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Modelling human exposures to air pollution control (APC) residues released from landfills in England and Wales

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Abstract

Human exposures to air pollution control (APC) residues released from 6 landfills were modeled and assessed. Following a qualitative risk characterisation, direct and indirect exposures were quantified. Site-specific air dispersion modelling was conducted for PM_{10}, PCDDs/PCDFs, Pb, Cd, As and Cr^{VI} concentrations at the closest residential points of exposure for 4 landfill sites accepting, in total, 75 $\%^{w}/_{w}$ of the APC residues disposed of in 2000-2001 (UK). Inhalation risks, assessed by reference to air quality standards at residential exposure points were assessed as insignificant. Preliminary modelling suggested that indirect exposures from PCDDs/PCDFs at the 95^{th} percentile level for the site where APC deposition rates were highest, exceed the tolerable daily soil intake (TDSI) but warrant further study given model limitations. These results offer an initial screen of the significance of potential risks from APC disposal, which is of value in addressing concerns about the uncertainty of potential risks to human health from bulk APC disposal at strategic locations.

Keywords: air pollution control residues, risk, air quality impact, landfill, health

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1. Introduction

This study models human exposures to the air pollution control (APC) residues from municipal waste incinerators in England following their disposal to landfill. The research was initiated to help ensure the safe and effective management of these hazardous wastes at receiving landfill sites (Environment Agency, 2002). There are 11 municipal waste incinerators in England (Environment Agency, 2002). Most are located in and around major conurbations where landfills are more distant; with *ca.* two-thirds of the incineration capacity in England in London and the west Midlands (38.5% ^{w}/w and 30% ^{w}/w respectively). Each of the 11 facilities has been either recently (since 1996) commissioned or significantly modified to meet the requirements of the Waste Incineration Directive (2000/76/EC; European Parliament and Council of the European Union, 2000). The incinerators are employed at their design capacity, burning a total of *ca.* 2.65 MTpa (2002) of municipal solid waste (MSW). Between them, they recover heat to raise steam and generate a total of 197 MW_e of electricity for the national grid. In 2002, MSW accounted for *ca.* 90%^{w}/$_{w}$ of the waste burned by municipal waste incinerators, the rest being non-hazardous commercial and industrial waste, the greatest quantities of which were burned at the Edmonton and Lewisham sites in London (Environment Agency, 2002).

The potential public health risks from incinerators have been extensively reviewed (Rabl and Spadaro, 2002). Combustion gases from MSW incineration are acidic because materials in MSW contain chlorine and sulphur. The gases contain dioxins and furans (PCDDs/PCDFs) and high concentrations of fine particles (Basham and Whitwell, 1999; Weber *et al.,* 1999; Ma, 2002). Adding lime to neutralise excess acid cleans the exhaust gases and finely divided carbon is employed to remove dioxins and metals (Brna and Kilgroe, 1992). The fine ash particles, carbon and lime are removed by high efficiency bag filters. The carbon and fly ash contain most of the dioxins produced. The solid residues from

municipal waste incinerators, (i) bottom ash; and (ii) APC residues (the subject of this paper) are controlled wastes and regulated by the Environment Agency under the Environmental Protection Act, 1990. Methods for the safe disposal of these wastes have been summarised by Hjelmar (1996). Operators of landfills and treatment plant accepting bottom ash or APC residues require a permit from the Agency and are under a specific duty to ensure their activities do not harm the environment or human health.

1.1 Problem formulation and study rationale

This study was initiated before recent changes to hazardous waste legislation that have reduced the number of available outlets for APC residues. In 2002 within England and Wales, bottom ash was either landfilled, processed to produce an aggregate substitute or used in treatment plants. APC residues were either landfilled or used in licensed waste treatment plant to neutralise and/or solidify other hazardous wastes. In 2002, 88% $^{w}/_{w}$ of APC residues went directly to landfill (Environment Agency, 2002). The study reported here was initiated to assess the significance of the off-site risks associated with the landfill disposal of APC residues at the principal sites of bulk disposal. Off-site exposure may occur through APC residues becoming airborne with onward inhalation or through indirect exposure at some point distant from the site of disposal (Kosson *et al.*, 1996). On-site occupational risks were not the subject of this study.

To identify the disposal locations for APC residues, incinerators and energy-from-waste (EfW) plants in England and Wales were contacted and the relative amounts of APC residues disposed to a number of licensed landfills estimated. The Environment Agency (2002) identified 18 destinations for the disposal of APC residues - 12 landfill sites and 6 waste treatment plants. Of the 12 landfills, 6 received APC residues directly and 6 received treated wastes incorporating APC residues. The principal sites accepting APC residues (as of

September 2001; Table 1) were selected on the basis of available information on the relative amounts of APC residues disposed of in the year 2000-2001. Between them, the sites identified received 75 % $^{w}/_{w}$ of the total weight of APC residues (England and Wales) disposed of.

