Vopak-EXPERO3 - LIFE09/ENV/B/000407

Final Report - Annex 7265

Report on the technical and economic feasibility of ISCO using perozone in comparison to traditional remediation strategies

150974-R09(00)

AUGUST 2017

RSK GENERAL

Projectnumber: 150974-R09(00)

Title: Report on technical and economic feasibility of ISCO using perozone in comparison to traditional remediation strategies

LIFE project: Vopak-EXPERO3 - LIFE09/ENV/B/000407

Date: 17/08/2017

Office : Willebroek

Status: Final

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List of abbreviations

11-DCA	1.1-dichloroethane
111-TCA	1.1.1-trichloroethane
BATNEEC	Best Available Technology not entailing excessive costs
BOD	Biological oxygen demand
BTEX	Benzene, toluene, ethylbenzene, xylene
CATOX	Catalytic oxidation
CAH	Chlorinated aliphatic hydrocarbons
COD	Chemical oxygen demand
DOC	Dissolved organic carbon
GAC	Granular Activated Carbon
EC	European Commission
EX	Explosion sensitive
H&S	Health and safety
ISCO	In situ chemical oxidation
LEL	Lower explosion limit
MPE	Multi phase extraction
NAPL	Non aqueous phase liquid
mbgl	Meter below ground level
OVAM	Openbare Vlaamse Afvalstoffenmaatschappij (Public Waste Agency)
PID	Photo ionisation detector
P&T	Pump and treat
RAP	Remedial Action Plan
SVE/BLE	Soil vapour extraction
TOC	Total organic carbon
TPH	Total petroleum hydrocarbons
VOC	Volatile organic chlorocompounds

1 INTRODUCTION

This report evaluates the economic and technical feasibility of the remediation of the VOPAK ACS south site in the harbour of Antwerp. The remediation started in 2011 after the approval of the remedial action plan (RAP) by the authorities (OVAM). The soil and groundwater remediation aims to remove the risks related to the presence of a cocktail of organic compounds in soil and groundwater. The remedial approach takes into account the industrial use of the site, i.e. storage and handling of chemicals in above ground storage tanks.

Three relevant remediation techniques were applied during the remediation works. These are:

- Multi-phase extraction
- Excavation
- In-situ chemical oxidation (ISCO using perozone)

The following three remediation strategies are discussed.

1. Excavation after a period of P&T contaminant control;
2. Source excavation in combination with in situ chemical oxidation using perozone;
3. Source excavation in combination with multi-phase extraction.

An important factor of the economic feasibility is the cost of the contaminant treatment. We will consider for strategy 1 and 3 the cost for the contaminant treatment by granulated activated carbon (GAC) and by catalytic oxidation (catox).

The feasibility of a remediation technique is determined by the different factors such as but not limited to the aquifer depth, the construction area and underground infrastructure, the geology including the presence of peat layers, the nature and extent of the organic compounds. Therefore, this feasibility evaluation is site specific (for VOPAK ACS South). Results and conclusions are difficult to extrapolate to other contaminated sites.

2 TECHNICAL FEASIBILITY

2.1 Excavation

Excavation of contaminated soil is the most used remediation technique. However, it can be executed only under certain conditions. The remediation by excavation is limited by the presence of aboveground constructions and underground utilities within the contaminated areas. Where this infrastructure is present excavation cannot take place unless this infrastructure can be removed and afterwards replaced if necessary.

Specific for this site is that it has to remain in operation and that the industrial infrastructure has to remain in place at all time. This is especially the case for the tank park areas of this chemical storage facility. Therefore, for the biggest part of the contaminated area, excavation is not a feasible technique.

Because of the high groundwater levels, excavation needs to be executed in combination with groundwater level lowering through groundwater extraction and treatment. Due to the nearby constructions and the presence of a shallow peat layer, soil settlement and subsidence are restricting the amount of groundwater level lowering. Dewatered peat will create soil subsidence and can influence dangerous differential settlements of buildings and constructions. The stability study (RSK, phased RAP, annex 4, 2009) indicated that groundwater lowering deeper than 2 mbgl is not allowed. Therefore, the maximum excavation depth in the areas with constructions is 2 mbgl.

The source excavation removed 460 ton heavily contaminated soil. The deeper peaty fine sandy layer is still heavily contaminated. It is estimated that half of the original contamination mass is present in this layer.

Because of the limitations of aboveground constructions and because the contaminated deeper soil layer will remain in place, the excavation technique cannot be considered as a standalone remediation technique. The technique has to be used in combination with other remediation techniques in order to achieve the remediation targets.

The advantage of excavation is that it can remove in a short period a big amount of contaminant mass. This removal at the source zone shortens the following in-situ groundwater remediation. In the plume zone areas, less contaminant is adsorbed to the soil. Contaminant mass removal in these areas becomes less effective (see also economic feasibility).

As technique for remediation strategy 1, it would be the ideal technique and strategy in case site operations would cease, all infrastructure would be removed in view of developed for future use. However, since there is contaminant migration risk as long as the site is in operation, the contaminant migration needs to be contained by P&T. The full scale remediation includes the excavation, removal and off-site treatment of 6000 m³ of contaminated soil.

2.2 In-situ chemical oxidation using perozone

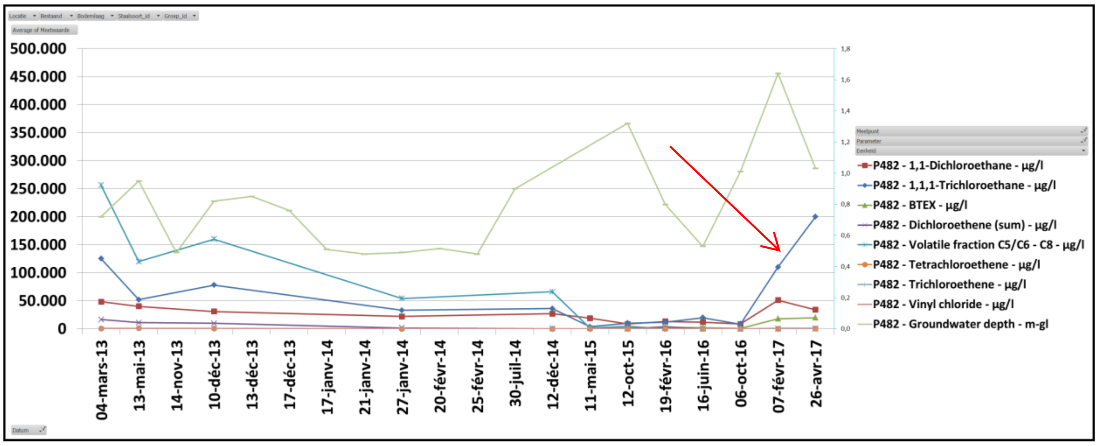
The feasibility of the in-situ chemical oxidation technique depends strongly upon the soil oxidant demand. The presence of organics (both natural and contaminants) influences the oxidant demand. The presence of shallow peat layers and NAPL in the source zone are influencing the duration of the ISCO treatment. This will be further discussed as part of the economic feasibility (see next paragraphs).

