



Assessment of the Leaching Risk to the Environment from the use of Pulverised Fuel Ash (PFA)

Preface

The document forms part of a series of documents relating to the environmental aspects and the use of pulverised fuel ash (PFA) in construction applications. PFA has a long history of successful use in a wide range of applications from use as an engineering fill material, as a pozzolanic cement, brick and block manufacture, grouting of caverns and mines, etc. Full details of the possible applications are available on the UKQAA web site at www.ukqaa.org.uk as a series of datasheets and case studies. There is no known UK incident of PFA causing any environmental problems in any of these applications.

This series of documents explain the background to the uses of PFA, the relevant legislation, the environmental risks and what practices are recommended to ensure that no environmental damage occurs. For the full picture, one should read all these documents. These documents, by the very nature of the subject matter are frequently reviewed to ensure they reflect changes in environmental legislation and findings of testing and research projects. The user should ensure they have the latest version of the documents, which are freely available on the UKQAA web site www.ukqaa.org.uk. The documents are as follows:

- The production and applications for PFA.
- Environmental Testing and Emerging UK and European Legislation.
- Assessment of the Risk to the Environment from the use of Pulverised Fuel Ash.
- Environmental Code of Practice for the Sale and Use of Pulverised Fuel Ash (PFA).

PFA and its potential for harmful leachates – a generic risk assessment

Introduction

Any environmental risk assessment should consider the source, pathways and possible receptors in a site specific manner. Clearly this is not possible for a generic assessment and it was decided to use an example that represented potentially the greatest risk.

This generic risk assessment is primarily based on the use of PFA to construct an embankment adjacent to a stream or river. This was chosen as being the potentially worst case situation in which pollution is likely to occur, e.g. in an unbound application potentially exposed to rainfall, flooding, etc. The industry does not recommend the use of unbound PFA below the water table, for such applications cement/PFA grout or concrete is required. As the recommended design of PFA embankments¹ requires a capillary break/drainage layer beneath the PFA and protection in some manner to all exposed surfaces, this risk assessment has therefore particularly concentrated on impacts to the local surface water system.

The following sections consider the potential of PFA as a source of pollutant based on the many academic papers produced on the subject and the results of standard tests carried out by the power generation industry. Thereafter, the potential pathways to the environment are considered before conclusions are drawn. The discussion is supported using data extracts from various reports and supporting statements. The intention is to follow the logic of a source-pathway-receptor risk assessment model.

We shall consider the limiting values that may be applicable to assessing PFA for the various uses it may be put.

History of PFA

The introduction of modern steam raising plant in the UK, particularly after the 1939-1945 war, gave access to fly ash and it was the late 1940's which saw research into the use of the material. In particular the example of using fly ash in mass concrete dams was considered, and, following research at the University of Glasgow², the practice was adopted for construction of the Lednock³, Clatworthy and Lubreoch Dams. These dams formed part of the Scottish Hydro-Electric Board's Breadalbane scheme. Lednock involved some 82,000 cu yards (62,500 m³) of concrete saving some 3,000 tons of Portland cement. Subsequently, it has found uses in numerous cementitious applications including grouts, block manufacture, in road sub-base and road-base construction, etc.

PFA has been successfully used as a fill material for many years with the first recorded use in the UK being in 1952. There was a considerable amount of research done in the 1950's and 1960's, which form the basis of its use. It is acknowledged to have benefits of low density and high shear strength, which have been instrumental in developing its wide acceptance as a fill material.

Physical Properties of PFA

Because of the way they are produced, PFA particles, particularly those below 50 µm, are spherical in shape, as shown in Figure 1. As the coal is burnt, the minerals associated with it become molten and form the spherical shape. Because of the rapid cooling experienced by the fine ash particles as they pass out of the furnace, they solidify as an amorphous, glassy material in this shape. The rounded particles allow PFA to flow, which makes it ideal for pumpable grouts. PFA has a role in assisting mixtures such as asphalt or concrete to flow as a filler material. PFA also has relatively low density compared to many competing materials; a typical density range is 1300-1700 kg/m³.

Particles in the coarse silt/fine sand sizes have potential to become airborne in certain conditions. The particle size also means that compacted PFA has a low intrinsic permeability/hydraulic conductivity, typically 10⁻⁷ m/s⁴. The low hydraulic conductivity means that water infiltration occurs at a low rate. Experience has shown that even when PFA is subjected to heavy rain it is unusual for it to become saturated below the top 50mm. The flow rate through unsaturated PFA will depend on the permeability and the degree of saturation, as well as the hydraulic gradient, so any significant hydraulic flow through PFA is unlikely to occur.

The situation represented by a typical laboratory leaching test, i.e. being shaken in distilled water for 24 hours, is not replicated in practice in a deposit of PFA. In an actual deposit, the very low permeability produces very small throughput of water, this combined with the high alkalinity and very low solubility has been found to give no problems due to leaching in practice. A report by the Construction Industry Research and Information Association (CIRIA) on the use of industrial by-products in road construction⁵ concluded that it was reasonable to consider the in-situ leaching behaviour of PFA as similar to materials such as brick rubble and crushed concrete. The same report also highlighted the influence of the low permeability of PFA; "in the testing conducted PFA was the only material which had no water pass through it during the test period." The test period in the CIRIA permeameters tests totalled 25 hours using hydraulic gradients of between 2.5% and 7.0% cross fall.

Fresh conditioned and stockpile PFA is like a fine-grained soil and, as shown in Figure 2, it is mainly silt-sized and generally acts like silt. Finer PFA has a silky feel, although a coarser one may feel gritty, they exhibit dilatancy, are non-plastic and possess cohesion.

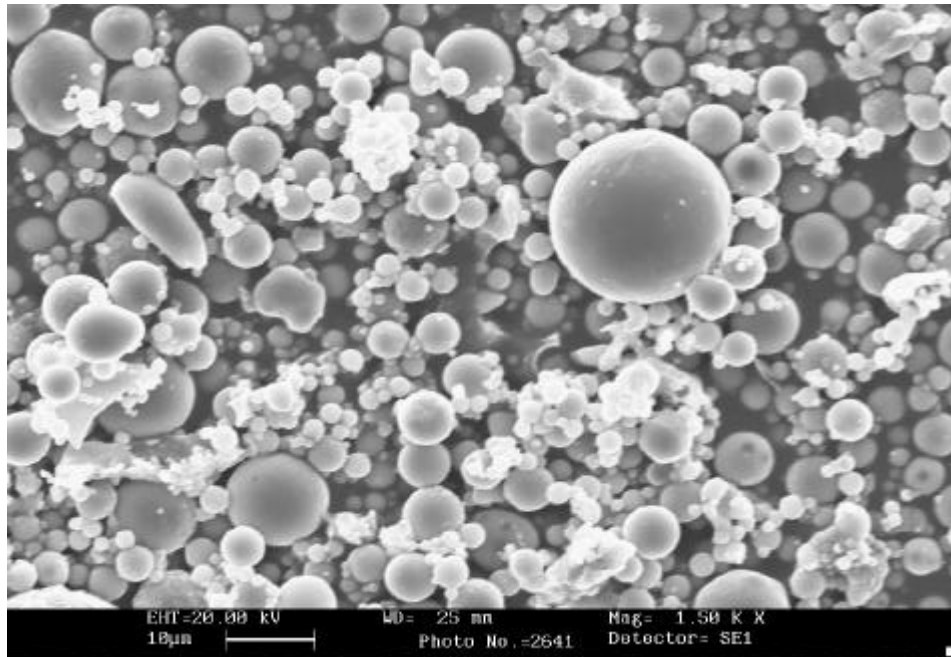


Figure 1 - Photomicrograph of fly ash / PFA.

Chemistry Properties of PFA

Around 60 % to 90 % of PFA is present as an amorphous glassy material composed of silica, alumina and iron oxides, with other metals present in smaller quantities, as shown in Table A, which is taken from a variety of sources. The constituents, apart from the glass, that are of most significance to the properties of PFA are calcium oxide content (lime) and sulfate.

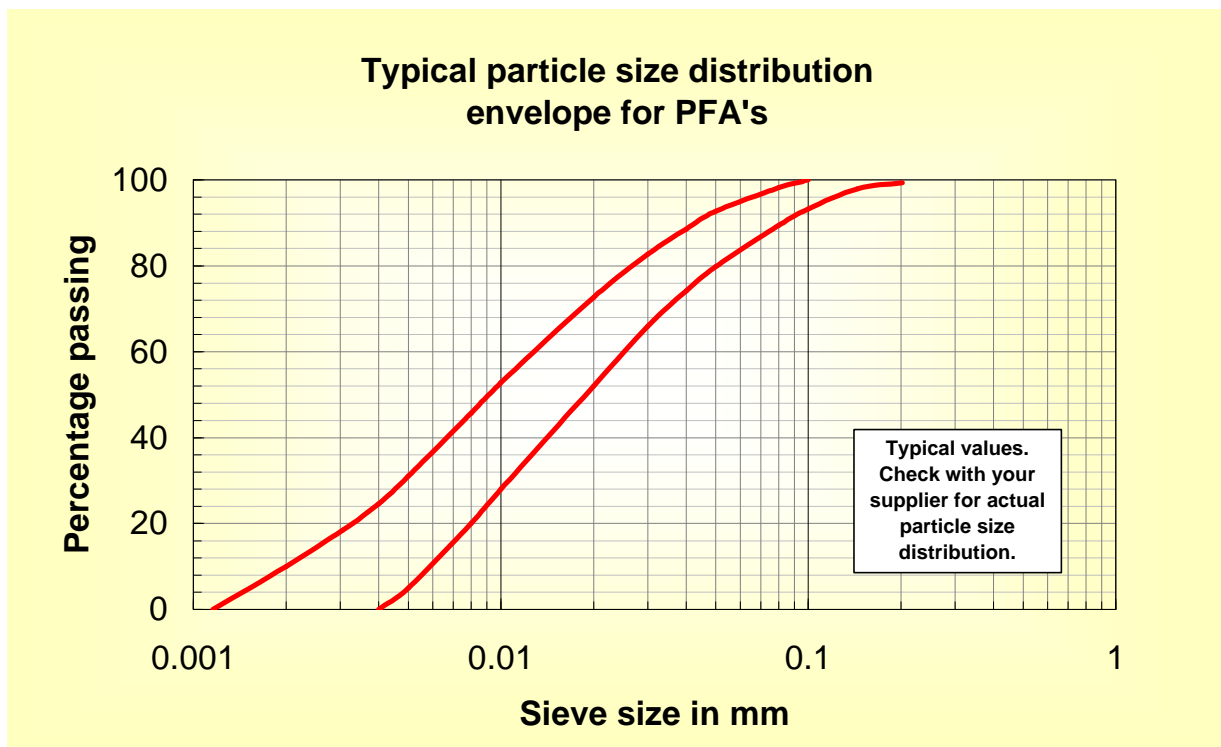


Figure 2 – Typical particle size distribution of PFA.

PFA is a pozzolana. This means that in the presence of lime and water PFA forms stable cementitious compounds. This is a particularly useful property when used in concrete, building block manufacture etc. The longer-term strength gain and enhanced durability properties are a result of this pozzolanic reaction. PFA in cementitious systems has excellent low heat and chloride diffusion properties, plus resistance to alkali silica reaction and sulfate attack.

If sufficient lime is present in the PFA, either from the PFA or from external sources, then it will result in further hardening. This is due to a combination of crystal formation and reaction between the lime and the glassy material in the PFA, the pozzolanic reaction. The high pH is also likely to reduce the availability of the trace elements.

Table A – Typical oxide analysis of PFA

Element	Typical range of values for PFA
Silicon (% as SiO ₂)	45 – 52
Aluminium (% as Al ₂ O ₃)	24 – 32
Iron (% as Fe ₂ O ₃)	7 – 15
Calcium (% as CaO)	1.1 – 5.4
Magnesium (% as MgO)	1.2 – 4.4
Sodium (% as Na ₂ O)	0.8 – 1.8
Potassium (% as K ₂ O)	2.3 – 4.5
Titanium (% as TiO ₂)	0.9 – 1.1
Chloride (% as Cl)	0.005 – 0.02*
Phosphorus Pentoxide (P ₂ O ₅)	0.09 – 0.65
Loss on ignition (%)	3 – 20
Sulfate (% as SO ₃)	0.35 – 1.7
Free calcium oxide (%)	<0.1 – 1.8
Water soluble sulfate (g/L as SO ₄)	1.3 – 4.0
2:1 water solid extract PH	9 – 12

* Chloride may be up to 0.3 % for PFA conditioned with sea water

When water is added to PFA, it initially has a low pH as the sulfate deposited on the surface of the particles is brought into solution as sulphuric acid. This is a transient situation and after a short time, the pH rapidly rises as calcium is leached into solution. The pH is typically 8 to 11 for PFA, although the pH for those ashes with higher free calcium oxide contents can rise to 12. Only a very small quantity of free calcium is required to achieve the higher pH. Because most of the water soluble material that influences pH has been washed out of lagoon PFA's, the pH is lower, typically around 9.

The calcium content of PFA means that most of the sulfate is present as gypsum, which has a limited solubility and will precipitate out in compacted PFA. The sulfate level of lagoon PFA is usually very low because the water/solids ratio used to slurry the PFA means the majority of the sulfate is washed out. Other water-soluble materials are also removed in the process. Therefore, the sulfate content of lagoon ash is typically less than 0.1 g/L.

The sulfate content of PFA means that it cannot be placed within 500 mm of metallic items according to the Department of Transport Specification for Highway Works (SHW). The water-soluble sulfate content of PFA is also sufficiently high to restrict the types of reinforcement that can be used in reinforced earth structures.

Trace Elements in PFA

Typical trace elemental analyses are shown in Table B, which demonstrates that other elements are present in only small quantities, less than 1 % of the total. The values quoted are generally in agreement with other quoted values^{6, 7}.

**Table B – Solid phase trace element analysis
Typical ranges from UK sources of PFA.**

	Typical range of results
Arsenic	4 to 128
Boron	5 to 310
Barium	0 to 36,000
Cadmium	<1.0* to 4
Chloride	0 to 2,990 ⁺
Cobalt	2 to 115
Chromium	33 to 192
Copper	33 to 474
Fluoride	0 to 200
Mercury	<0.01* to 0.61
Manganese	103 to 1,555
Molybdenum	2 to 81
Nickel	35 to 583
Phosphorus	372 to 2,818
Lead	<1* to 976
Antimony	1 to 325
Selenium	<1 to 162
Tin	<10 to 1,847
Vanadium	96 to 1,339
Zinc	49 to 918

All expressed as mg/kg
* Indicates below the limit of detection
+ Includes seawater conditioned PFA

Limiting values that may be applicable to PFA

Numerous documents exist by which leaching determinants can be compared. However, there are no environmental standards or regulatory limits against which ash leachate values can be directly compared. In the absence of such values we are often forced to make inappropriate comparisons. The three documents that are normally used for environmental assessment relate to materials in contact with drinking water, BS6920⁸, the criteria for inert waste (RGN2⁹) under the Landfill Directive¹⁰ and the assessment of contaminated soils (CLEA¹¹). In addition, the World Health Organisation¹² gives a comprehensive list of determinants that may be used.

Results are frequently compared to BS6920: Materials in Contact with Drinking Water, 2000, British Standard (Table C) for most metals and inorganic determinants.

Table C - Maximum allowable metals from BS6920: 2000

Metal	Maximum allowable concentrations - µg/litre	Reporting limits - µg/litre ^a
Aluminium	200	20
Antimony	10	0.5
Arsenic	50	1
Barium	1000	100
Cadmium	5	0.5
Chromium	50	5
Iron	200	20
Lead	50	1
Manganese	50	5
Mercury	1	0.1
Nickel	50	2
Selenium	10	1
Silver	10	1

^a: The reporting limits required by the National Regulator for some metals are based upon the new lower requirements specified in EC Directive on the quality of water intended for human consumption (98/83/EC).