Having identified the principal locations, the study applied Government guidelines on environmental risk assessment and management (DETR *et al*., 2000; Figure 1) and, in the latter stages, focused on the site-specific assessment of potential exposures at key sites of concern using the best available data and a defensible, albeit conservative, modeling approach. The aim of the study was to assess the significance of these potential exposures adopting a modeling approach.

2. Methodology

2.1 Risk screening

A tiered risk assessment approach to the study was adopted consistent with current guidance in England and Wales (DETR *et al*., 2000; Figure 1). Relevant baseline information, *e.g.* volumes of APC disposed of, chemical characteristics, potential human exposure pathways and the proximity of potential receptors was collated from the published literature (Greenberg *et al*., 1978; Kosson *et al*., 1996), interviews with operational and technical staff and site visits. Summary information (Tables 2 and 3) was used to assemble a generalised conceptual model of exposure and to inform a qualitative risk-screening in which key exposure pathways, comprising source-pathway-receptor relationships of relevance, were identified. Environment Agency staff with regulatory responsibilities for these sites considered the applicability of the conceptual model to the APC landfill for which they had responsibility and confirmed, or otherwise, the likely existence of pollutant linkages at the sites. A sub-set of feasible pollutant linkages with a ‘medium’ or ‘high’ interim risk

characterisation (Table 4) was examined in more detail. Air dispersion modelling was employed to estimate air quality impacts and screen for the significance of exposures through direct inhalation. Indirect exposures were then assessed using a generic soil exposure assessment model.

2.2 Generic quantitative risk assessment –inhalation of airborne dusts

For inhalation exposures, two complementary air modelling approaches were adopted to provide a range of estimated dust emission factors from all of the potential dust release activities that might occur on landfill sites:

(i) a simple dust blow model incorporating deposition and dispersion components based on the USEPA's fugitive dust model (FDM), used widely to assess the influence of fugitive dust emissions from landfills and similar industrial activities (Fisher and Macqueen, 1981; Cowherd *et al*., 1988) and

(ii) the application of AERMOD (Cimorelli *et al.,* 1998), a USEPA air dispersion model designed to predict pollutant concentrations from continuous point, area and open pit sources. This enables the concentrations of windblown APC dusts and contaminant concentrations at nearby human receptors to be estimated. Application of the two approaches is described below.

2.2.1 Simple dust blow model (SDBM)

Defensible source term data are essential for risk assessment but difficult to obtain on account of the complexities of site topography, waste characteristics and local meteorological conditions. The generation of windblown dust is an important release mechanism for inhalation exposures and has historically been characterised by an analytical model describing the dispersion and settling of dust particles (Fisher and Macqueen, 1981). The

relationship is described by a single formula (Ermak, 1977) and the sensitivity of results to assumptions regarding the dispersion and deposition of particles can be tested with ease. The formula (Ermak, 1977) provides the theoretical basis of the USEPA fugitive dust model (FDM), a computerised Gaussian plume dispersion model developed by the USEPA for estimating airborne particulate concentrations (USEPA, 1995). The FDM employs an advanced gradient transfer particle deposition algorithm (Horst, 1977; Hanna *et al.,* 1982) but no explicit expression of the dust source term - this has to be supplied by the user.

Here, the analytical formulae in the dustblow model were setup in an EXCEL™ spreadsheet. Site operations that lead to the generation and emission of dust include (i) vehicle movements over previously deposited waste; (ii) wind erosion from recently deposited friable waste (before natural crusting of the surface binds material together); and (iii) release when the waste is deposited on the landfill (DoE, 1994; Table 2). Estimates of the potential dust emission factors from wind erosion of deposited APC residues were made using USEPA (1995) and DoE (1994) for both storage piles and exposed surfaces. It was assumed that daily disturbance of deposited piles would allow the surface to dry sufficiently for erosion to occur. The simple dust blow model calculates the wind shear stress at the surface and the threshold velocity above which erosion and dust release takes place. The simple dust blow model uses the AP-42 emission factors (USEPA, 1995) for dustblow including the particle size relationship (Table 5). The relationship (USEPA, 1995) was used to estimate the emissions (Table 6) of PM_{10} and PM_{30} particles, taking no account of dust suppression or rainfall. Generally, significant emissions of dust were associated with wind erosion from APC residues when wind speeds were greater than 6m/s and where recently deposited waste piles were spread to form an even layer. The amounts of APC residues released per disturbance event were expressed as an emission rate per day (Table 6) in order

to generate downwind concentrations of respirable dust and contaminants, and to allow comparisons with air quality standards for airborne dust (Table 7).

2.2.2 Limitations in the estimation of source terms

Significant approximations are entertained when applying these modelling techniques to episodic source terms to generate estimates of the impact on air quality (Sax and Isakov, 2003). Generalised assumptions included in the empirical relationship of dust generation include the silt and moisture content of the surface material and the mean vehicle weight. The resulting source term estimate is presented as a mass of APC residue emitted per vehicle-kilometre. Uncertainties in the source term model and in approximating the operating area of the landfill propagate further once air dispersion modelling is undertaken using a simple dust blow model (SDBM). Further, the particle size determines the likely distance that particles will travel. Large particles greater than about 100 μm diameter are likely to be deposited within a few tens of metres of their point of release. Given the necessities of approximation, verification of the model was attempted through comparison with a risk assessment already undertaken for the Wigmoor Farm Landfill, Bishops Cleeve and available site monitoring data (Applied Environmental Research Centre, 2001). These simplifications also mask an important reality that source term generation at operational waste management facilities is mostly episodic and short-term, consistent with operational cycles. Thus, comparing averaged concentrations to long term air quality standards, therefore, must be undertaken with caution.