Technical feasibility depends also upon the soil permeability influencing the contact between oxidants and contaminants. The geology of the contaminated aquifer is given in table below.

Depth (m-gl)	Soil layers	Permeability
0 -1.9/3.6	Sand	Good
1.9/3.6 - 4	sandy loam, peat	Moderate
4 -5	Clay, peat	Very Low
5 -9	Clay	Very low

According to the ISCO pilot test (2010), the upper sandy layer is sufficiently permeable to apply ISCO remediation technique. However, the depth of the sandy layer differs from location to location (2 and 3 mg-gl). Underneath this sandy layer is a sandy loam layer with a high peat content which is nearly impermeable for oxidant distribution. The peat in this soil layer adsorbs organic contaminants better than inorganic soil particles and therefore the peaty soil layer functions as a reservoir from where organic contaminants can release (the so called back diffusion). This potential back diffusion influences negatively the efficiency of the ISCO treatment. This seems to be the case within the source zone area where NAPL has migrated vertically into the peaty loam and clay layers. This seems less the case in the plume zone areas.

The contaminant release (the back diffusion) from the deeper layer to the upper layer is illustrated in the figure below. This figure shows the contaminant evolution in groundwater well P482. The concentration of chloroethanes (111TCA and 11DCA) (near the excavated source zone) has been increasing after October 2016. This increase could be related to the contaminant release from the deeper contaminated soil layer. This release could be triggered by the lower groundwater level (see on the graph the light green line indicating the groundwater depth), by the 50% flow injection increase of ozone and hydrogen peroxide since July 2016, or by local unknown NAPL pockets. This will be further examined after the LIFE project.



In the plume zone areas (former drum storage area and central road zone), ISCO injection using perozone is very effective for oxidising organic compounds. Contaminant concentrations have continuously gone down and the goal has been reached in a period of several months (former drum storage area) to several years (central road zone). In the plume area, no back diffusion contaminant flux from the deeper layer is occurring. This indicates that the deeper layers are less contaminated and it confirms that this area is a plume area where less contaminant mass is adsorbed. Most of the mass is found in the groundwater and migrates horizontally through the permeable soil layers, which are being treated completely by injecting perozone.

During the project implementation, periodical subsidence measurements were conducted. There is no indication that soil subsidence or subsidence of storage tanks due to peat oxidation is occurring.

The aim of this LIFE project is to demonstrate the ISCO using perozone on Ex-rated industrial sites. During the first stage of the work laborious testing on the injection discharge and the ozone and hydrogen peroxide load was performed in order to prevent any ozone or contaminant flux to the vadose soil zone, underground facilities and ambient air. As extra safety measures, the ISCO injection was accompanied by shallow soil vapour extraction and regular (fortnightly at least) monitoring of ozone, oxygen, LEL and PID levels at different locations.

No mayor incidents and no safety issues occurred. A minor incident was related to the leakage of a hydrogen peroxide supply pipe in the tank park. During the project it was demonstrated that all known risks were managed at all times. The main conclusion is that a proper risk management should be completed with a pro-active communication, and committed, dedicated and experienced personnel.

2.3 Multi-phase extraction

Multi-phase extraction is considered as a special variant of P & T. The difference with the ordinary P & T is that not only groundwater is extracted but also soil vapours. Based on the composition of the cocktail of organic compounds (volatile components such volatile chlorinated compounds, volatile mono-aromatic and aliphatic hydrocarbons) and the locally high soil permeability, a significant reduction of the volatile components is expected through the soil air. Groundwater lowering in and around the MPE filters increases the vadose soil zone enabling the extraction of volatiles from the soil matrix.

MPE extraction is a feasible remediation technique, as it was shown that mass removal of volatile organic compounds was successful. This was shown during the first phase of the project (nearby the excavation zone). The MPE was stopped due to the high GAC consumption (6000 kg) in three months. Assuming a GAC load of 5%, 300 kg of organic contaminants were removed. Since high contaminant mass is present in the aquifer and since the authorities demanding zero-emission for GAC treatment, the cost of GAC consumption will be very high (see economic feasibility). Therefore, the vapour treatment by GAC is not very suitable.

Other vapour treatment techniques such as catalytic oxidation (catox) are more favourable when confronted with high contaminant masses. Catox treatment removes the volatiles of the vapour phase by incineration with an efficiency of 90% to 95%. Based on the average groundwater concentration at the project start, emission concentrations have been calculated and compared to the current emission standards of the Flemish environmental regulation for the industry (see table below). The table shows that the emission standards will not be exceeded. However, for remedial action works, the emission standard is subject to the BATNEEC[1] approach (cfr. Remediation of VOPAK ACS North, the site adjacent to VOPAK ACS South). This BATNEEC approach includes an optimisation of the combustion temperature (and energy cost).

We consider the catalytic oxidation as a feasible vapour treatment technique.

