Sub ⑬

Submission to
WO 167-03

ENVIRONMENTAL PROTECTION
AGENCY
03 OCT 2012

Hands Lane
Rush
Co Dublin
30 Sept 2012

Indaver Application for licence review of Carranstown Incinerator, Duleek, Co Meath

To

Copy An Bord Pleanala PA0026 Oral Hearing, 1 Sept 2012

✓ EPA application ref WO 167-03

Copy EPA application ref WO 129-03 (MEHL Landfill , Hollywood, Naul, Co Dublin)

Dear Sirs,

The above application by Indaver has just recently come to the notice of the residents of Hollywood and district and contains a number of important matters upon which we would wish to submit comments.

In this regard we wish to draw your attention in particular to

- The Indaver Non-Technical Summary as submitted to the EPA
- EC Integrated Pollution Prevention and Control reference document on the Best Available Techniques for Waste Incineration (BREF 08-06-WI)
- The proposal by MEHL to accept fresh bottom ash from the Carranstown facility – WO 129-03

The Indaver NTS p12, A.1.11, Waste Arising , states that

"bottom ash is currently being sent to a nearby non-hazardous landfill" presumably the Louth County Council MSW landfill at Whiteriver, and

"-due to the inert nature of the ash, it will have less adverse impact than untreated waste"

BREF 08-06 Section 4.6.6 "Bottom ash treatment using aging" however outlines current BAT on the treatment and disposal of bottom ash and refers to the documents and studies from which the BAT is deduced by the EC Technical Working Group.

Quote, p404 " Fresh bottom ash is not a chemically inert material"

A detailed study of the section on bottom ash aging reveals that fresh bottom ash has a pH or causticity in excess of 12 (H 8) and requires "aging"- usually exposure to the elements for a period of approximately 12 weeks before the pH drops to approximately 10 and can be considered non-hazardous in this respect.

There are other "ecotoxic" properties associated with fresh bottom ash such as the presence of heavy metals which concentrations are lowered in some cases by the aging process as outlined in the BREF.

In addition the method recommended for the disposal of fresh bottom ash is unique and is detailed in the German studies referred to. It require the ash to be "layered", and **exposed** to the elements for up to 12 weeks, rather than bulk filled and covered daily, as is the case of MSW waste. The reason given for this is the danger of overheating and destruction of the landfill liner associated with exothermic reactions during the aging process.

All of the above would necessitate a separate risk assessment of an existing or proposed landfill to ensure that the site complies with the general requirments of the Landfill Directive, in particular that the site is

- Remote enough from humans to eliminate the risk of wind-blown caustic ash from the exposed surface,
- Adequately equipped with natural soil protection for groundwater from heavy metal - containing leachate contamination particularly when the liner reaches its end of life effectiveness as a barrier.
- Adequate ELRA and CRAMP to make provision for the additional and unique risks associated with fresh bottom ash disposal.

The residents of Hollywood and district are deeply concerned at the apparent disregard of the BREF document by both Indaver and MEHL in their respective EIS, and the impression given in both applications that fresh bottom ash may be considered non-hazardous and deposited in any MSW licenced landfill, which since 2006 is no longer the case.

We therefore request that it be made a condition of the licence that "fresh bottom ash" may only be disposed of by a waste incinerator operator in the manner prescribed and in a landfill suited to the method described in BREF 08-06 - WI and the associated reference studies.

Attached please find

- Extract from BREF 08-06-WI, Section 4.6.6 "Bottom ash treatment using aging"
- Email and documents from Dr. Thomas Baumann ref: "German study and field trials"

Yours truly,

On behalf of Hollywood and District Conservation Group

Patrick Boyle, BE

John Shortt, MBA

EUROPEAN COMMISSION

Integrated Pollution Prevention and Control

Reference Document on the Best Available
Techniques for

Waste Incineration

August 2006

Breaking up large chunks has several advantages:

- it reduces the amount of heavy rejects
- it increases the proportion of rough crushings in the material which give backbone to the aggregate and
- it improves its geotechnical qualities.

Separation of light unburned fractions or air stream separation is achieved by blowing or by aspiration.

Achieved environmental benefits

The main environmental benefit of installing a mechanical treatment process is a reduction of the volume of rejects and wastes, and therefore, a higher global recovery rate.

Cross-media effects

Energy consumption, and potential for noise and dust emissions are the most notable cross-media effects.

Applicability

The technique is, in principle, applicable to all incineration installations producing an ash requiring treatment before it can be used, or where such treatment may allow increased use.

Economics

The cost-effectiveness of installing a system for breaking up heavy rejects is to be evaluated on the basis of projected quantities and disposal costs. It is estimated that the payback period for a crusher is on the order of two years for 5 % of rejects to be crushed, for 40000 t/yr of bottom ash, and seven years for 20000 t/yr.

Driving force for implementation

Quality policy: it allows to reach a global recovery rate of more than 95 % for a bottom ash management facility, it produces less rejects and a product of a higher geotechnical quality, and is cost effective.

Reference literature

[64, TWGComments, 2003] See "Bottom ash management facilities for treatment and stabilisation of incineration bottom ash", ADEME, November 2002

4.6.6 Bottom ash treatment using ageing

Description

After metals separation, bottom ash may be stored in the open air or in specific covered buildings for several weeks. The storage is generally performed in stockpiles on a concrete floor. Drainage and run-off water are collected for treatment. The stockpiles may be wetted, if required, using a sprinkler or hose system in order to prevent dust formation and emissions and to favour the leaching of salts and the carbonisation if the bottom ashes are not sufficiently wet.

The stockpiles may be turned regularly to ensure homogeneity of the processes that occur during the ageing process (uptake of CO_2 from the air due to the moisture, draining of excess water, oxidation, etc.) and to reduce the residence time of every batch of bottom ash in the dedicated facilities.

In practice an ageing period of 6 to 20 weeks is commonly observed (or prescribed) for treated bottom ash before utilisation as a construction material or in some cases before landfilling. [74, TWGComments, 2004]

In some cases the entire process is performed inside a closed building. This assists with dust, odour, noise (from machinery and vehicles), and leachate control. In other cases, the entire process is totally or partially performed outdoors. This generally allows more space to easily handle bottom ash, and can give more air circulation for bottom ash to mature, [64, TWGComments, 2003] and may avoid the release of explosive hydrogen in combination with aluminium during the ageing process. [74, TWGComments, 2004]

Achieved environmental benefits
Fresh bottom ash is not a chemically inert material. Ageing is performed to reduce both the residual reactivity and the leachability of metals. CO_2 from the air and water from humidity, rain or water spraying are the main activities.

Aluminium in the bottom ash will react with $Ca(OH)_2$ and water to form aluminium hydroxide and hydrogen gas. The main problem of formation of aluminium hydroxide is the volume increase as this causes inflation of the material. The gas production will cause technical problems if fresh bottom ash is used directly for construction purposes. Thus, ageing is needed to allow utilisation of the bottom ash.

The impact of storage and ageing on leaching can be classified as:

lowering of the pH due to uptake of CO_2 from the air or biological activity
establishing of anoxic, reducing conditions due to biodegradation of residual organic matter
local reducing conditions due to hydrogen evolution
hydration and other changes in mineral phases causing particle cohesion.
[4, IAWG, 1997]

All these effects reduce the leachability of metals and cause a stabilisation of the bottom ash. This makes the bottom ash more suited for recovery or disposal (landfilling). [74, TWGComments, 2004]

Cross-media effects
Run-off water from rain or sprinkling may contain salts or metals and will need treatment. The water can be recirculated or used in the incinerator as process water.

Odour and dust controls may be required.

Vehicle and machinery noise may be an issue in some locations.

Anti explosive devices at indoor ageing facilities may be required. [74, TWGComments, 2004]

Operational data
Data from a test programme in a full scale German waste incineration plant illustrate the effect which 12 weeks ageing has on the pH of bottom ashes and on the test results obtained by the DEV S4 method. Figure 4.9(a) shows that the pH of the fresh bottom ashes in the DEV S4 test typically exceeds 12 and drops down by about two units during the ageing process.

As can be seen in Figure 4.9(b), this pH change has no effect on the leaching properties of Mo, which is present mainly as molybdate. The leaching stability of Cu and Zn is moderately improved in the aged material whereas the leaching of Pb is reduced by almost two orders of magnitude.

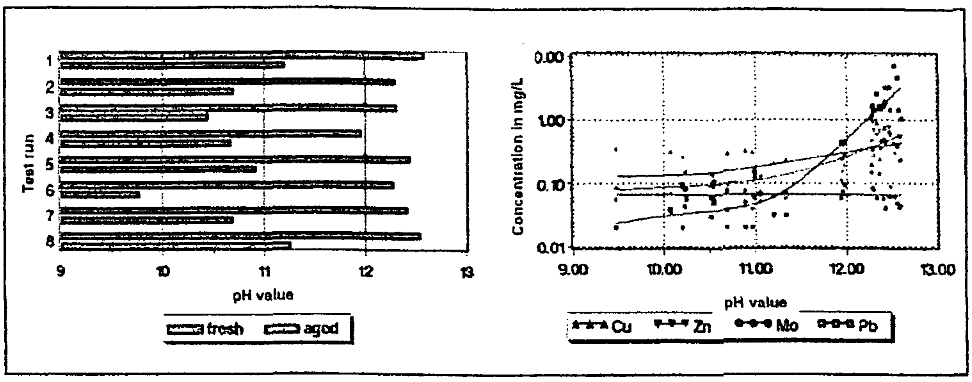

Figure 4.9: Effect of ageing on the leachability of selected metals: (left) effect on pH; (right) leaching as a function of pH
[Vehlow, 2002 #38]

The French Bureau of Mines conducted a study during 18 months about the ageing and its effect on leaching of a 400 tonnes stockpile of bottom ashes and concluded similarly to this German study. [64, TWGComments, 2003]

If longer ageing periods (e.g. >20 weeks) are used for ferrous free bottom ash without turning, the aged bottom ash will become increasingly solidified. [74, TWGComments, 2004]

Applicability
This technique can be applied to all new and existing installations producing bottom ashes. It is mainly used in practice for MSWI. [74, TWGComments, 2004]

For some waste streams the ash content may not improve sufficiently from treatment to permit its beneficial use – in such cases the driver for use of the technique may be simply to improve disposal characteristics.

Economics
The cost of ageing is low as compared to the rest of the treatment installation. [74, TWGComments, 2004]

Saving of disposal costs by recycling. [74, TWGComments, 2004]

Driving force for implementation
Legislation providing leaching limit values for recycling of bottom ash as a secondary raw material or for landfilling. [74, TWGComments, 2004]

Example plants
Various bottom ash treatment plants in the Netherlands, Germany, France, and Belgium.

Reference literature
[Vehlow, 2002 #38], [4, IAWG, 1997], [64, TWGComments, 2003]

4.6.7 Bottom ash treatment using dry treatment systems

Description
Dry bottom ash treatment installations combine the techniques of ferrous metals separation, size reduction and screening, non-ferrous metals separation, and ageing of the treated bottom ash. The product is a dry aggregate with controlled grain size (e.g. 0 - 4 mm, 0 - 10 mm, 4 - 10mm), which may be used as a secondary construction material.

Re: Exothermal Reactions in Bottom Ash Monofills

From: **Thomas Baumann** (tbaumann@tum.de)
Sent: 04 August 2012 09:38:28
To: Paddy Boyle (paddyboylerush@hotmail.com)

3 attachments
Klein_JHazardMat_2001.pdf (329.7 KB) , Klein_JHazardMat_2003.pdf (433.0 KB) , schluss_poster.pdf (1872.7 KB) ,

Dear Mr Boyle,

please find attached two reprints on the temperature development in a municipal waste incinerator bottom ash disposal and a poster (unfortunately in german) summarizing the results of our research project sponsored by the Bavarian State Ministry of the Environment.