2.2.3 Estimating dust emissions using AERMOD

AERMOD, the American Meteorology Society-Environmental Protection Agency Regulatory Model, is a stationary new generation dispersion model designed to predict

pollutant concentrations from continuous point, flare, area, line, and volume sources. Terrain effect was modelled and dust deposition was predicted at selected receptor locations downwind of the landfill site (Table 7). Concentrations were compared, where available, to the statutory UK air quality objectives (Table 7) and, for PM_{10}, to background concentrations at the nearest automatic monitoring network location (Table 8).

Amenity impacts from waste management activities are of increasing interest. The lower nuisance threshold for dust deposition is often taken to be 200-350 mg/m^2/d averaged over a month (Anon, 1986; Bate and Coppin, 1990; North Ayrshire Council, 2000), with a 'likely nuisance' level of 650 mg/m^2/d. Here, the lower threshold was used as a criterion for assessing the nuisance potential of APC deposition rates (Table 9).

2.3 Generic risk assessment - indirect exposures through ingestion and consumption

Whilst inhalation offers a direct route of exposure for airborne dust, indirect exposures may also occur through the deposition and subsequent uptake of contaminants from the soil (Harrop and Pollard, 1998). Here, the Contaminated Land Exposure Assessment (CLEA) (Environment Agency and Defra, 2002) model was used to estimate indirect exposures to key contaminants in APC residues deposited at receptor locations downwind of disposal sites. CLEA has been developed to generate generic soils guideline values for contaminated land in the UK. Information can, however, be incorporated into the model to inform estimates of exposure from more specific circumstances; for example, the consumption of allotment grown vegetables. CLEA was employed to estimate daily intakes for receptors of concern (e.g. a local child) and exposure estimates for evaluating the significance of potential risks to human health.

The CLEA model consists of a number of generic fate and transport algorithms that are normally reviewed and adapted, where necessary, to the requirements of a specific

compound before the soil guideline value is produced. Whilst this process has been carried out for the metals (lead, cadmium, chromium and arsenic), this is not the case for dioxins and furans. Hence, the model has not been properly validated for dioxins and the results should therefore be treated with caution. CLEA does not allow consideration of a source term increasing over time (such as annual deposition for a number of years) nor take account of changing fluxes in the source term. Further, at present, a critical pathway, the deposition of particulates on the leaves of fruit and vegetables, was not modelled in this screening assessment. A number of critical adaptations and assumptions were therefore required:

(i) it was assumed that deposition occurs at a constant annual rate and that deposited dust is mixed evenly into the top 0.1m of the soil;

(ii) a 6-year deposition period was assumed with the concentration at the end of the sixth year being assumed to have been present from the start. This is a conservative assumption and consistent with the exposure duration used in CLEA to assess risks to children from exposure to soil contamination;

(iii) local onward mobilisation of contaminated dusts was assumed to be negligible compared to the primary flux to the site and the relative contribution from other exposure pathways such as ingestion;

(iv) the most sensitive receptor and standard land-use was considered to be a female child aged 0-6 in a residential setting where the family consumes its own homegrown produce.

3. Results and discussion

3.1 Generic risk screening

From 31 potential pollutant linkages identified from the prior literature, reports and through initial interviews with Agency staff in the risk screening stage, seven were assessed

as key, with risk rankings of medium or high (Table 4). These were used as the basis for undertaking the site –specific assessment.

3.2 Generic risk assessment – inhalation of dusts

Application of the key generic linkages (Table 4) within a site-specific context by regulatory staff resulted in only four of the six sites being considered for site-specific assessment (Table 7). Two sites, Meece and Himleywood, had APC residues delivered and disposed of in sealed nylon bags with the reasonable presumption that a negligible probability of exposure to nearby human receptors existed.

3.2.1 Simple dust blow model

The emission rates in Table 6 were associated with wind erosion from APC residues in the case where recently deposited waste piles were periodically spread to form an even layer. These were in agreement with previously reported studies on the transport of APC residues from landfill sites (AERC, 2001). Through sensitivity testing with the SDBM (not presented here for brevity), it was established that:

(i) the particle sizes of the APC residues released from the landfill sites determine, in part, the distance the particles will travel;

(ii) moisture contents less than 20%$^{w}/_{w}$ result in increased dust release;

(iii) wind speeds greater than 6m/s are needed for significant erosion of dusts from active landfill cells; and

(iv) vehicle movements across bare APC residue leads to increased dust release.

