



ELSEVIER

Journal of Hazardous Materials A76 (2000) 39–58

**Journal of  
Hazardous  
Materials**

www.elsevier.nl/locate/jhazmat

## Case study

# Evaluating the risk from depleted uranium after the Boeing 747-258F crash in Amsterdam, 1992

P.A.M. Uijt de Haag<sup>a,\*</sup>, R.C.G.M. Smetsers<sup>a</sup>, H.W.M. Witlox<sup>b</sup>,  
H.W. Krüs<sup>c</sup>, A.H.M. Eisenga<sup>c</sup>

<sup>a</sup> RIVM, P.O. Box 1, 3720 BA Bilthoven, Netherlands

<sup>b</sup> DNV, Palace House, 3 Cathedral Street, London SE1 9DE, UK

<sup>c</sup> Cyclone Fluid Dynamics B.V., De Neerheide 12d, 5581 TP Waalre, Netherlands

Received 10 December 1999; received in revised form 10 February 2000; accepted 10 February 2000

---

## Abstract

On 4 October 1992, a large cargo plane crashed into an apartment building in the Bijlmermeer quarter of Amsterdam. In the years following the accident, an increasing number of people started reporting health complaints, which they attributed to exposure to dangerous substances after the crash. Since the aircraft had been carrying depleted uranium as counterbalance weights and about 150 kg uranium had been found missing after clearance of the crash site, exposure to uranium oxide particles was pointed out as the possible cause of their health complaints.

Six years after the accident, a risk analysis was therefore carried out to investigate whether the health complaints could be attributed to exposure to uranium oxide set free during the accident. The scientific challenge was to come up with reliable results, knowing that — considering the late date — virtually no data were available to validate any calculated result. The source term of uranium was estimated using both generic and specific data. Various dispersion models were applied in combination with the local setting and the meteorological conditions at the time of the accident to estimate the exposure of bystanders during the fire caused by the crash. Emphasis was given to analysing the input parameters, inter-comparing the various models and comparing model results with the scarce information available.

Uranium oxide formed in the fire has a low solubility, making the chemical toxicity to humans less important than the radiotoxicity. Best-estimate results indicated that bystanders may have been exposed to a radiation dose of less than 1  $\mu$ Sv, whereas a worst-case approach indicated an upper limit of less than 1 mSv. This value is considerably less than the radiation dose for which acute effects are to be expected. It is therefore considered to be improbable that the missing

---

\* Corresponding author. Tel.: +31-30-2743713; fax: +31-30-2744428.

E-mail address: paul.uijt.de.haag@rivm.nl (P.A. Uijt de Haag).

uranium had indeed led to the health complaints reported. © 2000 Elsevier Science B.V. All rights reserved.

*Keywords:* Risk analysis; Uranium; Radiation; Fire; Dispersion

---

## 1. Introduction

On 4 October 1992, a Boeing 747 cargo plane crashed into an apartment building in the Bijlmermeer quarter of Amsterdam, near Schiphol Airport in the Netherlands, leading to the immediate death of 43 people [1]. The aircraft, the cargo, the fuel and the remnants of the apartments caught fire immediately and burned for more than 1 h. In the years following the accident, an increasing number of people reported an array of physical and mental health complaints, which they attributed to exposure to dangerous substances. Especially depleted uranium received considerable attention by the public as a possible cause of their health problems. The aircraft was shown to have contained depleted uranium as counterbalance weights, and about 150 kg uranium was missing following clearance of the crash site. The public was, however, not informed of the presence of uranium in the aircraft for more than a year, although some officials were aware of the presence of the uranium immediately after the accident. In the years following, depleted uranium was also indicated as a possible cause of the Gulf War illnesses (see e.g. Ref. [2]). This prompted the growth of a common feeling of anxiety among the population about the consequences of possible exposure to depleted uranium.

In an attempt to deal with the widespread distress, a study was started — 6 years after the crash — to investigate whether the health complaints could be attributed to exposure to uranium or to any other toxic substance set free during the accident. At the time of the study, however, virtually no data were available to validate any calculated result, since hardly any accurate and validated measurements had been carried out in 1992. Furthermore, in the days following the crash, the area was cleared by removing the remnants of the aircraft and the contaminated surface soil. Hence, the challenge to science was how to come up with reliable results when measured data was lacking.

This paper presents the risk assessment carried out to determine whether the dispersion of uranium following the air crash could have led to long-term health complaints to bystanders in the vicinity of the crash site. The reader is further referred to Van Bruggen et al. [3] for details not included in this paper. Using a similar approach, we describe here the risk analysis of other hazardous substances released from the cargo or other burned material, such as hydrogen chloride, polycyclic aromatic hydrocarbons and heavy metals.

## 2. Approach

Literature studies and model calculations were used to estimate the exposure of bystanders to uranium and to evaluate the risk. Emphasis was put on an analysis of input parameters and a comparison between various models. When available, calculation

results from different models were compared with each other and with the scarce information available. As described in further detail in the following sections, the assessment was carried out according to the following consecutive steps:

- the local situation during the fire was determined on the basis of the fire-brigade reports and video material (Section 3);
- the characteristics of the fire were estimated on the basis of information on the cargo and general understanding of the combustion of chemicals (Section 4);
- the uranium source term was estimated on the basis of literature studies, the characteristics of the fire and the specifications of the uranium counterbalance weights (Section 5);
- the dispersion of the uranium in the environment during the fire was determined using various dispersion models ranging in complexity (Section 6);
- the exposure of bystanders to dangerous substances was estimated, and evaluated by comparison with known exposure limits and no-effect levels (Section 7).

The risk analysis was aimed at conservative, but realistic results. This approach is referred to in this document as the “best-estimate approach” and uses the most likely value for each parameter, based on the information available and conservative values when no information is available. However, considering the importance of exposure to uranium in the public perception, a worst-case approach was also adopted to find out the upper limit of the exposure and its consequences.

### **3. Local situation**

The local situation following the accident is illustrated in Fig. 1. The Boeing 747 cargo plane collided almost at right angles into the corner of two 11-storey apartment buildings. Eyewitnesses reported that at the moment of impact, part of the kerosene present in the aircraft exploded in the form of a fireball, lasting less than 30 s. The fireball was followed by a large fire in the remaining apartments and the heap of debris at the impact location. Cargo was dispersed over a large area in front of the apartment buildings and caught fire there along with plants and trees in the public garden (see Fig. 1). According to fire-brigade reports, the brigade arrived within 10 min after the accident and started rapidly dousing the fire with water. After about three-quarters of an hour foam was applied, rapidly diminishing the fire within minutes. About one-and-a-half-hours after the crash, the large fires were extinguished. It took more than 24 h to finally extinguish the smouldering fragments of cargo, aircraft and the apartments.

