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Modelling the deposition of airborne radionuclides into the urban environment

First report of the VAMP Urban Working Group

Part of the IAEA/CEC Co-ordinated Research Programme on the Validation of Environmental Model Predictions (VAMP)

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MODELLING THE DEPOSITION OF AIRBORNE RADIONUCLIDES
INTO THE URBAN ENVIRONMENT

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FOREWORD

The injection of radionuclides into the environment as a result of the Chernobyl accident has provided a unique opportunity for improving and validating radiological assessment models. Such models are used at the planning and design stage to predict the radiological impact of planned nuclear facilities; in assessing the possible consequences of accidents with releases of radioactive material to the environment; and in planning the response and any associated protective actions. Under normal operating conditions, they are used together with the results of environmental monitoring to demonstrate compliance with regulatory requirements regarding release limitation. In all these applications, there is a need to provide evidence of the reliability of model predictions. Ideally models should be developed and tested with data on the transfer of the nuclides of interest in the actual environment being modelled. Very often such measurements are not available and, in some cases, are impossible to obtain. Reliance has usually to be placed on results taken from similar but different environmental conditions or from laboratory studies.

The very special opportunities that exist at the present time in the European parts of the former USSR and in Europe generally for the acquisition of datasets appropriate for the validation of radiological assessment models justified the establishment of an international programme aimed at collating suitable data from Member States and at co-ordinating work on model testing studies.

To this end, a co-ordinated research programme was begun at the IAEA in 1988 with the short title of *Va*lidation of Environmental *M*odel *P*redictions (VAMP). The principal aims of the VAMP programme are:

- To facilitate the validation of assessment models for radionuclide transfer in the terrestrial, urban and aquatic environments;

- To guide, if necessary, environmental research and monitoring efforts to acquire data for the validation of models used to assess the radiologically most significant exposure pathways;

- To produce a report or reports reviewing the current status of environmental assessment modelling, including a review of the improvements achieved as a result of efforts to validate them with data obtained after the Chernobyl accident, and identifying the principal remaining areas of uncertainty in models used for radiation dose assessment.

The programme is jointly sponsored by the Division of Nuclear Fuel Cycle and Waste Management and the Division of Nuclear Safety and is also supported by the Commission of the European Communities. There are four working groups within the programme: the Terrestrial Working Group, the Urban Working Group, the Aquatic Working Group and the Multiple Pathways Working Group.

The **VAMP Urban Working Group** aims to examine, by means of expert review combined with formal validation exercises, modelling for the assessment of the radiation exposure of urban populations through the external irradiation and inhalation pathways. An aim of the studies is to evaluate the lessons learned and to document the improvements in modelling capability as a result of experience gained following the Chernobyl accident. The topics for review were decided upon following the first Working Group meeting. In making this choice, consideration was given to the relative importance of a given process as a potential contributor to human radiation dose, the degree of uncertainty associated with the topic for lack of knowledge, and the possibilities presented by the situation following the Chernobyl accident for improving understanding of the particular process.

This Technical Document, the first report of the Group, addresses the subject of the deposition of airborne radionuclides into the urban environment. It summarizes not only the present status of modelling in this field, but also the results of a limited validation exercise that was performed under

the auspices of VAMP. The document was prepared by J. Roed (Risø National Laboratory, Roskilde, Denmark), P. Jacob (GSF–Forschungszentrum für Umwelt und Gesundheit, Neuherberg, Germany) and M.J. Crick (International Atomic Energy Agency, Vienna), but has had the benefit of a review process that involved comment by the members of the Urban Working Group of VAMP. Publication was finally decided upon at a meeting of the full VAMP Research Co-ordination Meeting in March 1992. Subsequent Technical Documents from this group will address External and Inhalation Dose Assessment, and Weathering, Decontamination and Sewerage Systems.

EDITORIAL NOTE

CONTENTS

1. GENERAL INTRODUCTION

Pollutants in air may take the form of liquid drops, reactive and non-reactive gases or aerosols. Dispersed pollution can be removed from the air by various processes. Removal in the absence of precipitation and fog is normally called **dry deposition**; when precipitation is present, removal is called **wet deposition**. In addition, deposition can occur under foggy conditions. All these forms of deposition are of particular interest in assessing the consequences of reactor accidents in the context of risk assessment, emergency planning and accident mitigation, in assessing the environmental impact of routine releases. One of the principal exposure pathways to man following deposition is that from external gamma radiation, with regard to both short and long term exposure [1].

Since in many countries much of the population lives in urban and semi-urban areas, it is important to consider the deposition processes for these specific environments. Whilst it may be enough to know the total deposition in urban areas in order to make simplistic dose assessments, this may not be sufficient for an accurate assessment of doses. It is certainly not adequate for the purposes of assisting in specific decontamination. For this purpose, the spatial distribution of the deposition in the urban area must be known as well, i.e. it is necessary to know the deposition on the relevant surfaces in the urban area, e.g. roofs, buildings, walls, streets, squares, indoor surfaces and surfaces of vegetation, such as bushes, trees, gardens and lawns.

The first study of the VAMP Urban Working Group concerned dry and wet radionuclide deposition in urban environments. To this end, a questionnaire was developed and circulated addressing available data, current understanding of concepts, models for simulating deposition, and problems for directly testing model predictions. This Technical Document considers wet and dry deposition processes separately, presenting and reviewing current scientific understanding of their nature, and discussing the available empirical data to support this current understanding and the results of the partial model validation exercise carried out under the auspices of the project.

2. DRY DEPOSITION

In estimating the radiological consequences of an atmospheric release, the assessment of dry deposition in the urban environment can be a significant source of uncertainty. This is because deposition directly influences the levels of contamination on different surfaces in the urban area, and thus on the estimated short and long term exposure.

Dry deposition is known to depend on a number of factors. Sehmel [2] suggested that the meteorological conditions as well as the characteristics of the released material and of the deposition surface can all be important. In all, he presented over fifty factors that may well affect dry deposition.

The deposition velocity, defined as the particle flux toward a surface (often horizontal) divided by the particle concentration in air, is a strong function of particle size. Different mechanisms are important for different particle sizes. For very small particles (< 0.1 μm) Brownian motion is the dominant mechanism influencing the deposition process. For large particles (> 2 μm) the gravitational sedimentation effect is of great importance for deposition to both inclined and horizontal surfaces. In the intermediate size range, impaction and interception are important. It is this intermediate region of particle size (0.1 μm $- 2$ μm) that is of greatest interest in considering likely releases from many nuclear facilities.

2.1. THEORY

To describe dry deposition, Gregory [3] and Chamberlain and Chadwick [4] introduced the concept of a deposition velocity:

$$v_d(z_d) = \frac{F(z_d)}{\bar{\chi}(z_d)} \quad (1)$$

where $F(z_d)$ is the flux of the contaminant towards the surface considered at a distance z_d from the surface and $\bar{\chi}(z_d)$ is the concentration of the contaminant in air at the same distance.