The main uncertainties in the model are the source terms describing the amount of material becoming airborne and the size distribution of these particles. The source terms used were conservative and did not allow for rainfall that would contribute to dust suppression.

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3.2.2 AERMOD dispersion of APC residues

Data from the AERMOD air dispersion modelling are presented in Table 7. The air quality standards or objective were not exceeded at any human receptor for any of the landfill sites studied (using 1997 meteorological data) based on the site-specific emissions rates. Additional analysis using meteorological data from 1995, 1996 and 1997 indicated pollutant concentrations typically <10% of the air quality strategy objectives at the 90^{th} percentile. Using a reasonable worst case scenario of two source areas of 14 560 m^2 (88m x 145m and 40m x 45m) emitting 1000 mg APC residue/m^2/d, the PM_{10} air quality objective was not exceeded. Predicted PM_{10} concentrations in Table 7 were, at maximum, *ca.*10% of the measured annual mean background PM_{10} concentrations close to these sites (Table 8).

3.3 Generic risk assessment – indirect exposures

Deposition data for APC residues in soils are presented in Table 9. For Pb, Cd, As and Cr^{VI}, volume averaged soil concentrations are very low. Assuming a uniform mixing of APC residues in the top 0.1 m of soil for six years resulted in concentrations for most contaminants of < 1 mg/kg, and in many cases, < 100 μg/kg. The estimated soil concentrations for the site with the highest predicted deposition rates are presented in Table 10. The highest soil concentration is for Pb at *ca.* 15 mg/kg and this can be compared with typical soil lead concentration of between 10–30 mg/kg in many areas of the UK (Davis, 1995).

Comparison of these modelled metals concentrations to UK soil guideline values indicate that these concentrations would not present regulatory concern with respect to risks to human health. For the highest deposition rates, in excess of 100 years' deposition would be required for Pb and Cd and more than 1000 years for As and Cr^{VI} for concentrations to meet the soil guideline values. This said, two issues warrant further consideration. The calculations above, for a hypothetical site, assume that the soil is not already contaminated with metals found

in the APC residues. It might be the case that background or point-source contamination of the soil could be close to, or above the levels indicated by the soil guideline values, in which case further deposition of dust may be more significant. In addition, both As and Pb are considered to be non-threshold substances by the UK Department of Health under which concentrations in soil are subject to ALARP risk management principles where even small additions to the soil must be considered by reference to the cost and benefits of control.

In the case of dioxins (expressed in terms of 2,3,7,8-TCDD toxic equivalents; TEQs), CLEA was used to assess exposure at Glebe Farm (Table 10). The CLEA model has not been externally validated for dioxins. The results are tentative and demand qualification. The estimated soil concentration for the highest deposition rate was 8 ng TEQ/kg of soil. This is within the typical mean soil concentration of 3 to 23 ng TEQ/kg reported in the UK and elsewhere for PCDD/PCDFs in rural and urban soils (Duarte-Davidson et al., 1997). The average daily human exposure (ADE) to the critical receptor was estimated to be 0.8 pg TEQ/kg bw/day, which is twice the health criteria value derived for dioxins (0.4 pg TEQ/kg bw day; Defra and Environment Agency, 2003). Based on this initial assessment, it would be useful to explore this exposure assessment further using more realistic parameters and to refine the CLEA model to allow for the derivation of soil guideline values for PCDD/PCDFs and this is currently under consideration.

3.4 Key limitations and uncertainties

An exposure assessment was undertaken for a representative number of sites using a limited data set. There are a number of uncertainties that affect the results of any such assessment and these could lead to a larger or smaller risk of exposure. The results presented here can only be described as an indication of the likely risks posed by the contamination. Further sampling, analysis, and a more detailed risk assessment would increase the

confidence in these results. However, the assumptions underlying exposure assessment were carefully selected, making it necessarily conservative at this stage. A number of important uncertainties that need to be considered when considering the outcome of this study:

(i) *Source term considerations* – estimating the mass of APC residue likely to be lost from the site has large levels of uncertainty associated with it. The main contributors to the source term are included and are hypothetically large and designed to incorporate smaller non-quantifiable sources.

(ii) *Dispersion and indirect exposure modelling* – modelling is reliant on the quality and quantity of the data supplied. Key parameters have been estimated and would need to be refined to reduce uncertainties associated with the estimates. A conservative approach was taken to counter these uncertainties.

(iii) *Contaminants assessed* – only a few selected contaminants were assessed. These were selected on the basis of concentrations reported in APC residues and the health effects that might result from exposure to these contaminants. The reported TEQ levels, for example, only account for dioxins and furans. The contribution of dioxin-like PCBs was not considered. If incorporated, this would lead to a higher TEQ daily intake than that estimated here. Similarly only those metals deemed hazardous to human health were assessed.

(iv) *Exposure dynamics* - the CLEA model does not allow any consideration of a soil source term that is increasing over time (such as continuation of annual deposition for a number of years) nor does it take account of changing fluxes in this source term. CLEA is designed to deal with the risk posed by historical soil contamination.

