Power consumption | P = power (kWh)  v = volume (m3)  k = conversion factor Joules to kWh, 2.78x10-7 | Used to calculate the amount of power expended |
| Treatment time | See above | Alshawabkeh et al. (1999). |

Table M.3. Input values for EK-BIO treatment duration.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Value** | **Unit** | **Minimum duration time estimate** | | **Middle duration time estimate** | | **Maximum duration time estimate** | |
| **High K** | **Low K** | **High K** | **Low K** | **High K** | **Low K** |
| Hydraulic conductivity | m s-1 | 1.5x10-5 | 1.6x10-6 | 1.5x10-5 | 1.2x10-7 | 1.5x10-5 | 4.5x10-9 |
| Porosity | - | 0.37 | 0.29 | 0.37 | 0.34 | 0.37 | 0.41 |
| Tortuosity | - | 0.55 | 0.47 | 0.55 | 0.3 | 0.55 | 0.22 |
| Effective ionic mobility | m2/d/V | 1.3x10-3 | 8.8x10-4 | 1.3x10-3 | 6.6 x10-4 | 1.3x10-3 | 5.8 x10-4 |
| Electroosmotic permeability | m2/d/V | 1.0x10-4 | 1.0x10-4 | 1.0x10-4 | 2.3x10-4 | 1.0x10-4 | 2.3x10-4 |

*Air Sparge / Soil Vapour Extraction*

The assumptions associated with the AS/SVE treatment include:

* The same domain dimensions as used for the EK-BIO electron balance model, with the low hydraulic conductivity layer excluded to simplify the treatment. Also, the contaminant mass is the same as in the EK-BIO electron balance model.
* Treatment duration is a function of the attenuation rate derived from the consultant reports (Table M.4). The range of attenuation rates in the reports reflects the range of treatment duration (Table M.5).
* The treatment area was divided into two sections (720 m2 each) and treated sequentially. This was in order to allow better management and tuning of air sparge wells.
* The radius of influence for the AS well is 3.3 m and the SVE well is 9.2 m, as derived from consultant reports. The number of AS and SVE wells in total was 56 and 8, respectively and 28 and 4 for both stages of treatment
* A rebound event was included at the end of this treatment, equivalent to 33% of the original contamination value, to represent contaminant back-diffusion from low hydraulic conductivity zones. The extent of rebound is consistent with observed values from other sites (Bass et al., 2000).

Table M.4. Equations used to derive AS/SVE treatment design.

|  |  |  |
| --- | --- | --- |
| **Equation** | **Inputs / outputs** | **Reference and notes** |
| AS and SVE well number | Nwell= Number of AS or SVE wells  Atarget = Target treatment area  Rwell  = Radius of influence for AS or SVE well | NFESC (2001) |
| First order attenuation rate | C = representative chemical concentration  C0 = starting concentration at time 0  k = attenuation rate  t = time | Mchugh et al. (2013) |

Table M.5. Input values that inform AS/SVE treatment duration.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Value** | **Unit** | **Minimum duration time estimate** | **Middle duration time estimate** | **Maximum duration time estimate** |
| Pilot test SVE extraction rate | kg d-1 | 2.7 | 2.0 | 1.3 |
| Attenuation rate | days-1 | 5.9x10-3 | 8.9x10-3 | 1.2x-2 |

*Pump and Treatment*

The assumptions associated with the PT treatment include:

* Attenuation rates are taken from McHugh et al. (2013) which compiles data on thousands of contaminated sites in the Geotracker database. The paper provides minimum, medium and maximum MtBE attenuation rates that are used to inform the treatment duration range (Table M.7). The same first order attenuation rate equation shown in Table M.4 is used.
* Well spacing is determined by the pump area of influence. A drawdown of 5% saturated aquifer thickness is assumed to give a radius of influence of 20 m, thus 2 pumping wells are required (Table M.6).
* A rebound event was included at the end of this treatment, equivalent to 33% of the original contamination value, to represent contaminant back-diffusion from low hydraulic conductivity zones similar to the AS/SVE treatment.

Table M.6. Equation used to derive PT treatment design.

|  |  |  |
| --- | --- | --- |
| **Equation** | **Inputs / outputs** | **Reference and notes** |
| Pump radius (based on Theis equation for un-confined aquifer) | r2 = radius maximum extent  r1 = radius minimum extent  Q = pumping rate  h1 = water head lowest extent  h2 = water head highest extent | Hiscock (2005).  K value used for high K material |

Table M.7. Input values that inform PT treatment duration.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Value** | **Unit** | **Minimum duration time estimate** | **Middle duration time estimate** | **Maximum duration time estimate** |
| Attenuation rate | days-1 | 1.5x10-3 | 1.2x10-3 | 1.1x10-3 |

**M.2 Tier 1 Assessment**

The following tables are linked to the Tier 1 assessment (see main article for details).