The applicability of the deposition velocity concept to the urban environment was discussed by Underwood [5]. He highlighted the convenience of relating the downward flux of a contaminant to the mean concentration near the surface via a simple coefficient of proportionality, namely the deposition velocity. Employing this idea enables the problem to be factored into (1) dispersion outside the influence of near surface phenomena and (2) behaviour near the surface. The two regions can thus be separated by an imaginary boundary at height z_r, at which the v_d concept acts as a boundary condition for the equation describing dispersion in the outer region.

The deposition velocity comprises two components: v_i due to **eddy diffusion** and v_s due to **sedimentation**. These components are discussed in Sections 2.1.1 and 2.1.2 respectively.

2.1.1. Eddy diffusion

2.1.1.1. Vertical flux and wind speed

Consider a moving air mass in contact with a surface. The air mass is subject to a drag force due to its contact with that surface. The drag force per unit area of the surface is called the shearing stress τ_0, where the subscript indicates that the value applies to ground level. This force sets up rotating eddies in the air mass, which can act as a transport/deposition mechanism.

It is possible to define the so-called friction velocity u_* such that

$$\tau_0 = \rho_a \cdot u_*^2 \quad (2)$$

where ρ_a is the density of the air and u_* is proportional to the tangential rate of rotation of the frictionally driven eddies in the flow.

In a turbulent surface layer, it can be shown that the vertical flux of air is nearly constant with height [6]. Assuming horizontal homogeneity, the following equation describes the rate of change of the mean horizontal wind speed with height under adiabatic weather conditions:

$$\frac{d\bar{u}}{dz} = \frac{u_*}{k.z} \quad (3)$$

where k is the so-called von Karman constant (k is empirically determined to be ≈ 0.4), $\bar{u}$ is the mean horizontal wind speed (averaged over small fluctuations), and z is the height above ground level [7].

It has been shown that the influence of surface roughness, typically in connexion with high and dense vegetation, may be taken into account by a change in the co-ordinate system [8]. Equation (3) can then be rewritten as:

$$\frac{d\bar{u}}{dz} = \frac{u_*}{k(z - d)} \quad (4)$$

where d typically is 0.6 H and H is the mean height of the roughness element, which in the urban environment corresponds to the height of the buildings. On integration, one obtains:

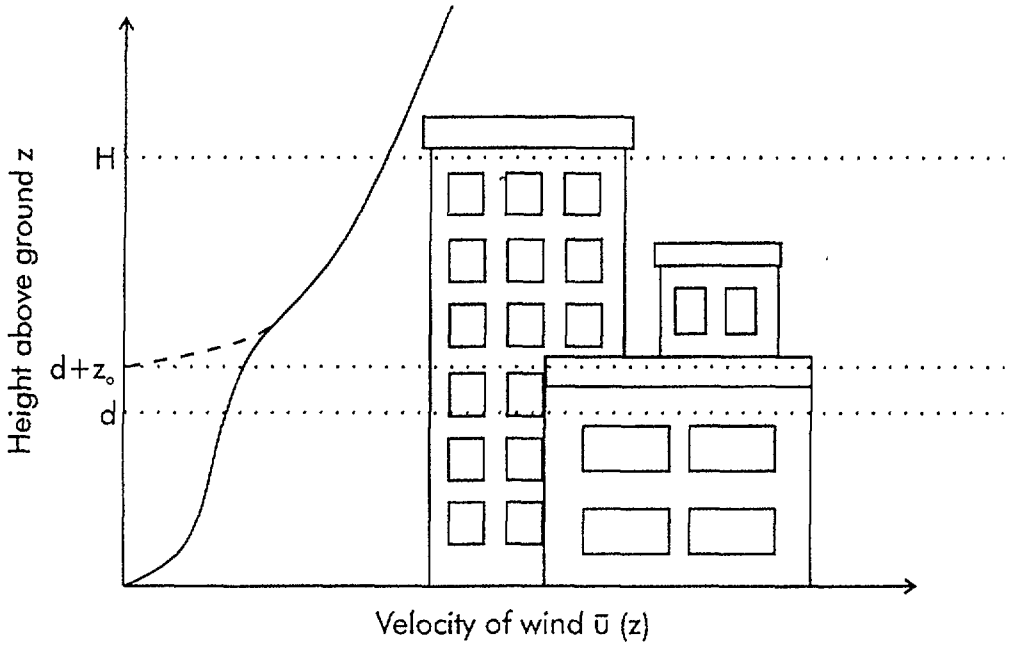

FIG. 1. Mean horizontal wind velocity as a function of height above ground.

$$\bar{u}(z) = \frac{u_*}{k} \ln\left(\frac{z - d}{z_0}\right) \tag{5}$$

where z_0 is called the aerodynamic roughness length. z_0 is defined through this equation and physically it is of the same order as the variability in height of the roughness elements. It can be seen that $\bar{u} = 0$ for $z = d+z_o$, that is to say that at a height $d+z_0$ the mean horizontal wind speed is zero, rising logarithmically above this height. This theoretical relationship is illustrated in Fig. 1 by the dashed line. However, in practice real wind profiles look like those given by the solid line in Fig. 1 as there is a non-zero windspeed above the surface.

2.1.1.2. Particle concentration and its dependence on height

In a similar way as for the mean horizontal wind speed above, a parallel expression for the rate of change of particle concentration with height can be derived [6]:

$$\frac{d\bar{\chi}}{dz} = \frac{\chi_*}{k.z} \tag{6}$$

where $\bar{\chi}$ is the average particle concentration at height z and χ_* is defined so that $\chi_* u_*$ is equal to the vertical particle flux F_i, due to eddy diffusion.

Integration of Eq. (6) gives

$$\bar{\chi} - \bar{\chi}_0 = \frac{\chi_*}{k} \ln\left(\frac{z}{z_0}\right) \tag{7}$$

where $\bar{\chi}_0$ is the mean concentration at height z_o.