4. Conclusions

A generic risk-screening approach was developed for the potential pollutant linkages that exist at landfill sites accepting APC residues. Potential exposures were modelled using data from the literature, not site monitoring data. The results provide an indication of the relative magnitude of the risks posed. They are generic, and do not reflect all exposure circumstances at all locations. The following conclusions demand qualification given the assumptions adopted.

1. Seven important pollutant linkages were identified with medium and high risk to human health. These considered the atmospheric transport and subsequent direct and indirect exposure to nearby workers and residents. The key pollutant linkages were potentially present at 4 of the 6 landfill sites studied.
2. Direct exposure through ingestion and inhalation are the critical exposure pathways.
3. Dust does not appear to be of major concern give the deposition rates modelled. However, it would be prudent to control dust release through the enforcement of control measures in the permit conditions and working plans.
4. The main APC landfill site (> 40% of the total APC residues disposed in 2000-1) was found not to cause significant release of APC residues that reached the nearby receptors. The predicted annual mean of PM_{10} at the nearest sensitive human receptor was 1.8 $\mu g/m^3$, significantly lower than the air quality strategy objective of 40 $\mu g/m^3$.
5. The long term accumulation of dioxins from deposited dust are tentative and warrant further study. Indications in this work are that indirect exposures require more detailed investigation.
6. On the basis of this preliminary analysis, the disposal of APC residues at landfill sites does not appear to pose significant harm to nearby human receptors. However, this

assessment was made using a restricted data set and more information is required to fully understand the nature of the hazard.

7. Future work will have the opportunity to utilise updated research on APC residues and their characteristics (WRc, 2004).

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Table 1. Summary of APC residue disposal at landfill sites in 2000-2001 (April-April), based on 10 /12 returns from incinerators as of 14th September 2001

Landfill site	Type of landfill	APC receipt (t/yr)	% E&W total	Method of disposal
Wigmoor Farm	monofill hazardous waste landfill, lined with clay.	32 479	41.3	pre-treated on site and disposed of to open cells.
Sidegate		5 331	6.8	arrives in dry form and treated on site prior to disposal
Dorkethead	engineered	4 433	5.6	buried immediately on deposit and covered immediately
Bilsthorpe		1 816	2.3	-
Himley Wood[1]		8 828	11.2	delivered in nylon bags
Meece[1]	mixed disposal site with composite liner of engineered clay and Bentomatt.	6 472	8.2	delivered in nylon bags and buried in trench and covered in MSW.

[1] not considered for detailed risk assessment

Table 2. Information on generic APC disposal practice pertinent to qualitative risk assessment including that summarised in Environment Agency (2002)

A. Source of hazard
APC residues are transferred from incinerators to treatment sites and treated before final disposal at licensed landfill sites, the treatment site may or may not be in the same location as the landfill site. Treatment of APC residues varies with location. Treatment involves the controlled mixing of the APC residues with a variety of waste liquids, including landfill leachates and industrial waste fluids. To reduce the source of the hazard 'ordinary control procedures' are required, for example use of daily and intermediate cover. Assessment of the source needs to include all potential dust releasing operations and scenarios where emissions can take place, for example, disposal of APC residue to a raised void will increase potential for wind erosion of material.
B. Hazard
APC residues are potentially hazardous due to their: high pH (pH 11-12.5); high levels of PCDD/F 2500 ng I-TEQ / kg; Pb 5000 mg/kg; Cd 250 mg/kg; As 200 mg/kg; and Cr (vi) 116 mg/kg) (maximum concentrations taken from analysis). APC residues are 'dust like' due to their particulate nature with small diameters (<100 µm), with the potential for atmospheric transport under energetic conditions. Data from one analysis indicates that 100% of APC residues were smaller than 63µm, with 50% smaller than 12µm. Waste Management Licence may have protocols for sampling APC residues and determining their chemical content, this should be carried out by the producer of the waste disposal site.
C. Transport mechanisms
Potential sources for atmospheric APC residue release, include: accidental release from APC residue delivery vehicles; waste transfer stations; loading waste treatment silos; loading open dumper trucks; transfer to active landfill cells; and activities at active landfill cell. Available evidence suggests that dioxins have low volatility [some dioxins, i.e. the lower chlorinated ones are semi-volatile] to undergo appreciable evaporation from ash disposal sites. The potential and extent of any dust release is based on the amount of APC residues being disposed and the method of disposal. Depending on whether the APC residues are mono- or co-disposed influences the potential for the transport of APC residues off site. Co-disposed APC residues tend to be covered daily. Mono-disposal sites may not use daily cover.
D. Pathways
Atmospheric transport of dusts is the main potential pathway for identified hazards reaching a nearby human receptor. Appreciable exposure only likely to occur when a young child is present on the site, perimeter fences should mitigate against this. Leachates recirculated or collected for off-site disposal. All potential exposure pathways need to be included in risk assessments.
E. Targets / receptors and exposure
Risk assessments and licence conditions need to include fundamental aspects of current operations and monitoring programme e.g. they need to include dust sources other than active cell and minimum moisture content of 20%. Predicted APC deposition rates are well below nuisance threshold quotes for all receptors at Wingmoor Farm landfill site. Use of 'more realistic' scenarios in applicants risk assessment, may not be conservative enough. Evidence is needed that these accurately represent the operations of the site. Dispersion modelling based on a Gaussian decay curve indicate an approximately 100-fold reduction in dust levels over the minimum distances between the tipping face and the perimeter of the site.