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[1] BATNEEC: Best available technique not entailing excessive costs

Tabel 2-1: Expected emission of catox vapour treatment

parameter	VLAREM emission limit value	VLAREM Mas flux	Emission concentration	Mass flux
	(mg/Nm³)	(g/u)	(mg/Nm³)	(g/u)
VC	5	25	0,24	0.05
DCE	150	3000	2.54	0.5
TCE	100	2000	0.23	0.05
PCE	100	2000	2.89	0.6
11-DCA	100	2000	8.25	1.7
111-TCA	100	2000	14.8	3.0
BTEX	5	25	2.9	0.6
Volatile TPH	-	-	10.4	2.1

3 ECONOMIC FEASIBILITY

3.1 Excavation after a period of P&T contaminant control

Because the site currently is operated, excavation of all contaminant mass can only occur when all industrial activities are stopped and all infrastructures has been demolished and removed. For the cost evaluation, we hypothetically assume that this is after 30 years of continued operation. In the meantime, contaminant migration has to be contained if there is a risk for migration. The remediation strategy consists of hydraulic containment by pump & treats during 30 years and followed by the excavation of the remaining contaminant mass.

As indicated by the table below, remediation costs are estimated to be 3.2 million euro (excl VAT). If no P&T measures are necessary (immediately excavation due to absence of industrial activities), the remediation costs is estimated to be 1.1 million euro (excl VAT). This cost includes the cost for excavation without any stability restrictions, removal and treatment of 6000 m³ contaminated soil. See annex for details. The annual cost for P&T is estimated at 62 500 euro (excl VAT).

Estimated remediation cost by excavation after a period of P&T contaminant control*

Overview				Total Cost
P&T (30 year)				1.906.764,50 €
Excavation				1.077.000,00 €
ISCO / BLE				- €
MPE				- €
Env Ass				170.000,00 €
Safety				44.000,00 €
Total (excl VAT)				3.197.764,50 €

*cost for the demolition of above ground infrastructure is not included

The cost of the P&T is based on a contaminant treatment by catalytic oxidation. GAC treatment would be too expensive as discussed in chapter 3.3 on MPE.

3.2 Source excavation and in-situ chemical oxidation using perozone

This remediation strategy is applied in the current LIFE project.

Contaminant degradation by perozone

The cost of the ISCO remediation is related to the duration of the remediation, which in turn related to the presence of contaminant mass. The duration of the ISCO treatment is limited by the maximum oxidant injection rate (in this project 50 g/hour of ozone). In the table below, the contaminant mass present in the different areas has been calculated using groundwater concentrations from 2013 and April 2017. Based on this data the expected timeframe needed for complete oxidation was calculated, assuming that 100% of the injected ozone is used for the degradation of volatile organic compounds. In reality, perozone reagents increase the oxygen in the aquifer resulting in aerobic degradation.

Estimation of the contaminant in the soil and groundwater of each zone (based on concentration in groundwater)

Contaminant mass (kg) in 2013		**Central road**		**near loading pump**		**tank park**	**former drum storage**			**big source**	**tank park**		**near excavation**			**Total**
Well		**P446**	**P463A**	**P448**	**P465A**	**P451**	**P462**	**P464**	**P473**	**P474**	**P475**	**P476**	**P481**	**P482**	**P483**	
Surface	m²	450,00	340,00	190,00	220,00	270,00	400,00	240,00	60,00	40,00	100,00	90,00	90,00	75,00	170,00	2735,00
depth	m	2,00	2,00	2,00	2,00	2,00	2,00	2,00	2,00	2,00	2,00	2,00	3,00	3,00	2,00	
volume	m³	900,00	680,00	380,00	440,00	540,00	800,00	480,00	120,00	80,00	200,00	180,00	270,00	225,00	340,00	5635,00
Totaal mass per zone	**kg**	23	46	7.061	8.640	42.072	2.770	547	13.037	245	13.758	2.265	16.470	13.574	726	121.233
Ozone consumption*	kg	61	123	19.064	23.327	113.594	7.480	1.478	35.200	662	37.145	6.116	44.470	36.651	1.959	327.329
Duration	year	*0,1*	*0,3*	*43,5*	*53,3*	*259,3*	*17,1*	*3,4*	*80,4*	*1,5*	*84,8*	*14,0*	*101,5*	*83,7*	*4,5*	747,3
Contaminant mass (kg) in april 2017		Midway		near loading pump		tank park	former drum storage			big source	tank park		near excavation			Total
Well		**P446**	**P463A**	**P448**	**P465A**	**P451**	**P462**	**P464**	**P473**	**P474**	**P475**	**P476**	**P481**	**P482**	**P483**	
Surface	m²	450,00	340,00	190,00	220,00	270,00	400,00	240,00	60,00	40,00	100,00	90,00	90,00	75,00	170,00	2735,00
depth	m	2,00	2,00	2,00	2,00	2,00	2,00	2,00	2,00	2,00	2,00	2,00	3,00	3,00	2,00	
volume	m³	900,00	680,00	380,00	440,00	540,00	800,00	480,00	120,00	80,00	200,00	180,00	270,00	225,00	340,00	5635,00
Totaal mass per zone	**kg**	306	59	550	221	29	n.a.	n.a.	2.772	59	41	53	1.918	4.940	22	10.971
Ozone consumption*	kg	826	161	1.484	598	80			7.486	159	111	142	5.179	13.337	60	29.622
Duration	year	*1,9*	*0,4*	*3,4*	*1,4*	*0,2*			*17,1*	*0,4*	*0,3*	*0,3*	*11,8*	*30,5*	*0,1*	67,6
ozon injection rate (kg/uur)	0,05	*2,7 kg ozon per kg organic contaminant;														

2.2 ton ozone and 33 ton of hydrogen peroxide has been injected as perozone. More hydrogen peroxide than ozone is injected. Perozone is created by coating nanosized to micro-sized bubbles of air-encapsulated ozone with a liquid oxidant (hydrogen peroxide), creating the 'perozone' oxidant. The reaction of this coating is presented below. In this reaction, free OH-radicals are formed, which creates a high oxidation potential. Due this high oxidation potential, different types of contaminants can be treated with perozone. In addition, oxygen is released during the reaction which enhances biological aerobic degradation.

$$2O_3 + H_2O_2 \longrightarrow 2OH\cdot + 3O_2$$

We have calculated stochiometrically that 2.7 kg ozone can degrade maximal 1 kg organic compounds. In reality, this will be higher depending upon geological factors (f.i. natural demand such as presence of organic matter, permeability, soil heterogeneity), the remediation installation and operation (f.i. distance of injection wells, flow rates) and type of organic contaminants (f.i. chlorinated, long of short chain hydrocarbons, volatiles). Some tests on ISCO using ozone mentions a tenfold or more than the calculated ozone degradation efficiency (on gasoil). Assuming the best case ozone degradation efficiency of 2.7 kg ozone per kg OC, the duration of the ISCO using perozone is more than 4 years with an ozone injection rate of 50 g/hr, if 650 kg of contaminant mass is present. This is the quantity of contaminant mass to be degraded under this ozone injection rate.