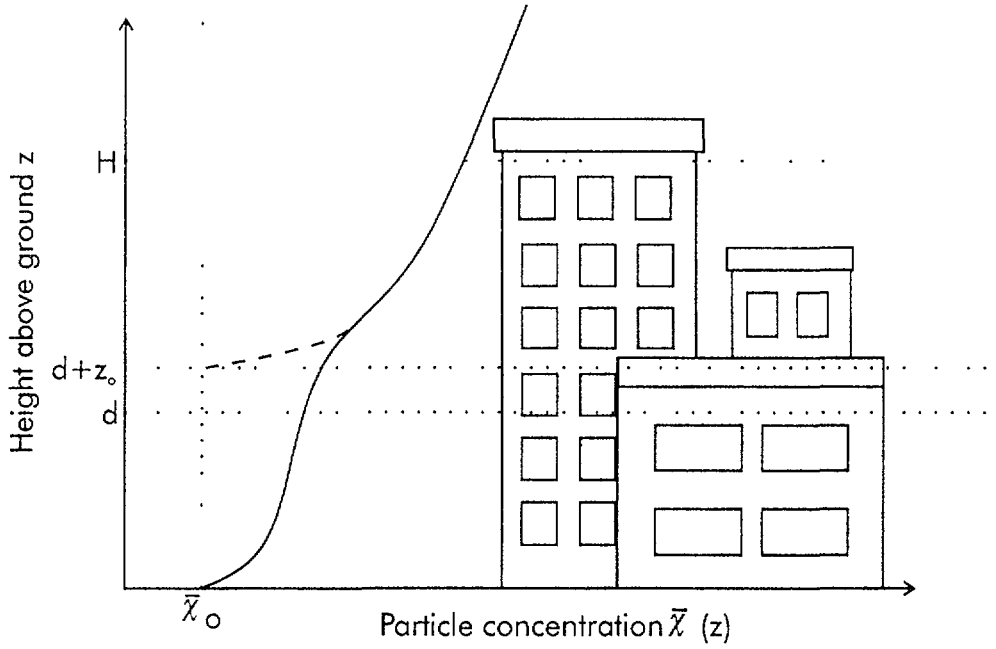

FIG. 2. Mean particle concentration as a function of height above ground.

Whereas the mean wind speed, $\bar{u}_0$, at the ground surface is always zero, $\bar{\chi}_0$ is only zero if the surface absorbs all the particles that reach it. This is usually not the case. The co-ordinate system can again be shifted to accommodate and describe this effect. The equation then becomes

$$\bar{\chi} - \bar{\chi}_0 = \frac{\chi_*}{k} \ln\left(\frac{z-d}{z_0}\right) \tag{8}$$

where $\bar{\chi}_o$ is redefined as the mean concentration at height $d+z_o$. Again, the particle concentration rises logarithmically with height above $d+z_0$, as is illustrated in Fig. 2. However, as was the case for the wind speed, in practice the profile is different from this.

2.1.1.3. Deposition velocity due to eddy diffusion

From Eqs (1), (8) and $F_i = u_* \cdot \chi_*$ the contribution v_i of the eddy diffusion to the total deposition velocity v_d can be found as

$$v_i = \frac{k.u_*}{\ln\left(\frac{z-d}{z_0}\right) + k\frac{\bar{\chi}_0}{\chi_*}} \tag{9}$$

If $\bar{\chi}_o$ alone is varied, we obtain a maximum for $\bar{\chi}_0 = 0$, valid when the surface is a perfect absorber. Thus the following expression can be derived:

$$v_i \leq \frac{k.u_*}{\ln\left(\frac{z-d}{z_0}\right)} \tag{10}$$

From Eq. (5) the following expression holds:

$$\ln\left(\frac{z-d}{z_0}\right) = \frac{u.k}{u_*} \tag{11}$$

and by inserting this into Eq. (10) we obtain:

$$v_i \leq \frac{u_*^2}{u} \tag{12}$$

which is an important expression that places an upper limit for the eddy diffusion component of the total deposition velocity.

2.1.2. Sedimentation

Besides the flux of particles to the surface that arises from eddy diffusion, there is also a downward flux to the surface due to gravity; this contribution to deposition is called **sedimentation.**

In the region where Stokes' law is valid, the drag force K_s in the vertical direction for spherical particles in thermal equilibrium can be expressed by:

$$K_s = 3.\pi.\rho_a.\nu.d_a.v_s \tag{13}$$

where ρ_a is the density of the air, ν the kinematic viscosity of the air, d_a the aerodynamic particle diameter and v_s the settling velocity.

The gravitational force K_g on the particles is

$$K_g = \frac{1}{6}.\pi.d_a^3(\rho_p - \rho_a).g \tag{14}$$

where ρ_p is the density of the particle and g the gravitational acceleration.

The drag force and the gravitational force can be equated, thus : $K_s = K_g$, which gives the following expression for the settling velocity, or the sedimentation component of the total deposition velocity:

$$v_s = \frac{d_a^2.g}{18\nu} \cdot \frac{\rho_p - \rho_a}{\rho_a} \tag{15}$$

2.1.3. Dry deposition of gases

Three main classes of nuclides can be released in gaseous form, namely noble gases (argon, krypton, xenon), tritium and iodine. Dry deposition of the noble gases can be assumed as negligible [9, 10]. When tritium is released into the atmosphere it will normally be in the form of tritiated aqueous vapour; the deposition pattern will follow that of aqueous vapour (i.e. high deposition onto surfaces when the vapour is below the dew point). This cannot be considered dry deposition in the strict sense. However, dry deposition of iodine in the form of inorganic iodine (mainly methyl iodide) and iodine vapour (elemental iodine) is of importance.

For the moving air mass in contact with a surface, it can be shown that as the height tends to zero, the mean wind speed and the formation of eddies also tend to zero. Theoretically, at the surface itself, eddy diffusion disappears altogether, and a gas moves under the influence of molecular diffusion or Brownian motion [11].

The total diffusivity can then be written as

$$K = k \cdot u_* \cdot z + D \tag{16}$$

where the first term represents the eddy diffusion and D the molecular diffusion. In a layer of constant flux one obtains

$$F = (k \cdot u_* \cdot z + D) \cdot \frac{\partial \bar{\chi}}{\partial z} = \text{constant} \tag{17}$$

On integration, this becomes

$$\frac{F}{\bar{\chi} - \bar{\chi}_0} = \frac{k \cdot u_*}{\ln\left(\frac{k.u_*.z}{D} + 1\right)} \tag{18}$$

For a highly reactive gas such as elemental iodine the surface can be assumed to be a perfect absorber ($\bar{\chi}_0 = 0$) and thus the following expression for $v_d(z)$ can be derived:

$$\frac{F}{\bar{\chi}(z)} = v_d(z) = \frac{k \cdot u_*}{\ln\left(\frac{k.u_*.z}{D} + 1\right)} \tag{19}$$

However, this equation must be regarded as only a crude approximation for $v_d(z)$ since, in reality, the conditions near the surface are more complex.

2.1.4. Dry deposition velocity

According to theory, the deposition velocity is the sum of the two components represented by Eqs (9) and (15). The processes and parameters involved depend on a number of variables, e.g. the physicochemical form of the matter being deposited, weather conditions and the nature of the surface onto which the deposition takes place.

Some of the functional relations of v_d to various parameters are discussed in the following.

2.1.4.1. Dependence on reference height

For very small particles, where the sedimentation component is negligible, Eq. (9) can be used to represent the total deposition velocity and the dependence of v_d. Note that v_d is dependent on the height above the surface that is chosen as reference height.

Considering a grass field, over which air flows under adiabatic conditions (neutral stability), with $z_o = 1 \times 10^{-2}$ m and $u_* = 0.3$ m s^{-1}, and where the field is a total sink (i.e. $\bar{\chi}_0 = 0$), we find from Eq. (9) that

$v_d = 2.3 \times 10^{-2}$ m s^{-1} for $z - d = 2$ m
$v_d = 2.6 \times 10^{-2}$ m s^{-1} for $z - d = 1$ m and
$v_d = 5.2 \times 10^{-2}$ m s^{-1} for $z - d = 0.1$ m.