Table 3. Composition of selected APC residues from a range of literature sources

determinand	study reference					
	WRc 2000 (range)	Tyseley (range)	EA S-90456	EA S-90455	Bolton (hall)	SELCHP
pH	12.2-12.5	-[2]	12.4	12.5	-	-
organic carbon (%^{w}/$_{w}$)	1.6-4.0	-	-	-	-	1.7-2.0
dioxins I-TEQ (ng/kg)	-	2402-2598	4180	88	450-653	1256
polynuclear aromatic hydrocarbons (mg/kg)	-	-	-	-	-	270
chloride (mg/kg)	111000-207750	197100-236000	-	-	-	-
sulphate (mg/kg)	2600-14250	58800-94900	-	-	-	-
iron (mg/kg)	646-7844	3900-7800	4400 (0.7)[1]	1700 (0.42)	-	3740
manganese (mg/kg)	94-486	268-404	280 (<0.5)	210 (<0.4)	297 (<0.03)	431
copper (mg/kg)	37-769	623-1067	370 (0.7)	66 (<0.4)	435 (<0.08)	386
zinc (mg/kg)	829-13950	12600-17600	8100 (40)	650 (<0.4)	-	6580
nickel (mg/kg)	3-36	<1-89	20 (<0.5)	9 (<0.4)	19 (<0.33)	22
chromium (mg/kg)	11-113	51-324	100 (0.7)	41 (<0.4)	68 (1.04)	12
lead (mg/kg)	422-5331	4300-6000	2000 (280)	140 (1.4)	2420 (215)	2690
cadmium (mg/kg)	20-215	190-516	94 (<0.5)	5 (<0.4)	122 (<0.06)	103
mercury (mg/kg)	11-30	2-25	6 (0)	<2	11 (<0.27)	12
arsenic (mg/kg)	200	2-166	<20	<20	24 (<0.9)	14
aluminium (mg/kg)	17000	17300-29700	28000 (0.8)	9000	-	-
barium (mg/kg)	250	147-952	-	-	-	72
cobalt (mg/kg)	10	9-620	-	-	-	9
antimony (mg/kg)	450	-	-	-	-	-
tin (mg/kg)	500	940-1438	-	-	60 (<1.7)	271
vanadium (mg/kg)	30	16-175	-	-	-	-
fluoride (mg/kg)	1500	2-54	-	-	-	-

[1] as leachable (mg /kg)

[2] not determined

Table 4. Summary of key pollutant linkages identified from the qualitative risk screening exercise

No.	Source of hazard	Pathways	Receptors	Probability of exposure[1]	Consequences[2]	Interim qualitative risk characterisation [3]	Justification for interim risk characterisation
1	PCDD/Fs	Inhalation of airborne dust	Local residents/workers.	Medium	Severe	High	Direct pathway, high load, assumes close proximity to site and outdoor exposure, high potency.
2		Incidental ingestion of soil, dust	Local residents, particularly children.	Medium	Severe	High	Indirect pathway, low load dispersion but local hot spots, limited intake, high potency.
3		Ingestion of maternal breast milk.	Local breast-fed babies.	Medium	Severe	High	Indirect pathway, low load, limited uptake and storage by mothers, local hotspots where mother is long term resident regularly consuming home grown produce, bioaccumulation in fatty tissue and release through breast feeding, high potency.
4		Consumption of contaminated produce	Residential consumers of home grown produce (fruit and vegetables).	Low	Severe	Medium	Indirect pathway, low load, removal due to rainfall and washing produce, assumes root crops unpeeled, limited contribution to diet, high potency.
5		Consumption of contaminated dairy and meat products.	Consumers of locally produced dairy and meat products (eggs and poultry).	Medium	Severe	High	Indirect pathway, low load but local hotspots adjacent to site, limited transfer to dairy and meat products, evidence of bioaccumulation in eggs and poultry, high potency.
6	As, Pb, Cd, Cr^{VI}	Inhalation of airborne dusts.	Local residents.	Medium	Severe	High	Direct pathway, high load, assumes close proximity to site and outdoor exposure, known health effects
7		Incidental ingestion of soil, dust.	Local residents.	Medium	Severe	High	Indirect pathway, low load, dispersion but local hot spots, limited intake, known health effects.

1 Key: Probability of exposure

Probability of exposure is defined as the likelihood of the receptors being exposed to the hazard.

High: direct exposure likely with no / few barriers between hazard source and receptor; medium: feasible exposure possible - barriers to exposure less controllable; low: several barriers exist between hazards source and receptors, to mitigate against exposure; negligible: effective, multiple barriers in place to mitigate against exposure.