The contractor Verhoeve estimates a lower ozone use since the oxygen can degrade aerobically the BTEX and total petroleum hydrocarbons. Therefore, the ozone use is estimated at 1.5 kg per kg total petroleum hydrocarbons/BTEX and 0.5 kg per kg chlorinated solvents. 30% to 80% less perozone is needed than indicated in the table above. At perozone injection rate of 50 g/hr, 33 g/hr of petroleum hydrocarbons would be degraded.

The table above only gives an order of magnitude of the duration of perozone remediation. The duration is based on an estimation of the contaminant mass by groundwater analyses. For source zones (P473, P481 and P82), we consider a minimum duration of 12 to 17 years.

The evaluation of the contaminant mass by soil samples and NAPL will give a more realistic calculation of the perozone duration. The evaluation of the contamination mass in the excavation zone in 2012 by soil samples demonstrated the presence of total petroleum hydrocarbons (fraction C10-C40) consisting of 50% of the total contaminant mass in the saturated zone.

In reality, a cocktail of contaminants is present. Perozone is non-selective. Maximum concentration of contaminants is lower than indicated in the table above since the total sum of the contaminant mass to be degraded in a certain time should be taken into consideration.

Since perozone degradation is non-selective, the degradation of a type of contaminant is proportional to its contaminant mass. Perozone degrades mainly petroleum hydrocarbons (more than 95% of the total contaminant mass in source areas) and nearly no chlorinates solvents. Therefore, the groundwater concentration of volatile petroleum hydrocarbons decreases in sources zones, but the groundwater concentrations of chlorinated solvents remain quasi stable. In plume areas, relatively less volatile petroleum hydrocarbons than in source zones are present due to the high retardation (and absorption) than chlorinated solvents. Due to a relatively higher contaminant mass of chlorinated solvents in plume areas than in source areas, groundwater concentrations of chlorinated solvents are decreasing as a result of perozone injection.

Degradation of volatile petroleum hydrocarbons (C6-C10 fractions) could result in the formation of short chained gaseous hydrocarbons (C1-C4 fractions) such as methane,

ethane, propane and butane. This has to be further controlled, because this could have an impact on the removal of hydrocarbons.

On the other hand, oxygen is released as a result of the perozone reaction. (Volatile) petroleum hydrocarbons and monoaromatic hydrocarbons can be degraded aerobically not chlorinated solvents except DCE and VC. This aerobic degradation process is contaminant selective and favours again non-chlorinated hydrocarbons.

Applied remediation strategy

In 2012, the source zone at the central road was excavated. In 2013, ISCO and MPE were operational, but MPE was stopped after three months due to the costly GAC consumption. The second phase continued in 2014 with only ISCO remediation and soil vapour extraction through drains after optimising the perozone injection scheme. The different areas were treated in different phases, starting in January 2016 at the big source area in the tank park. The aquifer at the last treated area contains the highest contaminant concentrations and has only been treated during 15 months. However, near the excavated area the ISCO treatment is already in operation during nearly three years.

Starting in 2013, at an ozone injection rate of 50 g/hour, parts of the former storage area (P464), and the tank park (P474) and the central road (P446, P463A) can theoretically be treated with only ISCO using perozone within some years. In reality, these areas are effectively treated and concentration levels are below the clean-up standard as defined in the remedial action plan.

In April 2017 at the end of the life project, both source zone areas in the tank park (P473), near the loading pumps (P448 and P465A) and near the excavation zone (P481 and P482) still have to be treated. Concentrations of chlorinated solvents are quasi stable at this slow ozone injection regime. In these areas, NAPL is present and the contaminant release from the deeper soil layer could jeopardise the ISCO treatment.. Only ISCO using perozone in these source zone areas would not be economic feasible since the duration of the remediation is very uncertain and could be long.

However, in plume areas, where less contaminant mass is adsorbed to the soil matrix, ISCO remediation using perozone is possible within a reasonable time frame. Current results demonstrated the efficiency of ISCO remediation in the former drum storage area and at parts of the central road. At the end of the ISCO remediation, plumes areas are remediated. The remaining areas under ISCO treatment are to the former source zone areas. We can conclude the plume area treatment is economic feasible.

Assuming a remediation period of 8 years (duration is taken equal as for MPE strategy to compare both techniques, in reality duration could different, see report on validation in annex 7267), the remediation cost based on the current cost structure of the full scale remediation and environmental assistance was calculated. The electricity consumption of the ISCO remediation system and related costs also were considered (see also report on the benefits of the ISCO remediation in annex 7266 of the Final Report). The estimated remediation cost is presented in the table below.

The remediation cost is estimated at 1.5 million euro (excl VAT). The annual cost of ISCO is estimated at 134 000 euro (excl VAT).

Estimated remediation cost of source excavation and ISCO treatment

Overview				Total Cost
P&T				- €
Excavation				82.447,50 €
ISCO/SVE (8 years)				1.101.761,38 €
MPE (0,66 year)				- €
Env Ass				230.000,00 €
Safety				68.200,00 €
TOTAL (excl VAT)				1.482.408,88 €

The perozone injection rate is limited due to safety restrictions and directly influences the contaminant degradation rate and the remediation time. Additionally, the contaminant mass in the subsurface is higher than originally estimated. The big source area in the tank park was not identified prior to the project start up. Since contaminant degradation is non-selective and since more than 95% of the contaminant mass consist of volatile petroleum hydrocarbons, perozone degrades mainly the volatile petroleum hydrocarbons.