It can be seen that if the reference height is chosen to be greater than about 1 m above d, then up to a few metres the deposition velocity is fairly independent of the reference height.

To get a feeling for the maximum deposition velocity due to eddy diffusion, consider an example for a wooded area where $z_0 = 0.5$ m, with a windspeed of 5 m s^{-1} for a height corresponding to $(z-d) = 20$ m. Then from Eq. (5) u_* can be found as 0.54 m s^{-1} and hence from Eq. (12) $v_i < 6 \times 10^{-2}$ m s^{-1}.

Thus even in a forest area v_i will under normal conditions be no greater than 6×10^{-2} m s^{-1}. In practice, with $\bar{\chi}_0 \neq 0$ the actual deposition velocity would be considerably less, as can be inferred from Eq. (9).

2.1.4.2. Dependence on stability of the atmosphere

It can be seen that the maximum deposition velocity under the aforementioned conditions is about 6×10^{-2} m s^{-1}. However, the deposition velocity is also a function of atmospheric stability. In moderately stable atmospheric conditions (typically night-time, clear skies), Jensen [7] has demonstrated that u_* becomes only half of its value in neutral conditions. Thus the maximum deposition velocity will then, according to Eq. (12), be only a quarter of the aforementioned value, ie $< 1.5 \times 10^{-2}$ m s^{-1}. Reported deposition velocities higher than, say, 2×10^{-2} m s^{-1} would require careful scrutiny of the associated conditions.

2.1.4.3. Dependence on wind speed

Again from Eq. (9), it can be seen that v_i is proportional to $\bar{u}$ (the mean wind speed) if $\bar{\chi}_0 = 0$. However, the term

$$k \cdot \frac{\bar{\chi}_0}{\chi_*} \tag{20}$$

in the denominator of Eq. (9) modifies this, so that it must be expected that the deposition velocity increases with wind speed but less than the ratio in windspeed. These theoretical considerations are in good agreement with Chamberlain's [12] measurement of deposition velocities for different friction velocities (u_*), Garland's [13] measurement of dry deposition of small particles to grass, and Ahmed's measurements of deposition velocities as a function of windspeed (see Fig. 3).

2.1.4.4. Dependence on particle size

From a report of McMahon and Deninson [14] a curve is presented in Fig. 4 that shows the relation between the deposition velocity on grass and particle size. This is constructed from the deposition velocities found in the literature. Figure 5 presents more recent but similar data [15]. From these it can be seen that the deposition velocity has a minimum around a particle size of 0.5 μm. The higher deposition velocities for smaller particles are due to Brownian motion (molecular diffusion), whereas the increase in v_d for particles larger than 0.5 μm is due to the gravitational force (the sedimentation component). On both sets of curves the theoretical settling velocity due to sedimentation and given by Eq. (15) is also presented.

2.1.4.5. Dependence on surface roughness

Surface roughness is expressed by the parameter z_0 in Eq. (9). As can be seen from that equation, the eddy diffusion component increases as the value of z_0 increases, i.e. the deposition

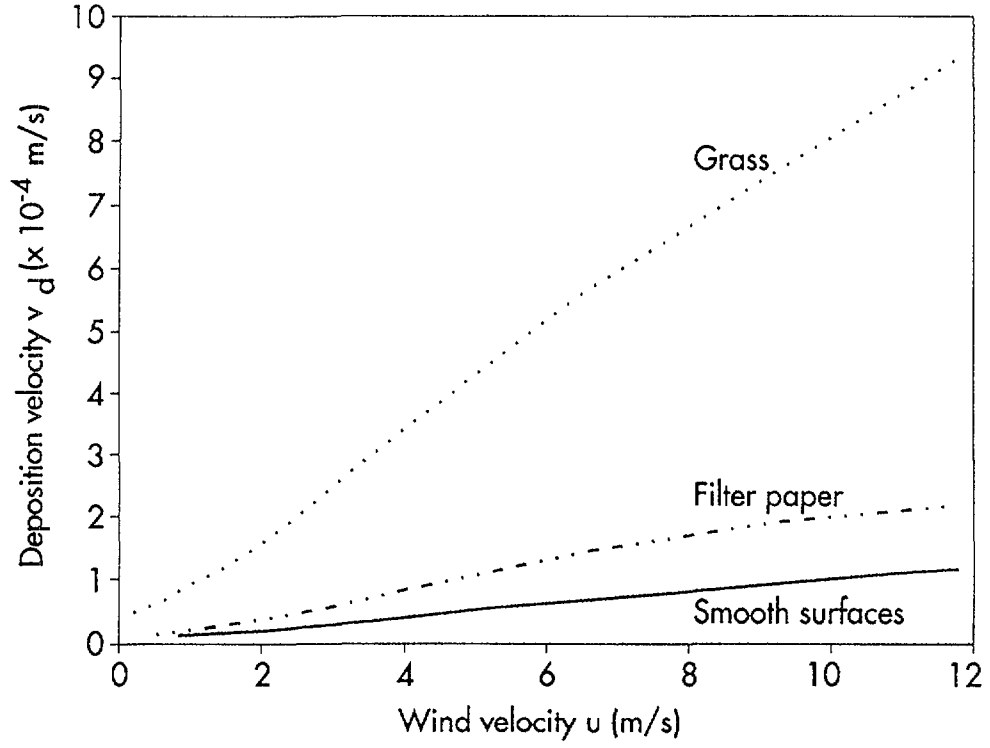

FIG. 3. Deposition velocity for natural radioactive aerosols as a function of wind velocity [8].