The fire brigade carried out routine measurements of concentrations in air to determine dangerous concentrations of various gases like carbon monoxide, sulphur dioxide and cyanide, to check for the presence of flammable substances above their lower flammability limit, and to check on dangerous radiation levels. An excess of threshold values was not measured; actual concentrations of substances were not reported. In the weeks after the accident, the crash site was cleared and contaminated soil was removed and replaced with clean soil. Measurements of concentrations of

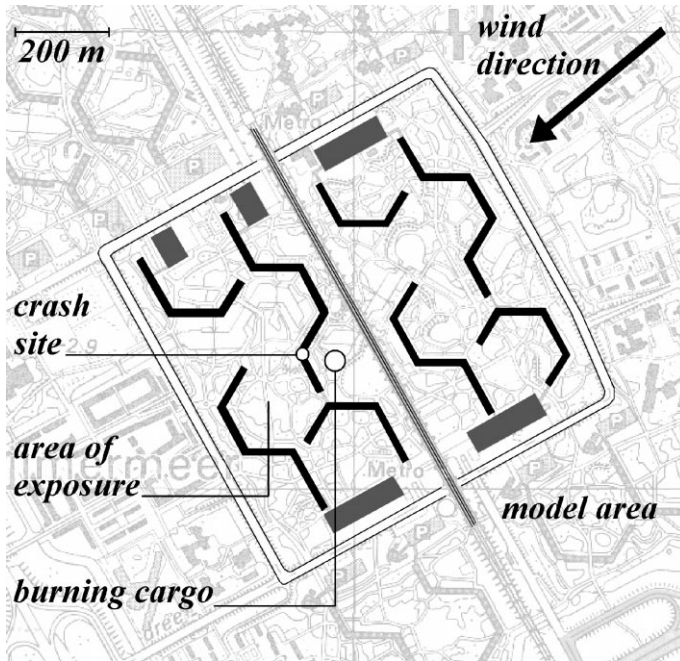


Fig. 1. Overview of the crash site.

dangerous substances in the soil and the groundwater in the crash site were not carried out until the contaminated soil was removed. Measurements in soil and groundwater at the crash location carried out after the removal of contaminated soil showed increased concentrations of hydrocarbons like kerosene in the lower soil layer and in the groundwater [4,5].

#### 4. Characteristics of the fire

To determine the generation of combustion products and the dispersion of the smoke, smoke gases and dangerous substances during the fire, the characteristics of the fire at the crash site had to be estimated. The fire is characterised by a number of parameters:

- the surface area and the duration of the fire;
- the burning velocity;
- the total amount of material burned;
- the generation of combustion products;
- the heat content of the fire.

#### 4.1. Surface area and the duration of the fire

The surface area and the duration of the fire were estimated using available video material and the reports of the fire brigade. Two burning sites for material could be distinguished: (1) the remnants of the cargo plane and the apartments burning at the junction of the two apartment buildings and (2) the cargo burning in the public garden in front of the apartment buildings (see Fig. 1). The fire at the crash site was estimated to cover about 270 m<sup>2</sup> on the basis of the surface area of the collapsed apartments. The (effective) area burning in the public garden was estimated to be a factor of 2 larger, i.e. 540 m<sup>2</sup>. It should be noted that these numbers were estimates of the areas effectively burning. Since the cargo was dispersed over a large area in the public garden, and trees and plants also caught fire, the total area containing burning material was considerably larger, estimated at 2500 m<sup>2</sup>.

According to the reports of the fire brigade, extinguishing the fires started to be effective after three-quarters of an hour; the fires were under control after one-and-a-half hours. Studies of the oxidation of uranium in fires show that the generation of uranium in respirable form increases with increasing temperature [6]. The source term of uranium may therefore be relatively high during the first three-quarters of an hour (the fully developed phase of the fire) and diminish to zero in the next three-quarters of an hour (the extinction phase of the fire). In the risk analysis of uranium, emphasis is therefore given to the processes in the fire during the fully developed phase; the fire envelope is approximated by a fire in a fully developed phase with a duration of 1 h. Thus, the fire in the extinguishing phase is mimicked by extending the fully developed phase from three-quarters to 1 h, meaning that this approximation could result in an overestimation of the source term of uranium by a maximum of a factor of 4/3 if uranium in respirable form is formed only in the fully developed phase of the fire. On the other hand, the source term of uranium may be underestimated by a factor of 2/3 if the generation of uranium in respirable form is continued in localised hot spots during the extinguishing phase of the fire.

#### 4.2. Burning rate

The burning rate of the fire is estimated using information from the literature on the combustion of kerosene and chemical waste. Apart from some specific dangerous substances in the cargo and as part of the aircraft, the aircraft and the cargo could be characterised as a mixture of chemical waste, consisting of large amounts of kerosene and flammable substances, including plastics. Since during the fire a strong breeze was present, it is assumed that the fire was not oxygen limited.

The burning rate of the fire is based on information available for pool fires. The burning rate of a pool fire,  $m$ , is given by [7]:

$$m = m_{\infty} \times (1 - e^{-k\beta D}) \quad (1)$$

where  $m_{\infty}$  is the infinite size burning rate in kg m<sup>-2</sup> s<sup>-1</sup>,  $D$  the pool diameter in m,  $k$  an absorption–extinction coefficient in m<sup>-1</sup> and  $\beta$  a mean beam length corrector. Tabulated values of  $m_{\infty}$  and  $k\beta$  of a number of substances and different types of chemical waste can be found in Refs. [7–12], for example.

The burning area of the fire at the crash site corresponds to a pool diameter,  $D$ , of 18.5 m. For kerosene, burning rates levels found in the literature for such a pool fire are  $0.039 \text{ kg m}^{-2} \text{ s}^{-1}$  [7],  $0.063 \text{ kg m}^{-2} \text{ s}^{-1}$  [11] and  $0.1 \text{ kg m}^{-2} \text{ s}^{-1}$  [12]. Since the corresponding values of  $k\beta$  were  $3.5 \text{ m}^{-1}$  [7] and  $1.296 \text{ m}^{-1}$  [11], the correction factor for small pool fire diameters can be ignored. For chemical waste, typical burning rate values are found in the range of  $0.04\text{--}0.06 \text{ kg m}^{-2} \text{ s}^{-1}$  [9,10]. Consequently, the burning rate in the fire is therefore estimated at  $0.05 \text{ kg m}^{-2} \text{ s}^{-1}$ .

In practice, the burning area of the fire was not a circular pool with fixed diameter, but debris was present and the ground was irregular. However, since the burning rate of the fire is practically independent of the diameter of the fire for the fire dimensions considered here and since the burning rates of different types of chemical wastes, including solids, are comparable to the burning rate of kerosene, the selected value of the burning rate seems reasonable for this situation. The validity of the burning rate analysis is further tested by a comparison between the calculated amount of material burned and the amount of flammable material likely to be present, as shown in the section below.

#### 4.3. Total amount of material burned

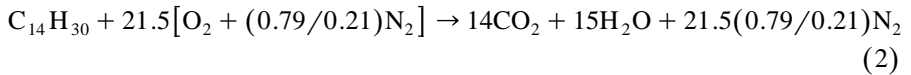
Using the previously determined values of the effective burning area, the duration of the fire and the burning rate, an estimation of the total amount of material burned was made. In total, about 146 tonnes ( $= 0.05 \text{ kg m}^{-2} \text{ s}^{-1} \times (270 + 540) \text{ m}^2 \times 3600 \text{ s}$ ) of material was assumed to be burned.

To test the validity of the various assumptions, an estimation of the total amount of flammable material of the aircraft, cargo and fuel was made. According to the information in the accident report, the mass of the (empty) aircraft was equal to 151 tonnes and the fraction of flammable materials was estimated to be 40 tonnes at the most. The total cargo was equal to 115 tonnes; expert judgement of the cargo list by two independent experts resulted in an estimation of 50–60 tonnes of flammable materials [3]. The amount of kerosene present in the aircraft at take-off was 71 tonnes. It was assumed that about 60 tonnes was present at the time of the crash [3]. Based on the concentration of kerosene measured in soil and groundwater, and the contaminated area, the amount of unburned kerosene in the contaminated soil was estimated to be about 10 tonnes [3]. Therefore, about 50 tonnes of kerosene were burned in the fire. The total amount of flammable material in the cargo plane is thus equal to about 140–150 tonnes. Moreover, about 20 to 30 apartments collapsed, yielding at least another 50 tonnes of flammable material at the junction of the two apartment buildings. So it appears that the estimation of the total amount of material actually burned using the characteristics of fire (146 tonnes) is approximately three-quarters of the amount of flammable material present (200 tonnes), which seems a reasonable estimation.