2 Key: Consequences

The consequences of a particular hazard being realised may be actual or potential harm to human health, incorporating spatial and temporal extents of potential harm and reversibility. Assumes child as most sensitive human receptor.

Severe: there is sufficient evidence that short- or long-term exposure to chemical may result in serious damage to health (e.g. death, clear functional disturbance or morphological changes which are toxicologically significant). Latency of effect and irreversibility (during or following exposure) should be considered here; moderate: there is sufficient evidence that exposure to chemical may result in health effects that are not severe in nature and are reversible once exposure ceases (e.g. irritant); mild: health effect not apparent though chemical exerts reversible physiological and/or pathological changes (e.g. biochemical, haematological changes or enzyme induction but no other apparent effect); negligible: no evidence of adverse health effects and/or physiological and pathological effects following exposure to chemical.

3 Qualitative evaluation of the significance of the risk

Determined by combining the probability of the consequences (i.e. probability of (a) the hazard occurring; (b) the receptor being exposed to the hazard and (c) harm resulting from that hazard) and the magnitude of the consequences.

Table 5. Emission factors used for a range of particle sizes

Particle diameter (μm)	30	<15	<10	<2.5
Emission factor	1.0	0.6	0.5	0.2

Table 6. APC source term release assumptions adopted

Dust sources	PM_{10} ($mg/m^2/day$)[a]	PM_{30} ($mg/m^2/day$)[a]	landfill average and range ($\mu g/m^3$)[b]
Total	1000	3000	13 (0-158)

[a] reasonable worst case emissions rates calculated using the simple dust blow model
[b] values measured at other landfill sites and comparable industrial sources

Table 7. Pollutant concentrations at receptor locations from primary landfill source estimated using site-specific emission terms.

		PM_{10}		annual mean				
landfill AQ stds/objectives Source	human receptors at (location; m from source)	90.2 %ile of daily mean ($\mu g/m^3$) 50 DETR air quality strategy objectives 2000	PM_{10} annual mean ($\mu g/m^3$) 40	PCDD/F μg I-TEQ/m^3) none set	Pb ($\mu g/m^3$) 0.5	Cd ($\mu g/m^3$) $5.0x10^{-3}$ WHO 2000	As ($\mu g/m^3$) 0.2 EA assessment level	Cr^{VI} ($\mu g/m^3$) 0.1
Wigmoor Farm	Wigmoor farm; 100	5.5	2.1	$5.1x10^{-9}$	$1.0x10^{-2}$	$5.1x10^{-4}$	$4.1x10^{-4}$	$2.4x10^{-4}$
	Glebe farm; 690	2.0	$7.0x10^{-1}$	$1.8x10^{-9}$	$3.5x10^{-3}$	$1.8x10^{-4}$	$1.4x10^{-4}$	$8.2x10^{-5}$
	Hayden; 450	5.5	1.8	$4.4x10^{-9}$	$8.9x10^{-3}$	$4.4x10^{-4}$	$3.5x10^{-4}$	$2.1x10^{-4}$
	Court farm; 610	$7.2x10^{-1}$	$3.2x10^{-1}$	$8.0x10^{-10}$	$1.6x10^{-3}$	$8.0x10^{-5}$	$6.4x10^{-5}$	$3.7x10^{-5}$
	Rugby ground; 570	1.7	$5.4x10^{-1}$	$1.3x10^{-9}$	$2.7x10^{-3}$	$1.3x10^{-4}$	$1.1x10^{-4}$	$6.3x10^{-5}$
	Cattery; 500	1.2	$4.6x10^{-1}$	$1.1x10^{-9}$	$2.3x10^{-3}$	$1.1x10^{-4}$	$9.1x10^{-5}$	$5.3x10^{-5}$
Sidegate	Hillside farm; 960	$1.3x10^{-3}$	$4.0x10^{-4}$	$1.0x10^{-12}$	$2.0x10^{-6}$	$1.0x10^{-7}$	$8.0x10^{-8}$	$4.6x10^{-8}$
	House 1; 375	$3.5x10^{-3}$	$1.5x10^{-3}$	$3.8x10^{-12}$	$7.5x10^{-6}$	$3.8x10^{-7}$	$3.0x10^{-7}$	$1.7x10^{-7}$
	Finedonhill farm; 450	$1.2x10^{-3}$	$5.7x10^{-4}$	$1.4x10^{-12}$	$2.9x10^{-6}$	$1.4x10^{-7}$	$1.1x10^{-7}$	$6.6x10^{-8}$
Dorkethead	Road; 185	$1.9x10^{-2}$	$7.5x10^{-3}$	$1.9x10^{-11}$	$3.8x10^{-5}$	$1.9x10^{-6}$	$1.5x10^{-6}$	$8.7x10^{-7}$
	Jenned road; 495	$2.0x10^{-3}$	$8.0x10^{-4}$	$2.0x10^{-12}$	$4.0x10^{-6}$	$2.0x10^{-7}$	$1.6x10^{-7}$	$9.3x10^{-8}$
	Surgey's lane; 445	$3.0x10^{-3}$	$1.1x10^{-3}$	$2.8x10^{-12}$	$5.5x10^{-6}$	$2.8x10^{-7}$	$2.2x10^{-7}$	$1.3x10^{-7}$
	Dorket Head farm; 435	$2.7x10^{-3}$	$1.0x10^{-3}$	$2.5x10^{-12}$	$5.0x10^{-6}$	$2.5x10^{-7}$	$2.0x10^{-7}$	$1.2x10^{-7}$
	Quarry; 17	$2.7x10^{-3}$	$1.0x10^{-3}$	$2.5x10^{-12}$	$5.0x10^{-6}$	$2.5x10^{-7}$	$2.0x10^{-7}$	$1.2x10^{-7}$
Bilsthorpe	Manor farm; 500	$1.9x10^{-3}$	$8.0x10^{-4}$	$2.0x10^{-12}$	$4.0x10^{-6}$	$2.0x10^{-7}$	$1.6x10^{-7}$	$9.3x10^{-8}$
	Houses; 750	$7.1x10^{-4}$	$3.0x10^{-4}$	$7.5x10^{-13}$	$1.5x10^{-6}$	$7.5x10^{-8}$	$6.0x10^{-8}$	$3.5x10^{-8}$
	Scrapyard; 235	$7.9x10^{-3}$	$2.4x10^{-3}$	$6.0x10^{-12}$	$1.2x10^{-5}$	$6.0x10^{-7}$	$4.8x10^{-7}$	$2.8x10^{-7}$
	Industrial depot; 350	$5.8x10^{-3}$	$1.6x10^{-3}$	$4.0x10^{-12}$	$8.0x10^{-6}$	$4.0x10^{-7}$	$3.2x10^{-7}$	$1.9x10^{-7}$
	Footpath; 205	$9.4x10^{-3}$	$4.3x10^{-3}$	$1.1\ x10^{-11}$	$2.2x10^{-5}$	$1.1x10^{-6}$	$8.6x10^{-7}$	$5.0x10^{-7}$