Table M.8. Idealised scenario used to frame each sustainability indicator.

|  |  |  |
| --- | --- | --- |
|  | **Assessment criteria** | **Ideal** |
| ECON 1 | Direct economic costs and benefits | Minimise cost maximise benefit |
| ECON 2 | Indirect economic costs and benefits | Minimise cost maximise benefit |
| ECON 3 | Employment and employment capital | Maximise |
| ECON 4 | Induced economic costs and benefits | Minimise cost maximise benefit |
| ECON 5 | Project lifespan and flexibility | Most robust, most flexible, best permanent solution, minimum operation period |
| ENV 1 | Emissions to air | No emissions to air |
| ENV 2 | Soil and ground conditions | Maximum feasible improvement in soil properties. |
| ENV 3 | Groundwater and surface water | Maximum feasible improvement in groundwater quality within spatial boundary |
| ENV 4 | Ecology | Prevent deterioration in ecological systems |
| ENV 5 | Natural resources and waste | Minimise resource usage and waste generation |
| SOC 1 | Human health and safety | Goal Zero (site safety and spills). Hazard removal preferable to long-term risk management. |
| SOC 2 | Ethics and equality | Meet Shell's ethics and equality standards, in particular inter generation effects. |
| SOC 3 | Neighbourhood and locality | Minimise impact and maximise benefit |
| SOC 4 | Communities and community involvement | Maximise |
| SOC 5 | Uncertainty and evidence | Best available information |

Table M.9. Supporting evidence for economic criteria, Tier 1 assessment.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  |  | **Option 1** | **Option 2** | **Option 3** | **Option 4** |
| ECON 1 | Direct financial costs and benefits of remediation: assume units of O&M for each activity x time  (O&M units: 0.5 = limited activity [e.g. MNA]; 1 = non-intensive activity [e.g. EK-BIO\*, HCS]; and 1.5 intensive activity [e.g. AS/SVE PT]). | 30 | 14 | 13 | 16 |
| Additional capital expenditure required to support Option Y/N – Assume all tech at same level | N | Y | Y | Y |
| Relative additional capital cost | Low | Medium | Medium | High |
| Delivery of value for remediation services | Latest | ~1.2 years after Opt 3 | Soonest | Slightly slower than Opt 2 |
| ECON 2 | Which option releases the domestic properties to market quickest? † | Soonest | Latest | Quicker than 2 and 4 | Latest |
| ECON 3 | Assumes more employment for enhanced options | Lowest | Medium | High | High |
| ECON 4 | Which option will release the petrol filling station (PFS) to market quickest? ‡ | Soonest | Latest | Quicker than 2 and 4 | Latest |
| ECON 5 | Consider time for operation of each system. | 20.0 | 6.2 | 5.0 | 6.4 |
| \* EK-BIO is coupled with HCS as non-intensive because no specific treatment plants are required.  † Releasing domestic housing to market is an indirect economic benefit because the properties and associated land have value that can only be recovered once remediation has been complete.  ‡Releasing the PFS to market quickest is an induced economic benefit because the commercial business will provide jobs and improve the local economy. | | | | | |

Table M.10. Supporting evidence for environment criteria, Tier 1 assessment.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
|  |  | **Option 1** | | **Option 2** | **Option 3** | | **Option 4** |
| ENV 1 | Emissions directly linked to power consumption from treatment and HCS assume 1kW/hr. = 1 unit emissions. (Power consumption for Options: HCS, 10 kWh; EK-BIO\*, 10 kWh; AS/SVE, 20 kWh†; PT, 20kWh‡ | 1,752,000 | | 1,079,503 | 1,315,510 | | 1,669,203 |
| Particulates? Vehicle emissions for routine maintenance and installation of new equipment. | Assume same for routine O&M for all options. In reality there would be only marginal differences. | | | | | |
| ENV 2 | Changes in physical, chemical soil condition and soil quality as a result of mass removal of TPH fractions | Greatest impact – TPH fractions present longest | | Better than Option 1 – quicker TPH removal time | Lowest impact – quickest removal + SVE treats unsaturated zone | | Better than Option 1 – quicker TPH removal time |
| ENV 3 | Change in release of contaminants | Not anticipated for any Option | | | | | |
| Suitability of water for potable supply | None of the water is potable but remediation protects the potable supply from the chalk | | | | | |
| Does it meet WFD | NAPL has been removed. | | | | | |
| Chemical function: Improvements based on removal of TPH mass | Long term removal of dissolved phase NAPL. | | Greatest negative impact: introduces large amount of nitrate to subsurface. | SVE will remove any residual free phase NAPL on the water table. AS targets all contaminants | | PT targets all contaminants. |
| Mobilisation of dissolved phase | NAPL has been removed. | | | | | |
| Effects/benefits of water abstraction | All protect Drinking Water array | | | | | |
| ENV 4 | Ecology | Marginal difference between each option: ecology not really an issue at the site. No protected species or habitats. | | | | | |
| ENV 5 | Waste Water discharge from treatment and HCS. (P+T 100, AS SVE 60 and HCS 300) (discharge consent (m3/day)\* operational time) | 2,190,000 | 752,645 | | 657,755 | 927,335 | |
| Dosing chemicals (air stripper for SVE, PT and EK-BIO)◊ | Low | High | | High | High | |
| General waste | All equal | | | | | |
| \* Power consumption for EK-BIO is only for electricity used during treatment and recirculation pumps  † Power consumption for AS/SVE is assumed to be 20 kWh, 10 kWh for air pump and vacuum and 10 kWh for catalytic oxidizer  ‡ Power consumption for PT is assumed to be 20 kWh, 10 kWh for pumps and 10 kWh for treatment units (oil-water separator and GAC unit)  ◊ No treatment for water withdrawn using the HCS, it is discharged direct to sewer. | | | | | | | |