Our measurements, mineralogical data, and modelling results indicate that the temperature development can be controlled by removing metals, intermediate storage and layered emplacement into the landfill. While removal of metals decreases the exothermal reactions, intermediate storage promotes the development of less reactive coatings thus leading to diffusion limited processes and a layered emplacement assists the heat transfer to the surrounding, thus avoiding hot spots in the disposal.

I hope that you will find this information useful and I will be ready to answer further questions in late September.

Best
Thomas Baumann

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PD Dr. Thomas Baumann

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Numerical modelling of the generation and transport of heat in a bottom ash monofill

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Abstract

Municipal solid waste is incinerated to reduce its volume, toxicity and reactivity. Several studies have shown that the resulting bottom ash has a high exothermic capacity. Temperature measurements in municipal solid waste incineration (MSWI) bottom ash landfills have found temperatures up to 90 °C. Such high temperatures may affect the stability of the landfill's flexible polymer membrane liner (FML) and may also lead to an accelerated desiccation of the clay barrier. The purpose of this study was to gain detailed knowledge of temperature development under several disposal conditions in relation to the rate of ash disposal, the variation of layer thickness, and the environmental conditions in a modern landfill. Based on this knowledge, a simulation was developed to predict temperature development. Temperature development was simulated using several storage periods prior to the deposition and several modes of emplacement. Both the storage time and the mode of emplacement have a significant influence on the temperature development at the sensitive base of the landfill. Without a preliminary storage of the fresh quenched bottom ash, high temperatures at the bottom of a landfill cannot be avoided.

Keywords: Bottom ash; Temperature development; Municipal solid waste incineration; Landfill

1. Introduction

Until the 1970s, bottom ash from municipal solid waste incineration was believed to be almost inert, but since then several studies have shown that many exothermic reactions may cause a temperature increase of up to 90 °C in the landfill [1].

High temperatures at the bottom of a landfill may affect the stability of the landfill liner system (flexible membrane liner, polymer membrane liner (FML) and mineral clay layer).

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Temperatures above 40 °C may damage the stability of the FML (made of high-density-polyethylene, HDPE) due to depolymerisation and oxidation [2]. Due to diffusive transport of water and water vapour along the temperature gradient in the mineral clay layer, the clay barrier may desiccate and fail to retain leachate [3,4]. In order to prevent thermal damages to the liner system, it is necessary to minimise the temperatures in the landfill. There are several factors such as the storage time prior to the deposition and the surface-to-volume ratio influencing the temperature development in a landfill [1]. The most important reactions that cause a temperature increase in the stored bottom ash are the corrosion of iron and aluminium, the hydration of lime (CaO) and the carbonation of portlandite ($Ca(OH)_2$) [5–7]. Table 1 shows the identified reactions. Speiser [8] has pointed out that the corrosion of iron is followed by carbonation of portlandite which are the most relevant heat sources in bottom ash material.

Assessing the thermal capacity of the residues is essential since bottom ash has been deposited in landfills with poor landfill liner systems in Europe and in other countries during the last decade [7]. In the US, bottom ash was commonly landfilled without processing, even though metals and other materials can be recovered by magnetic separation and screening [9]. In some European countries (e.g. Germany, The Netherlands and France) approximately 60% of the bottom ash is reused in road construction or as raw material for the ceramic and cement industry [10–12], whereas in Switzerland almost 100% of the bottom ash is disposed in landfills [9].

Although the exothermic reactions in bottom ash are well known, their speed and the amount of heat released are still unknown. Klein et al. [1] have shown that the main temperature increase due to the exothermic reactions has a time scale of 2–3 months. Speiser [8] calculated an average specific heat production of 5.3 $W\,m^{-3}$ of the bottom ash material during the first 2 years of deposition. The released energy in this period amounts to 313–331 $MJ\,m^{-3}$. The bottom ash investigated in this study is comparable to a common bottom ash analysed in the EU [6].

The objective of this work was to develop a numerical model incorporating basic concepts from chemistry and physics to simulate the spatial and temporal distribution of heat in a bottom ash landfill. This objective was accomplished in two steps: (1) the observation of the temperature development in a bottom ash landfill under several modes of emplacement, and (2) the development of a heat generation and transport model and validation of this with the data obtained from field experiments. This numerical simulation provides the possibility of

Table 1
Exothermic reactions in bottom ash materials [5–7]

Reaction	Enthalpy of reactions, ΔH ($kJ\,mol^{-1}$)
$2Al + 6H_2O \rightleftharpoons 2Al(OH)_3 + H_2\uparrow$	−422
$FeS + (9/4)O_2 + (5/2)H_2O \rightleftharpoons Fe(OH)_3 + H_2SO_4$	−921
$CaO + H_2O \rightleftharpoons Ca(OH)_2$	−65
$Ca(OH)_2 + H_2CO_3 \rightleftharpoons CaCO_3 + 2H_2O$	−111
$Ca(OH)_2 + CO_2 \rightleftharpoons CaCO_3 + H_2O$	−120
$Ca(OH)_2 + SiO_2 \rightleftharpoons CaH_2SiO_4$	−140
$CaH_2SiO_4 + CO_2 \rightleftharpoons CaCO_3 + SiO_2 + H_2O$	−25

predicting the temperature development in a bottom ash landfill under different modes of emplacement.

2. Experimental

2.1. Field observations

Three vertical sensorfields (SF1, SF2, SF3) were embedded in two bottom ash landfills in the south of Germany. Temperatures were recorded using Pt-100 temperature sensors (R + S Components, Moerfelden, Germany, measurement range from −200 to +300 °C). The bottom ash in SF1 was deposited in irregular time intervals (see Table 2) depending on the amount bottom ash to be disposed, over an 8-month period to a maximum thickness of ten meters [1]. SF2 was emplaced within 3 weeks to its final height of 10 m. The bottom ash for SF1 and SF2 was stored for 3–6 weeks before being deposited at the landfill. In SF3, bottom ash was emplaced in layers with a thickness of 1 m every 2 months up to a final height of 5 m. The bottom ash in this sensorfield was stored for a maximum duration of 3 days prior to deposition.

2.2. Numerical simulation

The landfill is represented in a computer model as a one-dimensional column, consisting of a geological barrier (GB) underneath the landfill, a liner system (LS), the main bottom ash (BA) body, and (optionally) a surface sealing (SS) (Fig. 1). The individual layers of this linear model used in this work are represented by discrete volume elements with a thickness

Table 2
Bottom ash deposition parameters during the installation of the test field

Location within the landfill	Date of depositing, corresponding ambient temperature and bottom ash amount		
	SF1	SF2	SF3
At the FML	13 June 1997 (24 °C)	18 May 1999 (21 °C)	6 December 2000 (4 °C)
In the drain	27 June 1997 (22 °C)	18 May 1999 (21 °C)	6 December 2000 (4 °C)
0.5 m above drain	27 June 1997 (22 °C, 600 m^3)	18 May 1999 (21 °C, 300 m^3)	6 December 2000 (4 °C, 1280 m^3)
1.5 m above drain	17 July 1997 (26 °C, 800 m^3)	18 May 1999 (21 °C, 410 m^3)	7 February 2001 (−3 °C, 1500 m3)
3.0 m above drain	17 July 1997 (26 °C, 750 m^3)	18 May 1999 (21 °C, 580 m^3)	11 April 2001 (7 °C, 1620 m3)
4.5 m above drain	27 August 1997 (27 °C, 650 m^3)	18 May 1999 (21 °C, 750 m^3)	3 August 2001 (26 °C, 1800 m3)
6.0 m above drain	24 October 1997 (7 °C, 810 m^3)	18 May 1999 (21 °C, 620 m^3)	
7.5 m above drain	1 November 1997 (15 °C, 720 m^3)	6 June 1999 (23 °C, 580 m^3)	
9.0 m above drain	3 February 1998 (−1 °C, 760 m^3)	6 June 1999 (23 °C, 610 m^3)	

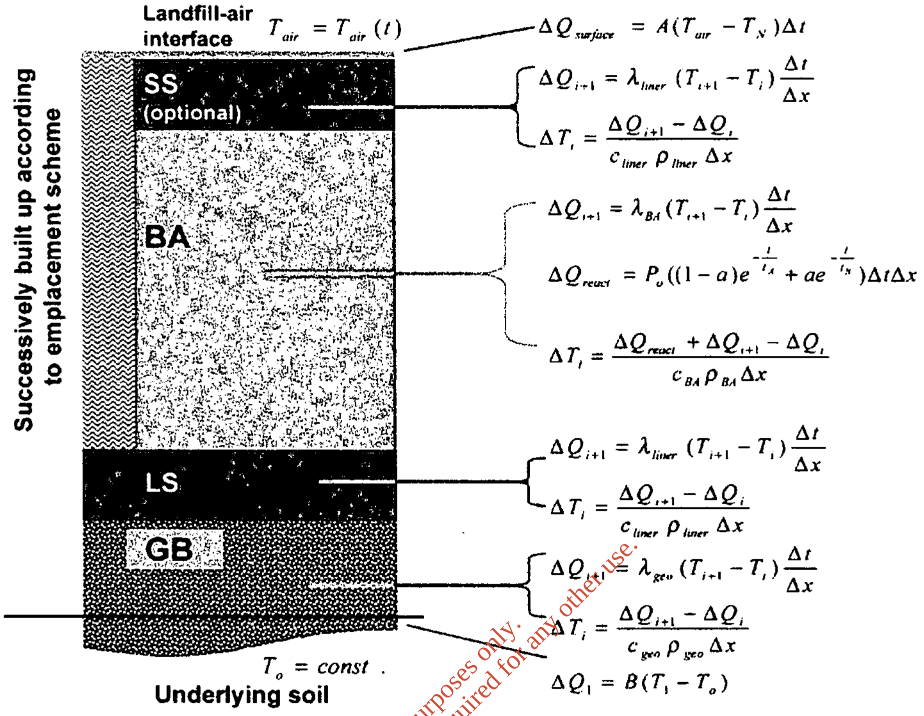

Fig. 1. Schematic structure of the linear column consisting of a geological barrier underneath the landfill (GB), a liner system (LS), the main bottom ash (BA) body as well as (optionally) a surface sealing (SS). The equations on the right side show how the heat balance of the individual layers used in the simulation model. The index 0 indicates the underlying soil, the index n corresponds to the air (i.e. the topmost layer).

of $d = 5$ cm. Heat conduction was computed according to Fourier's law:

$$q_{\mathrm{eff}} = -\lambda_{\mathrm{eff}}\frac{\partial\vartheta}{\partial z} \tag{1}$$

(q_{eff}: effective heat stream, λ_{eff}: effective heat conductivity, $\partial\vartheta/\partial z$: temperature gradient) with a discrete time step of $\Delta t = 30$ min. The heat capacities and thermal conductivities of the different layers in the landfill are given in Table 3. The bottom of the geological barrier was implemented as a fixed head boundary (i.e. a fixed-temperature element with a temperature of 8 °C and an infinite heat capacity; experimentally, the natural groundwater temperature was found to vary only in a temperature range between 6 and 10 °C). By choosing a sufficiently thick GB layer, influences of the boundary on the model area were kept to a minimum. Heat transfer between bottom ash and either surface sealing or atmospheric air (air temperatures were recorded at the dump location) was approximated by a linear heat transmission. Precipitation, wind and sunshine were known from field measurements to have minor impact on landfill temperature [1]. Vapour and fluid phase convection processes which also appear to have minor influence [1] are not explicitly considered in the model.