Under the Landfill Directive, whether a material is classified as an 'inert' waste depends on an assessment of the leaching of toxic materials. The UK Environment Agency has produced a guidance note to reflect the requirements of the European Directive. Table D is taken from Regulatory Guidance Note 2 "Interim Waste Acceptance Criteria" (RGN2)¹:

These values are determined using CEN Technical Committee (TC) 292 'Characterisation of Waste' test methods as follows:

- BS EN 12457-1:2002 (One stage batch test performed at liquid/solid ratio of 2l/kg with high solid content and with particle size below 4mm (with and without size reduction).
- BS EN 12457-2:2002 (One stage batch test performed at liquid/solid ratio of 10l/kg for materials with a particle size below 10mm (with and with size reduction).
- BS EN 12457-3:2002 (Two-stage batch test performed at liquid/solid ratio of 2l/kg and 8l/kg for materials with a high solid content and with a particle size below 4mm (with and without size reduction).

Various materials are predefined as being 'inert' in the Landfill Directive including waste glass, concrete, bricks, soil and stones, tiles and ceramics. Unfortunately, PFA is not one of the materials mentioned.

Table D - Environment Agency Thresholds for inert wastes from RGN 2

Component	L/S = 2 litres/kg mg/kg	L/S=10 litres/kg mg/kg
As	0.1	0.5
Ba	7	20
Cd	0.03	0.04
Cr	0.2	0.5
Cu	0.9	2
Hg	0.003	0.01
Mo	0.3	0.5
Ni	0.2	0.4
Pb	0.2	0.5
Sb	0.02	0.06
Se	0.06	0.1
Zn	2	4
Chloride*	550	800
Fluoride	4	10
Sulfate*	**	**

Note: These values may be subject to some change in the near future
 NB: No explanation is given for * or ** annotation in RGN2

¹ At the time of writing (December 2002) this document is due to be revised.

Since March 2002, the CLEA software has been available from the Environment Agency. This software is specifically designed for assessing contaminated soils. Guideline values are given for a number of determinants as follows:

Table E – Soils Guideline values as a function of land use (CLEA March 2002)

Determinant ¹³	Residential – with plant uptake	Allotment	Industrial
Arsenic	20 mg/kg	20 mg/kg	500 mg/kg
Lead	450 mg/kg	450 mg/kg	750 mg/kg
Cadmium (pH 6 data used)	1 mg/kg	1 mg/kg	1400 mg/kg
Chromium	130 mg/kg	130 mg/kg	5000 mg/kg
Mercury	8 mg/kg	8 mg/kg	480 mg/kg
Nickel	50 mg/kg	50 mg/kg	5000 mg/kg
Selenium	35 mg/kg	35 mg/kg	8000 mg/kg

The software and supporting documentation appears not account for materials such as PFA where the trace elements are held in a form that they could not leach. If one presumes all the trace metals are available in the PFA, some failures occur. However, the glassy nature of the PFA particles means that little material is leachable and available for plant uptake. It would seem appropriate to use the leachate data rather than the total content for assessment purposes.

It should be noted there are a considerable number of other test methods considered by many more appropriate to PFA, especially when used as a fill material, for example the TC292 document 'Characterisation of waste – Leaching behaviour test – Leaching behaviour of a waste material under standardised percolation conditions – Up flow percolation test.'. These are detailed in the Environmental Testing and Emerging UK and EU Legislation document.

Leachable compounds within PFA

Over a period of many years, a considerable amount of work has been carried out to determine the leaching characteristics of PFA. PFA is widely reported as having very low solubility. This is because most of the solid elemental inventory is held within the largely insoluble "glassy" aluminosilicate matrix. Typically, ~2% of PFA is found soluble and the eluates are dominated by calcium sulfate (gypsum), which is a naturally occurring compound found in many soils, with lesser contributions from sodium, potassium and chloride ions. Most of the metals and metalloids present in the ash are either retained in the glass beads or firmly adhered to them, resulting in a very low leaching potential. PFA is also alkaline with a pH of typically 9 to 12, which materially assists in retaining metals.

Many other compounds are believed to be present as oxides, sulfates and chlorides in the enriched surface layer of the PFA particles. These may be released or precipitated as secondary solids or adsorbed onto the solid substrate depending on their solubility limits. Only a few elements are fully soluble in the initial leachate because of their limited solubility at high pH.

Other than the calcium referred to above, the most mobile metallic element is boron, which exists primarily as borate. The availability of boron is due to it existing as a vapour at the temperature of molten ash. When the ash solidifies, the boron condenses on its surface rather than being incorporated in the glass matrix. Weathering may eventually mobilise up to 50% of any boron and molybdenum together with 25 to 30% of the arsenic and selenium in the PFA. The actual behaviour of these and other elements in this respect appears to be specific to the source of ash and the total amounts present.

The composition of PFA is dependent upon the mineral matter present within the coal that is fired in the furnace and the effectiveness of combustion that has taken place.

In older power stations, surplus PFA is often transported as slurry in pipelines. The slurry typically contains 15 to 20% ash. This is allowed to sediment out under gravity in a lagoon. During this process a large part of the water-soluble material present in the PFA can be dissolved, which is removed along with the decanting water. As lagooning the ash is not a 24-hour process, for much of the time clean water is passed down the pipelines. This is done to control scaling and it further dilutes the water-soluble species within the lagoon.

The lagooning process removes most of the soluble species, excepting those limited by solubility constraints or by diffusion within the aluminosilicate matrix. Almost all of the water-soluble elements found in PFA show a gradual decline after being lagooned. The remaining soluble material consists of the sulfate and chlorides of alkali metals plus trace levels of metallic elements that can form soluble anions at high pH.

The buffering effect of PFA reduces the leaching potential. Should the high buffering capacity ever be exhausted some of the trace elements can be expected to become more mobile. However, the low permeability and reserve alkalinity of PFA is such that only few centimetres of a deposit, embankment, etc and likely to be affected by the acid media type normally present in the environment. The risk of a mass release of these trace elements is correspondingly small.

Inorganic Compounds

DIN and NRA Leaching tests

As discussed above, there is only a small fraction of the constituents that are present on the surface of PFA and that are leachable in water. Typical data obtained from routine analysis are shown in Table F, the extraction is based on results from both the German standard DIN 38414-S4¹⁴ (10:1 water/solids ratio) and NRA extraction test.

Table F – Leachates found using the DIN 38414-S4 and NRA extraction methods.

Typical range of leachable elements for UK PFA (mg/L except pH)			
Aluminium	<0.01* to 9.8	Manganese	<0.01*
Arsenic	<0.1*	Molybdenum	<0.1* to 0.6
Boron	<0.1* to 6	Sodium	12 to 33
Barium	0.2 to 0.4	Nickel	<0.01*
Calcium	15 to 216	Phosphorus	<0.1* to 0.4
Cadmium	<0.04*	Lead	<0.01*
Chloride	1.6 to 17.5	Sulfur	24 to 510
Cobalt	<0.01*	Antimony	<0.01*
Chromium	<0.1*	Selenium	<0.01* to 0.15
Copper	<0.01*	Silicon	0.5 to 1.5
Fluoride	0.2 to 2.3	Tin	<0.1*
Iron	<0.1*	Titanium	<0.1*
Mercury	<0.001*	Vanadium	<0.01* to 0.5
Potassium	1 to 19	Zinc	<0.02*
Magnesium	<0.1* to 3.9	pH	7 to 11.7

Notes: The above data include a seawater-conditioned sample resulting in higher chloride values.
The Boron content may also be increased.

* Indicates below detection limit.

From the data, it can be seen that the major water-soluble constituents are calcium and sulfur (usually present as sulfate). There are smaller amounts of sodium and potassium, and traces of chloride, magnesium, aluminium and silicon. If it is assumed that all the water soluble calcium, sodium and potassium is present as hydroxide, ignoring the sulfate or chloride, then the total water soluble hydroxide, based on the highest values from Table F would be 2.1% (m/m). However, calcium hydroxide would make up approximately 2.0%, the others would represent less than 0.1 %. In all instances quoted the calcium is very dominant with sodium and potassium present in very small quantities in comparison.

Harwell Test

Samples¹⁵ of stockpile PFA were subjected to extraction by the Harwell¹⁶ method and the results are summarised in Table G. Although it is stockpile PFA, the leachate still shows that the calcium content is dominant, with lesser amounts of other elements. There is a more significant amount of magnesium, probably due to the low pH of these samples.

Table G – Leachates found using the Harwell method.

Typical range of leachable elements, 10 samples, single source (mg/L except pH)			
Bed Volume	1	Molybdenum	0.15 to 0.88
pH	8.1 –8.8	Sodium	5 to 44
Aluminium	<0.1* to 0.5	Nickel	<0.01*
Arsenic	0.06 to 0.16	Lead	<0.01*
Boron	1.8 to 4.3	Tin	<0.01*
Calcium	33 to 250	Titanium	<0.01*
Cadmium	<0.005*	Vanadium	0.22 to 0.55
Cobalt	<0.01*	Zinc	<0.01*
Chromium	0.02 to 0.06	Nitrogen	0.2 to 1
Copper	<0.01*	Phosphorus	<0.1*
Iron	<0.01*	Sulfur	15 to 70
Mercury	<0.001*	Chloride	5 to 9
Potassium	5 to 29	Fluoride	<0.1*
Magnesium	16 to 100	Selenium	0.04 to 0.16
Manganese	<0.01*	Antimony	<0.2

*Indicates value below detection limit.

The CIRIA report¹⁷ compared the CEN two-stage leaching method to the Harwell method. It demonstrated that the total leachate was similar for both techniques for the three PFA's examined. Both showed that with the Harwell method the calcium and sulfate were present either in the ranges 100 to 1000mg/L or 1000 to 10000 mg/L for the first bed volume extracted. These fell to the 100 to 1000 mg/L range for the next four bed volumes extracted. The concentration for the 6-10th bed volumes fell to 10 – 100 mg/L. The only other elements that were present in these levels were sodium and potassium, but these had significantly reduced by the third bed volume for all but one of the PFA's examined.

More recent data on inorganic leachable compounds

The following results have been supplied by the power generation industry during 2001 and 2002. Analysis of leachates is regularly carried out to ensure compliance with Integrated Pollution Control (IPC), now Integrated Pollution Prevention and Control (IPPC), requirements and for to obtain planning consents for landfill operations. These results are ash supplied and given in their entirety in the supporting data section below. Table K, Table M and

Table O indicate the total trace metal contents for a range of coals supplied to a range of UK Power Stations. These include West Burton (Bole Ings ash disposal site), High Marnham, Ratcliffe on Soar and Drakelow. These analyses are typical of coals supplied to UK power stations. It is of note that the List 1 metals, Mercury and Cadmium are very low and below the lower threshold concentration in the ICRC Guidance Note 59/83.

After a lagoon has been drained, the pore water within the PFA is difficult to extract. However, ash samples were taken from a lagoon in 1995 and 1996 in the East Midlands. A 1.5m core of PFA was removed and the pore water extracted using a centrifuge. The results from this analysis are shown in Table L.

Inorganic leaching test results from PFA samples from Ironbridge, Drakelow and Rugeley are summarised in Table N. These results are augmented by the routine analysis of leachates from the Bole Ings ash disposal site contained in Table P. These results are from tests from differing laboratories that are prepared to quote different threshold of detection. Commentary about these data is given in Table H.

Table H – Commentary on leachate data.

Determinants	Comments
Mercury, Lead, Copper, Nickel, Zinc.	Lead, copper, nickel and zinc are found at very low levels in PFA. Mercury concentrations are generally limited by the test methods used and reported as below detection limits. Assessments that have been carried out that are more accurate, give concentrations of < 0.1 µg/l – See Table U. All PFA's give values less than the limits given in BS 6920, CLEA and RGN2 limits (based on these determinants using the total metal concentrations).
Cadmium	Cadmium leachate concentrations generally below detection limits, quoted as less than 1, 5 or 10 µg/l. Where more accurate results are quoted these are around 1 to 2 µg/l and therefore below values within RGN2 - See Table U. Many PFA's would exceed the CLEA limits based on total metal concentrations; however, as the cadmium is held within the glassy matrix it is not available for leaching. NB: Cadmium has no beneficial health effects ¹⁸ . It is a carcinogen, may cause kidney disease and irritate the digestive tract.
Selenium	Selenium leachate tests results 10-50 µg/l on first flush a limit of 10 µg/l in BS6920. All PFA's comply with RGN2 and CLEA limits for all land uses. NB: Selenium is essential trace element ²⁰ . For adults the recommended dietary allowances are 70µg/day for males and 55µg/day for females.
Chromium	Many chromium leachate test results exceed BS6920 with generally between 50 and 100 µg/l against a limit of 50µg/l. However, they all are less than the 200 µg/l limit given in RGN2 and all PFA's comply with CLEA limits for all land uses. NB: The usual dietary intake for an adult is between 25 and 33µg/day ²⁰ . The estimated safe dose is 200µg/day.
Boron	There are no limits for boron in BS 6920, RGN2 or CLEA. However, the World Health Organisation guidelines give a value of 0.30mg/l. Boron levels vary significantly depending on PFA source. Some plant species are boron sensitive. For details of suitable tolerant species see 'Ashes to Assets' ¹⁹ . NB: The usual adult dietary intake of boron is 1mg/day ²⁰ . No minimum lethal dose is known, however, 18 to 20g in adults have been fatal.
Arsenic	Arsenic leachate tests typically quoted as less than 50 µg/l because of limit of detection. Where tests that are more accurate are used, the results are of the same order as leachate test limit of 10 µg/l, though exceed the reporting limit of 1µg/l in BS6920. However, all PFA's would comply with RGN2 limits. Many PFA's would not comply with CLEA limits based on total metal concentrations – but would comply based on leachable material. NB: The human diet contains about 12 to 50µg/day of arsenic from food and water. It has been estimated that between 12.5 and 25µg/day are required to prevent symptoms of arsenic deficiency ²⁰ . A dosage of 65mg, whether given in a single dose or from repeated small doses, is fatal ²¹ .
Sulfate	Sulfate leachate concentrations typically around 600mg/l on first flush, which is less than 3 times drinking water standard. Total concentrations typically 3,000-13,000 mg/kg. NB: Calcium sulfate is not classified as being hazardous to human health.
PH	PFA is alkaline with pH's ranging from 8 – 11. The high pH materially assists in the retention of leachable metals.

The following features should be considered when evaluating the actual environmental impact potential represented by these results.

- Where the material is to be used in the form of consolidated engineering fill with a permeability of around 10⁻⁷m/s. The amount of leachate that can be produced in these circumstances is very small indeed. The deposit should be separated from the groundwater by a capillary break. Both the leachate test results and threshold concentrations are based on the availability of a reasonable pathway to the environment, which does not exist in a deposit of PFA.
- Most metals are retained in or on the glassy, silicate matrix of the ash and not available to leach. Determining total concentrations by extraction with very strong acids is irrelevant to PFA where most of the metal is held in an alumino silicate matrix under alkaline conditions.
- The leachate test uses distilled water and dry ash. Under these circumstances, the pH of the liquor first falls as the sulfates are taken into solution. This can be exacerbated by the presence of additional sulfate from flue gas conditioning systems used to enhance dust capture in the precipitators. The result is that pH can fall to around 4 in the distilled water based solution for a period of time, until the effects of the alkaline constituents begin to take effect and drive the pH alkaline. On a power station, when ash is mixed with river water either to condition it or to produce slurry to transport the ash to a disposal site. The river water

is buffered alkaline that does not allow the pH to fall and cause mobilisation of metals on the scale represented by a leachate test. (This point is illustrated by the results in Table R containing results of analysis of ash slurry water, these giving significantly lower values than those obtained from leachate testing.)