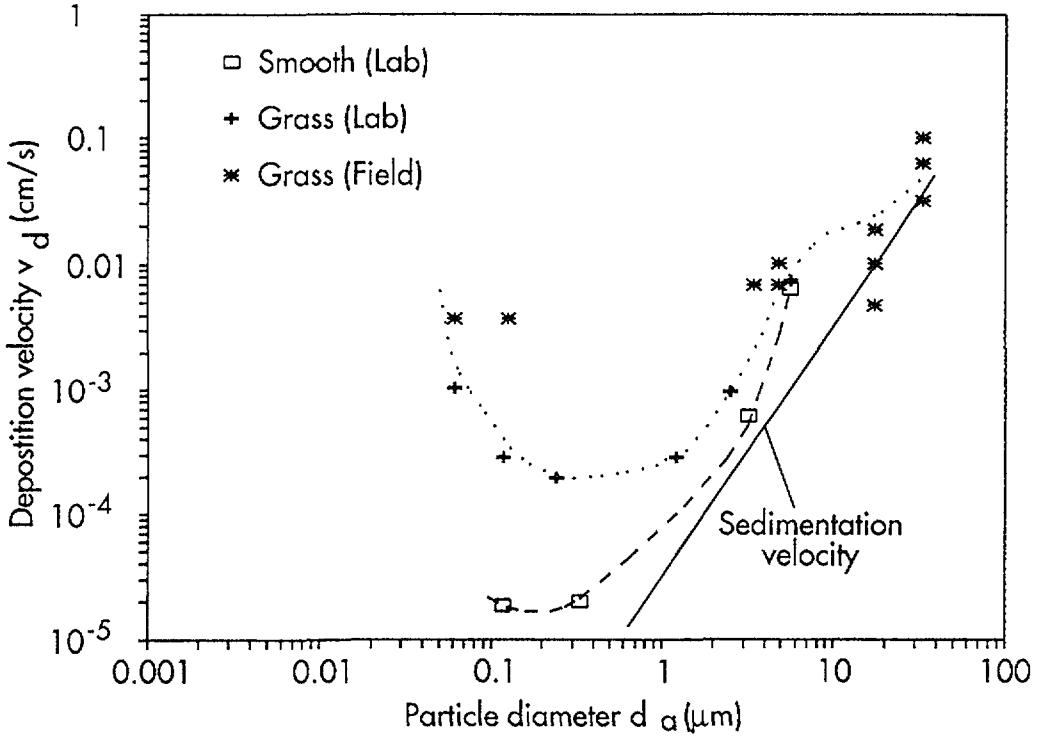

FIG. 4. Deposition velocity to grass and smooth surfaces as a function of particle size [14].

velocity increases with increasing surface roughness. This is in accordance with empirical evidence: for example, values of deposition velocities measured on grass before 1962 and reviewed by Gifford and Pack [16] were an order of magnitude higher than those on smooth surfaces. Horbert [17] also measured deposition velocities of $CuSO_4$ particles with a diameter of 4 μm and mean frictional velocity of 0.27 m s^{-1}. He found deposition velocities on grass (1×10^{-3} m s^{-1}) and clover

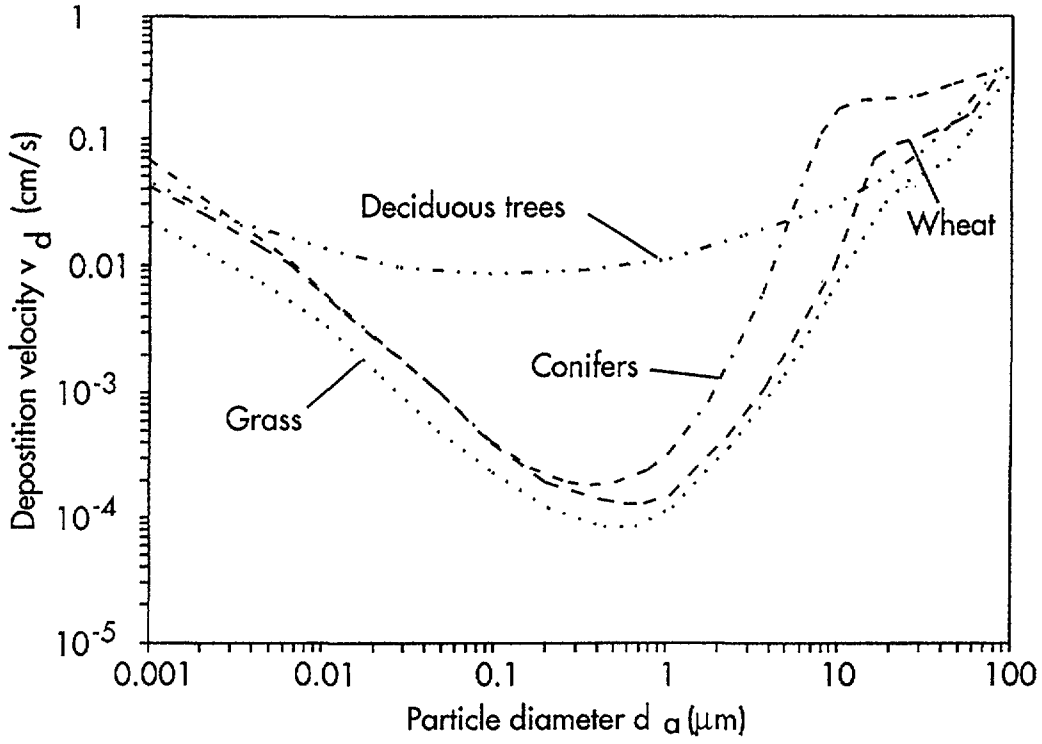

FIG. 5. Deposition velocity to grass, wheat, conifers and deciduous trees as a function of particle size for a mean windspeed of 5 m s^{-1} at 10 m above the surface [15].

(2.4×10^{-3} m s^{-1}) that are 3–8 times higher than those measured on smooth surfaces (3×10^{-4} m s^{-1}). Ahmed's [8] curves for deposition velocities as a function of windspeed (Fig. 3) are also given for smooth as well as rough surfaces. The deposition velocities for particle diameters between 0.05 μm and 2 μm on rough surfaces are again found to be about an order of magnitude higher than those to smooth surfaces. The data of McMahon and Deninson [14] also demonstrate the effect surface roughness has on deposition velocity and Fig. 4 additionally illustrates that sedimentation has relatively more influence on deposition velocity to smooth surfaces than to rough ones.

2.1.4.6. Dependence on orientation of the surface

According to theory, the component of deposition velocity due to eddy diffusion should be independent of surface orientation, and any difference in measured deposition velocities in this case should reflect only the different sedimentation components. Sehmel [18] made a series of wind tunnel experiments in which he measured the deposition velocity on walls, floors and ceilings as a function of particle size (see Fig. 6). It was found that the deposition on floors was higher than that on walls and very much higher than that on ceilings when the particle size was larger than about 0.1 μm up to a few μm. For the given friction velocity (u_*) of 3.41×10^{-2} m s^{-1}, the influence of sedimentation, however, should theoretically be very low for particulates smaller than 1 μm as the main deposition mechanism in this case is eddy diffusion.

Sehmel's data could be questioned because they were based on artificial wind tunnel experiments. Roed [19], however, has also found less deposition on vertical surfaces than on horizontal surfaces for ^{7}Be-particles (mean particle diameter 0.4 μm), and later found the same also for the volatile fraction of the Chernobyl fallout. These experiments were carried out under field conditions. It may be concluded that the deposition mechanism for geometries with horizontal and vertical surfaces are as yet not well understood.