Table 3
Initial and boundary conditions for the model of the generation and transport of heat in a bottom ash monofill

Initial and boundary conditions	
Initial heating rate, $P_{(0)}$	Variable
Rate constant of the first exponential, t_A (h^{-1})	0.0006
Rate constant of the second exponential, t_B (h^{-1})	0.00005
Heat transition to the air A	Variable
Heat transition to the soil B	Variable
Fraction of the slow heat generation process, a	0.07
Model height	
Geological barrier	Variable
Liner system	Variable
Bottom ash	Variable
Surface sealing	Variable
Heat conductivity ($W\,m^{-1}\,K^{-1}$)	
Bottom ash, λ_{BA}	0.7
Liner material (clay), λ_{liner}	1.3
Geological barrier, λ_{geo}	0.6
Specific heat capacity ($kJ\,kg^{-1}\,K^{-1}$)	
Bottom ash, c_{BA}	0.8
Liner system, c_{liner}	1.85
Geological barrier, c_{geo}	0.88
Temperature	
Bottom ash	Variable
Geological barrier	Variable

For the calculations done in the model I, a biexponential decaying heating rate was used. The use of this biexponential decaying heating rate is a somewhat crude approximation for a much more complicated superposition of many endothermic and exothermic reactions with both concentration and transport limitations going on in the bottom ash. For each layer of the bottom ash body, the heat production due to exothermic reactions in the bottom ash is computed with an overall heating rate $P(t)$ given as

$$P(t) = P_{(0)}((1-a)e^{-t/t_A} + ae^{-t/t_B}) \qquad (2)$$

with $P_{(0)}$ representing the initial heating rate of bottom ash, t_A and t_B being the rate constants of the fast and slow reaction processes, respectively, and a being the fraction of the slowly-decaying reaction of the overall heating rate.

The parameters of the biexponential heating rate curve were adjusted by repeatedly running the model with different parameter sets, comparing the model results with the experimental data and choosing new sets of parameters in order to achieve both good correspondence with the experimental data and consistence with the mineralogical observations. As our results show, the parameter set obtained in this process allows a good simulation of the experimentally observed temperature profiles. A possible explanation for two different time scales for the reaction can be the accessibility of reactive material in the bottom ash, which is straightforward on the outside of the bottom ash grains but strongly transport-limited in their cores.

Most parameters of the model were taken from [13–17]. The parameters of the heating rate function were calibrated with field data from SF1.

For all the calculated simulations, the time profile of the air temperature (daily averages) was used as recorded at the landfill site from June 1997 to June 2001. Circadian temperature fluctuations must not necessarily be taken into account for the experimental data since such short-time temperature changes reach only less than 1 m into the landfill body [18,19].

3. Results

3.1. Sensitivity analysis

In order to highlight the significance of chemical, physical and installation parameters controlling heat generation and transport in a bottom ash monofill, a sensitivity analysis was performed. The focus of the analysis was on the parameters that directly affect temperature development in the landfill and in its liner system. Several simulations were performed to assess the model's sensitivity to its chemical, physical and technical parameters. These parameters include the rate of heat release as a result of the exothermic chemical reactions in the bottom ash material, heat transition processes to the bottom and the air, the heat conductivity and the specific heat capacity of the bottom ash and the liner system. To assess the effects of these parameters, one parameter at a time was varied while keeping the others at their basic values. Table 4 summarises the selected sensitivity analysis simulations with the corresponding rationale behind the value chosen for the parameters at each simulation. The simulations performed for this purpose (Fig. 2) lead to the following conclusions:

- The heating rate is the most important factor influencing the temperature increase in the bottom ash landfill, both at the centre as well as at the landfill liner system.
- Heat conductivity of the bottom ash comes next in order of importance.
- At the liner system, heat conductivity of the liner system has a minor influence on temperature development.
- The remaining parameters do not affect the maximum temperature reached in the bottom ash landfill.

Table 4
Summary of the sensitivity analysis simulations

Variable	Basic values	Sensitivity values (basic value multiplied by the number in parentheses)
Heat conductivity of the bottom ash, λ_{BA} ($W\,m^{-1}\,K^{-1}$)	0.7	(0.05, 0.1, 0.2, 0.5)
Heat conductivity of the liner material, λ_{liner} ($W\,m^{-1}\,K^{-1}$)	1.3	(0.05, 0.1, 0.2, 0.5)
Specific heat capacity of the bottom ash, c_{BA} ($kJ\,kg^{-1}\,K^{-1}$)	0.8	(0.05, 0.1, 0.2, 0.5)
Specific heat capacity of the liner system, c_{liner} ($kJ\,kg^{-1}\,K^{-1}$)	1.85	(0.05, 0.1, 0.2, 0.5)
Initial heating rate of the bottom ash, $P_{(0)}$ ($W\,m^{-3}$)	25	(0.05, 0.1, 0.2, 0.5)
Heat transition to the air A ($W\,m^{-2}\,K^{-1}$)	1	(0.05, 0.1, 0.2, 0.5)
Heat transition to the soil B ($W\,m^{-2}\,K^{-1}$)	20	(0.05, 0.1, 0.2, 0.5)

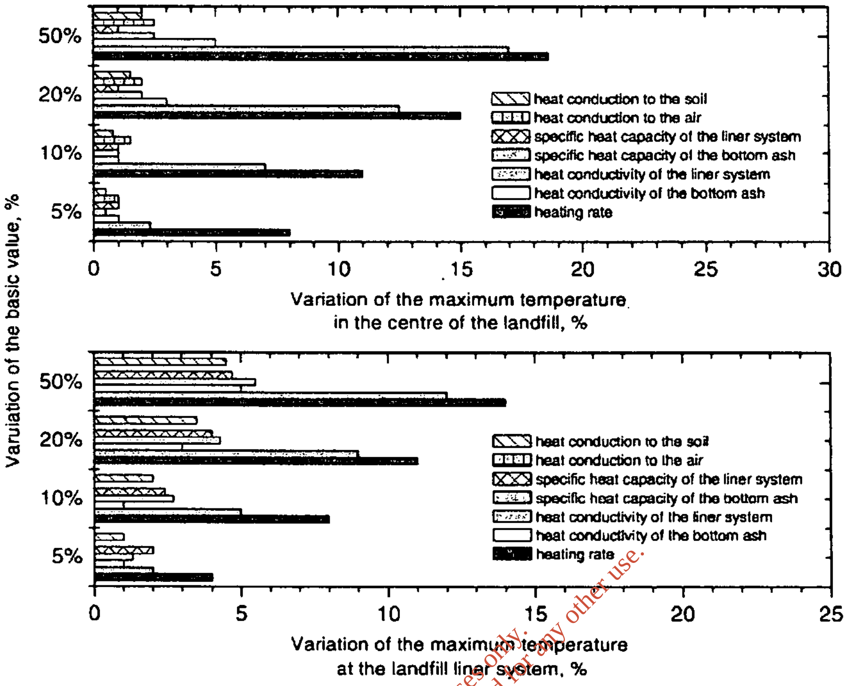

Fig. 2. Effect of variation of basic values on the maximum temperature in the centre of the landfill and at the landfill liner system.

- Heat exchange with the air seems to have no major influence on the temperature development at the landfill liner system.

3.2. Temperature development

Temperature development in selected landfill levels of SF1, SF2 and SF3 is shown in Fig. 3. There was an observed temperature increase immediately after the deposition of a bottom ash layer in each sensorfield. After reaching its maximum 90–160 days after bottom ash deposition, temperature decreased again in all observed landfill layers.

In the following we will present the simulation results for the installed sensorfields and a range of typical emplacement schemes which are summarised in Table 5.

3.3. Calibration and prediction

During model calibration, we have worked out the heating rate of the 3–6-week stored bottom ash material as used in SF1. In order to determine the heating rate of bottom ash when subjected to a previous storage period, the registered temperature development of SF1 was simulated by means of the model. A heating rate upon emplacement of approximately 25 W m^{-3} for the bottom ash material could be determined using the simulation. With

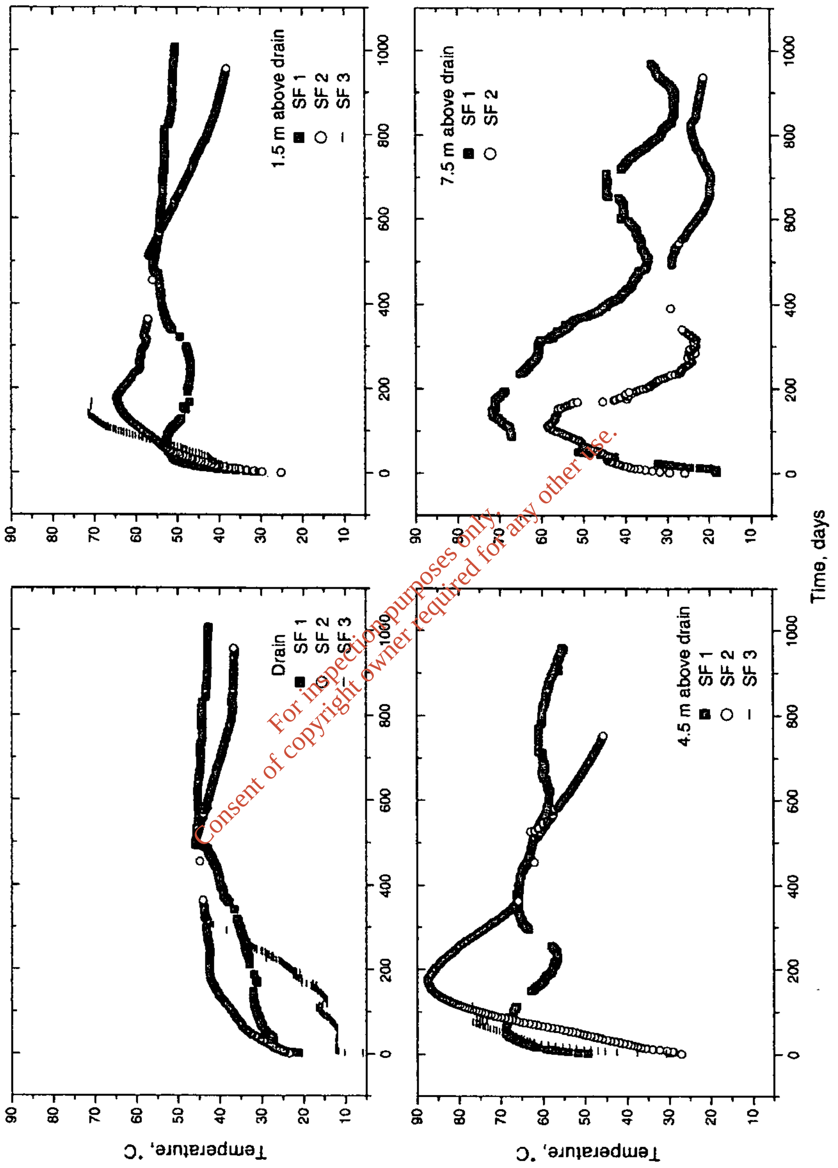

Fig. 3. Measured temperature development in the three sensorfields (SF1–SF3).

Table 5
Deposition procedure for the calculated temperature development in the several model runs of heat generation in a bottom ash landfill

Simulation no.	Emplacement mode	Bottom ash storage time	Heating rate upon emplacement ($W m^{-3}$)
A	Deposition in discrete intervals of 1 m every 2 months	3–6 weeks	25
B	Deposition within 2 weeks to its final height, surface sealing directly after the deposition of bottom ash	3–6 weeks	25
C	Deposition according to SF1, surface sealing after 3 years	3 months	15

the biexponential decrease of the initial heating rate described above, the experimentally observed temperature maximum of 87 °C in the centre of the landfill at SF1 after 4–5 months after deposition could be reproduced in the simulation. The maximum temperature at the landfill base was reached with 46 °C 18 months after the deposition of the first bottom ash layer. Fig. 4 shows the deviations of the calculated temperatures from the real data measured on the landfill site during the first 1000 days. As can be seen from the figure, the model closely describes temperature development in the lower (liner system) and central (4.5 m above liner system) landfill areas. In the upper landfill areas, there is slight deviation from the measured temperatures in the first winter minimum. This affect is possibly due to a variation in the bottom ash quality which is not accounted for in the simulation. There is an overall good correlation between the calculated and measured data ($R^2 = 0.834$, $N = 8443$).