Table M.11. Supporting evidence for social criteria, Tier 1 assessment.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  |  | **Option 1** | **Option 2** | **Option 3** | Option 4 |
| SOC 1 | Installation and operational risks | Least associated risk | More risk than 1, less than 3 and 4 | Joint highest with 4 | Joint highest with 3 |
| SOC 2 | All Options will be executed under property owner’s internal Ethics and Equality requirements | All equal | | | |
| Inter generation issues: Main driver for assessment: | All equal | | | |
| SOC 3 | Dust, traffic, noise, vibration | Least associated disturbance | More disturbance than 1, less than 3 and 4 | Joint highest with 4 | Joint highest with 3 |
| SOC 4 | Communities and community involvement | All equally because they deliver same amenity benefit back to community and have all had the same community involvement via the Local Authority. | | | |
| SOC 5 | Robustness of sustainability assessment | Equal highest with 3 and 4 | Lowest due to lack of field or lit data | Equal highest with 1 and 4 | Equal highest with 1 and 3 |
| Quality of investigations | Equal highest with 3 and 4 | Lowest due to lack of field or lit data | Equal highest with 1 and 4 | Equal highest with 1 and 3 |
| Validation requirements the more activites the greater the level of validation required | Validation required over long time period but simple GW monitoring | High | High | High |
| CSM and remedial target robustness | All equal | | | |

Table M.. Rankings and justifications for the Tier 1 sustainability assessment (continues over page).

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Category** | **Score** | | | | **Justification** |
| **Opt 1**  **(MNA+ HCS)** | **Opt 2**  **(EK-BIO + HCS)** | **Opt 3**  **(AS/SVE + HCS)** | **Opt 4**  **(PT + HCS)** |
| **ECON 1** | 4 | 2 | 2 | 3 | * Opt 1 requires no start-up capital but requires a long period of treatment operation * Opt 2 and 3 have similar costs despite Opt 2 having a longer duration period * Opt 2 is considered to have lower operation costs because there are no treatment plants required, unlike Opt 3 and 4. * Capital for Opt 3 will be lower as SVE system already in place |
| **ECON 2** | 1 | 3 | 2 | 3 | * Opt 1 releases properties onto the market quickest * Opt 3 is a quicker treatment compared to Opt 2 and 4 so will deliver properties sooner |
| **ECON 3** | 3 | 2 | 1 | 1 | * Opt 3 and 4 represent treatments likely to require additional employment capital because treatment plant are required * Opt 1 will provide the least employment capital |
| **ECON 4** | 1 | 3 | 2 | 3 | * Opt 1 allows the quickest sale of the PFS compared to the other techniques * Opt 3 is a quicker treatment than Opt 2 and 4 so will deliver the PFS to market sooner |
| **ECON 5** | 4 | 3 | 2 | 3 | * Driven by risk of MtBE in the channel sands system to the PWS. This is considered longest for Opt 1 * Opt 3 should meet remedial objectives quicker than Opt 2 and 4 * Opt 2 could take a similar length of time to Opt 4, however there is a high degree of uncertainty around treatment duration |
| **ENV 1** | 4 | 1 | 3 | 2 | * Opt 1 is highest due to long duration of the HCS * Opt 3 has higher power consumption than Opt 4 because both AS and SVE system are operating * Opt 2 has longer running time than Opt 3 and Opt 4 but lower power consumption |
| **ENV 2** | 3 | 2 | 1 | 2 | * Opt 1 is the worst due to long duration of treatment * Opt 2 is the best because SVE element treats the unsaturated zone |
| **ENV 3** | 3 | 4 | 1 | 2 | * All options treat groundwater, Opt 3 will also treat residual NAPL that may be present * Opt 2 introduces a large mass of nitrate to the subsurface with potential sharp pH changes if not controlled managed correctly |
| **ENV 4** | 1 | 1 | 1 | 1 | * Anticipated to be no significant differences between the options |
| **ENV 5** | 4 | 3 | 3 | 3 | * Waste water is highest from Opt 1 due to long duration of HCS * Opt 2, 3 and 4 require large amounts of additive such as granular activated carbon or NaNO3 amendment, thus no difference can be appreciated. |
| **SOC 1** | 1 | 2 | 3 | 3 | * There are no significant human health risks for any of the options as safety features are designed into them * Opt 1 has the lease associated risk with the operation * Opt 3 and 4 require containers with pressurized VOC gases * Opt 2 requires the handling of NaNO3 fertiliser which can be controlled and there are minimal safety risks associated with applying a low voltage DC to the subsurface |
| **SOC 2** | 1 | 1 | 1 | 1 | * All equal, inter-generational effects are similar |
| **SOC 3** | 1 | 2 | 3 | 3 | * Dominated by intensity of noise, dust, vibration and traffic * Opt 2 , 3 and 4 are highest because of infrastructure * Opt 2 is considered lower than Opt 3 and 4 as no treatment plants are needed reducing the overall noise and emissions from the site. |
| **SOC 4** | 1 | 1 | 1 | 1 | * All equal, no significant differences between options |
| **SOC 5** | 1 | 4 | 2 | 2 | * Opt 2, 3 and 4 have the most work required to validate operations * Option 2 has the highest level of uncertainty because very few sites have applied EK-BIO under these conditions |

**M.3 Tier 2 Assessment**

*Tier 2 Supporting Evidence*

The following tables (Table M.13, Table M.14 and Table M.15) cover the calculations and assumptions used to inform the Tier 2 sustainability assessment. Indicators that do not have an associated quantitative metric are excluded because the qualitative rankings from the Tier 1 assessment are carried over. These indicators include: ECON 3, ENV 4, SOC 2, SOC 3, SOC 4 and SOC 5.