- It has been widely reported that the available materials in PFA are rapidly depleted and that successive leaching reduces concentrations significantly. This is illustrated by the test results from ash that has been transported by slurring to the lagoons at Rugeley. The final column of Table N shows the results of leaching tests on PFA from the Rugeley power station lagoons and the results are generally lower than Rugeley PFA.

Leachable Inorganic compounds in PFA - Summary

1. The majority of the ash is present as an alumino-silicate glass;
2. Most elements are present in very small quantities and are largely entrained in the glassy material;
3. Typically, less than 2 % of the PFA is water-soluble; calcium and sulfate constitute the majority of the water-soluble fraction. There are smaller amounts of sodium, potassium and, in low pH leachate, magnesium;
4. The pH is mainly determined by the water-soluble calcium and sulfate producing an alkaline environment.

Organic Compounds

PFA contains very little organic material, other than elemental carbon. Combustion in the power station furnace, which has peak temperatures in excess of 1250C, will remove and break down most organic compounds present in the original coal. There are no synthetic organic compounds such as pesticides etc.

Polycyclic Aromatic Hydrocarbons in PFA

PFA contains only trace quantities of organic materials because the main organic content has been burned. There is usually a small amount of elemental carbon, but nothing that will undergo organic degradation. Consequently, a deposit of PFA does not produce gas. The elemental carbon is partially activated and capable of absorbing some deleterious compounds, such as polycyclic aromatic hydrocarbons (PAH).

PAH's can result from the incomplete combustion of fuels such as wood, coal and oil. They are widespread in the environment, largely because of inefficient coal combustion during the years prior to development of pulverised coal fired furnaces. Metabolic transformations, by aquatic and terrestrial organisms, result in carcinogenic substances²². The most potent PAH's are benzofluoranthenes, benzo[a]pyrene, benz[a]anthracene, dibenzo[a,h]anthracene and indeno[1,2,3-cd]pyrene. Although there has been a significant amount of work on PAH's arising from combustion of coal, most effort has been focussed on airborne particulate matter. PAH's will undergo photo-degradation and are therefore thought to have a limited life span in the atmosphere. PAH's are only sparingly soluble in water, the solubility decreases with increasing size of molecule, for example naphthalene with 2 benzene rings has a solubility of 32 mg/L whereas benzo[a]pyrene with five rings has a solubility of 1.6×10^{-3} mg/L.

Wild and Jones²² reviewed PAH's in the environment in 1995. The major sources, apart from gasworks sites, were found to be coal fired electricity generation (3140 tonnes per annum), domestic coal combustion (600 tonnes per annum), incinerators (56 tonnes per annum) and vehicles (80 tonnes per annum), with lesser amounts from oil and wood combustion and stubble burning. Sharkey et al²³ noted that PAH's could also arise from a number of other sources such as coke ovens and metal smelting and processing plants. Although power generation consumes the largest proportion of coal, the emissions of PAH's are less per tonne than for coal used for domestic consumption. This is due to the higher temperatures and greater control over combustion conditions in the former. It was noted also that concentrations of PAH were higher in urban areas and by the roadsides as might be expected. When deposited in water, PAH's tended to bind to sediments rather than remain in solution, the estimated burden of PAH's in sediments was ten times greater than in fresh water). Levels in the soil are rising due to atmospheric deposition and binding of the PAH's by the soil particles, especially the organic matter. The report concludes that leaching of PAH's from soils was unlikely to be significant.

Wright²⁴ working for the CEEB, indicated that the amount of PAH present in PFA is small, typically in the range 141 to 935 ng/g. However, it was noted that the amount detected was likely to be a small fraction of the total due to difficulties in extracting them. The conclusion was that the quantities found and the inert nature of PFA meant that PFA was not a major contributor to "active" PAH in the environment.

Another study²⁵ by Zenon Environmental detected no extractable trace organics in fly ash from large coal-fired power stations in concentrations above 0.5 µg/g, similar levels to those found by the CEEB.

Leaching tests on PFA in accordance with the Environment Agency extraction method²⁶ have indicated levels of the PAH's benzo[b]fluoranthene, benzo[k]fluoranthene, benzo[a]pyrene, benzo[ghi]perylene, fluoranthene and indeno[1,2,3-

cd]pyrene to be less than 0.2 µg/L for each species, confirming the above findings that the amount of available PAH on PFA is negligible.

There have been a number of studies in the United States of America investigating the interactions between PAH's and PFA (known as fly ash in the USA).

One recurring theme is the difficulty in extracting PAH's from particulate matter. Janssen and Kanij²⁷ carried out desorption tests using C¹⁴ labelled 3,4-benzopyrene (BaP). They found that recovery from fly ash was lower than for aluminium powder of a slightly greater surface area. Extraction using xylene was found to give lowest recovery of BaP. Tests on a number of different fly ashes gave recoveries up to 50%, compared to up to 95% for aluminium powder. Thermal treatment of the fly ash at 400°C reduced recovery significantly, the lowest recovery being 8%.

Natusch²⁸ found that PAH tended to adsorb onto the surface of fly ash, rather than just being a surface deposit. It was noted that adsorption was very temperature dependent, little adsorption was noted on stack ash at 290°C but there was significantly more at 5°C. The adsorption occurred rapidly but it was found to be difficult to desorb PAH's. Adsorbed PAH is resistant to photo-degradation although some oxidation may occur at a lower rate on ash that has not been exposed to light. The behaviour of PAH's with respect to fly ash was found to be similar to that with activated carbon. The report noted that the bulk of the PAH's not adsorbed by carbonaceous matter would be adsorbed on the fine particles due to the large surface area, the particles most likely to become airborne.

Harrison et al²⁹ studied both solid and liquid wastes from Four Corners power station in New Mexico. They found, that recovery of PAH's from fly ash was difficult and they did not detect any PAH with more than four rings, although they could not confirm that these were not present on the surface of the ash. The levels in precipitator ash were slightly higher than for ash collected by the water scrubbing system. Total extractable hydrocarbons in sluice water were low at 7.9 ppb, with many species at levels less than 1 ppt. No PAH's larger than naphthalene in molecular weight were found in sluice waters.

Junk et al³⁰ studied levels of PAH's and other organics from stack vapour, stack ash, fly ash and grate ash from Ames power station in the USA. Only small amounts were found on both respirable and non-respirable particles, the results are summarised in Table I. Although there were measurable amounts in the vapour phase, it was noted that if all the vapour were to condense on the particulate matter the amount would still be less than for ambient air particles.

In addition to the above, measurements were made on sluice water carrying fly ash and grate ash to settling ponds. The water used was from an aquifer that had been contaminated by coal tar. The sluice water contained no contaminants above the detection limit of 1 ppb, less than was found in the aquifer water. This indicated that the fly ash actually reduced the level of PAH's in the water. This was confirmed by a small trial where water containing 20 to 50 ppb of PAH's was mixed with fly ash in a ratio of 10:1. Within 10 minutes the PAH level was reduced to below the detection limit.

Table I - PAH levels in emissions from coal fired power stations (Junk et al)

Compound	Concentration range (ng/g)		Concentration Range (ng/m ³)
	Respirable Particles	Non-Respirable Particles	Vapour Phase
Naphthalene	ND ^a -18	0.5-23	10-1800
Phenanthrene	-	-	26-640
Anthracene	-	-	0.4-100
Fluoranthene	0.2-0.3	0.05-1.5	0.5-240
Pyrene	0.2-7	0.08-1.1	0.2-2850
Chrysene	ND	ND-4	0.1-28
Benz[a]pyrene	ND	ND	0.1-120
Benz[a]anthracene	ND	ND-0.3	NM ^b
Benz[ghi]perylene	NM	NM	3-22

a. ND = not detected at the limit of 0.05 ng/g

b. NM = not measured

Mamantov and Wehry (1989)³¹ separated fly ash into carbonaceous, magnetic, light mineral and heavy mineral fractions. They reported that PAH's with 3 or 4 rings may be found in equilibrium in the atmosphere both as adsorbates on particulate surfaces and in the vapour phase. Larger PAH's were present as adsorbates. Although PAH's will photo-degrade, the extent to which this occurs is dependent on the surface on which they are adsorbed, so they may be more persistent on some surfaces than on others. It was noted that resistance to degradation was increased when the PAH's were adsorbed on carbonaceous and magnetic fractions. Their study used a vapour deposition technique instead of the more usual solution based techniques to deposit pyrene on to the surface of fractions from two sources of fly ash. This was considered to be a more realistic method of deposition of the PAH's. Their conclusions were:

1. Pyrene had a greater affinity for the carbonaceous fraction of the fly ash than the other fractions.
2. In the absence of carbonaceous material pyrene preferentially adsorbs on the non-magnetic fraction.

3. Pyrene adsorbed on the carbonaceous fraction was very resistant to photo-degradation.
4. Although the pyrene is not readily adsorbed on the magnetic fraction, any that is will be resistant to photo-degradation.
5. Carbonaceous matter tends to be in the coarser fraction of the fly ash but it is the finer respirable material that may result in atmospheric emissions via the stack.

Further work by the same authors was reported in 1995³². This involved trying to ascertain the effect of surface roughness on photo-degradation. By measuring the surface area of the various fractions, they showed that the carbonaceous fraction had the greatest influence on the surface area. In one sample, the carbonaceous fraction represented 4.7 % of the material by mass but accounted for 80 % of the measured surface area.

The work confirmed that the surface roughness was important and that the iron content, which tends to produce dark coloured particles that may absorb light, had little effect. The concentration of effort on airborne emissions rather than waterborne PAH's indicates the relative significance of each.

When PFA is used as a fill, the amount that may become airborne is small, especially if dust suppression is effective, and transient, occurring only during construction. This means that this is not likely to be a major source of PAH's in the air. PFA used as a fill material will be well compacted and therefore have a low permeability, typically 10^{-7} m/s. Furthermore, if used in road embankments it will be protected by topsoil/vegetation as well as the construction of the road. Thus, water movement through the PFA will be very slow. Given the difficulty in extracting PAH's from PFA and their low permeability, the risk of movement of them from the PFA fill is extremely low.

Furthermore, as discussed by Wild and Jones when used in a road embankment the emission of PAH's from vehicles is likely to be a greater threat than any leaching of them from the PFA.

More recent data on PAH's

The results of a series of leaching tests for organic determinants taken in 2001 are summarised in Table S and Table T.

The PAH results are expressed in nanograms per litre (ng/l), which is equivalent to parts per trillion and the phenol results in hundredths of a parts per million. The compounds are therefore present in very small quantities indeed. The aggregate total of all 16 PAH's species analysed is between 0.2 ppb and 1 ppb. These are very low concentrations from a leachate test on new material without any opportunity for degradation to take place.

The leachate tests produce a total for the required determinants, which is compliant with the drinking water standards. The Drinking Water Standards are based on the detected concentrations of the PAH compounds in the shaded sections of Table S. The standard is 200 ng/l and the highest concentration obtained is around half this value. By complying with the Drinking Water Standards the leachate tests for PAHs also complies with the EA document Interim Guidance on the Disposal of Contaminated Soils Table 1, which uses the same standard.

It is notable that the principal species of the PAH present is Naphthalene which has a standard under the Surface Waters, Dangerous Substances Classification Regulations of 10,000 ng/l (10 µg/l). The highest test concentration measured was 682 ng/l. The sample of Newbold ash lagoon water (Drakelow Power Station ash disposal site). The lagoon water is more representative of actual conditions than the leachate test and gives a concentration of 74ng/l or 0.7% of the standard.

Naphthalene, Phenanthrene, Acenaphthene and the other compounds which give greater measurements are in general the least toxic compounds and subject to rapid adsorption and reasonably rapid degradation. The more toxic PAH's and more slowly degrading substances are either not detected or present at very low concentrations compared to Naphthalene etc.

The total PAH concentration in PFA is generally less than 0.5 mg/kg, which is less than 1% of the lower Threshold total concentration requirement in the EA Interim Guidance on the Disposal of Contaminated Soils Table 1.

PAHs all adsorb readily and strongly onto other organic materials such as soils. In aerobic conditions, they are degraded with half-lives from a few days to a few years. Degradation is particularly rapid (half-life in hours) if the compounds are exposed to UV radiation from sunlight. Thus even though the concentrations of PAHs are fully compliant with standards and the very low permeability etc mitigates against leachate production the minute amount of PAH will be locally adsorbed and degraded and cannot affect the broader environment.

PAH's in PFA - Summary

In summary it can be noted:

- Most work has been done on PAH's associated with particulate matter that is released to the atmosphere. Little work has been done on water-borne PAH's.
- There are traces of PAH present on PFA, typically up to 900 ng/g, although the difficulty in recovering PAH's from PFA mean that the figure may be higher.

- PAH's, particularly those with high molecular mass tend to be adsorbed onto the surface of the PFA and recovery of the adsorbed PAH's is very difficult.
- PAH's have an affinity for particulate matter, especially carbonaceous matter and dissolved PAH's can be removed from solution by PFA.
- The leachate from PFA contains very small amounts of PAH's.
- PAH's adsorbed onto PFA tend to be resistant to photo-degradation, although it is possible that PAH's not exposed to light can still undergo oxidation.

Phenols

The test results for Phenols are below the level of detection. The limit of detection meets the drinking water standard limits and is 20% of the standard set for bathing waters. It is notable that the drinking water standards have been fixed to avoid the production of compounds with Chlorine in the drinking water treatment process and not because of the effects of phenols at these very low concentrations.

The fate of Phenols will be broadly similar to PAH's except that the half-life of most phenols is considerably less than the half-life of PAH. They are present in very low concentrations that will be retained in ash deposits and released very slowly, if at all. There will be some slow "in deposit" degradation and the minute amount of Phenols, which could be released, will be rapidly adsorbed and degraded in the environment. Since the source concentrations are undetectable and rapid adsorption degradation will reduce the concentrations, it is therefore inconceivable that phenols can cause pollution

Dioxins in PFA

Polychlorinated dibenzo-p-dioxins (PCDD) are a family of chemicals based on the tri-cyclic molecule benzo-p-dioxin, which has two benzene rings, linked by two oxygen atoms. PCDD's have some or all of the hydrogen on the benzene rings replaced by chlorine (up to the maximum of eight chlorine's). These are often associated with polychlorinated dibenzofurans, (PCDF) which have only a single oxygen atom. Dioxins are considered to be toxic to humans, as are furans although less so than dioxins. 2,3,7,8-tetra CDD (TCDD) is considered the most toxic and therefore the most studied.

Dioxins are usually associated with the incomplete combustion of material containing chlorine and as such are commonly associated with the ash from municipal waste incineration, but can be found in small traces in soils. The low chlorine content of coal combined with the high temperatures found in the furnaces of power stations mean that dioxins are unlikely to form and only traces would be expected in the resulting ash. Dioxins are ubiquitous and are present in a wide range of soils and although they can be persistent, they rapidly decay when exposed to light.

Work by the CEBG³³ in the 1980's examined 18 PFA samples from a range of sources for dioxins from the tetrachlorinated to the octachlorinated. The findings were that the levels were very low, typically less than 25 pg/g, with levels of 2,3,7,8-TCDD less than 2 pg/g in all but two samples. The only exceptions were samples of PFA from the low NO_x burners at one station (A). It was thought that the low NO_x burners might have had some effect, although the same increase was not observed for samples from another power station utilising similar burners. Although the dioxin levels in the samples from low NO_x burners at station (A) were higher, 210 and 270 pg/g, they were still within the range found in soils in the UK; data from unpublished work cited an upper limit in soils of 290 pg/g.