With the initial heating rate of 25 $W m^{-3}$ and the biexponential decay, we have calculated a released energy of 250 $MJ m^{-3}$ for the first 2 years of storage in the landfill. This amount corresponds with the data observed by Speiser [8].

3.4. Validation and prediction (SF2)

After this calibration, the model was validated using the measured temperature data of SF2 (900 days measurements). With the heating rate value upon emplacement of 25 $W m^{-3}$ determined above, there was good agreement between simulated and observed data. Fig. 5 shows the deviations of the calculated temperatures from the real data measured on the landfill site during the first 850 days. With these data, a good correlation between the calculated and measured data ($R^2 = 0.867$, $N = 7521$) was found.

3.5. Validation and prediction (SF3)

In the second validation phase, the initial heating rate of the fresh quenched bottom ash material, as used in SF3 was measured. In order to determine the initial heating rate of the bottom ash, the measured temperature development during the first 6 months of storage in SF3 with its new emplacement mode was simulated by means of the model. An initial heating rate of approximately 45 $W m^{-3}$ for the bottom ash material in the absence of a preliminary storage period could be determined. With the biexponential decrease of the

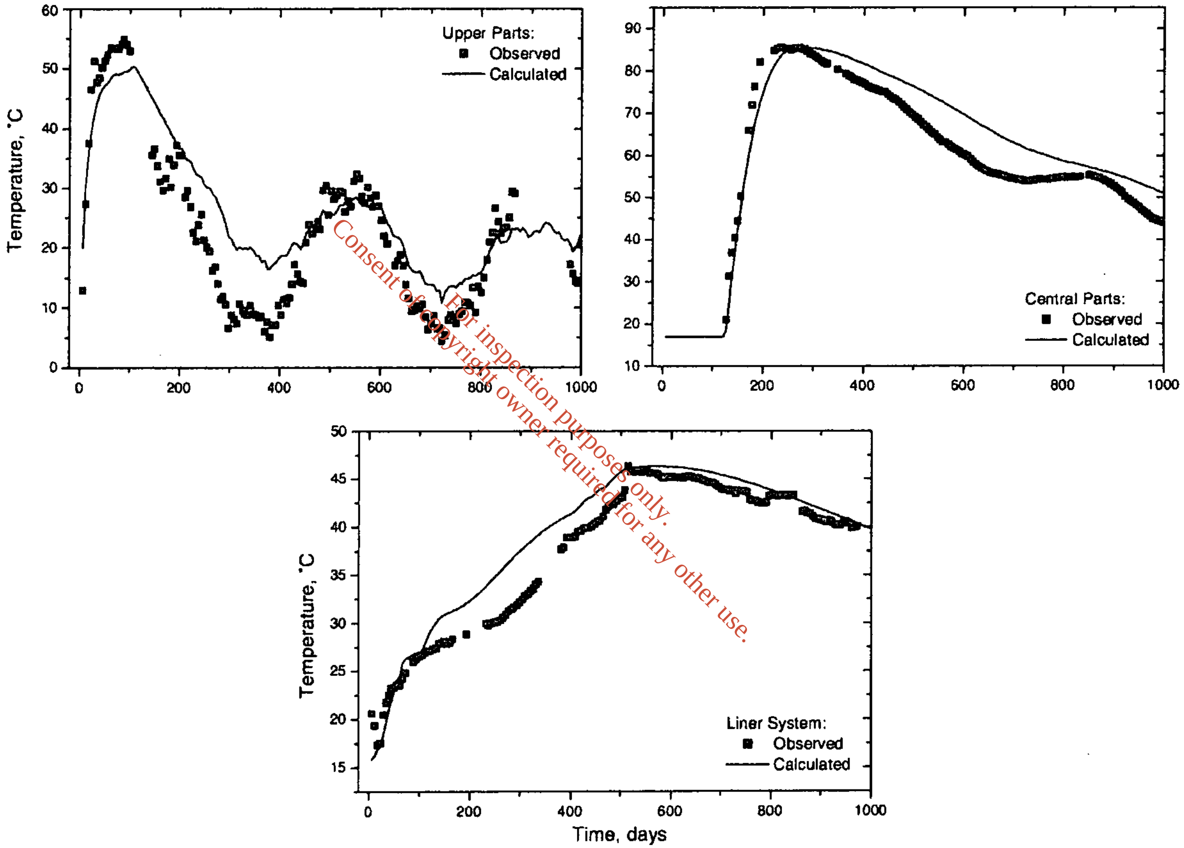

Fig. 4. Comparison of the numeric simulation and at the landfill measured temperatures in selected horizons of the landfill base (liner system), the central area (4.5 m above liner system) as well as the upper landfill area (1 m below surface) for the calibration of the model.

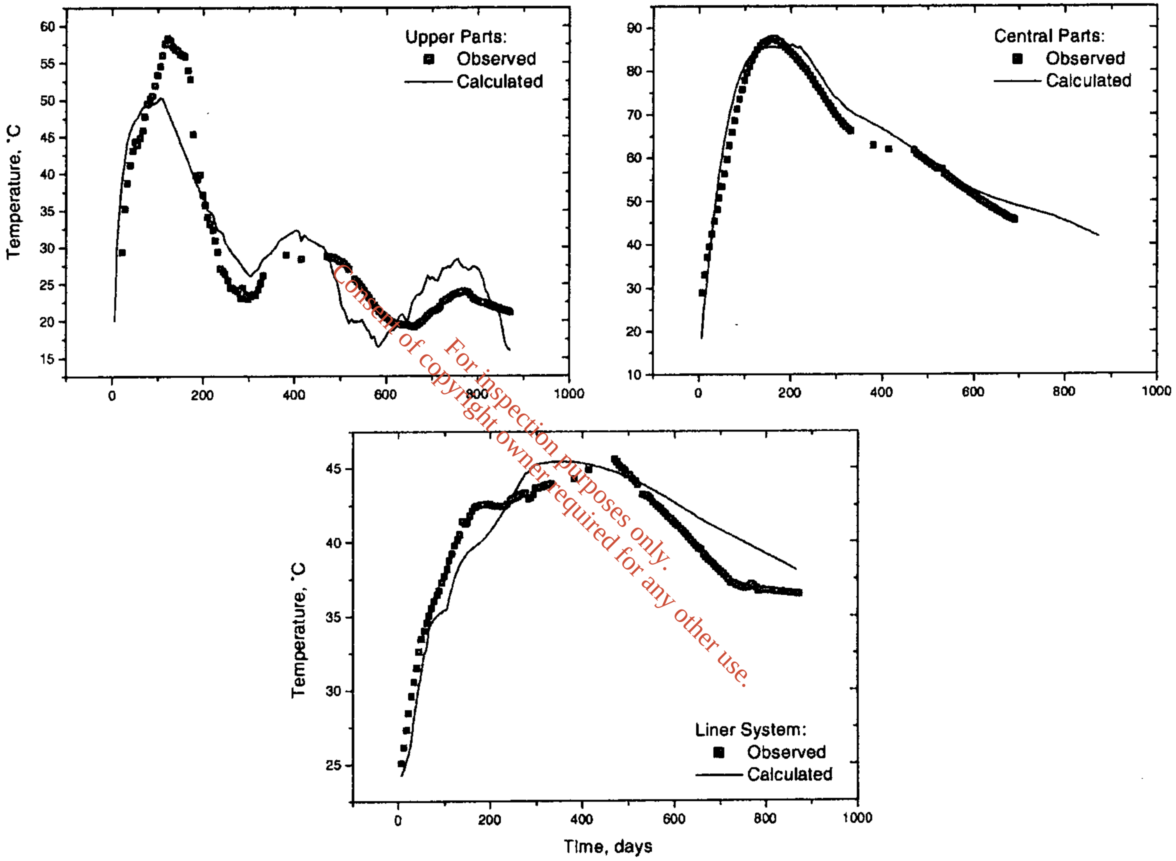

Fig. 5. Comparison of the numeric simulation and at the landfill measured temperatures in selected horizons of the landfill base (liner system), the central area (4.5 m above liner system) as well as the upper landfill area (1 m below surface) for the validation of the model (SF2).

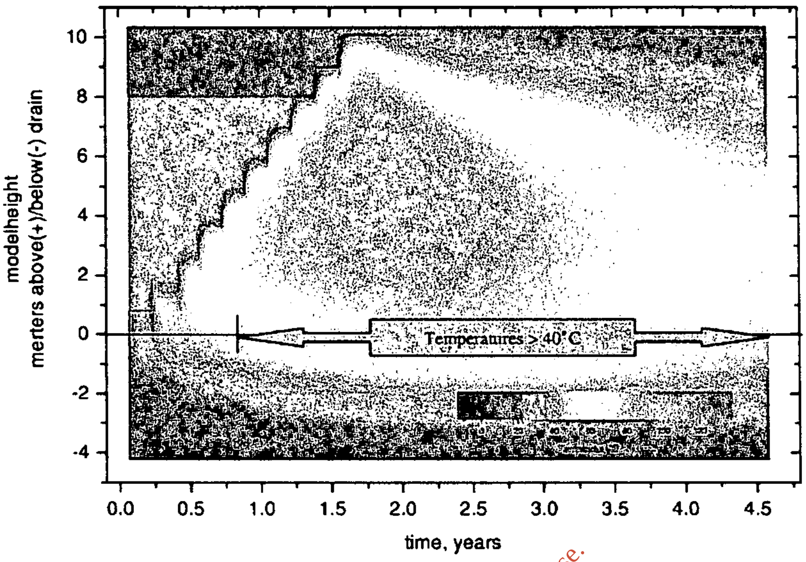

Fig. 6. Predicted temperature development in the second model validation (SF3). Initial heating rate for the fresh quenched bottom ash was set to 45 W m^{-3}, final bottom ash height to 10 m (deposited in discrete intervals of one meter every 2 months).

initial heating rate described above the observed temperature development during the first 6 months could be simulated by the model. The computer simulation results in a temperature maximum of 96 °C in the centre of the landfill (approximately 9 months after the deposition of this bottom ash layer) and 66 °C at its bottom. Fig. 6 shows the calculated temperature development in the landfill over a simulation time of 4.5 years. The high initial heating rate causes higher maximum temperatures in the bottom ash material that result also in higher temperatures in the landfill liner system, and thus may lead to thermal damage of the liner. Temperatures above 40 °C are calculated there from the sixth month after first deposition of bottom ash. Fig. 7 shows the deviations of the calculated temperatures from the real data measured on the landfill site. There is a good correlation between the calculated and measured data ($R^2 = 0.872$, $N = 4287$). With the calibrated and validated model several scenarios were calculated to generate an optimal handling scheme for municipal solid waste incineration (MSWI) bottom ash.

3.6. Simulation no. A: stepwise emplacement of previously stored ash

With the results achieved from the prior simulation, a step-wise emplacement strategy was simulated with bottom ash that was stored for 3–6 weeks before depositing at the landfill with a consequently reduced heating rate from initially 45 to 25 W m^{-3}. This reduced heating rate is also reflected in the temperature development in the landfill body. The maximum temperature reaches only 54 °C in centre and 38 °C at the basis of the landfill (Fig. 8). So there is no temperature above 40 °C at the liner system.