#### 4.4. Generation of combustion products

The burning of the flammable materials results in the generation of combustion products. To estimate the total amount of combustion products formed in the fire,

kerosene, a mixture of hydrocarbons in the range  $C_{10}$ – $C_{18}$  [13,14], is used as example. As sample substance,  $C_{14}H_{30}$  is selected. Since it is assumed that the fire is not oxygen limited, complete combustion is assumed and the reaction in air is:



The stoichiometric oxidant to fuel mass ratio,  $S$ , is the mass ratio between the amount of kerosene burned and the amount of air needed, and is given by:

$$S = 21.5 \times [M_{O_2} + (0.79/0.21)M_{N_2}] / M_{C_{14}H_{30}} = 15 \quad (3)$$

where  $M_{O_2}$ ,  $M_{N_2}$  and  $M_{C_{14}H_{30}}$  are the respective molecular masses. In general, for hydrocarbons with a structure formula  $C_nH_{2n+2}$ ,  $S$  varies from 15.4 to 14.7 for  $n \geq 4$ . The combustion of 1 kg kerosene thus results in 16 kg combustion products. This value is assumed to be valid for the situation studied here.

As a result, the total mass flow of combustion products generated in the fire at the crash site is  $216 \text{ kg s}^{-1}$  ( $= 0.05 \text{ kg m}^{-2} \text{ s}^{-1} \times 270 \text{ m}^2 \times 16 \text{ kg kg}^{-1}$ ) and  $432 \text{ kg s}^{-1}$  ( $= 0.05 \text{ kg m}^{-2} \text{ s}^{-1} \times 540 \text{ m}^2 \times 16 \text{ kg kg}^{-1}$ ) in the fire in the public garden.

#### 4.5. Heat content of the combustion products

The heat generated in the fire is an important parameter in the calculation of the plume rise. The heat generated was estimated using the heat of combustion of various substances. The heat of combustion of kerosene is equal to  $44 \text{ MJ kg}^{-1}$  [15]; the heat of combustion of various types of chemical wastes is about  $33 \text{ MJ kg}^{-1}$  [9]. Typically, a fraction of 0.2–0.4 of the generated heat is emitted as heat radiation [7]. The heat available for a plume rise per kg material burned is therefore equal to 20–35 MJ. The lower value is used in the dispersion calculations to yield a conservative estimation: a lower heat results in less plume rise and thus in higher concentrations at living height. The heat available for plume rise in the fire at the crash location is  $270 \text{ MW}$  ( $= 20 \text{ MJ kg}^{-1} \times 0.05 \text{ kg m}^{-2} \text{ s}^{-1} \times 270 \text{ m}^2$ ) and  $540 \text{ MW}$  ( $= 20 \text{ MJ kg}^{-1} \times 0.05 \text{ kg m}^{-2} \text{ s}^{-1} \times 540 \text{ m}^2$ ) in the fire in the public garden.

#### 4.6. Summary of the fire characteristics

The characteristics of the fire as used in the dispersion calculations are summarised in Table 1.

Table 1  
Summary of the fire characteristics

	Fire at crash site	Fire in public garden
Duration of the fire	1 h	1 h
Effective burning area	$270 \text{ m}^2$	$540 \text{ m}^2$
Burning rate	$0.05 \text{ kg m}^{-2} \text{ s}^{-1}$	$0.05 \text{ kg m}^{-2} \text{ s}^{-1}$
Total burned	50 tonnes	100 tonnes
Flux of combustion products	$216 \text{ kg s}^{-1}$	$432 \text{ kg s}^{-1}$
Heat content	270 MW	540 MW

## 5. Source term uranium

The cargo plane contained about 24 pieces of depleted uranium used as counterbalance weights [16]. The mass of a single piece ranged from 6 to 30 kg, with specific areas between 0.005 and 0.015 m<sup>2</sup> kg<sup>-1</sup>. The mass-weighted average specific area was equal to 0.007 m<sup>2</sup> kg<sup>-1</sup>. The total amount of depleted uranium present in the aircraft at the time of the crash was equal to 282 kg. Following the clean-up of the crash site, 130 kg uranium was recovered, leaving 152 kg depleted uranium missing. Up to now, it is not known what happened to the uranium not recovered. Various scenarios are possible. Since knowledge of the presence of uranium in the aircraft was not well communicated in the period directly after the accident, it is possible that pieces of uranium were handled as normal trash and dumped with the contaminated soil. Another possibility to be considered was that uranium was (partly) oxidised in the fire and dispersed in the environment. To estimate the source term and its consequence, the oxidation rate, chemical appearance and the particle distribution of the uranium oxide had to be determined.

The oxidation rate of uranium at high temperatures has been reviewed by Mishima et al. [6]. Experiments were conducted on the oxidation of uranium penetrators in fires. Oxidation of significant amounts of uranium only occurs at high temperatures. The overall oxidation rate depends among other aspects on the turbulence, the temperature and the specific area, where increasing temperatures and increasing specific areas result in increasing oxidation rates. The oxidation rate at temperatures likely to be present in the fires, i.e. between 600 and 1200°C, is typically 10 kg uranium m<sup>-2</sup> h<sup>-1</sup> for a penetrator with a specific area of 0.02 m<sup>2</sup> kg<sup>-1</sup>. High turbulence may increase the oxidation rate by a factor of 4. An oxidation rate of 10 kg uranium m<sup>-2</sup> h<sup>-1</sup> for the counterbalance weights during 1 h would result in the oxidation of typically 7% of the missing uranium. In the case of high turbulence, a fourfold higher oxidation rate may be applicable, resulting in maximally 30% of the missing uranium being oxidised (46 kg). Since high turbulence in the fire cannot be excluded, the latter value is used for the “best-estimate approach”. It should be noted that this value is probably conservative, since the average specific area of the counterbalance weights is less than the specific area of the penetrators used in the experiments.

Apart from the comparatively slow process of “normal oxidation” described above, (small) parts of uranium may ignite. Baker et al., who studied the ignition of uranium in detail, found a relationship between the ignition temperature and the specific area of the uranium parts [17]. For the smallest part included in their experiment, a cube with a specific area of 0.033 m<sup>2</sup> kg<sup>-1</sup>, an ignition temperature of 700°C was found. Since the specific areas of the counterbalance weights are much smaller, and even less than the specific area of a typical uranium penetrator where no ignition effects were observed, it would seem very unlikely that missing uranium counter-balance parts were ignited during the fire. For the worst-case approach, however, it was assumed that all the missing uranium was fragmented into small pieces, and ignited, resulting in 100% oxidation (i.e. 152 kg).