A sample of cenospheres ("floaters") from one source was sent to Rechem International Ltd for analysis in 1993. The analysis included the 17 most significant dioxins and furans with the result quoted as a toxic equivalent (TEQ), relating the total concentration of the 17 species to the concentration of 2,3,7,8-TCDD with equivalent toxicity. This involves applying a weighting factor, the toxic equivalent factor (TEF), to each dioxin or furan, the factor being consistent with its perceived toxicity; the individual results for each species are added together to get the TEQ. The highest factor (1) is for 2,3,7,8-TCDD, the lowest is 0.001 for OCDD and OCDF. The results are shown in Table J.

Table J - Results of tests on cenospheres (floaters)

Dioxin/Furan	Concentration (pg/g)	Toxicity Equivalence Factor	Typical Background Level in Soils (pg/g)
2,3,7,8-TCDF	3.0	0.1	
Total TCDF	30		<0.5-237
2,3,7,8-TCDD	2.0	1	<0.5-2.1
Total TCDD	15		<0.05-69
1,2,3,7,8-PCDF	5.0	0.05	
2,3,4,7,8-PCDF	5.0	0.5	
Total PCDF	35		<0.5-185
1,2,3,7,8-PCDD	2.0	0.5	<0.5-2.4
Total PCDD	10		<0.5-165
1,2,3,4,7,8-HxCDF	10	0.1	
1,2,3,6,7,8-HxCDF	2.0	0.1	
1,2,3,7,8,9-HxCDF	1.0	0.1	
2,3,4,6,7,8-HxCDF	7.0	0.1	
Total HxCDF	35		4.3-212
1,2,3,4,7,8-HxCDD	40	0.1	
1,2,3,6,7,8-HxCDD	50	0.1	
1,2,3,7,8,9-HxCDD	60	0.1	
Total HxCDD	350		2.8-165
1,2,3,4,6,7,8-HpCDF	110	0.01	
1,2,3,4,7,8,9-HpCDF	20	0.01	
Total HpCDF	175		1.5-138
1,2,3,4,6,7,8-HpCDF	1000	0.01	
Total HpCDF	2000		7.5-234
OCDF	6000	0.001	<2.0-144
OCDD	25000	0.001	28-832
TEQ	65		10-40

The TEQ is shown as 65 pg/g, which is slightly higher than found in soils (10 to 40 pg/g) using this method of assessment. However, the density of the floater particles is low compared to soil, with a density of 0.5 Mg/m³ compared to 2.6 Mg/m³. If the value is corrected to an equivalent density, then the value would be 12.5 pg/g. This is similar to the background level in soils and in agreement with the earlier data.

Junk et al³⁰ looked at 2, 3, 7, 8 – Tetrachlorodibenzo-p-dioxin (TCDD) at a detection limit of 10 parts per trillion. No TCDD was found in the effluents in any of the boilers at two power stations tested. Even when refuse derived fuel was added, no dioxins were observed. This was explained by the high furnace temperature (~1100C) and the excess oxygen used in combustion.

Subsequent to television programmes broadcast in July 2001 and Dec 2001 that suggested that some forms of ash had high dioxin levels, the UK generating industry in England took samples of pulverised fuel ash (PFA) and furnace bottom ash (FBA) from seven coal-fired power stations. These samples were tested at accredited laboratories for the 17 dioxins and furans chlorinated at the 2,3,7,8 positions. All of the results show levels of dioxins and furans to be in the range 0.049ng/kg to 2.4ng/kg I-TEQ. These values are close to or below detection limits and are similar or lower than background levels typically found in soils.

Dioxins in PFA - Summary

1. These works confirm that no dioxins over 12.5 pg/g were found in the ashes tested.
2. Although dioxins are present in PFA, the levels are very low and similar to the background levels found in typical soils. Accordingly, PFA is no more hazardous than soil.

Conclusions – Leachable materials within PFA

PFA has very low permeability, which means that there is very little passage of water through it and very little potential leachate. Most trace metals are held in the aluminosilicate matrix and are not available to leach. A deposit of PFA is alkaline which further aids retention of metals. PFA has almost no biodegradable organic material and produces no gas as a product of such degradation. Its total concentrations and leachate test concentrations for organic compounds

(PAH's and Phenols) are below the limits set in the EA Interim Guidance on the Disposal of Contaminated Soils Table 1. When fully mixed with natural water, as in an ash slurry system, the pick up of trace elements is substantially less than the values obtained in a standard leaching test.

The following assessment concentrates on inorganic determinants, considering that no significant levels of organic compounds are present in PFA.

Potential impacts and pathways to groundwater

The PFA is often used to form embankments with sloping sides and a road pavement on the top. Such embankment should be protected, usually by being in topsoil and planted. The whole embankment should be built on a free draining granular starter layer covered by a permeable geo-synthetic membrane to prevent groundwater from being drawn upwards by capillary action into the PFA deposit, thus reducing its structural stability.

In these circumstances, the low permeability of compacted PFA will ensure that there is effectively no transmission of water through the deposit. Rainwater will pass down the sloping sides in the topsoil layer much readily than it will soak into the PFA. This is because the PFA permeability is around 10^{-7} m/s and the topsoil will be around 1000 times more permeable. In addition, the cementitious compounds will tend to form an even more impermeable layer a short distance into the PFA deposit at the maximum depth of root systems from the plants growing in the topsoil. The water, which does not run off the mound, will be evaporated or used by plants and transpired into the atmosphere.

At Ironbridge Power Station, an ash storage area has up to 500,000 tonnes of PFA in several mounds similar to the road embankments. These mounds have flat tops and are unlined. Furthermore, the area is regularly disturbed by placement and removal of ash. Analysis of water from near the bank of the river Severn, which is only around 30 metres away from the nearest ash deposits shows no effect. Notably there is no increase in Boron, which is the most mobile of metals in ash leachate.

An in depth study has been carried out at the ash disposal site at Girton in Nottinghamshire where several gravel pits have been filled with PFA both in the form of a slurry and as conditioned ash. Some of the deposits are over 20 years old and the final lagoon is still active. The quantified risk assessment and extensive groundwater sampling and analysis concluded that

"In summary the modelling outcomes and field testing results both suggest strongly that ash disposal does not have a material effect on the environmental quality of groundwater or the River Trent down gradient of the ash disposal site. This leads us to conclude that long term monitoring of groundwater is not warranted, in the context of future applications for new waste management license applications or surrenders. Also, there is no environmental benefit of potential future lagoons being lined"

The Girton QRA report has been submitted to the Environment Agency inspectors responsible for the Girton site. Extracts from the QRA are included in the appendices. In the report the following observation was made in the conclusions

"The leachate data for the pore water within MW4 and WW10 in the wet and dry ash deposits respectively are also in line with expectations for a "first flush" and therefore indicate that the deposit have been subject only to very limited leaching which in the case of Area 2 were deposited over 15 years ago. This is also consistent with expectations based on the hydraulic properties of ash as outlined in Section 8.2 and is further supported by field observations which indicated that the water table in restored ash deposits was measurably higher than in the surrounding strata"

The analysis in the Girton risk assessment represents a much more severe test than most embankments, the reasons for this are as follows:-

- The Girton study relates to several very large deposits of PFA below ground in a situation where they are permanently exposed to groundwater. The total ash involved is probably around 2 million tonnes in a very small area. Most embankments are very much smaller deposits and perched above a capillary breaker and geosynthetic membrane.
- The surface of the lagoons is flat which allows more rainwater to infiltrate than will be the case for the sloping embankments often used. This could provide a driving head to promote leaching.
- The results are confirmed by data from the routine monitoring of groundwater for metallic elements at Bole Ings (Disposal site for West Burton Power Station). Here there is a deposit of some 2 million tonnes of PFA in an unlined mound. The results of this monitoring are given in Table Q. With most embankments it is difficult to see any route for leachate to enter the groundwater because:-
 - There will be negligible infiltration of water into the deposit. This is confirmed by experience with the large above ground mounded disposal sites at Drax and West Burton Power stations.
 - The very low infiltration is caused by three attributes of PFA when used in this situation:
 - Very low permeability when used as engineered fill.

- Sloping sides of the deposit cause rapid water run off, and the top such mounds are capped by a either road surface or vegetation.
- Cementitious compounds in the ash cause the formation of a layer, which has even lower permeability than the PFA. This layer is just below the surface at the limit of water penetration.
- The deposit is separated from the groundwater by a capillary breaker and geosynthetic membrane.

Conclusions

Given the manner of construction of the typical embankments there is effectively no pathway for leachate to reach groundwater.

Potential impact on and pathways to surface water

The above assessment of the impacts to groundwater contains many relevant issues in assessing the potential for impacts to surface water. The construction of most embankments is with relatively steep sides using low permeability material. This means that most rainwater will run off.

There will be infiltration of the topsoil layer and some infiltration into the PFA but this will be transpired out by the grasses and plants on the embankments. Experience has shown that the layer of cementitious compounds builds up at the maximum depth of water infiltration, which is the depth of the root systems of the plants. The plants transpire out much of the infiltrated water. There is very little, if any, opportunity for contact between surface water and the ash deposit.

Once the embankments have been constructed, top soiled and planted there is no effective mechanism for surface water to contact the PFA. Therefore, the long-term effects of the presence of the embankments on local surface water will be undetectable against the background concentrations. This is what has been found in the large-scale mounds of PFA built up over some 30 years and in its use for road embankments, foundations and in bridge abutments all over the country and in Europe.

Construction Risks

The only opportunity for significant contamination of surface water would appear to be during the construction of the embankments. The construction of such embankments would run the risk of run off of suspended solids in heavy rainfall no matter what material was used to form the embankments. Indeed natural materials such as subsoil contain large amounts of colloidal material, which discolours water and is very difficult to remove before discharge to a watercourse.

If it is properly managed, PFA is actually less susceptible to construction risks than most other materials. This has been demonstrated at many above ground PFA storage and disposal sites including, Ironbridge, Bole Ings, Drax and Ratcliffe on Soar. At these sites millions of tonnes of PFA has been built into embankments frequently within feet of ditches and streams without any tendency for the deposits to wash into the watercourses in heavy rain. The fact that PFA is not washed away in heavy rain can be attested to by those who manage large PFA stocks and it is possible to point to reasons why this should be so.

PFA is pozzolanic, when moistened PFA is exposed to the air its surface hardens to form a cemented skin that retains PFA particles. The development of this skin occurs over several hours like the setting of cement. If this layer is not disturbed it has been found very effective at retaining material. The very low permeability of the material does not encourage the formation of material with a high liquid to solid ratio as occurs with mud formed from soil.

The size and shape and relative density of the PFA particles as small spheres of silicate glass does not aid retention in suspension in water. In PFA disposal lagoons the water clears quickly, leaving the PFA particles behind. It is noticeable that this is not the case with coal fines. They are easily moved in a flow of water, probably because they are larger, flat sided and have a lower relative density.

The contractor should always take precautions to allow settlement and filtration of all the water run off from the site including that from the local soils and sub soils, irrespective of the fill material chosen. There is no evidence that PFA will create additional hazards whilst there is evidence that PFA has properties that reduce the potential for such incidents.

The manager of the Bole Ings ash disposal site (Mr G Strutz of RMC) was asked for his comments, see appendix 1. Mr Strutz handles PFA every day and frequently building PFA embankments alongside very small drainage ditches, which have been designated as a Site of Importance for Nature Conservation and support populations of protected species such as water voles.

Chemical Quality of Run off During Construction

The formation of the cementitious skin on deposits of PFA means that there is very little, if any, possibility of surface water run off containing significant concentrations of mobile contaminants. The amount of infiltration will be minute and the amount of mobile material on the surface will be very small and can only be washed off once. Since the ash will have

been conditioned with river water, it will be alkaline and this will ensure that any run off is alkaline which will inhibit the mobilisation of metals.

Analysis of water in a ditch adjacent to 500,000 tonnes of PFA stockpiled at Ironbridge Power station is included in Table W. As can be seen the analyses meet all the appropriate EQS standards. It is worth noting that many of the readings are very low indeed. The spot analyses are variable because of rainfall patterns, degree of disturbance to the site etc. The ditch does not flow in periods of dry weather and this is bound to increase concentrations due to evaporation in the static water. The highest concentration observed was in July when the rainfall is the lowest. It is likely, therefore, that the highest concentrations occur when the flow is very small and do not carry much of the trace elements into the River Severn. Table V shows that both the natural groundwater in the river terrace gravels and the water in the River Trent have significantly higher boron concentrations than the ditch running through the Ironbridge A power station site.

Analysis of the water in the river Severn is included as Table X. The samples for these analyses are taken from downstream of both the outfall from the ash disposal site at Devils Dingle and the discharge from the Ironbridge A ash storage site. The concentrations monitored in the river are low indicating no measurable effect from the millions of tonnes of ash in the two sites.

Water leaving a construction site during the construction period should have considerably lower concentrations than the ditch at the Ironbridge A site because: -

- Usually for fill applications, the amount of PFA would be smaller than the size of the Ironbridge A mounds.
- The embankments will be constructed and then covered in topsoil giving a very much smaller exposed area.

The Ironbridge A site ditch gives a good practical indication that there will be no adverse effect from trace metals in the PFA during construction. The Ironbridge A site data allows an assessment to be made which covers all the foreseeable situations likely to be encountered in building the embankments.

When considering the run off from the construction site, the amount of PFA surface that will be uncovered and so new that it has not formed a cementitious crust, will be relatively small. At any one time, the new surface is unlikely to be greater than 10% of the total. The opportunities for pickup of contaminants are therefore less than at the Ironbridge A site. It follows that the pickup of trace elements from ash should also be less.

The EQS's are expressed as long-term averages, typically over a year. The measurements are taken in the environment and would normally allow for substantial dilution of an individual discharge. If run off from the PFA embankments during construction will only cause instantaneous concentrations, which meet EQS levels, the discharge cannot cause an exceedance in the stream. The site drainage would normally only be a small fraction of the annual water flow in the stream. The effect on the annual average values in the stream would probably not be measurable and would have no effect on connecting rivers.

To give additional confirmation that the use of PFA will not affect aquatic life a consultant aquatic biologist (Mr T Langford) to comment, see appendix 2, on the risk based on observations at Ironbridge power station over many years. At Ironbridge there has been storage of ash alongside the River Severn for almost 20 years and disposal to an off site lagoon at Devils Dingle since the 1960s. Mr Langford has been able to observe the effects on aquatic ecology of the Devils Dingle lagoon and the streams fed from it and its effect on the river Severn local to the outfall. The exposure to ash under these circumstances is obviously significantly greater and more long-lived than the potential at most construction sites, but there has been no observable impact. Thus, the temporary exposure to much lower concentrations will have no impact on streams and rivers adjacent to construction using PFA.

A recent project carried out by the Arnold et al³⁴ from the University of Nottingham looked at the levels of radon and leachable contaminants in groundwater and surface water adjacent to PFA embankments of various ages. The reports conclusions are as follows:

- Concentrations of contaminants in ground water were all rather low.
- In the vicinity of three of the five embankments studied, some contaminant concentrations greater than that typically permitted for drinking water quality were found.
- Four determinants (out of 31) which may be attributable to PFA gave values above typical drinking water quality levels on at least one occasion. These were Magnesium, Selenium, Potassium and Sodium.
- Of the four contaminants listed above, only Potassium and Sodium appear to be of any significance.
- Agriculture and traffic are much more credible sources for all the contaminants which appear at high concentrations, than is the PFA.
- One non-PFA site investigated yielded similar concentration levels to the PFA sites.
- On the basis of this investigation, it is very unlikely that PFA is a significant cause of contamination of groundwater at a level of concern to the environment.
- PFA is not the source of any generic contamination problem.
- No Radon was detected anywhere at levels above the most onerous intervention level.