3.3 Source excavation and multi-phase extraction

For the feasibility study, the duration of the multi-phase extraction is estimated at 8 year. Similar to the ISCO remediation strategy, the source zone area at the central road (100 x 15) m is excavated under the imposed stability constraint (maximum excavation of 2 m-gl). 44 MPE filters are installed and connected to a MPE extraction unit (capacity less than 5 m³/hr). The water treatment consists of an influent buffer, sand filter and a unit which strips the volatiles to the vapour phase. This vapour phase is treated by granulated activated carbon filters or by catalytic oxidation.

The cost structure of the remediation system and energy consumption is based upon RSK's information and sources collected during its activities as a remediation expert. For both vapour treatment systems, the remediation costs are presented in the tables below. The remediation cost with catox and GAC treatment is estimated at 1.9 million euro (excl VAT) and 5,1 million euro (excl VAT) respectively.

Estimated remediation cost of source excavation and multi-phase extraction with catox

Overview				Total Cost
P&T				- €
Excavation				82.447,50 €
ISCO / BLE				- €
MPE -catox (8 year)				1.660.974,52 €
Env Ass				150.000,00 €
Safety				38.000,00 €
Total				1.931.422,02 €

Estimated remediation cost of source excavation and multi-phase extraction with GAC

Overview				Total cost
P&T				- €
Excavation				82.447,50 €
ISCO / BLE				- €
MPE - GAC (8 year)				4.827.878,16 €
Env Ass				150.000,00 €
Safety				38.000,00 €
Total				5.098.325,66 €

GAC soil vapour treatment is financial not feasible, leaving the catox treatment system the most economic. The annual cost of MPE with catox is estimated at 152 000 euro (excl VAT). This annual cost is higher than the annual cost of ISCO using perozone. MPE can only be advantageous on condition that the contaminant removal rate of MPE is higher than the contaminant removal rate of ISCO using perozone. Indicative, this contaminant removal rate should be more than 66 g/hr (double of ISCO). Since the contaminant removal is proportional to the contaminant mass, the removal rate can be easier obtained in the source zones.

4 SUMMARY AND CONCLUSION

At the VOPAK site, the excavation technique is not a standalone remediation technique due to stability restrictions. If the site is still operational, this technique has to be used in combination with other in-situ remediation techniques such as ISCO or MPE in order to achieve the remediation targets.

If a full scale excavation will be carried out after termination of industrial activities, contaminant containment using P&T needs to be implemented. The implementation of this containment system makes this remedial approach economic not feasible. Remedial cost for 30 year of P&T control and full-scale excavation are estimated at 3.2 million euro (excl VAT).

Based on current site conditions and constraints, two in-situ remediation strategies are possible: source excavation in combination with ISCO using perozone or multi-phase extraction. Both strategies limit the action to the shallow aquifer above the peaty soil layer at a depth of more than 2 m. The deeper soil layer in the source zone areas is heavily contaminated but insufficiently permeable to be treated by the in-situ remediation techniques. The duration of both in-situ remediation techniques depends upon the presence of NAPL and the release from the deeper soil layer.

Currently, the duration of ISCO treatment depends on the available contaminant mass in the subsurface. The remediation by ISCO using perozone is limited by the ozone injection rate imposed by the safety restrictions. Since contaminant degradation is non-selective and since more than 95% of the contaminant mass consists of petroleum hydrocarbons, perozone degrades mainly the petroleum hydrocarbons. Remediation using ISCO with perozone in the source zone areas is very uncertain (minimum 12-17 years) and could last longer. In the plume zone areas, the duration would be shorter (months to years) as already demonstrated during the LIFE project. Therefore, ISCO is considered as economic feasible in plume zone areas but not in source zone areas.

The MPE remediation of source zone areas would be more efficient because the removal rate of contaminant mass is proportional to contaminant mass present in the soil. MPE would be economic feasible on the condition that the high extracted vapour mass load istreated by catalytic oxidation. The GAC treatment is not feasible for high vapour masses. It should be evaluated at which extracted vapour mass load MPE is advantageous against ISCO using perozone using GAC or using catalytic oxidation as vapour treatment.

The estimated annual operational cost of ISCO using perozone is lower than that of MPE. However, the economic efficiency is determined by the contaminant mass removal rate, which is better for MPE. Therefore, the remediation time and cost of ISCO using perozone compared to MPE would be longer and higher in sources zones. The ISCO technique is most likely not economic feasible in source zones with NAPL and /or high concentrations.

Remediation strategy	Excavation	ISCO*	MPE-Katox*	MPE-GAC*
P&T (30 year)	1.906.764,50 €	- €	- €	- €
Excavation	1.077.000,00 €	82.447,50 €	82.447,50 €	82.447,50 €
ISCO / BLE	- €	1.101.761,38 €	- €	- €
MPE	- €	- €	1.660.974,52 €	4.827.878,16 €
Env Ass	170.000,00 €	230.000,00 €	150.000,00 €	150.000,00 €
Safety	44.000,00 €	68.200,00 €	38.000,00 €	38.000,00 €
Total (excl VAT)	3.197.764,50 €	1.482.408,88 €	1.931.422,02 €	5.098.325,66 €
*inclusif source excavation				
annual cost - in-situ remediation	62.598,40 €	133.987,79 €	152.024,32 €	

ANNEX

ANNEX 1
REMEDIATION COST ESTIMATION

SOIL REMEDIATION Vopak ACS Zuid
Remediation cost
Excavation after 30 year: P&T during 30 years; EA and H&S