The dispersion and exposure to uranium strongly depends on the chemical appearance of the uranium oxides formed and the resulting particle size distribution. Oxidation of



Table 2  
Source term of uranium oxide for dispersion

	Best estimate	Worst case
Mass uranium not recovered	152 kg	152 kg
Mass uranium possibly oxidised	46 kg	152 kg
Mass in respirable fraction	0.46 kg	152 kg
Chemical appearance	UO <sub>2</sub> and U <sub>3</sub> O <sub>8</sub>	UO <sub>2</sub> and U <sub>3</sub> O <sub>8</sub>
Location	50% at crash site, 50% in public garden	100% at crash site

significant amounts of uranium only occurs at high temperatures (in the range 600–1200°C), which did exist during the fire. The uranium oxides formed under these conditions are the poorly soluble UO<sub>2</sub> and U<sub>3</sub>O<sub>8</sub>, [18–20]. The particle size distribution also depends on the temperature during the oxidation process [6]. For the conditions in the fire following the crash, the respirable fraction, i.e. the fraction having a particle-size diameter less than 20 μm, is less than 1 mass%. This value is therefore used as a best estimate. In the case of ignition, however, the respirable fraction may be as high as 100 mass%, which is used as a worst-case estimate.

The location of the pieces of uranium in the fire were not known. A best estimate assumed the pieces to be evenly distributed between the fire at the crash site and the fire in the public garden. The worst-case estimate assumes that all pieces of uranium were located at the crash site.

The source terms of uranium for both scenarios are summarised in Table 2.

## 6. Dispersion of smoke gases and uranium

Bystanders are exposed to uranium during the fire through the inhalation of uranium in aerosol form. The dispersion of uranium is calculated to determine the concentrations of uranium in air and the exposure to bystanders. The calculation is based on the perception that the vast part of the emissions in the fire consists of gases like N<sub>2</sub>, CO, CO<sub>2</sub> and H<sub>2</sub>O. It is therefore to be expected that the smoke gases behave to a large extent as normal air, with excess heat. Since the concentrations of uranium and other specific substances formed in the combustion process are very small relative to the amount of smoke gases, these specific substances will not affect the dispersion properties of the plume of smoke gases. Consequently, it suffices to calculate the dispersion of smoke gases in the environment. Next, the concentration of the aerosol-bound uranium in the environment can be derived from the calculated concentration of smoke gases by considering the mass fraction of uranium versus the mass fraction of the smoke gases.

To calculate the dispersion of smoke gases in the environment, three different models were used, ranging from very simple, rule-of-thumb calculations to a complex 3D Computational Fluid Dynamics (CFD) model. The first model used was a Building Wake Model, which estimates the concentration in the recirculation zone behind a building using simple equations. The second model applied is a pool fire model connected to a free-field dispersion model. Finally, the third model applied is a CFD model, incorporating all the important location-specific structures.

Table 3

Meteorological data from weather station at Schiphol Airport at the time of the crash

Wind speed at 10 m	12 m s <sup>-1</sup>
Wind direction (clockwise from north)	50°
Stability of the atmosphere	Neutral
Atmospheric pressure	1013 hPa
Temperature at 1.5 m	13°C
Relative humidity at 1.5 m	69%
Rain	None

### 6.1. Meteorological information

At the time of the accident, a strong breeze from the northeast prevailed, promoting a strong dispersion of the contaminants. Data from the nearest meteorological station (Schiphol Airport, about 12 km west of the crash site) at the time of the accident are given in Table 3 [21].

### 6.2. Building Wake Model calculation

The Building Wake Model is a simple model used to estimate the concentration in the recirculation zone behind a building following a continuous release from the roof or in the lee of the building. A uniform concentration is assumed in the recirculation zone [22]:

$$C_{\text{lee}} = Q / (K \times u \times A) \quad (4)$$

with  $C_{\text{lee}}$  the concentration in the recirculation zone behind the building (in kg m<sup>-3</sup>),  $Q$  the source term (in kg s<sup>-1</sup>),  $u$  the wind speed (in m s<sup>-1</sup>),  $A$  the effective area of the building perpendicular to the wind direction (m<sup>2</sup>) and  $K$  a dimensionless correction factor to account for the orientation of the building, varying between 0.2 and 2.

To calculate the effective area of the building perpendicular to the wind direction, take note that the wind comes in at a near to right angle to the remaining part of the apartment building south of the crash location (see Fig. 1). The dimensions of this building are 30 m high and 100 m long, resulting in an effective area of 3000 m<sup>2</sup>. Applying the formula to the fire at the crash site, where  $Q = 216 \text{ kg s}^{-1}$ , the wind velocity  $u = 12 \text{ m s}^{-1}$ ,  $K = 1$  and  $A = 3000 \text{ m}^2$ , and assuming that the entire plume is captured in the recirculation zone, the resulting concentration in the recirculation zone is equal to 0.006 kg m<sup>-3</sup>. The length of the recirculation zone is about three times the height of the building, i.e. in the order of 100 m [22]. Consequently, the Building Wake Model calculation shows that bystanders within 100 m of the fire were exposed for 1 h to a concentration of smoke gases in the order of 6 g m<sup>-3</sup>.

### 6.3. Pool-fire model and free-field dispersion calculation

To arrive at an independent estimate of the generation of smoke gases and their dispersion in the environment, a generalised pool fire model, POLF, was used in combination with a free-field dispersion model, UDM.

The generalised pool-fire model, POLF, consists of the PHAST pool-fire model attached to a procedure to calculate the excess air entrainment [23–25]. The PHAST pool fire model calculates the burning rate and the fire dimensions (tilted cylinder; height, diameter and tilt angle) for a pool of flammable material. The excess air entrainment is calculated using the procedure developed by Delichatsios [15], resulting in the calculation of the temperature, and the mass fractions of excess air and of each individual compound in the initial combustion product (combustion oxide, nitrogen and water) as a function of distance along the flame axis. The output of the generalised pool-fire model, POLF, consists of data at the transition plane, which is situated at the Froude flame length at 90% excess air entrainment. The output data at the transition plane forms the input for the Unified Dispersion Model, UDM [26], currently implemented in version 6.0 of DNV's consequence modelling package PHAST.

To calculate the concentration of smoke gases in the environment, the POLF model is applied using the data of  $C_{14}H_{30}$  as sample substance. A burning rate of  $0.05 \text{ kg m}^{-2} \text{ s}^{-1}$ , a combustion efficiency of one and a radiative fraction of 0.4 are assumed. The dispersion was calculated using the meteorological data given in Table 3, assuming a uniform surface roughness of 2.0 m. The results of the calculation are shown in Fig. 2. The concentration of smoke gases at the ground level between 20 and 100 m from the edge of the fire varies from  $0.2$  to  $0.7 \text{ g m}^{-3}$ ; on the plume axis, the concentration varies from  $20 \text{ g m}^{-3}$  to  $4 \text{ g m}^{-3}$ .