- The highest Radon levels which were detected were in the PFA pore space. Thus even lower levels are expected, even in enclosed spaces, outside of the PFA.
- Radon levels in air adjacent to the PFA were extremely low.
- On the basis of this investigation, there is no evidence that PFA in embankments poses a hazard to health.
- The age of the PFA and the PFA source do not appear to have a noticeable influence on the levels of contamination or of Radon emissions.

Odour and dust blow

Moistened PFA has no odour and has never caused odour complaints. The formation of a cementitious crust on PFA has been found effective at preventing dust blow. There are two considerations in the prevention of; firstly, the surface must be wetted either by rain or dew or by the use of artificial sprays in prolonged dry weather. The surface should not be disturbed until it is covered by a further layer.

If the above management actions are undertaken, PFA has been found to have less dust blow potential than many other materials most of which would require regular moistening to prevent dust blow.

Discussions and conclusions

Discussion

The evidence presented in this document shows that PFA does contain trace metals but that in general these are closely bound with the structure of the material and have low potential to leach. The very low permeability of a PFA deposit and tendency to form a cementitious layer beneath the surface means that most embankments with their sloping sides will reject water and not create significant leachate. The embankment should also contain provision for a capillary breaker to prevent groundwater being drawn upwards into the deposit.

The organic content of PFA is very low except for some elemental carbon. This means that PFA does not biodegrade to produce gas or leachate. There are traces of organic compounds such as PAH's and phenols but these are present in very small quantities that comply with all standards. Traces of such compounds are strongly adsorbed and degraded in aerobic conditions and they will not cause environmental impact.

The analysis and leachate testing shows a consistent pattern of results for both organic and inorganic determinants. The data referenced in this document includes material from several other stations around the UK together with independently published "typical" data. PFA produced by modern plant is shown from these data to be reasonably consistent particularly with respect to its leaching characteristics. In the Girton risk assessment, a similar conclusion was drawn: -.

The leachate results are more consistent than total metals analyses of PFA, which is considered to reflect the fact that of the total metal concentration that may be present, only a very small proportion is leachable, the remainder being held in the silicate matrix or retained by the mechanisms discussed above.

Similar conclusions were drawn in a report characterising PFA that was produced by Jacobs-Gibb. An extract is provided in appendix 3.

A major construction project close to a watercourse poses a risk of run off and high suspended solids. These issues by the contractor and would apply to any material which is likely to be used to construct the embankments. PFA presents less risk than many potential materials because it forms a cementitious crust, which prevents water ingress until the deposit is completed. The cementitious crust also prevents dust blow if it is not disturbed.

It should be remembered that PFA is based on natural soils and clays. The trace elements present are ubiquitous in the environment and will be present in the vast bulk of material that could be used. For example, in the Girton risk assessment leachate tests were conducted on the PFA deposits and the surrounding gravels in the river terrace deposit, (See Table V). In most cases the leachate tests carried out on the gravels, produce similar results to the leachate tests carried out on the PFA deposits. (The relevant areas of the table are highlighted) Most other materials are more permeable than PFA leading to greater potential interchange with groundwater

Overall Conclusion

The use of PFA represents no appreciable hazard as a material for construction of embankments if the site is managed to prevent dust blow and run off into watercourses. The risk of dust blow and run off would be present for any material and these risks are no greater with PFA, in fact, the risks may well be reduced.

Any local rivers or streams do not need to be protected during construction of the embankments whichever material is used. The use of PFA does not pose any additional risks either in construction of the embankments, their use and eventual remodelling.

The use of PFA reduces the need for landfill to be used and the need for the quarrying of other aggregates. This means that the overall environmental benefits of the use of PFA are significant. Avoidance of landfill and reduction in the quarrying of aggregates are both supported by UK and EU Government policy and promoted by the Landfill Tax, and Aggregates Levy to be introduced shortly.

The use of PFA for such purposes is widespread and approved by the Highways Agency. PFA is an excellent material from a technical standpoint and has been shown ideal for such applications.

Supporting data

Table K - Detailed Analysis of PFA in High Marnham Ash Lagoons - Total Concentrations

Determinant	mg/kg	Determinant	mg/kg
Ammonia	< 3	Iron	26500
Nitrate	5.2	Magnesium	203
Total Organic Carbon	37	Arsenic	69.9
Calcium	9620	Boron	10.3
Sodium	2540	Cadmium	1.8
Potassium	8750	Chromium	33
Barium	463	Copper	86
Sulfate	658	Mercury	0.13
Fluorine		Molybdenum	2
Chlorine	21	Nickel	39
		Selenium	3.23
Total PAH	< 0.5	Strontium	114
		Zinc	49

Table L – Pore water composition in the base layers of an East Midlands PFA lagoon

Determinant	Range of Composition (mg/l)
pH	8.0 – 10.90
EC (μ S/cm)	2090 – 3260
Arsenic	0.040 – 0.155
Barium	0.030 – 0.160
Boron	1.4 – 4.2
Cadmium	<0.0002
Calcium	70 – 465
Chromium	<0.005 – 0.020
Copper	<0.002 – 0.011
Lead	<0.002
Mercury	<0.00002
Molybdenum	1.6 – 7.7
Nickel	<0.005 – 0.035
Selenium	0.026 – 0.190
Strontium	0.85 – 2.95
Sulfate	480 – 1485
Zinc	<0.002 – 0.070

NB: These samples were extracted from three cores located near the base of a full PFA lagoon about three years after PFA disposal ceased. Two further cores were obtained from the same depth one-year later.

Table M - Total Trace Metal Content of PFA (SLR Consulting, 2000/N Power 2000

Determinant (mg/kg)	High Marnham	Didcot A	Ratcliffe on-Soar	Drakelow	Mean
Arsenic	111	71	128	108	105
Boron	-	181	132	75	129
Cadmium	<0.1	3	4	3	2.5
Chromium	33	44	50	55	46
Cobalt	-	20	22	16	19
Copper	33	56	73	66	57
Lead	84	70	72	43	67
Mercury	0.75	<1	<1	<1	<1
Molybdenum	16	16	15	13	15
Nickel	37	42	50	35	41
Selenium	-	<1	<1	<1	<1
Tin	-	<10	<10	<10	<10
Vanadium	-	117	133	96	115
Zinc	101	142	136	65	111

Table N - Leachate Tests for PFA from Ironbridge, Drakelow and Rugeley Power Stations during 2001

Also a similar test on a sample from the ash in the storage lagoons at Rugeley.

(NB: Drakelow Results were from a different laboratory)

Determinant	Ironbridge (mg/l)	Rugeley (mg/l)	Drakelow * (mg/l)	Rugeley Lagoon (mg/l)
Aluminium			0.41	
Antimony	<0.05	0.12	<0.05	<0.05
Arsenic	<0.05	<0.05	<0.01	<0.05
Boron	2.21	2.49	1.40	2.01
Barium	0.21	0.63	0.14	0.2
Cadmium	<0.05	<0.05	<0.004	<0.05
Calcium	202.4	204.9	131	100.3
Chromium	0.07	0.1	0.43	0.1
Hexavalent Chromium	0.07	0.08	-	0.09
Cobalt	<0.05	<0.05	<0.01	<0.05
Copper	0.15	0.21	<0.02	0.13
Iron	<0.05	<0.05	<0.08	<0.05
Lead	<0.05	<0.05	<0.01	<0.05
Magnesium	0.17	0.11	0.35	0.07
Manganese	0.34	0.41	1.4	0.12
Mercury	<0.05	<0.05	<0.001	<0.05
Molybdenum	0.37	0.45	0.89	0.15
Nickel	<0.05	<0.05	<0.01	<0.05
Phosphorous	<0.05	<0.05	0.50	<0.05
Potassium	12	24	31	11
Selenium	0.13	0.21	<0.01	0.07
Silicon	0.16	1.55	6.10	0.92
Sodium	13	33	40	8
Tin	<0.5	<0.5	<0.1	<0.5
Titanium	<0.05	<0.05	<0.1	<0.05
Vanadium	<0.05	<0.05	0.21	<0.05
Zinc	<0.05	<0.05	<0.02	<0.05
Chloride	7	< 5	9	8
Fluoride	<0.01	0.97	<1	<0.01
Nitrate	0.3	<0.3	<1	0.3
Nitrite	0.05	<0.05	<0.5	0.09
Sulfate	444	473	380	164
EC (µS/cm)	940	1636	1043	620

Table O - Bole Ings Ash Analysis – Metals in ash (mg/kg air-dried)

Sample	Cd	Hg	As	B	Cr	Cu	Pb	Mo	Ni	Se	V	Zn
01/06/1997	2.0	0.47	144	122	42	71	39	20	40	5.24	112	46
01/12/1997	<1	0.45	112	94	47	97	44	21	40	3.92		46
01/06/1998	<1	0.38	90	164	38	62	53	14	31	3.84	93	51
01/06/1999	2.0	<0.5	103	97	46	74	72	15	51	4.20	141	103
01/12/1999	<1	<0.5	89	18	46	98	85	15	62	6.73	159	114
01/06/2000	<1	<0.5	92	28	53	82	74	20	88	5.26	146	113
01/12/2000	<1	<0.5	97	24	44	88	60	8	54	5.99	132	62
01/06/2001	<1	<0.5	77	30	60	91	92	<2	72	4.58	168	82
01/12/2001	<1	<0.5	48	5	32	30	19	4	25	3.78	94	21

Table P - Bole Ings Ash Leachate Analysis (mg/litre)

Sample	Cd	Hg	As	Sb	B	Ba	Be	Cr	Co	Cu	Fe	Pb
01/06/1997	<0.01	<0.0001	0.07					0.07		<0.01	0.02	<0.03
01/12/1997	<0.01	<0.0001	0.16					0.08		<0.01	<0.01	<0.03
01/06/1998	<0.01	<0.0001	0.07					0.06		<0.01	0.01	<0.03
01/06/1999	<0.01	<0.0001	0.03	0.010	0.74	0.12	<0.01	0.10	<0.02	<0.01	0.01	<0.03
01/12/1999	<0.01	<0.0001	0.05	0.006	0.23	0.16	<0.01	0.05	<0.02	<0.01	0.01	<0.03
01/06/2000	<0.01	<0.0001	<0.03	0.009	0.50	0.01	<0.01	<0.02	<0.02	<0.01	<0.01	<0.03
01/12/2000	<0.01	<0.0001	0.07	0.007	0.31	0.21	<0.01	0.03	<0.02	<0.01	<0.01	<0.03
01/06/2001	<0.01	<0.0001	<0.03	0.004	0.37	0.18	<0.01	0.07	<0.02	<0.01	<0.01	<0.03
01/12/2001	<0.01	<0.0001	<0.03	0.003	0.31	0.21	<0.01	0.14	<0.02	<0.01	<0.01	<0.03

Sample	Mo	Ni	Se	Ag	Sn	Ti	V	Zn	pH	Sulfate	Chloride
01/06/1997	1.42	<0.02	0.05				0.11	<0.01	10.6		
01/12/1997	1.20	0.07	0.026				0.17	<0.01	9.4		
01/06/1998	0.88	<0.02	0.024				0.15	0.03	10.8		
01/06/1999	0.93	<0.02	0.021	<0.001	<0.001	<0.001	0.16	0.01	10.6	240	10
01/12/1999	0.70	<0.02	0.02	<0.001	<0.001	<0.01	0.22	<0.01	11.1	242	12
01/06/2000	0.04	<0.02	0.018	<0.001	<0.001	<0.01	<0.02	0.05	10.5	25	6
01/12/2000	0.58	<0.02	0.020	<0.001	<0.001	<0.01	0.10	<0.01	10.1	235	9
01/06/2001	0.35	<0.02	0.010	<0.001	<0.001	<0.02	0.08	<0.01	10.6	194	6
01/12/2001	0.18	<0.02	0.009	<0.001	<0.001	<0.02	0.07	<0.01	10.7	26	5

Table Q – Bole Ings Ground Water Analysis (mg/litre)

Sample	Cd	Hg	As	Sb	B	Ba	Be	Cr	Co	Cu	Pb	Mo	Ni	Se	Sn	Zn	pH	Sulfate
20/02/1998 A	<0.01	<0.0001	<0.03	<0.001	0.19	0.35	<0.02	<0.02	<0.05	<0.01	<0.03	<0.02	<0.02	<0.0001	0.002	<0.01	7.0	93
B	<0.01	<0.0001	<0.03	<0.001	0.15	0.64	<0.02	<0.02	<0.05	<0.01	<0.03	<0.02	<0.02	<0.0001	0.012	<0.01	6.9	157
C	<0.01	<0.0001	<0.03	<0.001	0.15	0.11	<0.02	<0.02	<0.05	<0.01	<0.03	<0.02	<0.02	<0.0001	0.008	<0.01	6.8	220
D	<0.01	<0.0001	<0.03	<0.001	0.16	0.58	<0.02	<0.02	<0.05	<0.01	<0.03	<0.02	<0.02	<0.0001	<0.001	<0.01	7.0	97
E	<0.01	<0.0001	<0.03	<0.001	0.34	0.24	<0.02	<0.02	<0.05	<0.01	<0.03	<0.02	<0.02	<0.0001	0.002	<0.01	7.0	209
22/09/1998																		
A	<0.01	<0.0001	<0.03	0.002	0.14	0.28	<0.01	<0.02	<0.02	0.01	<0.03	<0.02	0.02	<0.0001	<0.001	0.01	7.1	118
B	<0.01	<0.0001	<0.03	<0.001	<0.05	0.68	<0.01	<0.02	<0.02	<0.01	<0.03	<0.02	<0.02	<0.0001	<0.001	0.04	7.0	147
C	<0.01	<0.0001	<0.03	<0.001	0.12	0.35	<0.01	<0.02	<0.02	<0.01	<0.03	<0.02	<0.02	<0.0001	<0.001	0.02	6.9	205
D	<0.01	<0.0001	<0.03	<0.001	<0.05	0.64	<0.01	<0.02	<0.02	<0.01	<0.03	<0.02	<0.02	0.0002	<0.001	0.04	7.1	95
E	<0.01	<0.0001	<0.03	<0.001	0.15	0.26	<0.01	<0.02	<0.02	<0.01	<0.03	<0.02	<0.02	<0.0001	<0.001	0.03	7.1	207
08/02/1999																		
A	<0.01	<0.0001	<0.03	0.002	0.15	0.22	<0.01	<0.02	<0.02	<0.01	<0.03	<0.02	<0.02	<0.0001	<0.001	0.04	7.0	115
B	<0.01	<0.0001	<0.03	<0.001	0.08	0.49	<0.01	<0.02	<0.02	<0.01	<0.03	<0.02	<0.02	0.0001	<0.001	0.02	7.0	144
C	<0.01	<0.0001	<0.03	<0.001	0.07	0.17	<0.01	<0.02	<0.02	<0.01	<0.03	<0.02	<0.02	0.0002	<0.001	0.02	6.8	173
D	<0.01	<0.0001	<0.03	<0.001	0.09	0.40	<0.01	<0.02	<0.02	<0.01	<0.03	<0.02	<0.02	<0.0001	<0.001	0.03	7.0	91
E	<0.01	<0.0001	<0.03	<0.001	0.27	0.24	<0.01	<0.02	<0.02	<0.01	<0.03	<0.02	<0.02	0.0001	<0.001	0.01	7.0	182
07/09/1999																		
A	<0.01	<0.0001	<0.03	<0.001	0.09	0.44	<0.01	<0.02	<0.02	<0.01	<0.03	<0.02	<0.02	0.001	<0.001	0.12	7.0	22
B	<0.01	<0.0001	<0.03	<0.001	0.06	0.51	<0.01	<0.02	<0.02	<0.01	<0.03	<0.02	<0.02	0.001	<0.001	0.01	6.9	120
C	<0.01	<0.0001	<0.03	<0.001	0.06	0.23	<0.01	<0.02	<0.02	<0.01	<0.03	<0.02	<0.02	0.001	<0.001	0.01	6.9	170
D	<0.01	<0.0001	<0.03	<0.001	0.08	0.54	<0.01	<0.02	<0.02	<0.01	<0.03	<0.02	<0.02	0.001	<0.001	0.01	7.0	77
E	<0.01	<0.0001	<0.03	<0.001	0.31	0.24	<0.01	<0.02	<0.02	<0.01	<0.03	<0.02	<0.02	<0.0001	<0.001	0.01	7.1	197
28/02/2000																		
A	<0.01	<0.0001	<0.03	<0.001	0.08	0.71	<0.01	<0.02	<0.02	<0.01	<0.03	<0.02	<0.02	0.002	0.003	0.03	6.7	48
B	<0.01	<0.0001	<0.03	<0.001	0.08	0.37	<0.01	<0.02	<0.02	<0.01	<0.03	<0.02	<0.02	0.001	0.001	0.01	6.7	108
C	<0.01	<0.0001	<0.03	<0.001	0.08	0.18	<0.01	<0.02	<0.02	<0.01	<0.03	<0.02	<0.02	0.001	0.001	0.02	6.8	161
D	<0.01	<0.0001	<0.03	<0.001	0.09	0.17	<0.01	<0.02	<0.02	<0.01	<0.03	<0.02	<0.02	0.001	<0.001	0.01	6.8	171
E	<0.01	<0.0001	<0.03	<0.001	0.09	0.15	<0.01	<0.02	<0.02	<0.01	<0.03	<0.02	<0.02	0.002	<0.001	0.02	6.8	172
02/10/2000																		
A	<0.01	<0.0001	<0.03	<0.001	0.10	0.53	<0.01	<0.02	<0.02	<0.01	<0.03	<0.02	<0.02	0.002	<0.001	0.03	7.0	152
B	<0.01	<0.0001	<0.03	<0.001	0.10	0.16	<0.01	<0.02	<0.02	<0.01	<0.03	<0.02	<0.02	0.001	<0.001	0.04	7.0	207
C	<0.01	<0.0001	<0.03	<0.001	0.09	0.40	<0.01	<0.02	<0.02	<0.01	<0.03	<0.02	<0.02	<0.0001	<0.001	0.03	7.0	165
D	<0.01	<0.0001	<0.03	<0.001	0.09	0.39	<0.01	<0.02	<0.02	<0.01	<0.03	<0.02	<0.02	0.001	<0.001	0.04	7.0	165
E	<0.01	<0.0001	<0.03	<0.001	0.10	0.17	<0.01	<0.02	<0.02	<0.01	<0.03	<0.02	<0.02	0.001	<0.001	0.01	7.0	208