Table M.13. Calculations and associated information for economic indicators. Note that all costs provided are estimates and subject to change.

|  |  |  |
| --- | --- | --- |
| **Indicator** | **Calculation** | **Notes** |
| ECON 1 | Total economic cost = capital cost + O&M cost (+ cost of photovoltaics in sustainability scenarios) | * See below |
| Capital cost = ∑ (cost per well x number of wells); labour; installation and commissioning; consents and power connections; and equipment | * Cost per well, £2,766A includes: Drilling cost, well material, well installation and cover * Labour for setup, £12,500B * Installation and commissioning, £40,000B * Consents and power connections, £40,000B * Treatment specific equipment, e.g. electrodes £2,115C per well |
| Operation and management costs = costs per year (∑ equipment rental, labour, amendment, lab analysis, transport cost, maintenance and water discharge if required) x number of years | * Equipment rental, £178,000B per year for treatment plant and £1,000 per year per well for compressor/pump/vacuum * Labour cost for AS/SVE, EK/BIO and PT: £81,000B per year * Labour cost for MNA: £10,000B per year * Amendment: Granulated activated carbon £30,000B per year; sodium nitrate, £4,400F per year * Lab analysis, £16,000B per year * Transport cost: £0.64A per km * Maintenance: £30,000B per year * Waste water discharge to foul sewer, £0.55B m-3 |
| Cost of photovoltaics = cost per m2 of array x predicted area of array † | * The cost per m2, £2,000D m-2 (for 1 kWh power system) based on estimate for a 4 kWh nominal power supply is £8,000D * Predicted area of array is calculated from total energy consumption per year / yearly energy generation at site-specific location, 1200E kWh m-2 from 1 kWh nominal power system |
| ECON 2 | Decrease in net present value = value of property – net present value at end of treatment | * Estimated value of properties, £575,000B * Discount rate, 3.5%G |
| ECON 4 | Decrease in net present value = value of PFS – net present value at end of treatment | * Estimated value of PFS, £500,000B * Discount rate, 3.5%G |
| ECON 5 | Duration of treatment | * Treatment specific, see table 3 in main article |
| A Detailed costing from consultants  B Site specific costing from consultants  C Quote from Water Star Inc ([www.waterstarinc.com](http://www.waterstarinc.com))  D Value from Energy Saving Trust, UK ([www.energysavingtrust.org.uk](http://www.energysavingtrust.org.uk))  E Value from European Commission, 2012. Photovoltaic Geographical Information System  F Listed price, £73.24 per 25 kg ([www.chemicals.co.uk](http://www.chemicals.co.uk))  G HM Treasury, (2003)  \*MNA is given a lower annual labour cost to reflect the low intensity of the treatment.  †Only included as part of the EK-BIO sustainability scenario analysis | | |

Table M.14. Calculations and associated information for environmental indicators.

|  |  |  |
| --- | --- | --- |
| **Indicator** | **Calculation** | **Notes** |
| ENV1 | Total CO2 emissions = CO2 transport + CO2 electricity + CO2 amendment production | * See below |
| CO2 transport = volume of petrol consumed x emission factor | * Distance travelled to site assumes 80 km for one trip * Fuel consumption for medium sized car, 9.69A km L-1 * Transport of materials to site including site setup and yearly amendment delivery. * Emission Factor for petrol (average biofuel blend) 2.2B kg CO2e per L |
| CO2 electricity = kWh consumed x emission factor | * kWh consumed is calculated differently for each treatment: * EK-BIO power consumption calculated using electron balance model; * AS/SVE: vacuum, 7.5C kWh; compressor, 4.5C kWh; catalytic oxidizer (CatOx) full load, 26.1C kWh; CatOx autotherm, 2.6C kWh (assumes CatOx running on autotherm 80% of time) * PT: pumps, 6.9D kWh; air stripper and GAC, 11C kWh; electricity required for GAC generation, 7.0A kWh per kg GAC * Emission factor for electricity production in 2015: 0.46B kg per kWh |
| CO2 amendment production = mass of amendment consumed x emission factor | * Mass of amendment consumed is based on electron balance model, for middle treatment duration, 9.5 t. * Emission factor from fertilizer production is equivalent to 3.2E kg CO2 per kg-N |
| ENV 3 | Value of groundwater extracted = volume of groundwater extracted by HCS x value of groundwater\* | * Groundwater extracted by HCS, 300F m3 per day * Value of groundwater, £0.8G m-3 |
| ENV 5 | Water discharge from treatment = ∑ well purge volume before sampling; and water discharge from treatment | * Volume of water purged assumed to be 3x the well volume (0.75 m3) * Water discharge from treatment only related to PT, minimum pumping rate 18 m3 per day |
| Volume of well cuttings = volume of well x number of wells | * Volume of well, 1.7 m3 * Number of wells varies between treatments |
| Raw material used in well construction = number of wells x mass of PVC | * Mass of PVC calculated from cumulative well length, multiplied by density, 0.28A kg per m |
| Volume of petrol used = distance travelled / fuel efficiency | * Distance travelled to site assumes 80 km for one trip * Fuel consumption for medium sized car, 9.69A km L-1 |
| \* Only the value of groundwater extracted by the HCS is included as opposed to PT and well purging because the latter two would require greater additional treatment because of higher levels of contamination. Furthermore, including them in ENV 3 would double counting as they are already included in ENV 5.  A Value from US Air Force, Sustainable Remediation Tool  B Value from Defra emission factors ([http://www.ukconversionfactorscarbonsmart.co.uk](http://www.ukconversionfactorscarbonsmart.co.uk/))  C Value from site specific supplier  D Value from pumps currently deployed in the HCS  E Value from Yara, 2014 ([www.yara.com](http://www.yara.com))  F Site specific value  G Value from Environment Agency (2007) | | |

Table M.15. Calculations and associated information for social indicators.