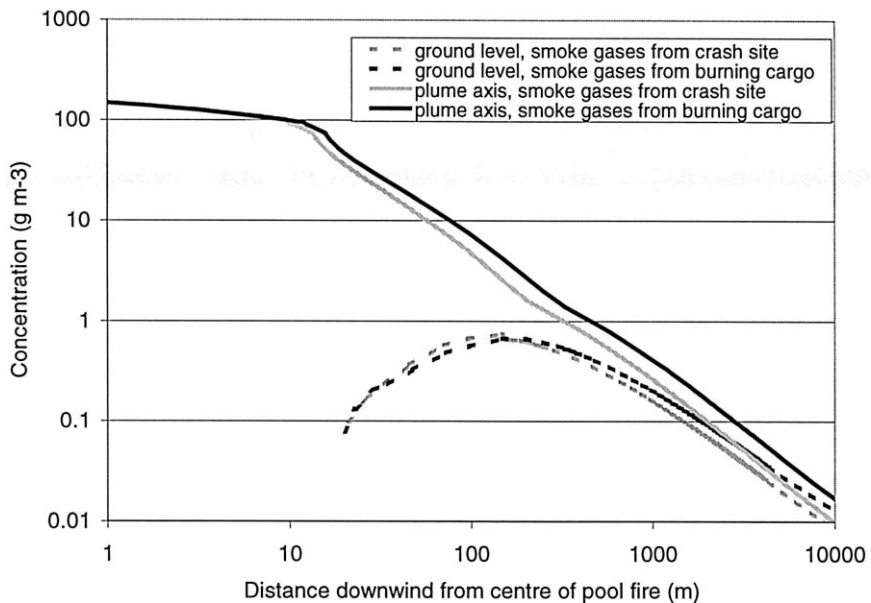


Fig. 2. Results of the POLF and UDM free field model calculation: centre-line and ground-level concentrations of smoke gases as a function of distance to the centre of the pool fire. Shown are the results for the fire at the crash site ( $270 \text{ m}^2$ ) and in the public garden ( $540 \text{ m}^2$ ).

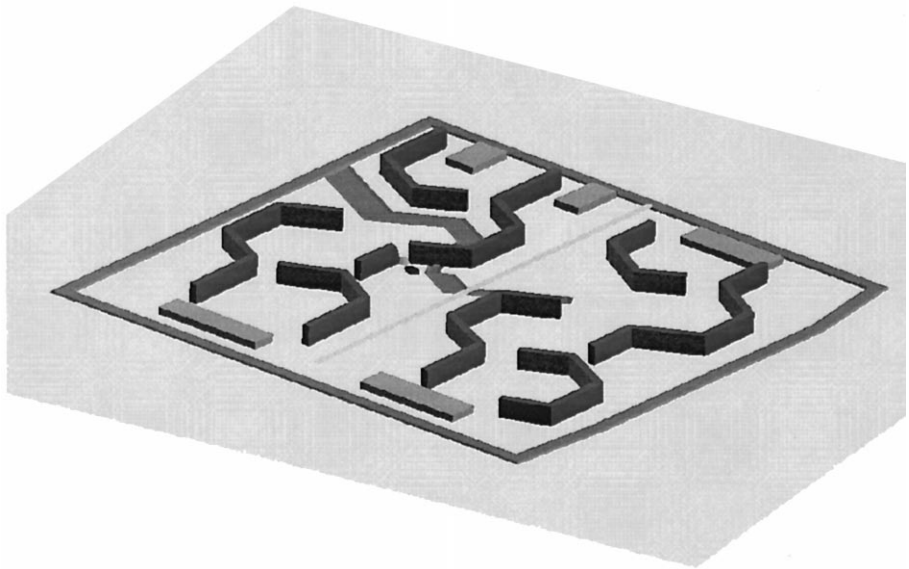


Fig. 3. Model area of the CFD calculation and the structures modelled.

#### 6.4. CFD calculation

To determine the influence of the buildings near the crash site on the dispersion of the smoke gases, a 3D CFD simulation was made of the built-up area. The area used for modelling and the apartment blockstructures included in the model are shown in Fig. 3. The fires were modelled as two distinct piles of debris, each with a height of a few metres. The total area modelled measures 1400 m long  $\times$  1400 m wide  $\times$  410 m high. The mesh of the calculations consists of over 320,000 hexahedral cells, using an increased density of cells near and downwind of the crash site. The Navier–Stokes equations were solved using a finite volume method and second-order accurate convective differencing schemes (details can be found in Ref. [27]). The turbulence of the flow was modelled using an anisotropic non-linear  $k-\varepsilon$  turbulence model [28]. At the inlet boundary of the model, an atmospheric boundary layer was imposed with a surface roughness length of 0.4 m (as an estimate for the low-rise buildings upstream of the flats). The source term is given in Table 1, while the meteorological conditions used are shown in Table 3. These meteorological conditions were kept constant during the simulations.

The results of the simulation are shown in Fig. 4 for smoke gases originating from the fire at the crash site and in Fig. 5 for smoke gases from the fire in the public garden in front of the apartment building. It should be noted that the results in Figs. 4 and 5 are derived from one simulation with the two fires present, since the buoyancy of the plumes may influence one another. The results of the CFD simulation show that smoke gases from both the fire at the crash site and in the public garden are transported

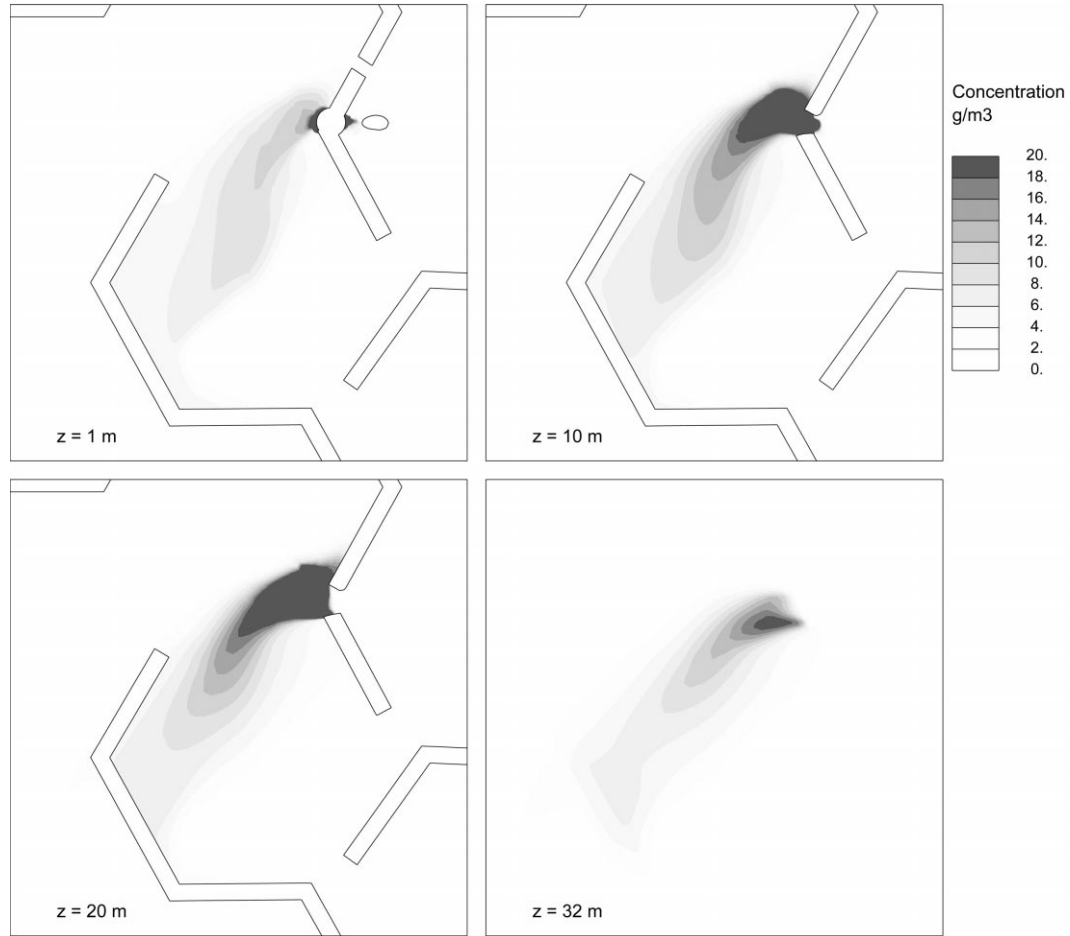


Fig. 4. Concentrations for smoke gases released at the crash site (source strength  $216\text{ kg s}^{-1}$ , heat input  $270\text{ MW}$ ). Concentrations are shown at four different heights: 1, 10, 20 and 32 m.