Description	Unity	Quantity	Unit cost	Total cost
CONTRACTOR WORKS				
P&T control (during 30 years)				
Preparatory works				
Sawing concrete	m	600	25 €	15.000 €
Removal concrete cover	ton	375	5 €	1.688 €
Transport concrete debris	ton	375	6 €	2.250 €
Renewal concrete cover	m²	150	250 €	37.500 €
Excavation and soil treatment				
Ontgraven verontreinigde grond	m³	1125	5 €	5.625 €
Transport naar verwerkingscentrum en verwerken verontreinigde grond	ton	1912,5	50 €	95.625 €
Leveren, aanvullen en verdichten van aangevoerde aanvulgrond	ton	1912,5	10 €	19.125 €
Mob/demob sledebekisting	pce	1	1.000 €	1.000 €
Huur sledebekisting	week	10	700 €	7.000 €
Groundwater extraction and treatment				
Leverage and installation drains	m	300	70 €	21.000 €
Rent and maintenance extractionpump excl. energyconsumption	week	1560	50 €	78.000 €
Mob/demob water treatment (capacity 2 m³/hr)	pce	1	3.000 €	3.000 €
Rental and maintenance water treatement, excl. energy consumption	week	1560	300 €	468.000 €
Leverage and installation GAC	kg	0	3 €	0 €
Katox (100 Nm³/uur)	week	1560	500 €	780.000 €
Elektricity - katox	month	360	387 €	139.320 €
Electricity (excl catox)	kWh	525600	0,22 €	115.632 €
Consumable NaOH	week	1560	75 €	117.000 €
Subtotal				**1.906.765 €**
Excavation (after 30 years)				
Preparatory works				
Sawing concrete	m	240	25 €	6.000 €
Removal concrete cover	ton	1500	5 €	6.750 €
Transport concrete debris	ton	1500	6 €	9.000 €
Renewal concrete cover	m²	1500	250 €	375.000 €
Groundwater extraction and treatment				
Leverage and installation extractionfilters	pce	1	5.000 €	5.000 €
Rental groundwater extractionpumps excl. Energyconsumption	week	15	350 €	5.250 €
Mob/demob water treatment	pce	1	3.000 €	3.000 €
Rental groundwater treatment for groundwater lowering, excl. Energy consumption	week	15	500 €	7.500 €
Leverage and installation vGAC	kg	7000	3 €	17.500 €
Excavation and soil treatment				
Ontgraven verontreinigde grond	m³	6000	5 €	30.000 €
Transport naar verwerkingscentrum en verwerken verontreinigde grond	ton	10200	50 €	510.000 €
Leveren, aanvullen en verdichten van aangevoerde aanvulgrond	ton	10200	10 €	102.000 €
Mob/demob sledebekisting	pce	0	1.000 €	0 €
Huur sledebekisting	week	0	700 €	0 €
Subtotal				**1.077.000 €**
Environmental assistance and direction				
Preparatory works (remediation investigation, start, negotiation)	TP	1	10.000 €	10.000 €
Excavation	TP	0	10.000 €	0 €
In-situ remediation- installation	TP	1	10.000 €	10.000 €
In-situ remediation- follow-up/reporting	year	30	5.000 €	150.000 €
Subtotal				**170.000 €**
Safety				
Health&safety plan	pce	2	1.500 €	3.000 €
Firewarden	TP	1	5.000 €	5.000 €
Safetycoordination - excavation/installation	TP	1	6.000 €	6.000 €
Safetycoordination - excavation in-situ	year	30	1.000 €	30.000 €
Subtotal				**44.000 €**
TOTAL excl. VAT				**3.197.765 €**
VAT (21%)				**671.531 €**
TOTAL incl. VAT				**3.869.295 €**

SOIL REMEDIATION Vopak ACS Zuid
Remediation cost
Excavation, in situ ISCO + SVE, MFE, EA and H&S
duration (year) 8

Description	Unity	Quantity	Unit cost	Total cost
CONTRACTOR WORKS				
Excavation				
Preparatory works				
Sawing concrete	m	60	25 €	1.500 €
Removal concrete cover	ton	115	5 €	518 €
Transport concrete debris	ton	115	6 €	690 €
Renewal concrete cover	m²	150	250 €	37.500 €
Groundwater extraction and treatment				
Leverage and installation extractionfilters	pce	1	5.000 €	5.000 €
Rental groundwater extractionpumps excl. Energyconsumpiton	week	2	350 €	700 €
Mob/demob water treatment	pce	1	3.000 €	3.000 €
Rental groundwater treatment for groundwater lowering, excl. Energy consumption	week	2	500 €	1.000 €
Leverage and installation vGAC	kg	500	3 €	1.250 €
Excavation and soil treatment				
Ontgraven verontreinigde grond	m³	270	5 €	1.350 €
Transport naar verwerkingscentrum en fysicochemisch verwerken verontreinigde grond	ton	459	50 €	22.950 €
Leveren, aanvullen en verdichten van aangevoerde aanvulgrond	ton	459	10 €	4.590 €
Mob/demob sledebekisting	pce	1	1.000 €	1.000 €
Huur sledebekisting	week	2	700 €	1.400 €
Subtotal				**82.448 €**
ISCO / SVE (Phase 1 and 2 of LIFE project)				
Preparatory works				
Sawing concrete	m	900	25 €	22.500 €
Removal concrete cover	ton	563	5 €	2.534 €
Transport concrete debris	ton	563	6 €	3.378 €
Renewal concrete cover	m²	225	250 €	56.250 €
Installation				
Leverage and installation ISCO Injectionfilters	st	61	600 €	36.600 €
Leverage and installation of conducts and drains	m	450	70 €	31.500 €
Mobilisation injectionunits	st	1	20.000 €	20.000 €
Blower and soil vapour treatment (vGAK)	st	1	2.500 €	2.500 €
Rental and maintenance				
Period march 2013 - may 2017				
Blower and soil vapour treatment (vGAK)	week	214	125 €	26.750 €
ISCO-system (ozonegenerator; injectionnunits)	week	214	1.100 €	235.400 €
Consumable hydrogenperoxide	liter	27870	0,8 €	20.903 €
Energycost ozoneproduction	kg	2179	8,0 €	17.432 €
Consumable vGAK/wGAK	kg	1425	3,0 €	4.275 €
Electricity (excl ozonegenerator)	kWh	220752	0,2 €	48.565 €
Period june 2017 - may 2021				
Blower and soil vapour treatment (vGAK)	week	208	125 €	26.000 €
ISCO-system (ozonegenerator; injectionnunits)	year	8	57.000 €	456.000 €
Consumable hydrogenperoxide	liter	27870	0,8 €	20.903 €
Energycost ozoneproduction	kg	2179	8,0 €	17.432 €
Consumable vGAK/wGAK	kg	1425	3,0 €	4.275 €
Electricity (excl ozonegenerator)	kWh	220.752	0,2 €	48.565 €
Subtotal				**1.101.761 €**
MFE (only Phase 1 of LIFE project)				
Preparatory works				
Sawing concrete	m	320	25 €	inbegrepen in ISCO
Removal concrete cover	ton	200	5 €	inbegrepen in ISCO
Transport concrete debris	ton	200	6 €	inbegrepen in ISCO
Renewal concrete cover	m²	200	250 €	inbegrepen in ISCO
Installation				
Leverage and installation of MPE filters	pce	22	720 €	only during Life project
Leverage and installation of conducts	m	160	50 €	only during Life project
Dualphase extraction unit	pce	1	5.000 €	only during Life project
Water treatment / soil vapour treatment	pce	1	5.000 €	only during Life project
Katox (150 Nm³/uur)	pce	0	10.000 €	only during Life project
Rental and maintenance (march-dec 2013)				
Dualphase extraction unit	week	34	1.000 €	only during Life project
Water treatment / soil vapour treatment	week	34	750 €	only during Life project
Katox (150 Nm³/uur)	week	0	750 €	only during Life project
Consumable vGAK/wGAK	kg	6000	3,5 €	only during Life project
Disposal Ironsludge	kg	0	10,4 €	only during Life project
Elektricity (excl katox)	kWh	34689,6	0,2 €	only during Life project
Elektricity - katox	month	0	387 €	only during Life project