Table R - High Marnham Power Station Ash Slurry System Water Analysis

These are typical data obtained from currently operating slurry systems such High Marnham, Drakelow and Rugeley. The pH of the outfall water was between 8.4 and 8.6 for all readings taken in 2001.

Determinant	River water extracted for use as Power Station Cooling Water (mg/l)	Water used for slurring after use in the cooling water system and evaporation of water vapour (mg/l) (Value A)	Discharge to River Trent from Besthorpe lagoon 14 discharge point (mg/l) (Value B)	Uplift in transporting ash (Value B-Value A) mg/l	EQS (where appropriate) (mg/l)
Mercury	<0.0001	<0.0001	<0.0001	Not Detected	0.001
Cadmium	<0.005	<0.005	<0.005	Not Detected	0.005
Antimony	<0.00075	0.00207	0.0113	0.009	
Arsenic	0.00103	0.00639	0.097	0.09	0.05
Barium	0.29	0.53	0.54	0.01	
Beryllium	<0.1	<0.1	<0.1	Not Detected	
Boron	0.21	0.37	0.85	0.48	2
Chromium	<0.1	<0.1	<0.1	Not Detected	0.25
Cobalt	<0.1	<0.1	<0.1	Not Detected	
Copper	<0.1	<0.1	<0.1	Not Detected	0.028
Lead	<0.1	<0.1	<0.1	Not Detected	
Molybdenum	<0.1	<0.1	0.21	0.15	
Nickel	<0.1	<0.1	<0.1	Not Detected	0.05
Selenium	<0.00075	0.00088	0.00827	Not Detected	
Silver	<0.1	<0.1	<0.1	Not Detected	
Tellurium	<0.005	<0.005	<0.005	Not Detected	
Tin	<0.1	<0.1	<0.1	Not Detected	
Titanium	<0.1	<0.1	<0.1	Not Detected	
Uranium	<0.005	<0.005	<0.005	Not Detected	
Vanadium	<0.1	<0.1	<0.1	Not Detected	
Zinc	<0.1	<0.1	<0.1	Not Detected	0.5

Table S – PAH Compounds

Compound	PFA LEACHATE				LAGOON WATER
	Drakelow	Ironbridge	High Marnham	Rugeley	Drakelow (Newbold)
	ng/l*	ng/l	ng/l	ng/l	ng/l
Naphthalene	682	171	178	166	74
Acenaphthylene	35	<10	19	<10	<10
Acenaphthene	75	14	28	12	13
Fluorene	57	<10	35	13	13
Phenanthrene	103	<10	71	16	27
Anthracene	27	<10	11	<10	<10
Fluoranthene	33	43	103	<10	51
Pyrene	25	37	73	<10	35
Benz(a)anthracene	<10	<10	<10	<10	<10
Chrysene	<10	<10	<10	<10	<10
Benzo(b)fluoranthene	<10	<10	<10	<10	<10
Benzo(k)fluoranthene	<10	<10	<10	<10	<10
Benzo(a)pyrene	<10	<10	<10	<10	<10
Indeno(123cd)pyrene	<10	<10	<10	<10	<10
Dibenzo(ah)anthracene	<10	<10	<10	<10	<10
Benzo(ghi)perylene	<10	<10	<10	<10	<10
Total					
Against Drinking Water Standard	33	43	103	<10	51
Total 16 PAH	1038	265	518	208	213
Total 16 PAH minus Naphthalene	356	87	340	42	139

* Units are nanogrammes per litre. The PAH standard in EA Interim Guidance on the Disposal of Contaminated Soils is 200 nanogrammes per litre measured based on the Drinking Water Standards determinants.

Table T - Phenols

Sample	Cresols ppm Limit of Detection 0.01	Naphthol ppm Limit of Detection 0.01	Phenol ppm Limit of Detection 0.01	Resorcinol ppm Limit of Detection 0.01	Trimethyl Phenol ppm Limit of Detection 0.01	Total Phenols ppm Limit of Detection 0.01
Drakelow	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Ironbridge	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
High Marnham	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Rugeley	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Newbold	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Lagoon Water						

Table U - Leachate Test Analysis for Mercury and Cadmium

In general, laboratories quote results for the very low-level concentrations as less than 10ppb or less than 50ppb. For some analyses, the results have been quoted more accurately. The following table summarises these results to give some quantification of the actual results, which are likely

Analysis of the water in the disposal site has also been included. This pore water has been in contact with the ash for a considerable period and is a realistic assessment of the water quality within an ash deposit.

Determinant	Provenance of Test	Leachate Test Result ppb (µg/l)
Cadmium	Dry ash sample from Girton Lagoons	< 1
	Wet deposited ash from Girton Lagoons	2
	In site pore water Girton wet deposited ash	< 1
	In site pore water Girton dry deposited ash	< 1
	Drakelow PFA leachate test	< 4
Mercury	All the Bole Ings Samples in Table 7.6	< 0.1
	Dry ash sample from Girton Lagoons	< 0.1
	Wet Deposited ash from Girton Lagoon	< 0.1
	In site pore water Girton wet deposited ash	0.15
	In site pore water Girton dry deposited ash	< 0.1
	Drakelow PFA leachate test	< 1

Table V - Girton Risk Assessment Maximum observed concentrations of soil and water determinants

¹ Soil concentration units:mg/kg² Leachate & water concentration units: mg/l

Scenario (sample points)		pH	TOC	PAHs	Ca	Na	K	Ba	SO ₄	F	Cl	Fe	Mn	As	B	Cd	Cr	Cu	Hg	Mo	Ni	Se	Sr	Zn
Up gradient (MW11, MW12) MW13)	Soils ¹		44		2,490	295	3,920	113	158		<20	15,400	417	5.5	1	<1.7	12	17	<0.05	<1	15	0.25	55	17
	Leachate ²	8.8	4.4		7	5	7	<0.1	62	0.3	<2	0.84	<0.04	0.001	1.3	<0.001	<0.005	<0.02	<0.0001	<0.1	0.009	0.001	0.13	<0.1
	Water ²	8.1			274	41	18	0.3	430	0.4	98	0.68	0.7	0.005	1.2	0.006	<0.005	<0.02	<0.0001	<0.1	<0.007	0.001	<0.03	1.4
Up gradient (MW2)	Soils ¹		328		5,130	295	5,100	57.9	183		40	39,700	832	17.1	2.2	<1.7	30	42	0.06	1	33	1.1	199	9
	Leachate ²	6.4	11.8		13	2	<2	<0.1	9	0.3	<2	0.23	0.32	0.002	1	<0.001	<0.005	<0.02	<0.0001	<0.1	<0.007	0.001	<0.03	0.1
	Water ²	8			392	36	6	<0.1	649	0.2	56	0.21	2.58	0.001	0.7	<0.001	<0.005	<0.02	<0.0001	<0.1	<0.007	0.001	<0.03	3.6
Bunding between disposal areas (MW3, MW5, MW6)	Soils ¹		258		6,130	313	5,330	283	356		78	28,300	608	9.8	1.5	<1.7	21	22	<0.05	2	19	0.54	129	55
	Leachate ²	7.9	8.4		13	2	<2	<0.1	33	0.4	<2	0.43	1.36	0.001	1.1	0.002	<0.005	<0.02	<0.0001	<0.1	0.008	0.001	0.12	<0.1
	Water ²	8.2			340	81	18	0.3	277	1	160	25.9	22.4	0.001	1.5	<0.001	<0.005	<0.02	<0.0001	0.1	0.011	0.002	<0.03	3.3
Wet ash (MW4)	Soils ¹		37	<0.5	9,620	2,540	8,750	463	658		42	26,500	203	74.8	10.3	2	33	86	0.13	3	39	3.23	49	114
	Leachate ²	9.2	2.1	<0.06	37	2	3	<0.1	42	0.2	<2	<0.05	<0.04	0.11	1.3	0.002	<0.005	<0.02	<0.0001	<0.1	<0.007	0.025	<0.03	<0.1
	Water ²	7.2		2.13	236			1.8	477		100	25.8	0.52	0.127	1.2	<0.001	0.065	0.27	0.0015	2.1	0.076	0.003	0.16	1.7
Dry ash (MW10)	Soils ¹		11	<0.5	8,260	1,450	1,290	178	3,506		<20	10,700	170	113	14.2	2.5	25	42	0.18	20	17	2.26	28	65
	Leachate ²	9.2	0.7	<0.06	84	42	21	<0.1	299	0.2	8	<0.05	<0.04	0.027	1.9	<0.001	<0.005	<0.02	<0.0001	1.4	<0.007	0.009	<0.03	0.3
	Water ²	7.3		<0.06	478			<0.1	4,860		309	<0.05	0.12	0.028	3.8	<0.001	<0.005	0.03	<0.0001	34	<0.007	<0.001	<0.03	3.4
Down gradient (MW1, MW7, MW8, MW9)	Soils ¹		133		22,600	223	7,440	695	3,200		520	52,100	7,630	17.7	1.4	4.6	32	35	<0.05	<1	45	1.39	322	159
	Leachate ²	7.3	6.5		116	2	<2	<0.1	294	0.2	2	0.46	0.8	0.001	1.1	0.002	<0.005	<0.02	0.0003	<0.1	0.008	0.001	0.12	0.7
	Water ²	8.2		<0.06	520	99	19	0.2	792	5	188	2	14	0.005	2	<0.001	<0.005	<0.02	<0.0001	0.2	0.014	0.001	<0.03	4.9
River Trent – upstream (SW1)	8.3			88	54	11	<0.1	135	0.3	51	0.25	0.06	0.002	1.2	<0.001	<0.005	<0.02	<0.0001	<0.1	0.009	0.001	0.4	<0.03	
River Trent – down stream (SW2)	8.4			83	53	10	<0.1	141	0.3	52	0.06	<0.04	0.002	1.2	<0.001	<0.005	<0.02	<0.0001	<0.1	<0.007	0.001	0.5	<0.03	
Old Trent (SW3)	8.3			242	62	7	<0.1	438	0.8	90	0.25	0.47	0.001	1.4	<0.001	<0.005	<0.02	<0.0001	<0.1	<0.007	<0.001	1.9	<0.03	
Lake in Area 7 (SW4, SW5)	8.1			106	21	8	<0.1	194	0.3	34	<0.05	0.06	0.003	1.2	<0.001	<0.005	<0.02	<0.0001	<0.1	<0.007	0.001	0.8	<0.03	

Table W - IRONBRIDGE A Station Drainage Ditch Water Analysis
Results of Recent Water Analysis

Note Results expressed in micro grams per litre ($\mu\text{g/l}$)

Date of Sample	15/05/2000	24/07/2000	23/04/2001	Oct-01	Appropriate
	Results $\mu\text{g/l}$	Results $\mu\text{g/l}$	Results $\mu\text{g/l}$	Results $\mu\text{g/l}$	EQS
Antimony	<5	<5	<5	<5	
Arsenic	9	20	<2	<2	50
Barium	<50	60	80	<50	
Beryllium	<50	<50	<50	<50	
Boron	250	820	<50	<50	2000
Cadmium	<0.4	<0.4	<0.4	<0.4	5
Chromium	<1	9	27	3	250
Cobalt	<1	<1	<1	<1	
Copper	<5	<5	5	<5	28
Lead	<5	<5	<5	<5	250
Mercury	<0.05	0.1	<0.05	<0.05	1
Molybdenum	10	70	<5	<5	
Nickel	<10	<10	<10	<10	50
Selenium	<5	<5	<5	<5	
Silver	<10	<10	<10	<10	
Tellurium	<50	<50	<50	<50	
Thallium	<50	<50	<50	<50	
Tin	<5	<5	<5	<5	
Titanium	<50	<50	80	<50	
Uranium	<2	<2	<2	<2	
Vanadium	6	14	<5	<5	
Zinc	15	5	13	7	500

**Table X - Ironbridge Power Station
Analysis of River Severn Water ant Station Intake**

Ironbridge Power Station							
Date of Sample UKAS Accredited	River Water Metals Analysis						
	10/05/1999	27/09/1999	15/05/2000	24/07/2000	23/04/2001	16/07/2001	Oct-01
	Results µg/l	Results µg/l	Results µg/l	Results µg/l	Results µg/l	Results µg/l	Results µg/l
Antimony	<5	<5	<5	<5	<5	<5	<5
Arsenic	<2	<1	<2	<2	<2	7	<2
Barium	<50	<50	<50	<50	50	<50	<50
Beryllium	<50	<50	<50	<50	<50	<50	<50
Boron	<50	<50	50	<50	<50	<50	60
Cadmium	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4
Chromium	<1	<1	<1	4	16	7	8
Cobalt	<1	<1	<1	<1	<1	<1	<1
Copper	<5	<5	6	7	<5	<5	7
Lead	9	<5	<5	<5	<5	<5	6
Mercury	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	0.07
Molybdenum	<50	13	6	5	<5	<5	57
Nickel	<10	<10	<10	<10	<10	<10	<10
Selenium	<100	<100	<5	<5	<5	<5	<5
Silver	<10	<10	<10	<10	<10	<10	<10
Tellurium	<50	<50	<50	<50	<50	<50	<50
Thallium	<50	50	<50	<50	<50	<50	<50
Tin	<5	15	<5	<5	<5	<5	<5
Titanium	<50	<50	<50	<50	190	<50	<50
Uranium	<20	<2	<2	<2	<2	<2	<2
Vanadium	<5	<5	<5	<5	<5	<5	<5
Zinc	<50	<50	7	8	14	9	12

Appendix 1

The following is a written statement from George Strutz, who has managed the Bole Ings ash disposal site for many years, to Phil Simmons of TXU. The Bole Ings site has several land drainage ditches that are designated by the local authority. PFA has been deposited alongside these ditches for many years without effect.