|  |  |  |
| --- | --- | --- |
| **Indicator** | **Calculation** | **Notes** |
| SOC 1 | Hours lost due to operation = hours spent on site x accident factor | * Hours of operation during setup assumes 10 workers on site, working for 10 days 8 hours per day. * Hours during operation and management assumes 3 workers on site, at the specified frequency of site visits (for Option 2, 3 and 4 site visits once a week, for Option 1 one site walkover every two weeks) * Accident factor 2.7x10-9 A injuries per hour worked * Time lost due to accident, 48A hours |
| Hours lost due to transport = distance travelled x accident factor | * Distance travelled to site assumes a 160 km round trip (80 km each way) * Accident factor, 9.1x10-7 A injuries per mile * Time lost due to accident, 48A hours |
| A Value from US Air Force, Sustainable Remediation Tool | | |

*Tier 2 MCA Results*

The following tables show the data used in the Tier 2 results section in the main text (Table M.16 - Table M.18). Indicators with quantitative metrics are calculated using the methods in Table M.13 - Table M.15), these include ENV 1, ENV 3, ENV 5, ECON 1, ECON 2, ECON 4, ECON 5 and SOC 1. Qualitative metrics are carried over from the Tier 1, qualitative assessment (Table M.12) and include ECON 3, ENV 4, SOC, 2, SOC 3, SOC 4 and SOC 5. Data used to inform the sustainability scenarios are shown in Table M.19; further details on this analysis can be found in the main text.

Table M.16. Input values and MCA scores for economic indicators.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | | **Input Value** | | | | | **Treatment + HCS Pre-Weighted MCA Score** | | | | **Sub Indicator Weight** | **Priority Weighting** | **Treatment + HCS Weighted MCA Score** | | | |
| **Opt 1** | **Opt 2** | **Opt 3** | **Opt 4** | **Unit** | **Opt 1** | **Opt 2** | **Opt 3** | **Opt 4** | **Opt 1** | **Opt 2** | **Opt 3** | **Opt 4** |
| **ECON 1** | **Min Est** | 2.5M | 1.8M | 2.5M | 3.7M | GBP | 51.9 | 36.1 | 50.5 | 75.8 | 1 | 1 | 51.9 | 36.1 | 50.5 | 75.8 |
| **Med Est** | 3.4M | 2.7M | 3.2M | 4.5M | GBP | 68.7 | 55.4 | 64.3 | 91.6 | 1 | 1 | 68.7 | 55.4 | 64.3 | 91.6 |
| **Max Est** | 4.2M | 3.2M | 4.5M | 4.9M | GBP | 85.6 | 64.8 | 91.8 | 100.0 | 1 | 1 | 85.6 | 64.8 | 91.8 | 100.0 |
| **ECON 2** | **Min Est** | 19.4K | 64.1K | 69.7K | 94.1K | GBP | 14.9 | 49.0 | 53.2 | 71.9 | 1 | 0.5 | 7.4 | 24.5 | 26.6 | 36.0 |
| **Med Est** | 19.4K | 109.8K | 91.0K | 112.9K | GBP | 14.9 | 83.9 | 69.5 | 86.2 | 1 | 0.5 | 7.4 | 42.0 | 34.7 | 43.1 |
| **Max Est** | 19.4K | 130.3K | 130.9K | 122.6K | GBP | 14.9 | 99.5 | 100.0 | 93.7 | 1 | 0.5 | 7.4 | 49.8 | 50.0 | 46.8 |
| **ECON 3** | **Min Est** | 3 | 2 | 1 | 1 | n/a | 100.0 | 66.7 | 33.3 | 33.3 | 1 | 0.5 | 50.0 | 33.3 | 16.7 | 16.7 |
| **Med Est** | 3 | 2 | 1 | 1 | n/a | 100.0 | 66.7 | 33.3 | 33.3 | 1 | 0.5 | 50.0 | 33.3 | 16.7 | 16.7 |
| **Max Est** | 3 | 2 | 1 | 1 | n/a | 100.0 | 66.7 | 33.3 | 33.3 | 1 | 0.5 | 50.0 | 33.3 | 16.7 | 16.7 |
| **ECON 4** | **Min Est** | 16.9K | 55.7K | 60.6K | 81.9K | GBP | 14.9 | 49.0 | 53.2 | 71.9 | 1 | 0.5 | 7.4 | 24.5 | 26.6 | 36.0 |
| **Med Est** | 16.9K | 95.5K | 79.1K | 98.1K | GBP | 14.9 | 83.9 | 69.5 | 86.2 | 1 | 0.5 | 7.4 | 42.0 | 34.7 | 43.1 |
| **Max Est** | 16.9K | 113.3K | 113.8K | 106.6K | GBP | 14.9 | 99.5 | 100.0 | 93.7 | 1 | 0.5 | 7.4 | 49.8 | 50.0 | 46.8 |
| **ECON 5** | **Min Est** | 15 | 3.4 | 3.8 | 5.2 | yr | 60.0 | 13.7 | 15.0 | 20.8 | 1 | 1 | 60.0 | 13.7 | 15.0 | 20.8 |
| **Med Est** | 20 | 6.2 | 5.0 | 6.4 | yr | 80.0 | 24.6 | 20.0 | 25.4 | 1 | 1 | 80.0 | 24.6 | 20.0 | 25.4 |
| **Max Est** | 25 | 7.5 | 7.5 | 7.0 | yr | 100.0 | 29.9 | 30.0 | 27.9 | 1 | 1 | 100.0 | 29.9 | 30.0 | 27.9 |