Consumable NaOH	week	0	100 €	only during Life project
Subtotal				**0 €**
Environmental assistance and direction				
Preparatory works (remediation investigation, start, negotiation)	TP	1	50.000 €	50.000 €
Excavation	TP	1	10.000 €	10.000 €
In-situ remediation- installation	TP	1	50.000 €	50.000 €
In-situ remediation- follow-up/reporting	year	8	15.000 €	120.000 €
Subtotal				**230.000 €**
Safety				
Health&safety plan	pce	3	1.500 €	4.500 €
Firewarden	TP	1	9.700 €	9.700 €
Safetycoordination - excavation/installation	TP	1	6.000 €	6.000 €
Safetycoordination - excavation in-situ	year	8	6.000 €	48.000 €
Subtotal				**68.200 €**
TOTAL excl. VAT				**1.482.409 €**
VAT (21%)				**311.306 €**
TOTAL incl. VAT				**1.793.715 €**

SOIL REMEDIATION Vopak ACS Zuid
Remediation cost
MPE, EA and H&S
duration (year) 8

Description	Unity	Quantity	Unit cost	Total cost
CONTRACTOR WORKS				
Excavation source				
Preparatory works				
Sawing concrete	m	60	25 €	1.500 €
Removal concrete cover	ton	115	5 €	518 €
Transport concrete debris	ton	115	6 €	690 €
Renewal concrete cover	m²	150	250 €	37.500 €
Groundwater extraction and treatment				
Leverage and installation extractionfilters	pce	1	5.000 €	5.000 €
Rental groundwater extractionpumps excl. Energyconsumption	week	2	350 €	700 €
Mob/demob water treatment	pce	1	3.000 €	3.000 €
Rental groundwater treatment for groundwater lowering, excl. Energy consumption	week	2	500 €	1.000 €
Leverage and installation vGAC	kg	500	3 €	1.250 €
Excavation and soil treatment				
Ontgraven verontreinigde grond	m³	270	5 €	1.350 €
Transport naar verwerkingscentrum en verwerken verontreinigde grond	ton	459	50 €	22.950 €
Leveren, aanvullen en verdichten van aangevoerde aanvulgrond	ton	459	10 €	4.590 €
Mob/demob sledebekisting	pce	1	1.000 €	1.000 €
Huur sledebekisting	week	2	700 €	1.400 €
Subtotal				**82.448 €**
ISCO / SVE during phase 1 and 2				
Preparatory works				
Sawing concrete	m	0	25 €	0 €
Removal concrete cover	ton	0	5 €	0 €
Transport concrete debris	ton	0	6 €	0 €
Renewal concrete cover	m²	0	250 €	0 €
Installation				
Leverage and installation ISCO Injectionfilters	st	0	600 €	0 €
Leverage and installation of conducts and drains	m	0	70 €	0 €
Mobilisation injectionunits	st	0	20.000 €	0 €
Blower and soil vapour treatment (vGAK)	st	0	2.500 €	0 €
Rental and maintenance				
Period march 2013 - may 2017				
Blower and soil vapour treatment (vGAK)	week	0	125 €	0 €
ISCO-system (ozonegenerator; injectionnunits)	year	0	57.000 €	0 €
Consumable hydrogenperoxide	liter	0	0,8 €	0 €
Energycost ozoneproduction	kg	0	8,0 €	0 €
Consumable vGAK/wGAK	kg	0	3,0 €	0 €
Electricity (excl ozonegenerator)	kWh	0	0,2 €	0 €
Period june 2017 - may 2021				
Blower and soil vapour treatment (vGAK)	week	0	125 €	0 €
ISCO-system (ozonegenerator; injectionnunits)	year	0	57.000 €	0 €
Consumable hydrogenperoxide	liter	0	0,8 €	0 €
Energycost ozoneproduction	kg	0	8,0 €	0 €
Consumable vGAK/wGAK	kg	0	3,0 €	0 €
Electricity (excl ozonegenerator)	kWh	0	0,2 €	0 €
Subtotal				**0 €**
MFE (only phase 1)				
Preparatory works				
Sawing concrete	m	320	25 €	8.000 €
Removal concrete cover	ton	200	5 €	900 €
Transport concrete debris	ton	200	6 €	1.200 €
Renewal concrete cover	m²	200	250 €	50.000 €
Installation				
Leverage and installation of MPE filters	pce	44	720 €	31.680 €
Leverage and installation of conducts	m	320	50 €	16.000 €
Dualphase extraction unit	pce	1	7.500 €	7.500 €
Water treatment	pce	1	7.500 €	7.500 €
Katox (150 Nm³/uur)	pce	1	10.000 €	10.000 €
Rental and maintenance				
Dualphase extraction unit	week	416	1.000 €	416.000 €
Water treatment (3 to 5 m³/hr)	week	416	750 €	312.000 €
Katox (150 Nm³/uur)	week	416	750 €	312.000 €
Consumable vGAK/wGAK	kg	0	3,5 €	0 €
Disposal Ironsludge	kg	0	10,4 €	0 €