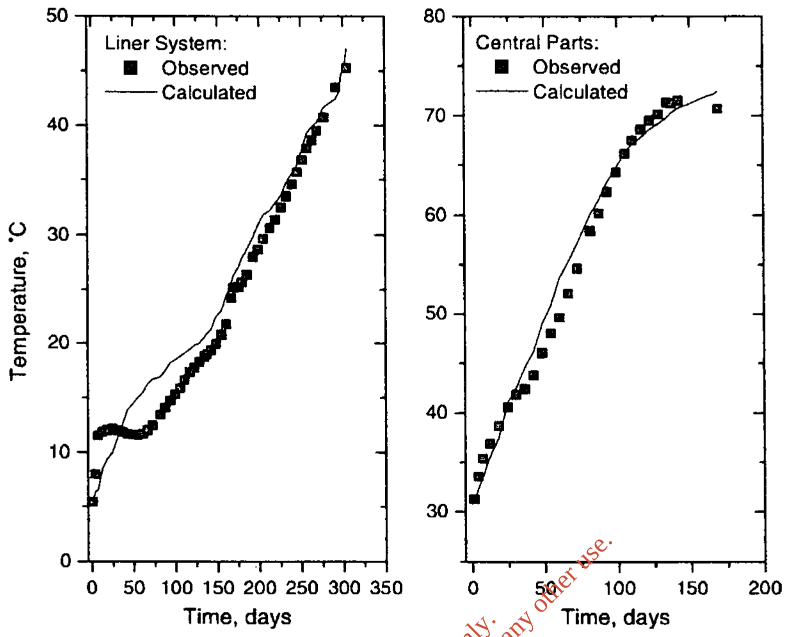

Fig. 7. Comparison of the numeric simulation and at the landfill measured temperatures in selected horizons of the landfill base (liner system) and the central area (3 m above liner system) for the validation of the model (SF3).

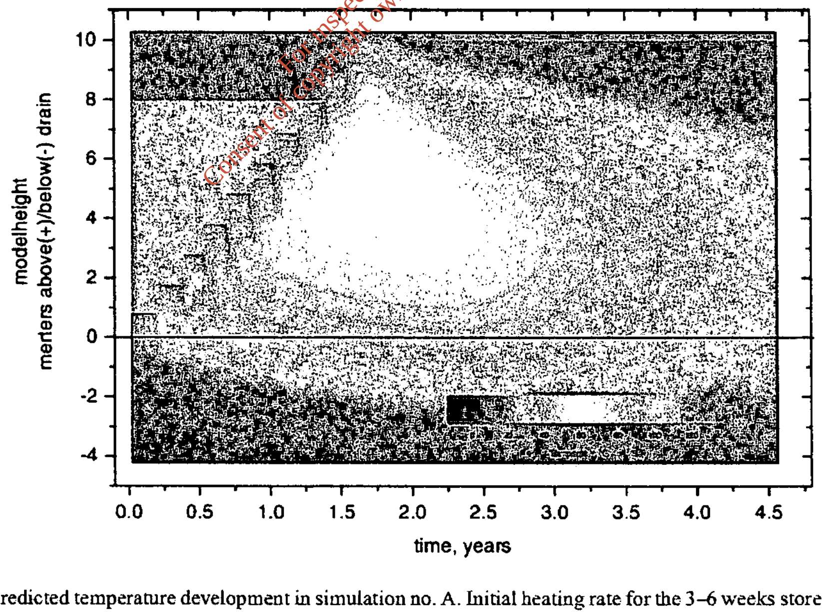

Fig. 8. Predicted temperature development in simulation no. A. Initial heating rate for the 3–6 weeks stored bottom ash was set to 25 W m^{-3}, final bottom ash height to 10 m (deposited in discrete intervals of 1 m every 2 months).

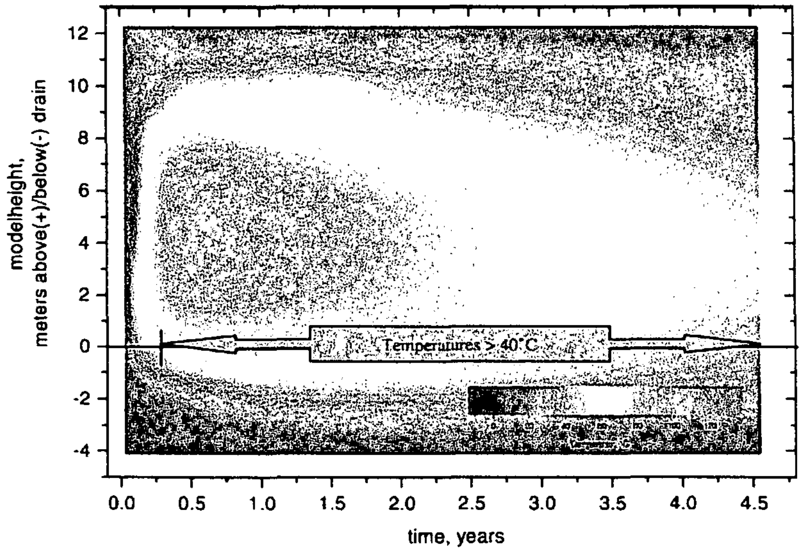

Fig. 9. Predicted temperature development in simulation no. B. Initial heating rate for the 3–6 weeks stored bottom ash was set to 25 W m^{-3}, final bottom ash height to 10 m (deposited in 3 weeks to its final height). Surface sealing was installed directly after the deposition of the bottom ash.

3.7. Simulation no. B: surface sealing

In the next simulation, the influence of a surface sealing on landfill temperature development was modelled. The simulated landfill has a bottom ash height of 10 m with a liner system (0.8 m) at its bottom and a geological barrier with a thickness of 3 m. In the model run, a surface sealing (2.5 m) was emplaced directly after the deposition of the 3–6 weeks stored bottom ash (initial heating rate: 25 W m^{-3}). With this sealing, the heat convection from the surface to the air is hampered. The result from this simulation shows that after a storage time of only 4 months, the temperature at the landfill centre rises to 97 °C (Fig. 9). Also at the liner system the maximum temperature (58 °C after a storage time of 7 months) is far beyond the critical temperature (40 °C) for the landfill liner durability. Here, temperatures above 40 °C are calculated from the third month after first deposition of bottom ash.

3.8. Simulation no. C: storage time

In the last simulation, the influence of the duration of preliminary bottom ash storage period on the landfill temperature was determined. The sensorfield was built-up according to SF1 and the surface sealing was installed after the final deposition of bottom ash. The initial heating rate was set to 15 W m^{-3}. This heating rate corresponds to a intermediate storage time of approximately 3 months. The calculated maximum temperature (56 °C in the centre of the bottom ash body) was obtained 300 days after the beginning of bottom ash

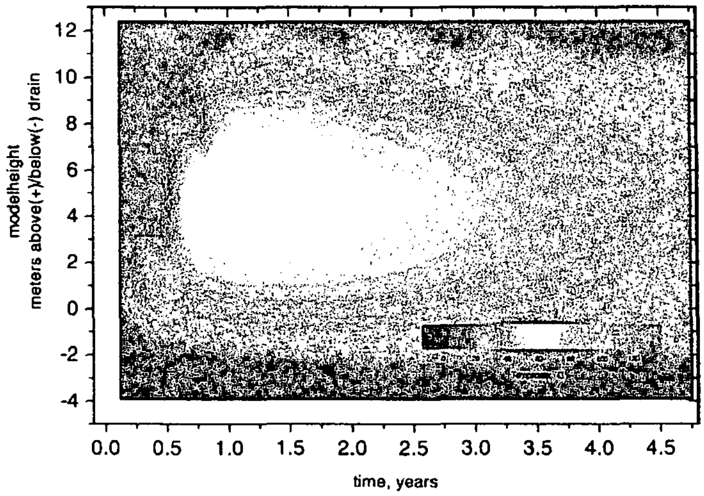

Fig. 10. Predicted temperature development in simulation no. C. Initial heating rate for the 3 months stored bottom ash was set to 15 W m^{-3}, final bottom ash height to 10 m (deposited in unequal intervals during a period of 8 months). Surface sealing was installed directly after the deposition of the bottom ash.

deposition (Fig. 10). At the liner system, a maximum temperature of 35 °C was calculated 1 year after the beginning of the bottom ash deposition.

4. Conclusions

In this paper, the temperature development under different modes of bottom ash emplacement was studied. According to the simulation of temperature development in MSWI bottom ash landfills, temperatures from 54 to 97 °C were calculated in the vertical centre of the bottom ash body depending on the emplacement strategy. At the liner system, temperatures reached 35–46 °C. It was shown, that the temperature increases are inversely correlated with the surface-to-volume ratio of the freshly applied ash layer (as realised in simulation B). Furthermore, a preliminary bottom ash storage period prior to disposal is necessary to prevent possible thermal damage at the landfill liner system. The simulation results show that the storage time is the key factor influencing the temperature development in the landfill. A storage time of 3–6 weeks reduces the initial heating rate from 45 to 25 W m^{-3} (reduction of 46%) a 3 months storage time reduces the heating rate to 15 W m^{-3} (reduction of 67%). The risk of a damage at the barrier systems is increased if preliminary storage of bottom ash is not utilised.

Comparatively, it was shown that a storage time of 3–6 weeks and a reduced surface-to-volume ratio lead to maximum temperature values (54 °C in the centre and 38 °C at the liner system) close to those calculated for a storage time of 3 months and a high surface-to-volume ratio (54 °C in the centre and 38 °C at the liner system).

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Case study

Temperature development in a modern municipal solid waste incineration (MSWI) bottom ash landfill with regard to sustainable waste management

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Abstract

Municipal solid waste is treated in incineration plants to reduce the volume, the toxicity and the reactivity of the waste. The final product, municipal solid waste incineration (MSWI) bottom ash, was considered as a material with a low reactivity, which can safely be deposited in a MSWI bottom ash landfill, or which can be used, e.g. in road construction after further treatment. However, temperature measurements in MSWI bottom ash landfills showed temperatures up to 90°C, caused by exothermic reactions within the landfill. Such high temperatures may affect the stability of the flexible polymer membrane liner (FML) and may also lead to an accelerated desiccation of the clay barrier. At the beginning of this study it was uncertain whether those reported results would be applicable to modern landfills, because the treatment techniques in MSWI and landfills have changed, bottom and fly ash are stored separately, and the composition of the incinerated waste has changed significantly since the publication of those results.

The aim of this study was to gain detailed knowledge of temperature development under standard disposal conditions in relation to the rate of ash disposal, the variation of layer thickness, and the environmental conditions in a modern landfill.

Temperatures were measured at nine levels within the body of a landfill for a period of nearly 3 years. Within 7 months of the start of the disposal, a temperature increase of up to 70°C within the vertical centre of the disposal was observed. In the upper and central part of the landfill this initial temperature increase was succeeded by a decrease in temperature. The maximum temperature at the time of writing (May 2000) is about 55°C in the central part of the landfill. The maximum temperature (45.9°C) at the FML was reached 17 months after the start of the deposition. Since then the temperatures decreased at a rate of 0.6°C per month.

Temperature variation within each individual layer corresponds to the temperature of the underlying layer and the overall surface-to-volume ratio of the landfill. The temperatures in the uppermost

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layer are significantly influenced by the ambient temperatures.

Keywords: Bottom ash; Temperature development; Municipal solid waste incineration; Landfill

1. Introduction

In OECD countries and the US, 15–20% of municipal solid waste is treated by incineration [1]. Municipal solid waste incineration (MSWI) aims to reduces the volume, the toxicity and the reactivity of the waste. Although the volume of the waste is reduced by about 90%, the residues (bottom ash, fly ash) still amount to roughly 17 Mt per year world-wide [2]. This amount is expected to double within the next 10 or 15 years [3]. Bottom ash, which is the object of this study, represents about 80% of the residues and contains various substances that may pose a threat to groundwater quality [2–4].