Table M.17 Input values and MCA scores for environmental indicators.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | | **Input Value** | | | | | **Treatment + HCS Pre-Weighted MCA Score** | | | | **Sub Indicator Weight** | **Priority Weighting** | **Treatment + HCS Weighted MCA Score** | | | |
| **Opt 1** | **Opt 2** | **Opt 3** | **Opt 4** | **Unit** | **Opt 1** | **Opt 2** | **Opt 3** | **Opt 4** | **Opt 1** | **Opt 2** | **Opt 3** | **Opt 4** |
| **ENV 1** | **Min Est** | 408.2K | 215.4K | 391.8K | 505.8K | kg CO2 | 52.4 | 27.6 | 50.3 | 64.9 | 1 | 1 | 52.4 | 27.6 | 50.3 | 64.9 |
| **Med Est** | 544.2K | 363.3K | 520.9K | 617.3K | kg CO2 | 69.8 | 46.6 | 66.9 | 79.2 | 1 | 1 | 69.8 | 46.6 | 66.9 | 79.2 |
| **Max Est** | 680.3K | 458.2K | 779.1K | 677.1K | kg CO2 | 87.3 | 58.8 | 100.0 | 86.9 | 1 | 1 | 87.3 | 58.8 | 100.0 | 86.9 |
| **ENV 2** | **Min Est** | 3 | 2 | 1 | 2 | n/a | 100.0 | 66.7 | 33.3 | 66.7 | 1 | 0.5 | 50.0 | 33.3 | 16.7 | 33.3 |
| **Med Est** | 3 | 2 | 1 | 2 | n/a | 100.0 | 66.7 | 33.3 | 66.7 | 1 | 0.5 | 50.0 | 33.3 | 16.7 | 33.3 |
| **Max Est** | 3 | 2 | 1 | 2 | n/a | 100.0 | 66.7 | 33.3 | 66.7 | 1 | 0.5 | 50.0 | 33.3 | 16.7 | 33.3 |
| **ENV 3.1** | **Min Est** | 1.3M | 301.0K | 328.9K | 455.2K | GBP | 60.0 | 13.7 | 15.0 | 20.8 | 0.5 | 1 | 30.0 | 6.9 | 7.5 | 10.4 |
| **Med Est** | 2.2M | 674.7K | 548.1K | 695.5K | GBP | 100.0 | 30.8 | 25.0 | 31.8 | 0.5 | 1 | 50.0 | 15.4 | 12.5 | 15.9 |
| **Max Est** | 2.2M | 654.3K | 657.8K | 610.7K | GBP | 100.0 | 29.9 | 30.0 | 27.9 | 0.5 | 1 | 50.0 | 14.9 | 15.0 | 13.9 |
| **ENV 3.2** | **Min Est** | 3 | 4 | 1 | 2 | n/a | 75.0 | 100.0 | 25.0 | 50.0 | 0.5 | 1 | 37.5 | 50.0 | 12.5 | 25.0 |
| **Med Est** | 3 | 4 | 1 | 2 | n/a | 75.0 | 100.0 | 25.0 | 50.0 | 0.5 | 1 | 37.5 | 50.0 | 12.5 | 25.0 |
| **Max Est** | 3 | 4 | 1 | 2 | n/a | 75.0 | 100.0 | 25.0 | 50.0 | 0.5 | 1 | 37.5 | 50.0 | 12.5 | 25.0 |
| **ENV 4** | **Min Est** | 1 | 1 | 1 | 1 | n/a | 100.0 | 100.0 | 100.0 | 100.0 | 1 | 0.5 | 50.0 | 50.0 | 50.0 | 50.0 |
| **Med Est** | 1 | 1 | 1 | 1 | n/a | 100.0 | 100.0 | 100.0 | 100.0 | 1 | 0.5 | 50.0 | 50.0 | 50.0 | 50.0 |
| **Max Est** | 1 | 1 | 1 | 1 | n/a | 100.0 | 100.0 | 100.0 | 100.0 | 1 | 0.5 | 50.0 | 50.0 | 50.0 | 50.0 |
| **ENV 5.1** | **Min Est** | 157.6 | 248.7 | 124.5 | 67662.9 | m3 | 0.2 | 0.3 | 0.1 | 74.5 | 0.25 | 0.5 | 0.0 | 0.0 | 0.0 | 9.3 |
| **Med Est** | 199.1 | 446.0 | 166.1 | 82699.1 | m3 | 0.2 | 0.5 | 0.2 | 91.1 | 0.25 | 0.5 | 0.0 | 0.1 | 0.0 | 11.4 |
| **Max Est** | 199.1 | 540.6 | 249.1 | 90767.3 | m3 | 0.2 | 0.6 | 0.3 | 100.0 | 0.25 | 0.5 | 0.0 | 0.1 | 0.0 | 12.5 |
| **ENV 5.2** | **Min Est** | 0.0 | 22.5 | 23.7 | 0.8 | m3 | 0.0 | 95.0 | 100.0 | 3.6 | 0.25 | 0.5 | 0.0 | 11.9 | 12.5 | 0.4 |
| **Med Est** | 0.0 | 22.5 | 23.7 | 0.8 | m3 | 0.0 | 95.0 | 100.0 | 3.6 | 0.25 | 0.5 | 0.0 | 11.9 | 12.5 | 0.4 |
| **Max Est** | 0.0 | 22.5 | 23.7 | 0.8 | m3 | 0.0 | 95.0 | 100.0 | 3.6 | 0.25 | 0.5 | 0.0 | 11.9 | 12.5 | 0.4 |
| **ENV 5.3** | **Min Est** | 0.0 | 269.9 | 313.3 | 125.5 | kg | 0.0 | 86.1 | 100.0 | 40.0 | 0.25 | 0.5 | 0.0 | 10.8 | 12.5 | 5.0 |
| **Med Est** | 0.0 | 269.9 | 313.3 | 125.5 | kg | 0.0 | 86.1 | 100.0 | 40.0 | 0.25 | 0.5 | 0.0 | 10.8 | 12.5 | 5.0 |
| **Max Est** | 0.0 | 269.9 | 313.3 | 125.5 | kg | 0.0 | 86.1 | 100.0 | 40.0 | 0.25 | 0.5 | 0.0 | 10.8 | 12.5 | 5.0 |
| **ENV 5.4** | **Min Est** | 13.9K | 7.2K | 8.1K | 10.7K | L | 60.0 | 31.3 | 35.2 | 46.2 | 0.25 | 0.5 | 7.5 | 3.9 | 4.4 | 5.8 |
| **Med Est** | 18.5K | 12.0K | 10.3K | 12.7K | L | 80.0 | 51.8 | 44.5 | 54.9 | 0.25 | 0.5 | 10.0 | 6.5 | 5.6 | 6.9 |
| **Max Est** | 23.1K | 14.2K | 14.6K | 13.8K | L | 100.0 | 61.6 | 63.1 | 59.5 | 0.25 | 0.5 | 12.5 | 7.7 | 7.9 | 7.4 |