Statement by George Strutz of RMC (Formerly Ash Resources Ltd)

Phil

I can confirm experience in handling PFA at the Bole Ings disposal site.

I manage the Bole Ings disposal site associated with the 2000MW West Burton power station in Nottinghamshire. The site is Managed and operated by RMC under contract to TXU. The site operates by building a new landform from PFA. The landform is constructed from PFA conditioned by mixing with around 15% water. The deposit of PFA is built by tipping conditioned PFA from large dump trucks and then consolidating and shaping it with a bulldozer. The deposits of PFA are around 7 meters thick and are laid directly on the ground after removal of topsoil. The site contains several ditches, which form part of the local land drainage system. The ash deposits have been taken right to the edges of these ditches in some areas.

Since the early 1990's, there has been an exposed working face at Bole Ings. On occasions, this working face has been 100 m long. The PFA surface has been exposed for extended periods of over a year without topsoil. I am not aware of a single incident in which PFA has been washed from the workings in heavy rain and it has certainly not been washed into the site ditches, despite operations in very close proximity of the ditches.

I can also confirm that an exposed surface of PFA forms a crust due to the cementitious properties of the material. The PFA surface needs to be wetted as the material is laid for this to occur. For most of the year the combination of the conditioning water and precipitation are sufficient to cause this crust to form. In very dry weather, we have found it necessary to spray the surface with water once to encourage the formation of the cementitious crust. Once formed the crust prevents dust blow and encourages shedding of rain from the surface. It is important not to drive on completed areas since this disrupts the surface crust.

Experience at Bole Ings indicates that there is no reason to suppose that PFA will be flushed into watercourses from the working face or that it will cause dust blow, provided that the precautions outlined above are followed.

George Strutz

Appendix 2

Statement by T E Langford, Consultant and Aquatic Biologist

Mr Langford has worked in the field of aquatic biology for many years and has specialised in the impacts of power stations. The following notes highlight the observable effects of operations involving PFA transport and storage on the surface waters around Ironbridge Power Station in Shropshire. They were prepared in relation to a large PFA being created at the A45 in Packington, nr Coventry during April 2002.

Assessment of the risk of polluting watercourses

Ash leachate and stream ecology

There are no published scientific data from field studies on the ecological effects of ash run-off or leachate on running water plant or animal communities in the UK. The only known data originate from a series of unpublished observations by T E L Langford at Ironbridge power station in the 1970s. The few samples taken showed that the invertebrate fauna of the operating ash lagoons was, even at that time, fairly diverse. Three samples contained a minimum of 22 species of invertebrates including caddis larvae, water boatmen, water snails and beetles (Table 1). Specimens of the common newt *Triturus vulgaris* were also collected and returned. At the time of sampling the ash lagoon was active and in the process of being filled. The substrate was mainly ash, mud and leaves and the water surface was partly covered with cenospheres and particulates. There was an abundant zooplankton, mainly *Cylops* sp. and *Daphnia* sp. This rich zooplankton was a permanent community and was characteristic of other ash lagoons, (Langford, unpublished)

The supernatant liquid from the ash lagoons discharged via settling ponds to a very small stream. This contained little natural flow and received some effluent from a farm. Much of the dry-weather flow was undiluted ash-effluent. Two and four years after the ash lagoon was in stable operation the stream was sampled for invertebrates (Table 2). The fauna was diverse and abundant for a small stream, containing at least 21 and 23 species (taxa) in 1972 and 1974 respectively. The species-richness total was 28. In the 1974 samples, species considered as intolerant of pollution (e.g. mayflies and caddis flies) were common and abundant. In the 1972 sample, they were less abundant but still present. The main feature of the stream was the high abundance of planktonic animals discharged from the lagoon. These led to a large abundance of filter-feeding insects such as *Hydropsyche* sp. and *Simulium* sp. These are also typical of normal lake-outflows (Hynes, 1970).

There was no evidence of adverse chemical or physical effects of the ash-effluent on the species present at the time and the stream had a higher invertebrate species-richness than two nearby streams (21, 23), though the species compositions of all three differed in detail.

The ash effluent stream entered the Severn approximately 1km upstream of a major sampling site (Langford, 1971,1975, Langford & Daffern, 1975) where studies of power station effects were in progress for several years. Over 100 species (taxa) of invertebrates were recorded at this site including all the major sensitive groups (Langford, 1971). There was never any evidence of pollution or contamination from the ash-stream during these studies and the stream was discounted as a factor in determining the composition of the fauna and ecological status of the river.

The river is an important salmonid fishery with a diverse, species-rich fish fauna that includes the bullhead and salmon, both species protected within Annex II of the EC Habitats Directive. The Severn also contains *Ranunculus* habitat in the Ironbridge reach. There has never been any suggestion of any effects on the habitat or the species originating from the riparian ash deposits or the Devils Dingle lagoon.

Studies of Ironbridge power station in 2001 for other purposes included an inspection of the ash lagoons and temporary ash deposit sites. There was no evidence of contamination in the river from the riparian deposits on the power station site (understood to approach 500,00 tonnes). The ash lagoon at Devils Dingle was maturing into a rich wildlife habitat. This is confirmed by Shropshire Wildlife Trust observations.

The Environment Agency has clearly not included the ash-stream as a significant factor in regular surveys and as far as I am aware, there is no recent ecological information on the public register. Reach-scale data from Cressage and Coalport, respectively upstream and downstream of Ironbridge power station, (including ash-lagoons and all other discharges), show Ecological Quality Indices (EQIs) of 0.66 -1.05 and 0.77-1.06 respectively. There is no difference as a result of the power station operation or any of its installations on this scale.

Suspended solids concentrations specified for the protection of Freshwater Fish (EC Freshwater Fish Directive) are 25mg^l⁻¹. Erosion from the ash used in construction should be contained sufficiently by normal methods and by its normal surface accretion so that river concentrations are not elevated significantly by the run-off.

At the experimental scale, preliminary assays of undiluted ash leachates and supernatant liquids indicate no acute effects on freshwater fish or invertebrates (Langford, 1983, JEP 2001).

Effects of ash for road construction (A45, Packington, nr Coventry)

The potential effects of building an embankment at Packington will give rise to very much less impact than the discharges of supernatant water from an ash lagoon or the potential from an unlined deposit of 500,00 tonnes of stored PFA which is regularly disturbed in the course of operation of the power station.

The technical details relating to ash are discussed in the risk assessment. However, once the flyover is completed there should be almost no interchange of water between the ash deposit and surface waters and the impact on water chemistry and ecology should be effectively nil.

During the construction period, there is some risk of a slight but measurable uplift in concentrations of a few inorganic determinants such as Boron during periods of heavy rain if it falls before a section of the PFA embankment has fully hardened its protective cementitious crust. Even for this brief period, the concentrations are not likely to exceed those experienced continuously for many years at the Devils Dingle stream. Such a small impact for such a short period should cause no measurable impact on the stream.

The River Blythe is a rich, diverse, and sensitive freshwater habitat and a noted SSSI and has been studied for many years (Hawkes, 1975). Even so, from these observations on Ironbridge ash and its supernatant liquids it is safe to conclude that there is little risk of significant ecological effects on either the River Blythe or its tributary from either leachate or controlled run-off from ash used for construction on the A45 site. Provided that the normal precautions are observed for controlling erosion of soils or other solids from rainfall, it is also safe to conclude that there would be no effects on the fish or the fishery in either the short or longer terms. I have no current information on the presence of Annex II species (EC Habitats Directive) in the River Blythe or its tributaries but assuming that the bullhead (*Cottus gobio*) is present there will be no acute or chronic effects on the species population in the river.

Conclusion

From the available data and from recent observations it is safe to conclude that, provided proper precautions are taken during construction to minimise run-off to watercourses, there will be no measurable effects on the water quality, ecological status or fishery of the local stream or the River Blythe, either in the short or longer terms.

NB. Please note this report is based on observations at Ironbridge by the author and on published data or verbal reports on the Blythe. As far as the author is aware, the deduction and conclusions are based on accurate observations and reports.

T.E. Langford - December 2001

**Table 1. Invertebrates collected from the ash-effluent stream at Devils Dingle
Ironbridge, 1967-74 (1967 before operation, 1972, 1974 during operation)**

Species/Taxon	1967	1972	1974
STONEFLIES			
Leuctra sp.			
Nemoura erratica			
MAYFLIES			
Habrophlebia fusca			
Heptagenia sulphurea			2
Baetis rhodani		22	10
Baetis vernus?			60
Baetis pumilus			
Baetis spp.			172
Caenis luctosa			2
CADDIS-FLIES			
Hydropsyche spp.	3	5	778
Psychomyia pusilla			16
Rhyacophila dorsalis		1	12
Goera pilosa			
Plectrocnemia geniculata			
Hydroptilidae (indet)		5	102
Arthripsodes sp.			2
Agapetus sp.			
BEETLES			
Elmis aenae		3	
Helodes minuta			
Dytiscidae (indet)		7	
TRUE-FLIES			
Simulium reptans		1220	
Pericoma sp.		1	140
Tipula sp.	2	2	4
Clinocera (indet)		125	4
Dixa sp.			
Orthoclaadiinae (indet)	3	300	300
Tanypodinae (indet)	2	70	60
Tanytarsini (indet)	7	400	300
Ceratopogonidae (indet)		5	8

Continued

Table 1 (Continued)

Species/Taxon	1967	1972	1974
CRUSTACEANS			
Gammarus pulex	37		
Daphnia (magna)		850	136
Cyclops spp.		1	34
MOLLUSCS			
Lymnea pereger	5	1	
Lymnea truncatula			
Potamopyrgus jenkinsi		8	2
Bithynia tentaculata			2
Sphaerium spp.		1	
WORMS			
Eiseniella tetraedra		3	
Naididae (indet)		350	26
Other Oligochaeta	105	300	54
LEECHES			
Erpobdella octoculata	8		
ROUNDWORMS			
Nematoda (indet)	10		
SPRINGTAILS			
Collembola (indet)			
WATER MITES			
Hydracarina (indet)			
NUMBERS OF INDIVIDUALS	182	3680	2226
NUMBER OF TAXA	10	21	23

Table 2. Invertebrates collected in the operating ash lagoons at Ironbridge Power station. 1974

Species/Taxa	N.BANK	S.BANK1	S.BANK2	ALL
CADDIS FLIES				
Polycentropodidae (indet)			4	4
BEEPLES				
Deronectes sp.		1		1
Hyphydrus sp.		4		4
Dytiscidae (indet)		2	4	6
WATER BOATMEN				
Corixidae (nymphs)		11	3	14
TRUE FLIES				
Pericoma sp.	1			1
Dicranota sp.	2		2	4
Tipula sp.	1			1
Chironomus spp.	10	142	3	155
Orthocladiinae (indet)	42	372	35	449
Tanypodinae (indet)		143	15	158
Tanytarsini (indet)		93	9	102
CRUSTACEANS				
Cyclops gigas?	27	45		72
Cyclops spp.	15	10		25
Daphnia magna?	3	5	75	83
Daphnia longispina			500	500
MOLLUSCS				
Lymnea truncatula		121	3	124
Zonitoides nitidus			1	1
WATER MITES				
Hydracarina		1		1
WORMS				
Enchytraeidae			1	1
Eiseniella tetraedra	1		1	2
Tubificidae	10			10
LEECHES				
Haemopsis sanguisuga		1		1
AMPHIBIANS (NEWTs)				
Triturus vulgaris		2	1	3
NUMBER OF INDIVIDUALS	112	953	657	1722
NUMBER OF TAXA	10	15	14	24

Appendix 3

Characteristics of PFA (Extract from a Report by Jacobs Gibb)

Basic Principles

Pulverised Fuel Ash (PFA) is the inorganic alumino-silicate based residue remaining after the combustion of coal in a power station.

Industry experience has shown that PFA deposits are in the large part homogeneous with low hydraulic conductivities of the order of 10^{-7} m/s (QAA, 2000), which is conferred through a combination of the spheroidal shape of the component PFA particles and their particle size distribution (between $\sim 3-25$ μm), which together allow the particles to pack tightly together upon compaction.

In any given field situation, however, the hydraulic and physico-chemical properties of the PFA deposit will be related to:

- The differential hydraulic conductivity of the PFA deposit compared with the surrounding geological conditions. Typically, ash lagoons are located in former workings within alluvial and fluvial deposits that have hydraulic conductivities of the order of 10^{-4} m/s or lower. In such circumstances, the predominant groundwater flow direction would be expected to be within the surrounding deposits as opposed to through the PFA bed itself. For this reason in this investigation, falling head tests were carried out in ash material both wet and dry and the River Terrace Gravels to assess the bulk permeability of these materials in order to better quantify potential flow volumes through each of the deposits and into the River Trent.
- The level of saturation of wet versus conditioned dry pits. As the ash within a slurried lagoon is saturated at the point of deposition it can give rise to leachate more or less immediately, whereas conditioned dry disposal sites which, at the point of disposal, contain only 8-12% water by volume first need to become near saturated with water. Combined with the often lower hydraulic conductivities that can be achieved with dry sites compared to wet due to more effective compaction, they are unlikely to give rise to leachate for at least 3-5 years or more under UK conditions (Woolley et al 2000). As stated above, permeability tests were carried out in wet and dry deposits.
- The potential for variation in the physico-chemical properties of fresh PFA over time, which could give rise to a heterogeneous rather than a homogenous deposit overall. Being derived from coal, a natural material, some level of variation in the physico-chemical characteristics of PFA must be expected. The site at Girton has received PFA from two power stations burning a variety of fuels. As is shown in Section 2.3 the characteristics of the PFA at Girton are similar to that from many other UK power stations. It is presumed that the Girton site is reasonably typical in terms of the nature of the ash but the scope of the site investigation was designed to gain an understanding of leachate generation from different ages of ash and the differences between wet/dry ash depositions.
- The particular disposal practices that have been used at any given disposal site which could influence the hydraulic properties of the deposit. The main issue in this regard is that as wet PFA is slurried from a particular discharge point, the potential exists for heavier components to settle out more quickly than finer components, which can cause stratification of the deposit and hence lead to the creation of areas of higher hydraulic conductivity which could give rise to preferential migration pathways for leachate. Indeed the potential for stratification around discharge points is well documented (Woolley et al. 2000). However, it is considered that given the relatively small particle size distribution of PFA (3-20 μm), the potential for major changes in permeability between different layers is in fact quite limited. In addition it is noted that lagoons are filled up by means of a number of different discharge points located around the site, and therefore should any layers of higher permeability exist they would be localised and surrounded by other areas of lower permeability thus preventing the creation of preferential pathways.
- The prevailing pH of the deposit, which will have a profound influence over the chemical speciation and mobility of trace metals associated with ash. In the UK, ash is generally of moderate to high pH, which minimises trace metal mobility and therefore leachability from the deposits. The principal buffer system is conferred through the dissolution of base metal oxides notably CaO and MgO that maintains pH above 7, however when these minerals are depleted pH may fall rapidly until another buffering system takes effect. The pH of ash is unlikely ever to fall below pH 4 due to pH buffering by iron and aluminium oxides, which are a major component of PFA (see Table 2-1). However, it is considered that the significant base metal oxide reserves combined with low infiltration rates and hydraulic conductivity will minimise the potential for acidification and therefore keep pH above 7 in the long term.