Table 8. A summary of background PM_{10} concentrations at representative PM_{10} monitoring points.

landfill	automatic monitoring network site	annual mean ($\mu g/m^3$) 1999	2000
Wigmoor Farm	Leamington Spa	22	20
Sidegate	Leamington Spa	22	20
Dorkethead	Nottingham centre	25	24
Bilsthorpe		-	20-23 (projected 2004)

Table 9. PM_{10} deposition fluxes for receptor locations

landfill nuisance threshold 350 $mg/m^2/d$	human receptors at:	Lower range for deposition flux[1] $mg/m^2/d$	Upper range for deposition flux[2] $mg/m^2/d$
Wigmoor Farm	Wigmoor farm	0.12	1.92
	Glebe farm	0.05	0.79
	Hayden	0.16	2.41
	Court farm	0.03	0.44
	Rugby ground	0.09	1.26
	Cattery	0.03	0.52
Sidegate	Hillside farm	$3.6x10^{-4}$	$5.2x10^{-3}$
	House 1	$1.3x10^{-3}$	$1.9x10^{-2}$
	Finedonhill farm	$4.9x10^{-4}$	$7.4x10^{-3}$
Dorkethead	Road	$6.6x10^{-3}$	0.10
	Jenned road	$6.8x10^{-4}$	0.01
	Surgey's lane	$9.6x10^{-4}$	0.01
	Dorket Head farm	$8.8x10^{-4}$	0.01
	Quarry	$8.8x10^{-4}$	0.01
Bilsthorpe	Manor farm	$6.8x10^{-4}$	0.01
	Houses	$2.6x10^{-4}$	$3.8x10^{-3}$
	Scrapyard	$2.1x10^{-3}$	0.03
	Industrial depot	$1.4x10^{-3}$	0.02
	Footpath	$3.8x10^{-3}$	0.05

[1]a value of 1 cm/s is used as a lower range value for the dry deposition velocity and
[2]a value of 15 cm/s is used as an upper range value for the dry deposition velocity.
In both cases, particles have a diameter of 10 μm, a density of 2.55 kg/m^3 and wet deposition is not included.

Table 10. Modelled indirect exposure assessment for windblown APC residues at Glebe Farm

contaminant	deposition rate $mg/m^2/y$	total deposition after 6y mg/m^2	concentration in 0.1 m of soil mg/kg^1	Deposition to exceedance[3] y
Pb	420	2520	15.75	152
Cd	2	13	0.08	130
As	2	10	0.06	1905
Cr	1	6	0.04	8214
PCDD/PCDFs	210 $x10^{-6}$	1260 $x10^{-6}$	8 $x10^{-6}$	

[1]assumes even mixing
[2]uses blood lead concentration as health criteria value
[3]based on time to exceed SGV at current deposition rate
[4]that is the ratio of the average daily human exposure of dioxins from the site divided by the tolerable daily soil intake

Figure 1. Approach to the study (*after* DETR, Environment Agency and IEH, 2000)