Table M.18 Input values and MCA scores for social indicators.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | | **Input Value** | | | | | **Treatment + HCS Pre-Weighted MCA Score** | | | | **Sub Indicator Weight** | **Priority Weighting** | **Treatment + HCS Weighted MCA Score** | | | |
| **Opt 1** | **Opt 2** | **Opt 3** | **Opt 4** | **Unit** | **Opt 1** | **Opt 2** | **Opt 3** | **Opt 4** | **Opt 1** | **Opt 2** | **Opt 3** | **Opt 4** |
| **SOC 1.1** | **Min Est** | 0.0027 | 0.0013 | 0.0013 | 0.0018 | hrs | 59.9 | 29.1 | 30.2 | 40.9 | 0.5 | 1 | 30.0 | 14.5 | 15.1 | 20.5 |
| **Med Est** | 0.0035 | 0.0022 | 0.0017 | 0.0022 | hrs | 79.9 | 49.3 | 39.5 | 49.5 | 0.5 | 1 | 39.9 | 24.6 | 19.8 | 24.7 |
| **Max Est** | 0.0044 | 0.0026 | 0.0026 | 0.0024 | hrs | 100.0 | 59.0 | 58.1 | 54.1 | 0.5 | 1 | 50.0 | 29.5 | 29.0 | 27.0 |
| **SOC 1.2** | **Min Est** | 5.9 | 3.0 | 3.4 | 4.5 | hrs | 59.9 | 30.8 | 35.0 | 45.7 | 0.5 | 1 | 30.0 | 15.4 | 17.5 | 22.8 |
| **Med Est** | 7.8 | 5.0 | 4.3 | 5.3 | hrs | 79.9 | 51.1 | 44.3 | 54.2 | 0.5 | 1 | 39.9 | 25.5 | 22.1 | 27.1 |
| **Max Est** | 9.8 | 6.0 | 6.2 | 5.8 | hrs | 100.0 | 60.8 | 62.8 | 58.8 | 0.5 | 1 | 50.0 | 30.4 | 31.4 | 29.4 |
| **SOC 2** | **Min Est** | 1 | 1 | 1 | 1 | n/a | 100.0 | 100.0 | 100.0 | 100.0 | 1 | 0.5 | 50.0 | 50.0 | 50.0 | 50.0 |
| **Med Est** | 1 | 1 | 1 | 1 | n/a | 100.0 | 100.0 | 100.0 | 100.0 | 1 | 0.5 | 50.0 | 50.0 | 50.0 | 50.0 |
| **Max Est** | 1 | 1 | 1 | 1 | n/a | 100.0 | 100.0 | 100.0 | 100.0 | 1 | 0.5 | 50.0 | 50.0 | 50.0 | 50.0 |
| **SOC 3** | **Min Est** | 1 | 2 | 3 | 3 | n/a | 33.3 | 66.7 | 100.0 | 100.0 | 1 | 1 | 33.3 | 66.7 | 100.0 | 100.0 |
| **Med Est** | 1 | 2 | 3 | 3 | n/a | 33.3 | 66.7 | 100.0 | 100.0 | 1 | 1 | 33.3 | 66.7 | 100.0 | 100.0 |
| **Max Est** | 1 | 2 | 3 | 3 | n/a | 33.3 | 66.7 | 100.0 | 100.0 | 1 | 1 | 33.3 | 66.7 | 100.0 | 100.0 |
| **SOC 4** | **Min Est** | 1 | 1 | 1 | 1 | n/a | 100.0 | 100.0 | 100.0 | 100.0 | 1 | 0.5 | 50.0 | 50.0 | 50.0 | 50.0 |
| **Med Est** | 1 | 1 | 1 | 1 | n/a | 100.0 | 100.0 | 100.0 | 100.0 | 1 | 0.5 | 50.0 | 50.0 | 50.0 | 50.0 |
| **Max Est** | 1 | 1 | 1 | 1 | n/a | 100.0 | 100.0 | 100.0 | 100.0 | 1 | 0.5 | 50.0 | 50.0 | 50.0 | 50.0 |
| **SOC 5** | **Min Est** | 1 | 4 | 2 | 2 | n/a | 25.0 | 100.0 | 50.0 | 50.0 | 1 | 0.5 | 12.5 | 50.0 | 25.0 | 25.0 |
| **Med Est** | 1 | 4 | 2 | 2 | n/a | 25.0 | 100.0 | 50.0 | 50.0 | 1 | 0.5 | 12.5 | 50.0 | 25.0 | 25.0 |
| **Max Est** | 1 | 4 | 2 | 2 | n/a | 25.0 | 100.0 | 50.0 | 50.0 | 1 | 0.5 | 12.5 | 50.0 | 25.0 | 25.0 |