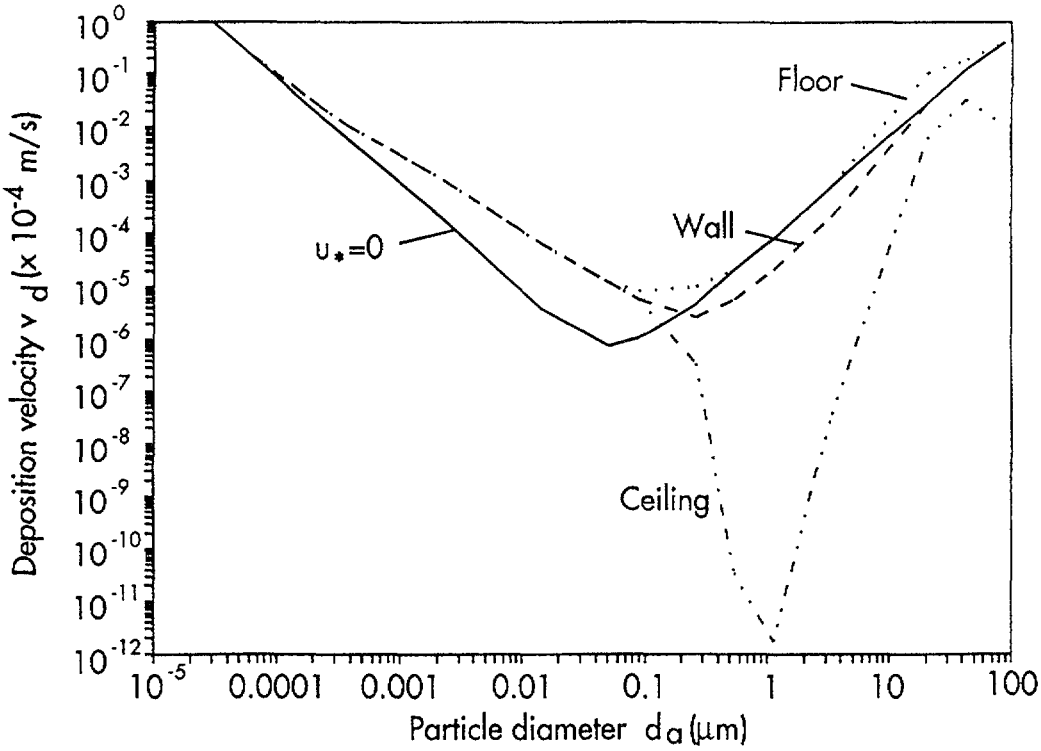

FIG. 6. Comparison of deposition velocity onto smooth surfaces (floor, wall and ceiling) for a friction velocity (u_*) of 3.41 × 10^{-2} m s^{-1} [18].

2.1.5. The urban area

In the case of an urban area, the deposition velocity may vary not only as a function of the pollutant's characteristics, meteorological variables and surface characteristics, but also as a function of such variables as the downwind distance from the rural–urban boundary or other local boundaries within the urban complex, such as edges of building clusters or parks [5].

One way of solving these problems might be to use local effective deposition velocities

$$v_d^i \quad \text{defined as} \quad \frac{F(i)}{\bar{\chi}(z_r)} \tag{21}$$

where $F(i)$ is the flux towards a local surface i, for example a building surface, and $\bar{\chi}(z_r)$ is the air concentration at the imaginary boundary surface well above the roughness elements of the city and also above the city canopy. These effective local deposition velocities can then be used for calculating the total flux to the area and hence the mean deposition velocity over the urban area. This simplified model was proposed by Roed [20] as *the Naive model.*

The surface types that occur, i.e. the local surfaces, are assigned their individual deposition velocities separately, each obtained as the result of experiments or calculations. In this way the deposition velocity to the urban canopy as a whole relative to the projected ground area is evaluated as the weighted aggregate of the local deposition velocity, i.e.

$$v_d(\text{urban}) = \sum_i A_i v_d^i \tag{22}$$

where A_i is the total surface area of surface type i in unit plan area of the city.

This *Naive model* contrasts with the usual one that makes use of the overall aerodynamic roughness length of the urban complex (the macrosurface roughness) [5]. In the former case, the spatial proximity of various microsurfaces plays no part, whereas in the latter case it is very important.

However, the total depositions predicted by each model are not incompatible. They both depend on the size of bluff bodies such as buildings. The *Naive model* predicts a higher deposition in a high building area (because there is a larger total surface area per unit ground area) than in surroundings with low houses. The more sophisticated model also gives higher deposition in these areas because of their higher aerodynamic roughness.

2.2. FIELD MEASUREMENTS

2.2.1. Measurements before the Chernobyl accident

Field measurements of the deposition on urban surfaces of aerosols with diameters smaller than 3 μm have been published only by Roed [19, 21]. The deposition of larger particles, as may well occur in the near vicinity of sites of some types of accidental release, have not been treated in the VAMP exercise. Only the results for smaller aerosols are discussed here.

In order to find the local deposition velocities onto given urban surfaces, Roed [19, 21] measured the deposition density of ^{137}Cs — mainly bomb fallout accumulated over many years — on portions of a vertical building surface; he then related this, correcting for radioactive decay, to the known time integrated concentration of ^{137}Cs in air. In addition, he measured the deposition of naturally produced ^{7}Be on artificial plates placed against vertical walls. This type of measurement has the advantage that the surfaces studied have been immersed in an actual turbulent environment generated by wind flow on an array of buildings and that the deposition velocity is averaged over a time long enough to include a wide variety of weather conditions.

The measurements also have a number of drawbacks, such as:

(1) The areas of plane surfaces chosen in the experiment may not be representative for a number of reasons: deposition could be highly non-uniform spatially, for example with enhancement occurring near edges, discontinuities, projections, etc. To resolve this uncertainty would call for measurements of large surface areas at many different types of locations.

(2) The ^{137}Cs deposited on walls had an unknown contribution from wet deposition for some of the samples, whereas others were well protected from rain. In addition, natural weathering can reduce the deposition density. Roed [19] presented an argument to explain why weathering was not expected to have a dominant influence on the results, and the ^{7}Be results seem to bear this out.

(3) The characteristics of the aerosols associated with the deposition of ^{137}Cs are not known in detail, whereas those associated with ^{7}Be have a mean aerodynamic diameter of about 0.4 μm.

The values of local deposition velocities obtained were notably low. Values for ^{137}Cs onto vertical surfaces fairly well protected from the rain were below 10^{-4} m s^{-1}. The ^{7}Be results for vertical surfaces (protected from the rain) were below 1.6×10^{-4} m s^{-1} and for horizontal surfaces below 7×10^{-4} m s^{-1}.

2.2.2. Measurements after the Chernobyl accident

Unfortunately very few experiments involving real urban surfaces have been performed to measure dry deposition onto different urban surfaces. Measurements of Roed [23, 24], however,

have provided some insight into how various isotopes may be distributed on different surfaces. These deposition measurements were made during the passage of the first radioactive cloud from the Chernobyl release over the Roskilde area, Denmark. They were carried out at noon on Sunday 27 April 1986, the cloud clearing the area at some time during the day. In the time interval during which the deposition took place the weather was steady, with a mean wind speed of 3 m s^{-1} at 8 m height, and in Pasquill stability category of B–C. Measurements were taken in the city as well as in suburban and rural areas.

Tables I and II list some of the results. Table I shows the deposition velocities measured for different isotopes originating from the Chernobyl accident [25, 26]. The deposition velocity for ^{137}Cs to walls measured was not inconsistent with that measured before the Chernobyl accident for ^{137}Cs in bomb fallout given above.