Assessing the potential pollution risks of the residues is essential since bottom ash has increasingly been used as building material or has been deposited in landfills with poor landfill liner systems in Europe and in other countries during the last decade [5]. In the US, bottom ash was commonly landfilled without processing, even though metals and other materials can be recovered by magnetic separation and screening [6]. In some European countries (e.g. Germany, The Netherlands and France) bottom ash is partly reused (about 60%) in road construction or as raw material for the ceramic and cement industry [7–9], whereas in Switzerland almost 100% of the bottom ash is disposed in landfills [6].

Until the 1970s, bottom ash was believed to be almost inert, but since then several studies have shown that a number of exothermic reactions occur in this material [10–15]. Other studies have shown that exothermic reactions may cause a temperature increase in the landfill of up to 90°C [16,17] which may constitute a major hazard to the flexible polymer membrane liner (FML) and the mineral clay layer. Temperatures above 40°C may affect the stability of the FML (made of high-density-polyethylene (HDPE)) due to depolymerisation and oxidation. Sudden ruptures of the FML may follow [18]. Due to a diffusive transport of water and water vapour along the temperature gradient in the mineral clay layer, the clay barrier may desiccate and fail to retain leachate [19–21]. Johnson et al. [22] observed a rapid increase in bottom ash landfill discharge following rainfall. Within 1–4 days, approximately 50% of precipitation discharged in response to a rain event.

Due to their limited time scale, published studies on exothermic reactions [23–26] have to be considered as a ‘snapshot’, hence giving no information on the long-term development of the landfill temperatures. Moreover, many of the basic conditions have changed since then. The incineration technique has been improved and the composition of the municipal waste has changed. For instance, the heating value of domestic waste increased from 6000 to 8000 kJ/kg over the last two decades caused by recycling activities and an augmented share of plastic contents in domestic waste [27]. In contrast to former landfills, fly ashes nowadays are stored in underground repositories, and ferromagnetic scrap metal of a diameter >16 mm is usually separated out by a magnetic separator. With these changes the mineralogical and chemical composition of the deposited residue has changed as well, thus putting the extrapolation of published results to state-of-the-art landfills under question.

The present study aims to provide data on the long-term development of the temperatures within a recent bottom ash landfill under normal disposal conditions.

2. Experimental

2.1. Bottom ash description

The bottom ash in this study was produced by MSWI in Ingolstadt in the south of Germany (MVA Ingolstadt/Germany). The incinerator (installation year 1996) operates at temperatures between 850 and 1200°C. The incineration capacity of each furnace is roughly 11 Mg/h and the material remains in the combustion chamber for about 1 h. Following incineration, the bottom ash is quenched in a water basin. After this quenching process, the bottom ash is temporarily stored in piles up to 2 m in height at an open dump site for 1–3 weeks, in order to reduce the reactivity [28]. Prior to deposition in the landfill, magnetic materials are removed. The grain size distribution of the bottom ash (Fig. 1), determined according to DIN 18123 [29], shows a badly sorted material with grain sizes from silt to gravel.

The determined bulk density has a mean value of $2.13 \pm 0.15\,\mathrm{Mg/m^3}$. The geotechnical water content (weight of water in a sample relative to the oven dry weight of the sample, expressed as percentage, DIN 18121 [30]), measured after a 3 weeks storage period, ranges from 8 to 15% by weight.

Although the bottom ash studied is a very inhomogeneous material, it is in general comparable with other MSWI bottom ashes investigated elsewhere [12,31] although there

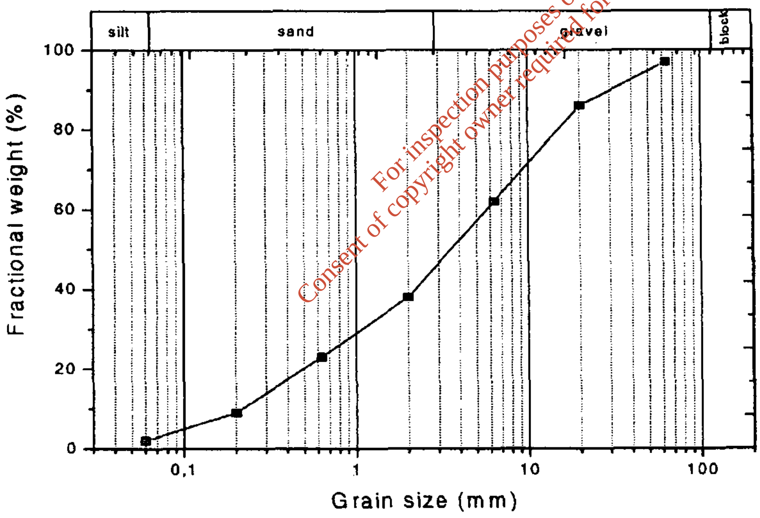

Fig. 1. Grain size distribution of the examined MSWI bottom ash as a function of fractional weight.

Table 1
Bottom ash composition (wt.%)

	Melting products and ashes	Metals	Ceramic	Stones	Glass	Organic waste
This study	82	8	2	1	6	1
Lichtensteiger (1996)	85	5	2	1	5	2
Reichelt (1996)	67	4	4	–	17	–

is a significant variation in the fraction of glass in the bottom ash, caused by increased recycling in municipal solid waste (Table 1).

The thermal conductivity of the investigated bottom ash ranges from 0.23 (dry) to 1.27 W/m K (saturated). It was determined with the thermal conductivity instrument TK04 (TeKa, Berlin/Germany). The samples were taken prior to deposition. The value for the deposited bottom ash at a water content between 10 and 20% by weight ranged between 0.5 and 0.6 W/m K.

2.1.1. Disposal site

The bottom ash landfill investigated in this study is located near Ingolstadt. The measured average ambient temperature in this area is 15°C, with a recorded maximum and minimum of 33 and −8°C during the observation period (June 1997–June 2000). The measured annual precipitation in this period was between 800 and 1000 mm with a maximum between May and July. The driest period was January–April. The summer rains tend to occur in short events with a high intensity.

The geology at the landfill location comprises fluvial and alluvial sediments. The elevation of the water table is approximately 2 m below the base of the landfill. The groundwater flows south towards the river Danube, which flows in an easterly direction approximately 800 m south of the landfill.

The landfill was constructed above ground adjacent to a hill side. The base of the landfill is a 0.6 m thick mineral clay layer, covered by a 2.5 mm FML made of HDPE. Between the FML and the bottom ash is a gravel drainage layer (16–32 mm grain size). The leachate is transported to a communal waste water treatment plant. Two geotextiles separate the bottom ash from the drainage layer and the drainage layer from the FML. A schematic of the test site is given in Figs. 2 and 3. The levelled ground directly below the clay liner consists of sand and gravel. Therefore the capillary rise of water from the ground water into the mineral clay layer may be hampered, leading to a forced desiccation.

Approximately 19,000 m^3 of bottom ash are deposited in the landfill per year at discrete and irregular intervals. The landfill is subdivided into four separated disposal sectors (Fig. 3) [32]. Sectors I–III were already completely filled at the start of the study. Sector IV was filled with bottom ash during the study period. The MSWI fly ash is stored elsewhere in a hazardous waste disposal site. Sector IV, where the sensors are located, has a filled surface area of 16,500 m^2 and a total bottom ash capacity of approximately 100,000 m^3. The sensors are located in the centre of sector IV, so no influence from the other sectors is to be expected. The surface of sector IV has not yet been covered or cultivated, so there is direct contact between the deposited bottom ash and the atmosphere.

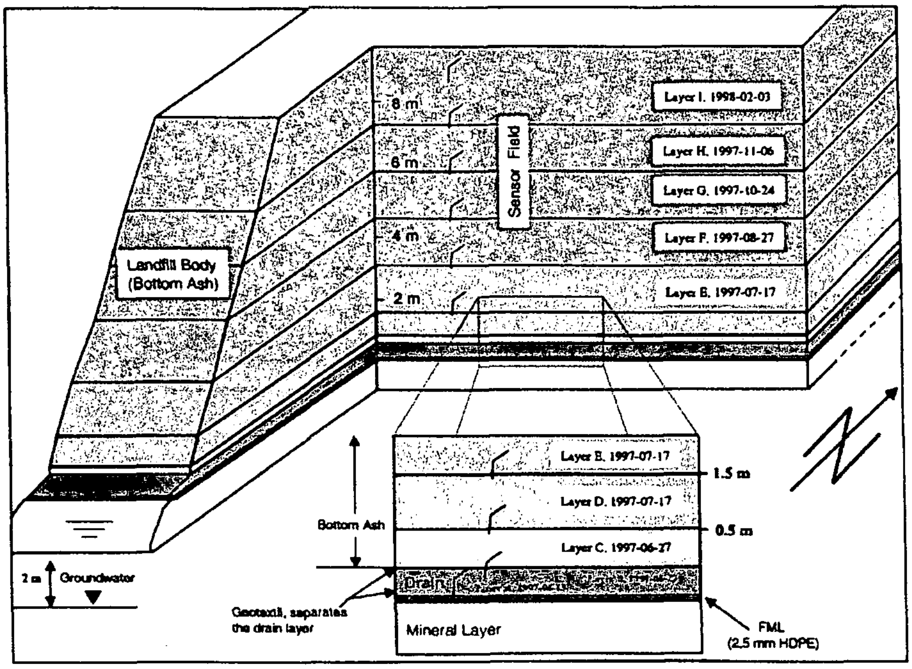

Fig. 2. Schematic cross section through the bottom ash landfill in Ingolstadt (Germany) showing locations of the temperature sensors installed within discrete layers (A–I).

2.1.2. Materials

Temperatures were recorded using Pt-100 temperature sensors (R + S Components, Moerfelden, Germany, measurement range from −200 to +300°C with an error of 0.3%) embedded directly into the bottom ash. The sensors were installed at the top of each layer before the deposition of a new layer (except of sensors in layer I which was placed in the middle of the layer, 9 m above drain, see Table 2, Fig. 2), thus reflecting the temperature development under ordinary disposal management conditions. Each of the nine discrete layers was equipped with two sensors, placed at a horizontal spacing of approximately 1 m.

The bottom ash was deposited in irregular time intervals (depending on bottom ash amount in the MSWI). The ash remained piled for 1–3 weeks on the landfill before it was levelled flat to 150 cm thick layers by dredging. The bottom ash piles were located in the eastern part of sector IV and in sector III. Bottom ash was not compacted and no temporary liner was used to cover the landfill between deposits. There has been no other activity in the test field area during the measurement period.

Data were recorded using a DL2e data logger (Delta-T-Devices, Cambridge, UK) at intervals of maximum 24 h. Additionally, in order to detect any temperature fluctuations, data were recorded at intervals of 1 h from 6 April to 13 April 2000. The following climatic

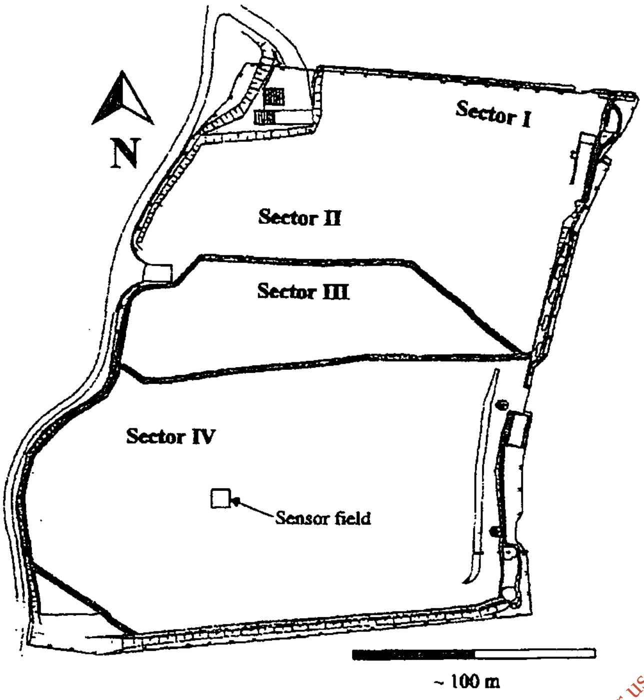

Fig. 3. Schematic section of the bottom ash landfill in Ingolstadt (Germany) showing locations of the temperature sensor field and the four landfill sectors.