Elektricity (excl katox)	kWh	1.776.666,0	0,2 €	390.867 €
Elektricity - katox	month	96	581 €	55.728 €
Consumable NaOH	week	416	100 €	41.600 €
Subtotal				**1.660.975 €**
Environmental assistance and direction				
Preparatory works (remediation investigation, start, negotiation)	TP	1	50.000 €	50.000 €
Excavation	TP	0	10.000 €	0 €
In-situ remediation- installation	TP	1	20.000 €	20.000 €
In-situ remediation- follow-up/reporting	year	8	10.000 €	80.000 €
Subtotal				**150.000 €**
Safety				
Health&safety plan	pce	2	1.500 €	3.000 €
Firewarden	TP	1	5.000 €	5.000 €
Safetycoordination - excavation/installation	TP	1	6.000 €	6.000 €
Safetycoordination - in-situ	year	8	3.000 €	24.000 €
Subtotal				**38.000 €**
TOTAL excl. VAT				**1.931.422 €**
VAT (21%)				**405.599 €**
TOTAL incl. VAT				**2.337.021 €**

SOIL REMEDIATION Vopak ACS Zuid

Remediation cost
MPE, EA and H&S
duration (year) 8

Description	Unity	Quantity	Unit cost	Total cost
Excavation source				
Preparatory works				
Sawing concrete	m	60	25 €	1.500 €
Removal concrete cover	ton	115	5 €	518 €
Transport concrete debris	ton	115	6 €	690 €
Renewal concrete cover	m²	150	250 €	37.500 €
Groundwater extraction and treatment				
Leverage and installation extractionfilters	pce	1	5.000 €	5.000 €
Rental groundwater extractionpumps excl. Energyconsumption	week	2	350 €	700 €
Mob/demob water treatment	pce	1	3.000 €	3.000 €
Rental groundwater treatment for groundwater lowering, excl. Energy consumption	week	2	500 €	1.000 €
Leverage and installation vGAC	kg	500	3 €	1.250 €
Excavation and soil treatment				
Ontgraven verontreinigde grond	m³	270	5 €	1.350 €
Transport naar verwerkingscentrum en verwerken verontreinigde grond	ton	459	50 €	22.950 €
Leveren, aanvullen en verdichten van aangevoerde aanvulgrond	ton	459	10 €	4.590 €
Mob/demob sledebekisting	pce	1	1.000 €	1.000 €
Huur sledebekisting	week	2	700 €	1.400 €
Subtotal				**82.448 €**
ISCO / SVE during phase 1 and 2				
Preparatory works				
Sawing concrete	m	0	25 €	0 €
Removal concrete cover	ton	0	5 €	0 €
Transport concrete debris	ton	0	6 €	0 €
Renewal concrete cover	m²	0	250 €	0 €
Installation				
Leverage and installation ISCO Injectionfilters	st	0	600 €	0 €
Leverage and installation of conducts and drains	m	0	70 €	0 €
Mobilisation injectionunits	st	0	20.000 €	0 €
Blower and soil vapour treatment (vGAK)	st	0	2.500 €	0 €
Rental and maintenance				
Period march 2013 - may 2017				
Blower and soil vapour treatment (vGAK)	week	0	125 €	0 €
ISCO-system (ozonegenerator; injectionnunits)	year	0	57.000 €	0 €
Consumable hydrogenperoxide	liter	0	0,8 €	0 €
Energycost ozoneproduction	kg	0	8,0 €	0 €
Consumable vGAK/wGAK	kg	0	3,0 €	0 €
Electricity (excl ozonegenerator)	kWh	0	0,2 €	0 €
Period june 2017 - may 2021				
Blower and soil vapour treatment (vGAK)	week	0	125 €	0 €
ISCO-system (ozonegenerator; injectionnunits)	year	0	57.000 €	0 €
Consumable hydrogenperoxide	liter	0	0,8 €	0 €
Energycost ozoneproduction	kg	0	8,0 €	0 €
Consumable vGAK/wGAK	kg	0	3,0 €	0 €
Electricity (excl ozonegenerator)	kWh	0	0,2 €	0 €
Subtotal				**0 €**
MFE (only phase 1)				
Preparatory works				
Sawing concrete	m	320	25 €	8.000 €
Removal concrete cover	ton	200	5 €	900 €
Transport concrete debris	ton	200	6 €	1.200 €
Renewal concrete cover	m²	200	250 €	50.000 €

Installation				
Leverage and installation of MPE filters	pce	44	720 €	31.680 €
Leverage and installation of conducts	m	320	50 €	16.000 €
Dualphase extraction unit	pce	1	7.500 €	7.500 €
Water treatment	pce	1	7.500 €	7.500 €
Katox (150 Nm³/uur)	pce	1	10.000 €	10.000 €
Rental and maintenance				
Dualphase extraction unit	week	416	1.000 €	416.000 €
Water treatment / soil vapour treatment	week	416	750 €	312.000 €
Katox (150 Nm³/uur)	week	0	750 €	0 €
Consumable vGAC/wGAC	kg	1.193.625	3,0 €	3.580.876 €
Disposal Ironsludge	kg	0	10,4 €	0 €
Elektricity (excl katox)	kWh	1.755.555	0,2 €	386.222 €
Elektricity - katox	month	0	387 €	0 €
Consumable NaOH	week	0	100 €	0 €
Subtotal				**4.827.878 €**
Environmental assistance and direction				
Preparatory works (remediation investigation, start, negotiation)	TP	1	50.000 €	50.000 €
Excavation	TP	0	10.000 €	0 €
In-situ remediation- installation	TP	1	20.000 €	20.000 €
In-situ remediation- follow-up/reporting	year	8	10.000 €	80.000 €
Subtotal				**150.000 €**
Safety				
Health&safety plan	pce	2	1.500 €	3.000 €
Firewarden	TP	1	5.000 €	5.000 €
Safetycoordination - excavation/installation	TP	1	6.000 €	6.000 €
Safetycoordination - in-situ	year	8	3.000 €	24.000 €
Subtotal				**38.000 €**
TOTAL excl. VAT				**5.098.326 €**
VAT (21%)				**1.070.648 €**
TOTAL incl. VAT				**6.168.974 €**