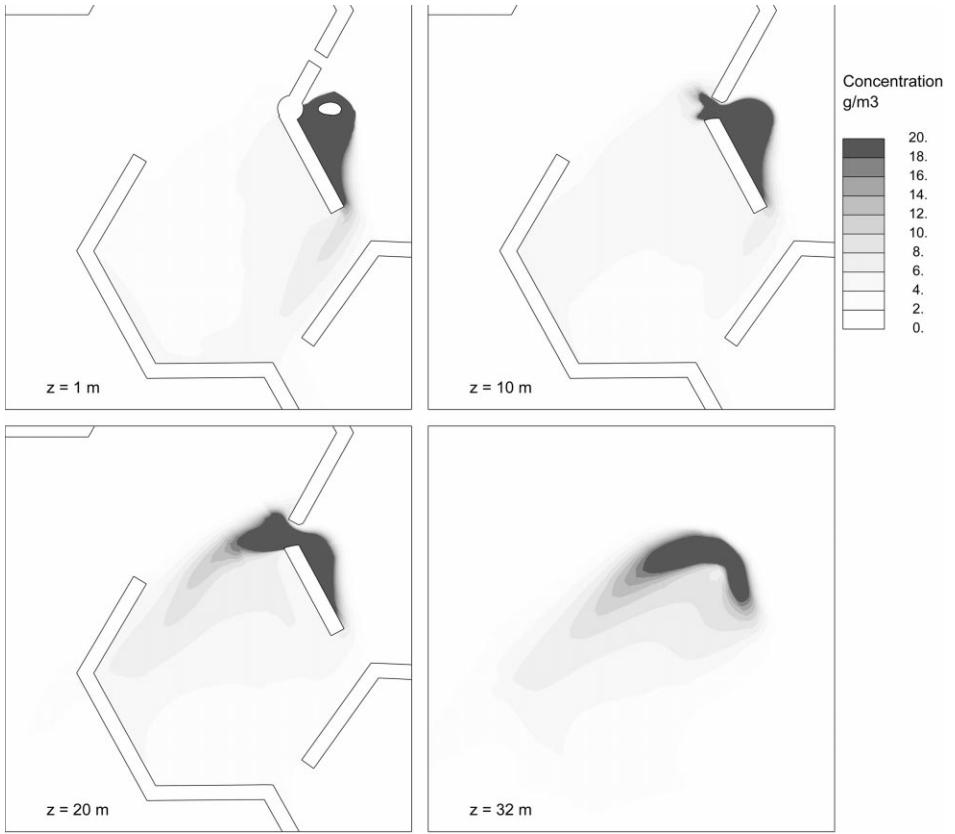


Fig. 5. Concentrations for smoke gases released in the public garden (source strength  $532 \text{ kg s}^{-1}$ , heat input  $540 \text{ MW}$ ). Concentrations are shown at four different heights: 1, 10, 20 and 32 m.

upwards through the gap between the apartment buildings, leading to reduced concentrations at ground level. These results are confirmed by the observations available on video. Note that these results differ considerably, of course, from the isothermal simulations also carried out.

The results in Figs. 4 and 5 should be interpreted as a time-averaged footprint of the pollution in the cloud during the fire, and thus as an estimation of the concentrations to which bystanders are exposed. It is assumed that unprotected bystanders were located at least 20 m away from the fire. The highest concentrations are found for the bystanders standing in the area downwind of the crash site, i.e. in the area between the apartment buildings (see Fig. 1). The concentrations in this area, calculated at living height, i.e. 1 m above the ground, range from 1 to  $10 \text{ g m}^{-3}$  (the highest concentrations can be found at heights above 5 m and up to to 10 m).

At a height of 1 m, the maximum concentration of the smoke gases released in the fire at the crash site is found to occur at a different location than the maximum

concentration of the smoke gases released in the fire in the public garden. Combining the exposure to smoke gases from the two fires therefore does not lead to an increase in the maximum concentration, but results in an increase in the area with high concentrations.

### 6.5. Discussion of the dispersion results

Three different models were used to calculate the concentration of smoke gases near the crash site. The calculation with the Building Wake Model results in an average smoke flue gas concentration of  $6 \text{ g m}^{-3}$  in the area downwind of the remnants of the apartment building; this area is calculated to be about 30 m high and extends to 100 m behind the remaining apartment building. The free-field calculation of the POLF and UDM model results for distances of 20 to 100 m from the edge of the fire pool in a concentration of  $0.2\text{--}0.7 \text{ g m}^{-3}$  smoke gases at ground level and  $4\text{--}20 \text{ g m}^{-3}$  on the plume axis. The plume rises to a height of 40 m at a distance of 100 m downwind from the pool. The dimensions of the free-field plume in this area are therefore comparable to the dimensions of the recirculation zone, resulting in concentrations in the same order of magnitude. The uniform concentration as calculated with the Building Wake Model occurs indeed in between the centre line concentration and the ground-level concentration in the region of interest. The close resemblance between the Building Wake Model and the free-field calculation is remarkable, since the Building Wake Model does not account for the buoyancy. However, due to the high wind speed at the time of the accident, the buoyancy effects were less important in this situation. Moreover, the cross-section area of the building wake (used in the Building Wake Model) was found to be of comparable size with that of the free-field dispersion model.

The concentrations at ground level, as calculated with the CFD model are in the order of  $1\text{--}10 \text{ g m}^{-3}$  and are therefore comparable to the concentrations calculated with the free-field approximation. This agreement in results can be accounted for by the observation that the smoke gases are transported through the gap between the apartment buildings and therefore the dispersion is not too restricted by the buildings. However, the CFD results reveal the influence of the structures near the fire and the overlap between the plumes of the two fires.

In conclusion, the model calculations are consistent with each other and show that bystanders, who are present at distances of 20–100 m from the fire downwind of the crash site may be exposed to concentrations of smoke gases in the order of  $1\text{--}10 \text{ g m}^{-3}$ . Bystanders at the closest distance downwind of the crash site, i.e. 20 m, which is fairly close to the blazing fire, are therefore exposed to smoke gases in the order of  $10 \text{ g m}^{-3}$ .

### 6.6. Uranium concentration

The concentrations of uranium at 20 m downwind of the crash site can be calculated with the relative source terms of the smoke gases and of uranium. The best estimate of the source term of uranium is 0.46 kg uranium in respirable form for 1 h, as given in Table 2. This corresponds to a source term of  $1.3 \times 10^{-4} \text{ kg s}^{-1}$ . Since uranium is assumed to be evenly distributed between the crash site and the public garden, the

source term at the crash site is  $6.4 \times 10^{-5} \text{ kg s}^{-1}$ . Using the source term of smoke gases ( $216 \text{ kg s}^{-1}$ ) and the resulting concentration of smoke gases ( $10 \text{ g m}^{-3}$ ), the concentration of uranium is calculated as  $3 \text{ } \mu\text{g m}^{-3}$ . The uranium oxidised in the fire in the public garden enlarges the area of exposure but not the maximum concentration. The worst-case estimate of the source term of uranium at the crash site is  $152 \text{ kg}$  uranium in respirable form for 1 h, resulting in a source term of  $4.2 \times 10^{-2} \text{ kg s}^{-1}$  and a concentration of uranium of  $2 \text{ mg m}^{-3}$ .