Table 2
Bottom ash depositing parameters during the installation of the test field and the corresponding temperature gradients during the first 50 days of depositing

Layer	Localization within the landfill	Date of depositing	Ambient temperature (°C)	Temperature of the underlying layer (°C)	Average temperature gradient (°C per day)
A	at the FML	13 June 1997	24	8.5	0.14
B	in the drain	27 June 1997	22	17.5	0.16
C	0.5 m above drain	27 June 1997	22	21.2	0.23
D	1.5 m above drain	17 July 1997	26	32.5	0.4
E	3.0 m above drain	17 July 1997	26	36.4	0.4
F	4.5 m above drain	27 August 1997	27	51.8	0.71
G	6.0 m above drain	24 October 1997	7	68.7	1.02
H	7.5 m above drain	1 November 1997	15	69.1	0.99
I	9.0 m above drain	3 February 1998	−1	67.5	Climatic changes

parameters were recorded daily using equipment provided by Delta-T-Devices (Cambridge, UK): Air temperature, air humidity, solar radiation, and rainfall. Data are available over a time period of 36 months from June 1997 to June 2000.

2.1.3. Heat transport

Heat is transported in the bottom ash landfill mainly by two ways. First, there is a conductive heat transport from one layer to each other. The second way is a convection heat transport from the bottom ash to the atmosphere.

The conductive heat transport j can be calculated with the thermal conductivity of the bottom ash λ and the temperature difference between two landfill layers ($T_2 - T_1$)

$$j = \lambda(T_2 - T_1) \tag{1}$$

The convection heat transport from the bottom ash to the atmosphere Φ is defined as the product of the temperature difference from the bottom ash to the atmosphere ($T_S - T_L$), the surface A, the time period Δt and the thermal coefficient α_C (6.2 W/m^2 K for the bottom ash surface)

$$\Phi = \alpha_C A(T_S - T_L)\Delta t \tag{2}$$

3. Results

3.1. Temperature development

The development of the temperatures (daily mean) in the different layers of the field site is given in Fig. 4. The mean temperature difference between the two sensors in each layer was between 0.1 and 0.5°C with an average of 0.24°C.

In every layer the temperature development started with an increase immediately after deposition. During the next 2.8 ± 0.3 months, the bottom ash temperatures increased by about 75°C, depending on the layer position. The average rate at which the temperatures rose was between 0.16 and 1.02°C per day (Table 2).

In layers A and B (FML and drain) the initial temperature rise (0.14°C per day in layer A and 0.16°C per day in layer B during the first 4 weeks) was followed by a levelling off for the next 2 months. Afterwards a second increase of temperatures, now at a rate of 0.065 ± 0.005°C per day was observed. The maximum temperature (45.9°C in layers A and B) was reached 17 months after the deposition of these layers. Subsequently, the temperatures in layers A and B decreased at a rate of 0.6°C per month (layer A), respectively 0.54°C per month (layer B). The temperature increase in these two layers is a result of the temperature increase in the bottom ash layers deposited above them and the heat flux from these layers. The gravel in the drainage (layer B) and the FML (layer A) do not generate their own heat.

Layer C (the lowest bottom ash layer) showed an initial temperature increase of up to 44°C (at a rate of 0.25°C per day) during the first 2 months of storage. The temperature increase showed a first levelling off after a storage time of 18 days. After depositing layer D, layer C showed a renewed small rise in the gradient of temperature increase. This

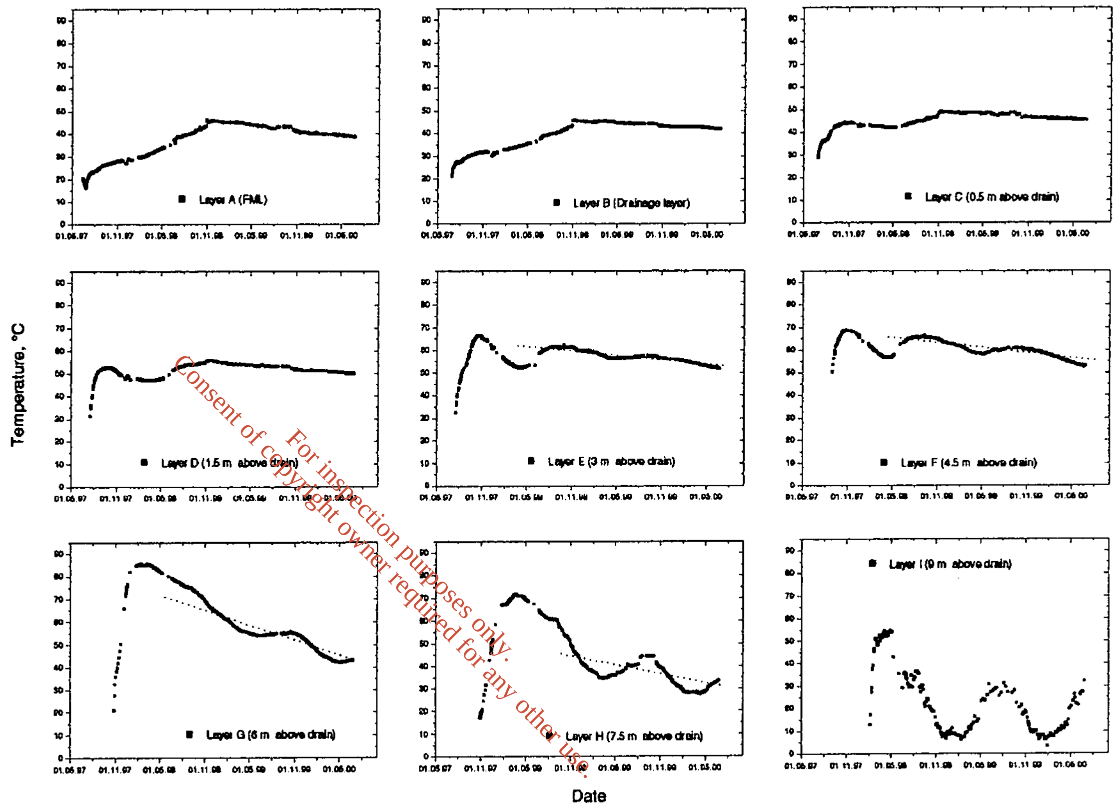

Fig. 4. Recorded temperatures in the various landfill layers. The different factors, explaining the variation of the temperatures are given in the text.

increase was followed by a 6 month temperature decrease (0.36°C per month). With a second temperature increase, this layer reached its maximum after 14 months of storage time (49°C for layer C). From that time temperatures decreased at an overall rate of 0.3°C per month.

Layer D showed a similar temperature development with an initial temperature increase of 0.35°C per day. It reached its maximum temperature after 14 months of storage time (56°C) and decreased then with an rate of 0.3°C per month.

In layers E–G, the temperature development after the initial increase (with its maximum at 87°C in layer G) shows an oscillation with a period of approximately 12 months. The monthly average temperatures (dotted line in Fig. 4) decline at a rate of 0.3°C per month in layers E and F and 0.9°C per month in layer G.

Layer H shows a similar temperature development. After a storage time of 80 days, the temperature increase in layer H levelled off. By depositing layer I, the temperature in layer H rose again for the next 50 days and reached its maximum with 72.2°C. The trend in this layer indicates a decline of temperatures at the rate of 0.6°C per month.

At the top of the landfill, layer I, the initial increase was followed by a rapid decrease and a following oscillation with a period of 12 months. The minimum temperatures were reached during winter, the maximum temperatures during summer. The temperature curve also shows an oscillation with a shorter period (24 h) reflecting the daily ambient temperature fluctuation (Fig. 5).

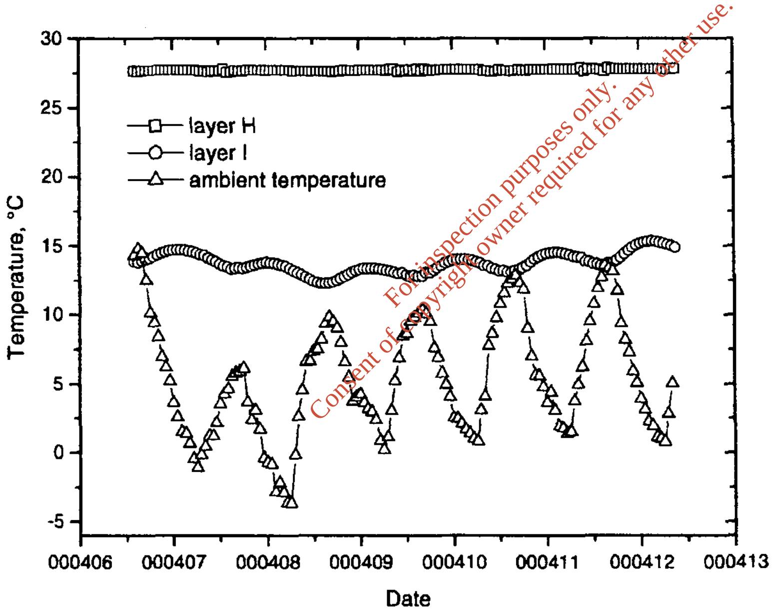

Fig. 5. Influence of measured daily temperature fluctuations (recorded for 1 week at intervals of 1 h) on selected bottom ash layers.

Three years after deposition, temperature development in the upper layers shows an overall decrease with a seasonal component. The lower layers in the lower landfill follow this overall trend, but they do not show the seasonal influence.

4. Analysis

There are several factors which are suspected to influence temperature development. A simplified description of the temperature change (ΔT) within a representative elemental volume (REV) leads to Eq. (1) as the sum of heat production (E_{exo}) due to exothermic reactions minus the heat consumption from endothermic reactions (E_{end}) plus external input (F_{in}) minus heat loss (F_{out}).

$$\Delta T = E_{\mathrm{exo}} - E_{\mathrm{end}} + F_{\mathrm{in}} - F_{\mathrm{out}} \tag{3}$$

Within this equation, the amount of exothermic and endothermic reactions is unknown. The heat exchange to and from the REV is a function of the temperature gradient, the thermal conductivity and the convection heat transfer between the REV and its environmental (e.g. other bottom ash REV, drain, atmosphere). On the field scale, each layer is considered as a REV.

The key factors influencing the temperature development thus can be defined as

1. the temperature gradient to the underlying layer or, if there is no underlying layer, the ground of the landfill,
2. the temperature gradient to the ambient temperature or, if another layer is on top of the REV, the temperature gradient to the upper layer,
3. the thermal conductivity between the REV and its environment,
4. the convection heat transfer from the bottom ash to the atmosphere,
5. the ratio between heat production and the heat flux at the boundaries of the REV, which is expected to be a function of the surface-to-volume ratio of the REV,
6. the effect of the precipitation as transport and reaction medium.

In the following section, the effects of these factors will be assessed semi-quantitatively based on the measurements of temperature development.

4.1. Temperature at the bottom of each layer

There is a positive correlation ($R^2 = 0.983$, $N = 6$) between the temperature gradient from the next deposited bottom ash layer to the underlying layer (at the time of depositing the next layer) and the rate of temperature increase in the newly deposited layer (Fig. 6). This effect is based on an addition of the internal generation of heat in each bottom ash layer (layers A and B do not generate their own heat) and the heat conduction from the underlying layer.