TABLE I. MEASURED DEPOSITION VELOCITIES ON VARIOUS URBAN SURFACES

	Deposition velocity ($\times 10^{-4}$ m s^{-1})					
	I	Cs	Ru	Ba	Ce	Zr
Paved areas	4.6	0.7	3.5	4.6	8.1	3.5
Walls[a]	3.0	0.1	0,4	0.4	0.9	1.3
Windows[a]	2.3	0.05	0.1	0.2	—	0.1
Grass (clipped)	26	4.3	4.1	5.8	7.7	7.1
Trees (coniferous)[b]	22	7	25	26	39	45
Roofs[c]	33	2.8	3.4	53	40	—

[a] Deposition per unit window or wall area.
[b] Total deposition per unit plan area.
[c] Deposition per unit roof area.

The measurement errors on the deposition velocities for paved areas, walls and roofs was ± 30% whilst for grass and trees it was ± 10%.

TABLE II. DEPOSITION ON VARIOUS URBAN SURFACES RELATIVE TO DEPOSITION ON PAVED AREAS

	I	Cs	Ru	Ba	Ce	Zr
Paved areas	1	1	1	1	1	1
Walls	0.65	0.14	0.1	0.1	0.1	0.37
Windows	0.5	0.07	0.03	0.04	—	0.03
Grass (clipped)	5.8	6	1.2	1.3	1.0	2
Trees (coniferous)	5	10	7	5.6	5	13
Roofs	7	4	1	12	5	—

Table II shows the deposition on different urban surfaces relative to deposition on smooth paved areas like roads and pavements. There is no obvious indication that the deposition velocity changed between the different areas in which measurements were made. However, it clearly differed between the various isotopes.

For street surfaces, particle bound caesium had the smallest values, with a mean v_d of about 1×10^{-4} m s^{-1}. The next group, comprising particulate ruthenium, barium/lanthanum and elemental iodine, had deposition velocities of around 5×10^{-4} m s^{-1}. The highest deposition velocity, 10×10^{-4} m s^{-1}, was found for particulate cerium.

The deposition velocity of iodine on walls was similar to that for road surfaces. For the other elements, however, it was one order of magnitude lower. The wall surface samples were identical, as they had been prefabricated in the laboratory specifically for deposition velocity measurement purposes. However, the walls of which they were part were situated at very different locations, varying from very open areas to very dense city areas. Nevertheless, the deposition velocities were surprisingly consistent.

The deposition velocities to grass of caesium and iodine were about 6 times higher than to road surfaces. For the other elements the deposition velocities were similar for both surfaces.

The caesium deposition on coniferous trees was only about a factor of two higher than that to grass, in agreement with the data presented in Fig. 5. Unfortunately no measurements on deciduous trees were available. For other nuclides the deposition to trees was relatively much higher.

These measured deposition velocities would be expected to depend on the size distribution of the particles. Several sets of measurements of the size distribution for the Chernobyl fallout have been published [27–31], and an example from Bavaria [22] is presented in Fig. 7. In general, it would be expected that the deposition velocities of the volatile group, I (bound to aerosols), Te, Cs and Ru be lower than those of the refractory group, La, Ba, Ce and Zr. As shown by Rulik [32], following the Chernobyl accident and at large distances, these two groups have different particle sizes: the first group has an AMAD of about 0.4 μm and the other group of 1–4 μm. This relation is supported by Table I for Cs, Ce and Zr. For Ba and especially Ru the relationship between the deposition velocities is not so evident; this may be due partly to statistical uncertainties and partly to contributions of hot fuel particles, which carried ruthenium.

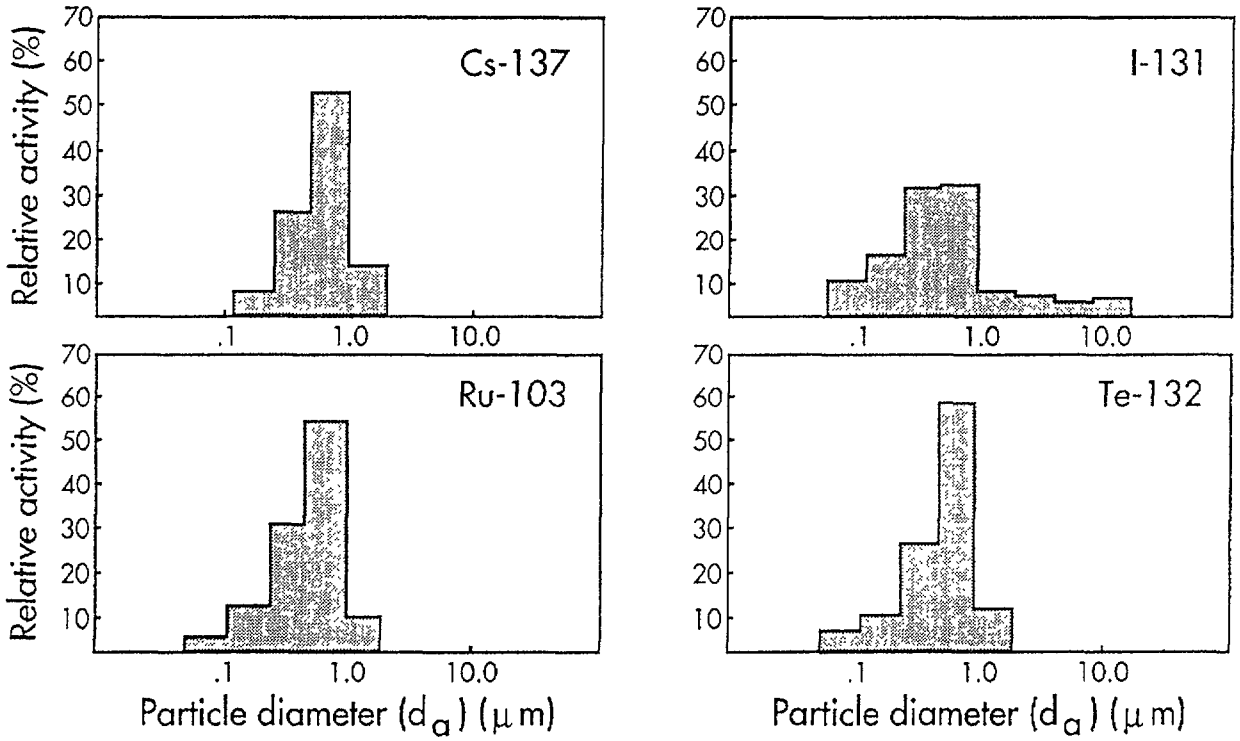

FIG. 7. Particle size distributions of the main Chernobyl fallout nuclides sampled on 6 May 1986 in Munich–Neuherberg [22].