## 7. Exposure and evaluation

Bystanders may be exposed to airborne uranium oxide by inhalation, external irradiation and ingestion following deposition. The radiological properties of depleted uranium used to evaluate the exposure to depleted uranium are given in Table 4. Since the abundance of the isotope uranium-234 in depleted uranium is reduced, the radioactivity of depleted uranium is less than the radioactivity of natural uranium.

Since uranium is primarily an alpha emitter, the radiation dose due to external irradiation is negligible compared to the radiation dose due to inhalation. The intake of uranium by ingestion following deposition on the ground is also negligible, and for two reasons. Firstly, measurements in soil samples of the area possibly contaminated by the plume do not show any detectable amount of depleted uranium [29–31]. At least, the amount of depleted uranium deposited is, in any case, negligible compared to the amount of naturally occurring uranium in soil. Secondly, more than 98% of ingested uranium is excreted by the human body within a few days [32]. The intake of uranium oxide by inhalation is thus by far the most dominant pathway. The amount of uranium inhaled is calculated by multiplying the airborne concentration by the duration of the exposure and the breathing rate. The best estimate of the breathing rate (for male adults) is  $1.5 \text{ m}^3 \text{ h}^{-1}$ , corresponding to light exercise, whereas the worst-case estimate is equal to  $3 \text{ m}^3 \text{ h}^{-1}$ , corresponding to heavy exercise [33]. The intake of uranium through inhalation is thus  $4.4 \text{ } \mu\text{g}$  (best-estimate) to  $5.9 \text{ mg}$  (worst-case). Applying the dose

Table 4  
Radiological properties of depleted uranium

Isotope	Abundance <sup>1</sup> (mol%)	Specific $\alpha$ -activity <sup>a</sup> (Bq (mg U) <sup>-1</sup> )	$e(\tau)$ <sup>b</sup> ( $\mu\text{Sv (mg U)}^{-1}$ )
U-238	99.8	12.4	99
U-235	0.2	0.16	1.4
U-234	0.0010	2.26	21
Total	100	14.8	122

<sup>a</sup>See Harley et al. [2].

<sup>b</sup> $e(\tau)$  is the effective committed dose for 70 years for an adult following inhalation of uranium oxides, assuming aerosols with an Activity Median Aerodynamic Diameter, AMAD, of  $1 \text{ } \mu\text{m}$  and inhalation class type S, i.e. deposited materials are relatively insoluble in the respiratory tract (slow absorption) [32].



Table 5  
Exposure and radiation dose to bystanders

	Best-estimate	Worst-case estimate
Uranium concentration	3 $\mu\text{g m}^{-3}$	2 $\text{mg m}^{-3}$
Breathing rate	1.5 $\text{m}^3 \text{h}^{-1}$	3 $\text{m}^3 \text{h}^{-1}$
Duration of exposure	1 h	1 h
Intake of depleted uranium	4.4 $\mu\text{g}$	5.9 mg
Effective committed dose	0.5 $\mu\text{Sv}$	0.7 mSv

conversion factors of Table 4 results in an effective radiation dose of 0.5  $\mu\text{Sv}$  (best-estimate) to 0.7 mSv (worst-case). The results are summarised in Table 5.

The consequences of uranium inhalation depend on the chemical properties of the uranium. Uranium compounds having a high solubility are removed from the body relatively rapidly via the urine, i.e. in several days. The time of exposure is thus low and the radiotoxicity of the uranium is less important than the chemical toxicity. Exposure to high levels of highly soluble uranium compounds may lead to (reversible) effects on the kidney functions. Such effects were not reported by the people with health complaints after the crash; this is in accordance with the information that the uranium oxides formed in the fire have a low solubility. These oxides have a long residence time in the lungs and irradiation of the lung tissue following deposition is more important than the chemical toxicity.

Exposure to high levels of radiation may lead to short-term effects. A safe threshold for avoiding acute effects to the lung is a 500 mSv organ dose, corresponding to an intake of 625 mg U-238 [34]. The results show that even in the worst-case estimate the intake is two orders of magnitude less than the threshold value and short-term effects can therefore be excluded.

The long-term effect of exposure to uranium is cancer induction. The probability of suffering fatal cancer due to radiation is estimated as 0.05 per Sievert [34]. The best estimate of the radiation dose leads to an increase in the probability of suffering death of one in 40 million and is therefore considered negligible.

The exposure and radiation dose can also be compared with international guidelines and natural background levels. For chronic occupational exposure to workers, concentration limits of 200–250  $\mu\text{g m}^{-3}$  for insoluble uranium in air are recommended, with short-time peak values of 600  $\mu\text{g m}^{-3}$  [2,35]. These values are derived for prolonged exposure over long periods using various safety factors. The best estimate of the air concentration is well below the concentration limit of 250  $\mu\text{g m}^{-3}$ , whereas the worst-case estimate would correspond to an exposure to the concentration limit for two working days. The average background radiation indoors in the Netherlands due to exposure to  $^{222}\text{Rn}$  is equal to 60 nSv  $\text{h}^{-1}$  [36]. The radiation dose due to depleted uranium is therefore comparable to the exposure to natural radiation for 9 h (best estimate). The radiation dose calculated in the worst-case scenario is comparable to the average radiation dose in the Netherlands in one year and is less than the recommended year limit of 1 mSv for exposure to radiation by human actions [34,37].

It is therefore concluded that inhalation of depleted uranium will not lead to detectable adverse effects to the bystanders.

## 8. Conclusions

Exposure to uranium was identified as a possible cause of health complaints of bystanders following an aircraft crash in the Bijlmer on October 4, 1992. To test this hypothesis, a complete risk analysis of the exposure to uranium was carried out. Although little information was available six years after the accident, since limited measurements had been carried out, it did seem possible to estimate the concentration of uranium oxide in air and to evaluate the exposure of bystanders. Two different estimates of the exposure were made. The best-estimate approach used the most likely value for each parameter based on the information available and conservative values when no information was available; the worst-case approach used conservative estimates for all parameters. Three different dispersion models were used to estimate the concentrations of uranium in air, yielding consistent results.

The model calculations show that the best estimate of the exposure to depleted uranium is several orders of magnitude less than the workers limit for chronic exposure to uranium. The best estimate of the radiation dose is comparable to exposure for 2 h to the natural radiation level in the Netherlands. The worst-case approach indicates that bystanders were exposed to airborne uranium concentrations for 1 h that are comparable to the limit for chronic exposure to workers. It is therefore highly improbable that exposure of bystanders to uranium would result in the health complaints reported.

## Acknowledgements

The authors would like to thank J. van Hienen of the Netherlands Energy Research Foundation, F. Kroonenberg from the Dutch Royal Meteorological Institute, A. Holt from DNV and J. Kliest and other colleagues from the RIVM for their contribution of valuable information and their useful comments.