The highest rate of increase (temperature increase per day, see Table 2) was observed in layer G, where the temperature of the underlying layer (layer F) had reached a temperature of almost 69°C when layer G was deposited. The lowest rate was observed in layer C, where

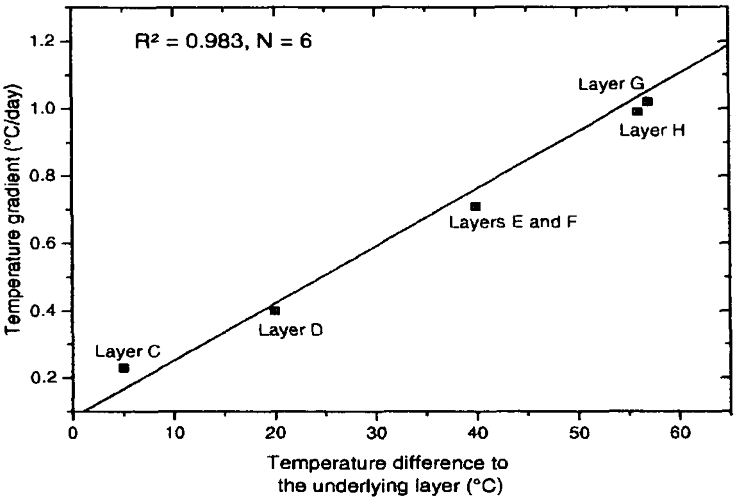

Fig. 6. Calculated gradient of temperature increase of the different layers vs. the temperature of the underlying layer in time of depositing the next one (shown is the regression line).

the underlying layer, which does not generate heat at all, had a temperature of only 21°C (see Table 2).

4.2. Ambient temperatures

There is a statistically significant correlation ($R^2 = 0.788$, $N = 522$) between the temperatures in the top layer (layer I) and the ambient temperature (Fig. 7). This effect is observed to be less pronounced with increasing depth in the landfill. Layers E to H show an oscillation in bottom ash temperature after having reached their maximum temperatures. This oscillation has a period of approximately 12 months and reflects the annual ambient temperature development with a delay of 28 days for layer H, 58 days for layer G, 82 days for layer F and 112 days for layer E. This growing delay reflects the thermal buffer capacity of the bottom ash.

4.3. Surface-to-volume ratio

Heat flux (Φ) from the bottom ash towards the cooler air is an important factor influencing the thermal development in the landfill.

With an upwards conductive heat transport in layer I of 2–35 W/m^2 (with an average of 15 W/m^2) and an average convection heat transport of 70–250 W/m^2 (with an average of 105 W/m^2) from the heated bottom ash of layer I to the air during the first 200 days of deposition, the addition of each new layer hampers the heat exchange between the bottom ash and the atmosphere.

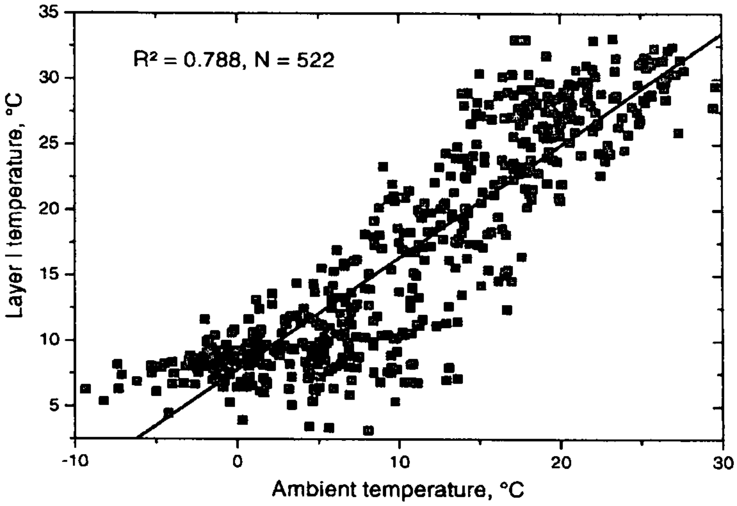

Fig. 7. Recorded ambient temperature plotted vs. recorded temperature in layer I (shown is the regression line).

There is a correlation ($R^2 = 0.987$, $N = 4$) between the surface-to-volume ratio (s/v) and the maximum temperature in the observed volume. The maximum temperature increases with decreasing s/v (Fig. 8) from 50°C (layer C) to 87°C (layer G) (see Table 2).

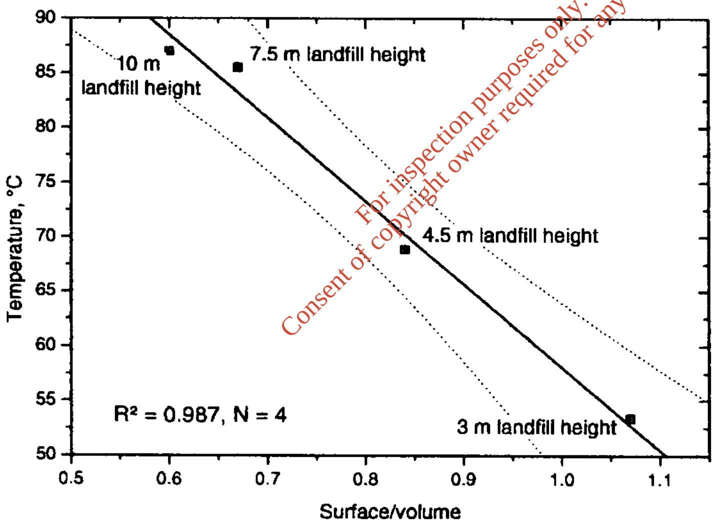

Fig. 8. Calculated surface-to-volume ratio of the growing landfill vs. the maximum temperatures in the middle of each volume at the given landfill height (shown is the regression line).

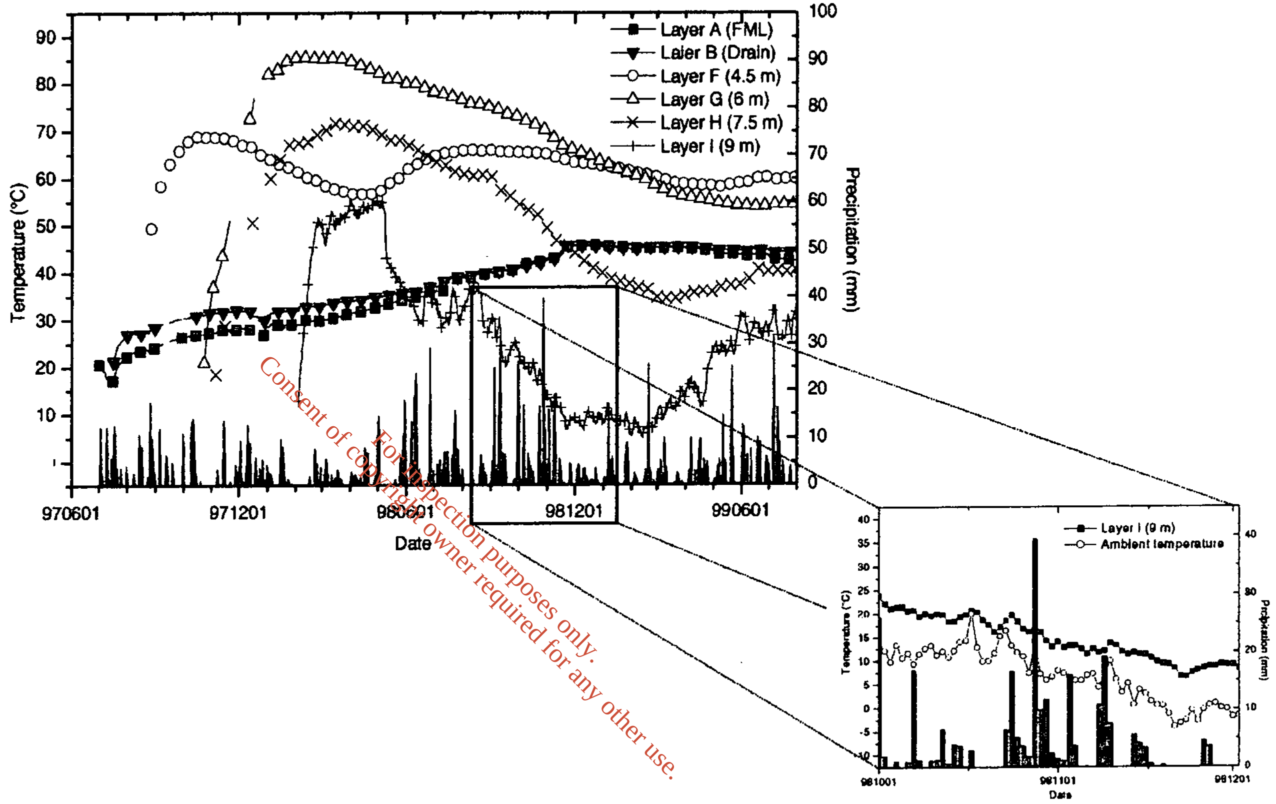

Fig. 9. Temporal change of bottom ash temperature in selected layers and precipitation intensity.

4.4. Precipitation

Rainwater seeping through the landfill body influences the temperature in two ways. First, it is a transport medium and contributes to the heat exchange. Second, it is a reaction medium and contributes to the heat production.

Although we observed that rainfall passes through the landfill within days (there is a direct discharge responding to rain events), precipitation seeping through the landfill body was not observed to have a significant effect on temperatures in the bottom ash (Fig. 9).

Seeping water passing the landfill showed a temperature increase regardless of the intensity of the rainfall of approximately 11.5°C. This is equivalent to an heat extraction of only 0.1 W/m^3 bottom ash from the landfill.

Even after an intensive period of rain (e.g. 85 mm within 6 days, 25 October 1998 until 11 November 1998) there was no observable influence on temperature development in the landfill body and on the temperature of the leachate. The temperature decrease in layer I during this rain period is mainly caused by ambient temperature fluctuations (Fig. 9). A dry period in spring (26 March 1999 until 30 May 1999, 120 mm within 70 days) also appears to have caused no change in the temperature development. Precipitating waters seeping through the landfill body, exhibited only a negligible cooling effect.

5. Conclusions

The monitoring of the temperatures in a MSWI bottom ash landfill over a 3-year-period showed a maximum temperature of 87°C 3 months after disposal followed by a decrease over the next 33 months. Temperatures at the FML reached a maximum of 45.9°C after 17 months. Subsequently, the temperature decreased at a rate of 0.6°C per month. We estimate that the temperature in this layer will stay in the critical region above 40°C (depolymerisation and oxidation in the FML, desiccation of the mineral clay layer) for the next year. These temperatures may jeopardise the integrity of the liner through depolymerisation of the HDPE and desiccation of the clay layer, resulting in leachate escaping into the groundwater.

From the temperature development, it can be seen that the main temperature increase due to the exothermic reactions have a time scale of 2–3 months, after which the reaction activity decreases. This suggests that the bottom ash should be stored in thin layers or small cones (which have a favourable s/v ratio) for at least 3 months prior to the final disposal.

The disposal should be given a significant amount of time to react before the next layer is deposited, since the temperature of the underlying layer controls the initial temperature development of the actual layer. From our investigations, it can be concluded that the disposal of the next layer should not start before the maximum temperatures of the underlying layer have been reached and the temperatures and the heat production in the underlying layer are decreasing again significantly. At the present stage of the experiments, we estimate that the time before depositing a new layer should be approximately 3–5 months.

If that time lag in the filling procedure is not possible, other cooling measures (e.g. reinjection of landfill leachate) have to be brought forward, since the precipitation shows a negligible cooling effect. In any case, if a sustainable liner system imperviousness has to be guaranteed, the capping and recultivation of the landfill, which will hamper any heat, gas, water or vapour exchange between bottom ash and atmosphere should be done only after the reactions within the landfill have reached a minimum and no further temperature rise is to be expected (at least 1 year after the final deposition of the bottom ash). A premature recultivation may lead to an additional temperature increase within the landfill body unless the exothermic reactions have decreased significantly.

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