Table M.19 Input values and MCA scores for different sustainable remediation treatment scenarios. Scn 1, scenario 1; Scn 2, scenario 2; Scn 3, scenario 3.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | | **Input Value** | | | | **Treatment + HCS Pre-Weighted MCA Score** | | | **Sub Indicator Weight** | **Priority Weighting** | **Treatment + HCS Weighted MCA Score** | | |
| **Scn 1** | **Scn 2** | **Scn 3** | **Unit** | **Scn 1** | **Scn 2** | **Scn 3** | **Scn 1** | **Scn 2** | **Scn 3** |
| **ECON 1** | **Min Est** | 1.3M | 3.1M | 3.1M | GBP | 26.7 | 63.9 | 64.0 | 1 | 1 | 26.7 | 63.9 | 64.0 |
| **Med Est** | 2.2M | 4.1M | 4.0M | GBP | 43.8 | 83.8 | 81.4 | 1 | 1 | 43.8 | 83.8 | 81.4 |
| **Max Est** | 2.4M | 4.2M | 4.2M | GBP | 49.2 | 84.8 | 85.0 | 1 | 1 | 49.2 | 84.8 | 85.0 |
| **ECON 5** | **Min Est** | 3.44 | 8.49 | 8.49 | yr | 13.7 | 34.0 | 34.0 | 1 | 1 | 13.7 | 34.0 | 34.0 |
| **Med Est** | 6.16 | 11.31 | 11.31 | yr | 24.6 | 45.2 | 45.2 | 1 | 1 | 24.6 | 45.2 | 45.2 |
| **Max Est** | 7.47 | 12.64 | 12.64 | yr | 29.9 | 50.6 | 50.6 | 1 | 1 | 29.9 | 50.6 | 50.6 |
| **ENV 1** | **Min Est** | 106.8K | 465.9K | 251.0K | kg CO2 | 13.7 | 59.8 | 32.2 | 1 | 1 | 13.7 | 59.8 | 32.2 |
| **Med Est** | 188.1K | 619.1K | 332.9K | kg CO2 | 24.1 | 79.5 | 42.7 | 1 | 1 | 24.1 | 79.5 | 42.7 |
| **Max Est** | 227.1K | 691.7K | 371.8K | kg CO2 | 29.2 | 88.8 | 47.7 | 1 | 1 | 29.2 | 88.8 | 47.7 |
| **ENV 3.1** | **Min Est** | 301.0K | 744.1K | 744.1K | GBP | 13.7 | 34.0 | 34.0 | 1 | 1 | 6.9 | 17.0 | 17.0 |
| **Med Est** | 539.8K | 990.7K | 990.7K | GBP | 24.6 | 45.2 | 45.2 | 1 | 1 | 12.3 | 22.6 | 22.6 |
| **Max Est** | 654.3K | 1.1M | 1.1M | GBP | 29.9 | 50.6 | 50.6 | 1 | 1 | 14.9 | 25.3 | 25.3 |
| **ENV 3.2** | **Min Est** | 4.00 | 4.00 | 4.00 | n/a | 100.0 | 100.0 | 100.0 | 1 | 1 | 50.0 | 50.0 | 50.0 |
| **Med Est** | 4.00 | 4.00 | 4.00 | n/a | 100.0 | 100.0 | 100.0 | 1 | 1 | 50.0 | 50.0 | 50.0 |
| **Max Est** | 4.00 | 4.00 | 4.00 | n/a | 100.0 | 100.0 | 100.0 | 1 | 1 | 50.0 | 50.0 | 50.0 |
| **SOC 1.1** | **Min Est** | 0.0013 | 0.0029 | 0.0029 | hrs | 29.1 | 66.6 | 66.6 | 1 | 1 | 14.5 | 33.3 | 33.3 |
| **Med Est** | 0.0022 | 0.0039 | 0.0039 | hrs | 49.3 | 87.5 | 87.5 | 1 | 1 | 24.6 | 43.7 | 43.7 |
| **Max Est** | 0.0026 | 0.0043 | 0.0043 | hrs | 59.0 | 97.4 | 97.4 | 1 | 1 | 29.5 | 48.7 | 48.7 |
| **SOC 1.2** | **Min Est** | 3.02 | 6.70 | 6.70 | hrs | 30.8 | 68.4 | 68.4 | 1 | 1 | 15.4 | 34.2 | 34.2 |
| **Med Est** | 5.00 | 8.74 | 8.74 | hrs | 51.1 | 89.2 | 89.2 | 1 | 1 | 25.5 | 44.6 | 44.6 |
| **Max Est** | 5.95 | 9.71 | 9.71 | hrs | 60.8 | 99.1 | 99.1 | 1 | 1 | 30.4 | 49.6 | 49.6 |
| **SOC 3** | **Min Est** | 2.00 | 2.00 | 2.00 | n/a | 66.7 | 66.7 | 66.7 | 1 | 1 | 66.7 | 66.7 | 66.7 |
| **Med Est** | 2.00 | 2.00 | 2.00 | n/a | 66.7 | 66.7 | 66.7 | 1 | 1 | 66.7 | 66.7 | 66.7 |
| **Max Est** | 2.00 | 2.00 | 2.00 | n/a | 66.7 | 66.7 | 66.7 | 1 | 1 | 66.7 | 66.7 | 66.7 |

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