## References

- [1] Dutch Parliament, Een beladen vlucht, Report of the national inquiry into the aircraft crash at the Bijlmer on 4th October 1992, Sdu, The Hague (in Dutch), 1999.
- [2] N.H. Harley, E.C. Foulkes, L.H. Hilborne, A. Hudson, C.R. Anthony, Depleted Uranium, A Review of the Scientific Literature As It Pertains to Gulf War Illnesses, RAND, Santa Monica, 1999.
- [3] M. van Bruggen, P.C.J.M. Janssen, J.J.G. Kliest, J. Meulenbelt, R.C.G.M. Smetsers, P.A.M. Uijt de Haag, G. de Mik, G. Elzinga, Gezondheidsrisico's brand El Al Boeing, RIVM report 609026002, RIVM, Bilthoven, 1998.
- [4] W.J. Arnold, Oriënterend bodemonderzoek op het terrein rond de flats Groeneveen en Kruitberg ter plaatse van het vliegtuig-ongeluk d.d. 4 oktober 1992 in de Bijlmermeer, OMEGAM Research company for environmental studies and soil mechanics, Amsterdam, 1993.

- [5] W.J. Arnold, Aanvullend bodemonderzoek op het terrein rond de flats Groeneveen en Kruitberg te Amsterdam Zuid-Oost, OMEGAM Research company for environmental studies and soil mechanics, Amsterdam, 1993.
- [6] J. Mishima, M.A. Parkhurst, R.I. Scherpelz, D.E. Hadlock, Potential behavior of depleted uranium penetrators under shipping and bulk storage accident scenarios, Pacific Northwest Laboratory, Richland, WA, 1985.
- [7] F.P. Lees, Loss prevention in the process industries: hazard identification, assessment and control, Butterworth-Heinemann, Oxford, 1996.
- [8] Committee for the Prevention of Disasters, Methods for the calculation of damage (the “Green Book”), Ministry of Social Affairs and Employment, Voorburg, 1990.
- [9] B. Rasmussen, N.-J. Duijm, F. Markert, Airborne releases from fires involving chemical waste — a multidisciplinary case study, *J. Hazard. Mater.* 57 (1998) 259–275.
- [10] Ministry of Housing, Spatial Planning and the Environment, Risico-analyse methodiek CPR-15 bedrijven, Ministry of Housing, Spatial Planning and the Environment, The Hague, 1997.
- [11] P.J. Rew, W.G. Hulbert, D.M. Deaves, Modelling of thermal radiation from external hydrocarbon pool fires, *Trans. I Chem. E* 75 (1997) 81–89, Part B.
- [12] M.J. Pritchard, T.M. Binding, FIRE2: A new approach for predicting thermal radiation levels from hydrocarbon pool fires, *I Chem. E Symp.* (1992) 491–505, Series no. 130.
- [13] R.J. Lewis Sr., Sax’s Dangerous Properties of Industrial Materials, 2nd edn., Van Nostrand Reinhold, New York, 1992, p. 2078.
- [14] N.L. Allinger, M.P. Cava, D.C. de Jongh, C.R. Johnson, N.A. Lebel, C.L. Stevens, in: *Organic Chemistry*, 1st edn., Worth Publishers, New York, 1971, p. 30.
- [15] M.A. Delichatsios, Air entrainment into buoyant jet flames and pool fires, Section 3-2 in *SFPE handbook of fire protection engineering*, National Fire Protection Association, Quincy, MA, 1995.
- [16] Energie Centrum Nederland, Onderzoek verarmd uranium vliegtuigongeval Bijlmermeer, ECN-CX-98-102, ECN, Petten, 1998.
- [17] L. Baker, J.G. Schnizlein, J.D. Bingle, The Ignition of Uranium, *J. Nucl. Mater.* 20 (1966) 22–38.
- [18] J.J. Katz, G.T. Seaborg, L.R. Morss, in: *The Chemistry of the Actinide Elements vol. 1* Chapman & Hall, London, 1986, 2nd edn.
- [19] CRC, *Handbook of Chemistry and Physics*, 70th edn., CRC Press, Boca Raton, FL, 1989.
- [20] ICRP, Individual Monitoring for Intakes of Radionuclides by Workers: Design and Interpretation, Publication 54, International Commission on Radiological Protection vol. 19 Pergamon, Oxford, 1987, no. 1–3.
- [21] KNMI, Report on the meteorological conditions in the period 4–6 October 1992, KNMI, De Bilt, The Netherlands (in Dutch), 1998.
- [22] P.J.H. Bultjes, Dispersion around buildings, in: *Atmospheric Pollution 1980, Studies in Environmental Science vol. 8* Elsevier, Amsterdam, 1980, pp. 91–96.
- [23] DNV Technica, SAFETI 3.4 Theory Manual, DNV Technica, London, 1998.
- [24] H.W.M. Witlox, J.L. Woodward, M.E. Rowley, K. Sharvanandhan, Modelling of phosphorus fires with hydrolysis in the plume, in: *Proc. 9th Int. Symposium on Loss Prevention and Safety Promotion in the Process Industries*, Barcelona, 1998, pp. 1100–1111.
- [25] H.W.M. Witlox, Model POLF for modelling pool fires and excess air entrainment into the fire, Contract C490005 for RIVM, Bilthoven, The Netherlands, DNV, London, 1999.
- [26] H.W.M. Witlox, A. Holt, A unified model for jet, heavy and passive dispersion including droplet rainout and re-evaporation, in: *International Conference and Workshop on Modelling the Consequences of Accidental Releases of Hazardous Materials*, CCPS, San Francisco, CA, September 28–October 1, 1999, 1999.
- [27] J.H. Ferziger, M. Peric, *Computational Methods for Fluid Dynamics*, Springer, New York, 1996.
- [28] C.G. Speziale, On non-linear  $k-l$  and  $k-\epsilon$  models of turbulence, *J. Fluid Mech.* 178 (1987) .
- [29] OMEGAM Research company for environmental studies and soil mechanics, Onderzoek naar uranium en wolfram ter plaatse van het vliegtuigongeval in de Bijlmermeer d.d. 4 oktober 1992, Project: 11016156, Amsterdam, 1993.
- [30] OMEGAM Research company for environmental studies and soil mechanics, Aanvullend onderzoek naar

- uranium ter plaatse van het vliegtuigongeval in de Bijlmermeer d.d. 4 oktober 1992, Project: 11017794, Amsterdam, 1994 (in Dutch).
- [31] OMEGAM Research company for environmental studies and soil mechanics, Nader onderzoek Uranium in de Bijlmermeer te Amsterdam-zuidoost, Project: 11023668, Amsterdam, 1995.
- [32] ICRP, Age-dependent Doses to Members of the Public from Intake of Radionuclides: Part 5. Compilation of Ingestion and Inhalation Dose Coefficients, Publication 72,, in: International Commission on Radiological Protection vol. 26 Pergamon, Oxford, 1996, no. 1.
- [33] ICRP, Human Respiratory Tract Model for Radiological Protection, Publication 66,, in: International Commission on Radiological Protection vol. 24 Pergamon, Oxford, 1994, no. 1–3.
- [34] ICRP, 1990 Recommendations of the International Commission on Radiological Protection, Publication no. 60, in: International Commission on Radiological Protection vol. 21 Pergamon, Oxford, 1991, no. 1–3.
- [35] NIOSH, Pocket Guide to Chemical Hazards, U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, 1994.
- [36] P. Stoop, P. Glastra, Y. Hiemstra, L. de Vries, J. Lembrechts, Results of the second Dutch national survey on radon in dwellings. RIVM report 610058006. RIVM, Bilthoven, 1998.
- [37] European Union, Council Directive 96/29/Euratom of 13 May 1996 laying down basic safety standards for the protection of the health of workers and the general public against the dangers arising from ionizing radiation, Official journal NO. L 159, 1996.