Chemical Composition & Behaviour of PFA

Major components

PFA is composed largely of alumino-silicates, which, due to rapid cooling from a molten state, take a predominantly non-crystalline "glassy" form.

The actual composition is dependent upon the mineral matter present within the coal fired in the furnace and the effectiveness of combustion that has taken place. However, Table 9-1 below summarises the typical major mineral constituents of PFA.

Table Y - Chemical Analysis of PFA (Woolley et al, 2000)

Compound	Maximum %	Minimum %	Typical %
SiO ₂	51	45	48
Al ₂ O ₃	32	24	27
Fe ₂ O ₃	11	7	9
CaO	5.4	1.1	3.3
MgO	4.4	1.5	2.0
K ₂ O	4.5	2.8	3.8
Na ₂ O	1.7	0.9	1.2
TiO ₂	1.1	0.8	0.9
SO ₃ (soluble)	1.3	0.3	0.6
Cl	0.015	0.005	0.008
P ₂ O ₅	0.65	0.09	0.2

The prevalence of aluminosilicates (SiO₂), aluminium and iron oxides (Al₂O₃ / Fe₂O₃) should be noted as they strongly influence the chemical behaviour and biological availability of trace metals and other contaminants that are also present. In addition, the relatively high concentration of CaO and MgO confer a high pH, which is likely to be stable in the long term, which also has a profound effect on contaminant mobility. These issues are discussed in more detail below and in Section 2.3.

Trace metal content

PFA may also contain a wide range of heavy metals associated with fossil fuel, including boron, lead, cadmium, chromium, zinc, arsenic, mercury, selenium, tin, barium, copper, manganese, uranium and vanadium. However not all these elements are present in significant concentrations in all types of coal and other fossil fuels, and therefore their concentrations in PFA will show marked variations (Alloway, 1990). The proportion of trace metals in PFA will also differ from that in the source fuel due to vapour losses of the more volatile species during the combustion process. For example, levels of mercury and selenium in PFA can be expected to be much lower than predicted based on fossil fuel content.

Table Z - Indicates the total trace metal content that may be expected from PFA including samples from High Marnham Power Station. Total Trace Metal Content of PFA (SLR Consulting, 2000 / N Power 2000)

Determinant (mg/kg)	High Marnham	Didcot A	Ratcliffe on-Soar	Drakelow	Mean
Arsenic	111	71	128	108	105
Boron	-	181	132	75	129
Cadmium	<0.1	3	4	3	2.5
Chromium	33	44	50	55	46
Cobalt	-	20	22	16	19
Copper	33	56	73	66	57
Lead	84	70	72	43	67
Mercury	0.75	<1	<1	<1	<1
Molybdenum	16	16	15	13	15
Nickel	37	42	50	35	41
Selenium	-	<1	<1	<1	<1
Tin	-	<10	<10	<10	<10
Vanadium	-	117	133	96	115
Zinc	101	142	136	65	111

The data indicate the variations that may be exhibited in the total concentration of trace metals in fresh PFA derived from different power stations, but in general terms metal concentrations appears to be low to moderate and not dissimilar with the range found for UK soils (see Alloway 1990).

Chemical partitioning of trace metals

As is the case with contaminated soils, whilst there may be a correlation between the total concentration of any given trace metal in PFA and its biological availability, from an ecotoxicological viewpoint it is the chemical form of those trace metals that are present which is of overriding significance in the expression of risk.

In complex matrices such as soils, it is not feasible to determine the precise chemical form of metals that are present owing to the considerable biogeochemical complexity of most soil-plant systems and therefore a number of relatively crude operationally defined methods were devised to broadly distinguish between different generic (e.g. exchangeable) or functional (e.g. leachable) fractions.

Viets (1962) identified the following pools:

- Water soluble fraction – i.e. the fraction present in solution / pore space
- Exchangeable – ions bound to reactive surfaces by electrostatic forces
- Complexed and adsorbed – organic chelates or metals bound specifically (i.e. covalently) to mineral and/or organo-mineral surfaces
- Occluded and co-precipitated – metals bound within secondary minerals or insoluble metal oxides
- Residual – metals bound in the silicate structures.

The lability of these pools decreases from water soluble through to residual but there is a broad distinction between the lability of the water-soluble / exchangeable / adsorbed pools and the more refractory occluded / co-precipitated / residual fraction. Metals associated with the latter pools generally account for the greater proportion of the total metal concentration, are relatively inert and therefore of little immediate biological or ecological significance (Herms & Brummer 1984; Kiekens 1995).

Although less complex than soils particularly through the lack of significant organic matter and low biological activity the same broad principles apply to ash. In PFA the vast majority of trace metals are incorporated into the aluminosilicate matrix (i.e. the residual fraction) and can therefore be regarded as being completely unavailable for leaching even in the long term and are therefore of no biological significance. This fraction can be extracted only by dissolution of the silicate structure of the PFA through refluxing with concentrated acids such as perchloric and hydrofluoric.

In addition, during the combustion process oxides of calcium, magnesium, iron, manganese and aluminium form as surface coatings on the glass spheres. As is the case in soils, trace metals may be co-precipitated or occluded in the formation of these oxides which therefore are also rendered largely unreactive until such time that the oxides / sesquioxides themselves become solubilised. High pH conditions, which are typical of PFA in the UK, are conducive to the stability of these oxides although it should be noted that under reducing conditions such as might occur during prolonged water logging the oxides may become more soluble.

Finally, these oxides provide on their surface weaker ionic and potentially stronger covalent or specifically sorbed exchange sites, which can retain trace metals. This represents in the large part the exchangeable fraction that is leachable and therefore of most biological significance and therefore health and environmental risk.

The proportion of trace metals associated with these broadly defined fractions will vary depending upon the physico-chemical properties of the metal but in general boron exists largely in the water soluble/easily exchangeable fraction associated with the outer coating of oxides whereas most other metals will tend to be associated more with the hydrous metal oxides with a very significant residual fraction. The partitioning of trace metals between the pools outlined above is consistent with the results of leachability tests as discussed below.

In addition, trace metals organic compounds may occur in PFA due to incomplete combustion of coal, which has become more likely since the introduction of low-NO_x burners in the 1990s due to the lower resulting furnace temperatures. However, studies have found that the amount of for example Polyaromatic Hydrocarbons (PAH) is generally very small, typically 0.14 – 0.94 µg/g (QAA, 2000), and that leaching tests have shown that less than 0.2 µg/l is "extractable".

Leaching Potential

Compared to the total concentration of metals that may be present PFA has been widely reported as having a low leaching potential. The main factors affecting the leachability of trace metals are:

The total concentration and chemical partitioning of metals that are present in the PFA as described in Section 2.2, with certain metals for example boron being present in more labile forms than others such as cadmium and lead.

The strong pH buffering effect in particular of CaO / MgO which maintains a high pH of the order of 7 or above which is stable in the long term. Above pH 4-5, the solubility of the majority of trace metals decreases markedly due mainly to the formation of inorganic metal salts and cation exchange.

The relatively low hydraulic conductivity of PFA which will minimise infiltration of precipitation and movement of groundwater through the deposit and therefore reduce the potential for solute transfer from the ash, as well as minimising the potential for acidification and maintaining high pH conditions.

The pH of fresh ash can fall rapidly to between 3-4 upon first coming into contact with water due to the formation of sulphuric acid from sulphur oxides which condense onto the ash particles in cooler parts of the furnace during firing. However, this lasts only a few minutes before CaO buffering takes effect and the pH increases to 8-9 (Woolley et al 2000; QAA, 2000). As shown in Table 2-1 in Section 2.2, PFA contains appreciable base metal oxides notably CaO and

MgO. Combined with the low hydraulic conductivity of ash whether wet or dry which will minimise the downward percolation of water through the deposit, it can reasonably be concluded that ash pH is likely to remain above neutrality over many decades. It follows therefore that the potential for metal leaching is very limited even in the long term. Lee (1995) found that conditions within PFA deposits in the UK are non-reducing and neutral to moderately basic, which minimises their metal leaching potential.

As stated above those metals which have a large weakly sorbed / exchangeable fraction such as boron are more leachable than those associated largely with metal oxides / sesquioxides. Theis (1977) reported chromium and copper to be very insoluble in PFA, finding them to be associated principally with the iron and manganese oxide coating of the PFA particles. Indeed the very high affinity of iron, manganese and aluminium oxides for a whole range of heavy metals including cadmium, lead, chromium and copper is well documented (Mannings 1994).

Whilst the majority of heavy metals become more insoluble as pH increases others notably arsenic can become more soluble. The chemistry and behaviour of arsenic in soils which is broadly applicable to that in PFA is very complex but essentially arsenic should be considered a non-metal forming covalent compounds or being found in anionic species whose solubility increases under basic conditions. There are a range of soluble oxyanions that can occur in soils which are stable over quite a wide pH range from 4-8 (O'Neill 1995) but despite this the concentration of arsenic in soil porewater is usually low (<10ug/l) and leaching of arsenic is inhibited by the presence of hydrated oxides of iron, manganese and aluminium all of which are present in abundance in PFA (see Table 2-1).

Table AA - Summarises the typical range of leachable elements found in UK PFA based on NRA leaching test guidelines (NRA, 1994b).

Typical range of leachable elements for UK PFA (mg/l except for pH)			
Aluminium	<0.1 to 9.8	Manganese	<0.1
Arsenic	<0.1	Molybdenum	<0.1 to 0.6
Boron	<0.1 to 6	Sodium	12 to 33
Barium	0.2 to 0.4	Nickel	<0.1
Calcium	15 to 216	Phosphorous	<0.1 to 0.4
Cadmium	<0.1	Lead	<0.2
Chloride	1.6 to 17.5	Sulfate	24 to 510
Cobalt	<0.1	Antimony	<0.01
Chromium	<0.1	Selenium	<0.01 to 0.15
Copper	<0.1	Silicon	0.5 to 1.5
Fluoride	0.2 to 2.3	Tin	<0.1
Iron	<0.1	Titanium	<0.1
Mercury	<0.01	Vanadium	<0.1 to 0.5
Potassium	1 to 19	Zinc	<0.1
Magnesium	<0.1 to 3.9	pH	7 to 11.7

The data show that of the total concentration of trace metals present, only a very small proportion is leachable, and in the majority of cases, this is likely to be conferred by the prevailing high pH, which renders them insoluble. The chemistry is dominated by calcium and sulfate with lower levels of chloride, potassium, and sodium and in some cases boron, all other constituents being present at low concentrations.

Leachate data for raw ash samples taken from a number of UK power stations including West Burton and High Marnham are outlined in Table S below.

Determinant	West Burton (mg/l)	High Marnham (mg/l)	Drakelow (mg/l)	Rugeley (mg/l)	Ironbridge (mg/l)
Aluminium	16.9		0.41		
Antimony	-	0.08	<0.05	0.12	<0.05
Arsenic	0.19	<0.05	<0.01	<0.05	<0.05
Boron	1.40	2.41	1.40	2.49	2.21
Barium	-	0.13	0.14	0.63	0.21
Cadmium	0.01	<0.05	<0.004	<0.05	<0.05
Calcium	274	127.1	131	204.9	202.4
Chromium	0.09	0.11	0.43	0.1	0.07
Hexavalent Chromium	-	< 0.03	-	0.08	0.07
Cobalt	<0.05	0.06	<0.01	<0.05	<0.05
Copper	<0.01	1.34	<0.02	0.21	0.15
Iron	0.01	3.25	<0.08	<0.05	<0.05
Lead	0.06	<0.05	<0.01	<0.05	<0.05
Magnesium	4.0	7.99	0.35	0.11	0.17
Manganese	<0.01	0.58	<0.01	0.41	0.34
Mercury	<0.05	<0.05	<0.001	<0.05	<0.05
Molybdenum	<0.05	0.25	0.89	0.45	0.37
Nickel	0.02	0.24	<0.01	<0.05	<0.05
Phosphorous	-	0.08	0.50	<0.05	<0.05
Potassium	42	38	31	24	12
Selenium	0.3	<0.05	<0.01	0.21	0.13
Silicon	0.4	2.75	6.10	1.55	0.16
Sodium	69	70	40	33	13
Tin	<0.5	<0.5	<0.1	<0.5	<0.5
Titanium	<0.02	0.1	<0.1	<0.05	<0.05
Vanadium	0.12	<0.05	0.21	<0.05	<0.05
Zinc	<0.01	0.44	<0.02	<0.05	<0.05
Chloride	8	< 5	9	< 5	7
Fluoride	1	<0.01	<1	0.97	<0.01
Nitrate	-	<0.3	<1	<0.3	0.3
Nitrite		<0.05	<0.5	<0.05	0.05
Sulfate	705	698	380	473	444
EC (µS/cm)	1280	1025	1043	1636	940

Table BB - Leachate analysis of raw ash samples – source TXU 2001

The above data demonstrate leaching behaviour across a wide range of UK power station ash. The leachate results are more consistent than total metals analyses of PFA, which is considered to reflect the fact that of the total metal concentration that may be present, only a very small proportion is leachable, the remainder being held in the silicate matrix or retained by the mechanisms discussed above.

It is considered that the transport of ash using water based slurry produces conditions similar to the leachate test. The routine analysis of ash lagoon outflow water compared to the analysis of water at the cooling water intake shows that the uplift in concentration is less than the concentrations obtained in the leachate test.

Further it is noteworthy in this regard that the above leachate data may be considered “worst-case” because there is a body of evidence from work undertaken by TXU, National Power and others that if PFA is repeatedly extracted, the concentrations of contaminants obtained after the initial extraction tail off rapidly. This suggests that concentrations of contaminants in leachate derived from ash deposits are likely to show a marked decrease after elution by the first bed volume and thereafter during subsequent bed volume changes.

Conclusions & Implications

Total concentrations of the majority of trace metals associated with fresh PFA are low to moderate and broadly consistent with the range in UK soils. The leaching characteristics of a range of PFA give results that are more consistent than the analysis of the raw PFA. This is because a substantial proportion of the total metal concentration present is likely to be associated with the residual fraction and is permanently bound into the silicate matrix of the ash and therefore of little or no biological significance. In addition ash deposits are strongly buffered at around neutral or above, with the result that the solubility and hence leachability of the non-residual trace metal fraction can be expected to be low even in the long term.

The data indicate that PFA deposits at a particular location can be expected to be fairly homogeneous with a low hydraulic conductivity of the order of 10^{-6} - 10^{-7} m/s, which will greatly limit their ability to interact with groundwater. The combination of very low leachability and very low permeability means that a deposit of PFA would be expected to produce a very limited effect on the adjacent groundwater.

Organic compounds, which may theoretically be present, are likely only to occur in very low concentrations and remain essentially insoluble.

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- P Simmons of TXU-Europe, "Assessment of the Risks to the Environment Arising from the use of PFA to form Road Embankments at Packington, Warwickshire", on behalf of Wrekin Construction, January 2002.
- Bob Coombs of Innogy, "The use of PFA as a fill material and the environment"; Joint submission by the UKQAA to the Environmental Agency by R Coombs and L K A Sear – July 2000.
- D Simpson of Power Technology, "An assessment of the environmental impact of lagooned pulverised fuel ash (PFA), March 2001.

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SGV3: Soil Guideline values for Cadmium.
SGV4: Soil Guideline values for Chromium.
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