TABLE III. SUMMARY OF EXPERIMENTAL VALUES OF DEPOSITION VELOCITIES v_d ($\times 10^{-2}$ m s^{-1}) FOR PARTICULATES AND GASES

Type of surface	Particle diameter (μm)			Chemical species		
	0.01 - 0.1	0.1 - 1	1 - 5	I_2	CH_3I	HIO
Smooth surfaces including paving and roofing materials	0.02[a]	0.01	0.02	0.2	$4\ 10^{-4}$	<0.02[a]
Vertical walls	-	0.03[b]	-	-	-	-
Leafy vegetation i.e. grass, clover	0.2	0.1	0.2	1.1	$5\ 10^{-4}$	0.05[a]
Woodland canopies[c]	2	1	2	-	-	-

Note: All values represent geometric means, best or upper estimates of information derived from the literature [33].

[a] Value based on laboratory experiments.
[b] Value representative for weapon test fallout at locations remote from the test site [19,34].
[c] Value adapted from [35].

2.3. DISCUSSION OF THE VAMP EXERCISE

2.3.1. Background of the exercise

The Urban Working Group of VAMP distributed a questionnaire on dry and wet deposition. The results from 19 replies are summarized in the Annex. When asked what studies should be performed additional to those planned within the VAMP programme, with regard to dry deposition, several suggestions were made by the respondents. In particular, it was suggested that the dependence on the physicochemical forms of the pollutants, their solubility, and the dependence on "external meteorology" and "micro-meteorology" around the urban surfaces be considered. While no additional results have been obtained up to now on the first two topics, the measurements of Roed [23, 24] seem to indicate that the presence and nature of the urban environment does not strongly influence the deposition velocities.

Compared to the situation before the Chernobyl accident, knowledge on dry deposition in urban environments has increased, but still very little is known on the influence of many parameters. This is especially true for the deposition of particles with diameters larger than 1 μm, which may occur in the vicinity of some sources of releases, as was the case close in for the Chernobyl accident. Indeed, any opportunity to access data measured early on around the Chernobyl power plant should be used to improve our knowledge on this topic.

Concerning the VAMP validation exercise, the generally good agreement of the answers from the respondents on caesium deposition reflects more that there is essentially only one solid source of information from which all have drawn rather than a comprehensive source of information and knowledge.

An evaluation of the pre-accident data on dry deposition in urban environments by Schwarz [33] resulted in the best estimates as given in Table III. In the following paragraphs the results on dry deposition from the VAMP exercise are discussed and compared with these pre-Chernobyl data and the post-Chernobyl measurements given in Table I. The problem in the VAMP exercise related to the behaviour of a 1 μm AMAD[1] aerosol. Strictly speaking, aerosols with very different particle size distributions can still have a 1μm AMAD, but the authors agreed that this ambiguity did not create

[1] Activity median aerodynamic diameter.

serious confusion among the respondents and that a distribution close to the natural aerosol size distribution or a monodispersed aerosol was assumed, both cases leading to about the same values, within the uncertainties in the deposition measurements.

2.3.2. ^{137}Cs deposition on grass

The estimate for the deposition velocity of 1–2 $\times$ 10^{-3} m s^{-1} in Table III made prior to the Chernobyl accident takes into account results from meadows. These often have a higher value of biomass per unit area than the lawns that are more typical of urban environments. It could therefore be expected that values measured after the Chernobyl accident on lawns are in the range of or lower than 1 $\times$ 10^{-3} m s^{-1}. This was indeed the case, as demonstrated by the measurements of Roed [23, 24], which lie in the range 1.5–9.9 $\times$ 10^{-4} m s^{-1} and have a mean value of 4.3 $\times$ 10^{-4} m s^{-1}, as shown in Table I. In the VAMP exercise (see Fig. A-1 in Annex) the answers of seven of nine respondents were within a factor of two of the measured value. The authors agreed that the other two deviating values do not have sufficient experimental or theoretical support to be considered as representative values. It may be concluded that the dry deposition of caesium onto grass is relatively well understood for aerosols with diameters in the range of 0.1–2 μm.

2.3.3. ^{137}Cs deposition on roads

The review of deposition velocity to road surfaces prior to the Chernobyl accident gave 1–2 $\times$ 10^{-4} m s^{-1} (Table III), and is supported by the post-accident measurements of Roed [23, 24], which are in the range of 4.5 10^{-5}–1.1 $\times$ 10^{-4} m s^{-1} with a mean value of 7 $\times$ 10^{-5} m s^{-1} (Table I). The answers of six of eight respondents from the VAMP exercise lie within a factor of 2 of the measured value (Fig. A-2). The other two answers were higher than the measured value by a factor of between 3 and 7.5. The authors agreed that these latter values did not have sufficient experimental or theoretical evidence to defend them, although they could be used for conservative assessments, since not much is known about dry deposition under other weather conditions.

2.3.4. ^{137}Cs deposition on walls

For ^{137}Cs deposition on walls the assessment prior to the Chernobyl accident of 3 $\times$ 10^{-4} m s^{-1} in Table III is higher by a factor of 30 than the value of 1 $\times$ 10^{-5} m s^{-1} representative of the post-accident results of Roed [24] and Nicholson [36] (Table I). The answers of the respondents to the VAMP questionnaire (Fig. A-3) span almost the entire range between these two values, and it may be concluded that the deposition velocity to walls is still not well known or understood.

2.3.5. ^{137}Cs deposition on roofs

The assessment prior to the Chernobyl accident of a deposition velocity of 1–2 $\times$ 10^{-4} m s^{-1} given in Table III is somewhat lower than the measured post-accident value of 2.8 $\times$ 10^{-4} m s^{-1} given in Table I. The answers given by VAMP respondents (Fig. A-4) span the range of 1–4 $\times$ 10^{-4} m s^{-1}, similar to the range of both pre-accident review and post-accident measurements. The authors agreed that it is not possible to decide on the base of existing data whether this range is representative for different possible physicochemical forms or different weather conditions other than a wind speed of 5 m s^{-1} as given in the VAMP questionnaire.

2.3.6. ^{137}Cs deposition on trees

The pre-accident review gave a range of 1–2 $\times$ 10^{-4} m s^{-1} for the value of this parameter (Table III). The value measured after the accident was 7 $\times$ 10^{-4} m s^{-1} and differs by more than one order of magnitude. This difference is in accordance with Fig. 5 [15], which shows much smaller deposition velocities for coniferous trees than for deciduous trees (these measurements were performed for relatively small coniferous trees). The type of tree was not specified in the VAMP questionnaire and the answers of the respondents (Fig. A-5) span a range of 5 $\times$ 10^{-4} – 10^{-2} m s^{-1},

similar to the range of pre- and post-accident data, although shifted somewhat towards lower values. The authors agree that too few experimental data exist for dry deposition on trees, and that considerable uncertainty remains.

2.3.7. ^{137}Cs deposition on internal surfaces

It appears to be convenient for dose assessment purposes to define the indoor deposition velocity with respect to outdoor concentrations in air. In the VAMP problem the average indoor deposition density on walls, floors and ceilings was requested. According to Fig. 6 a pre-accident assessment of indoor deposition would yield a value of the order of 2×10^{-5} m s^{-1}. Post-accident measurements of Roed and Cannell [37] are in agreement with this value. Only four respondents ventured to answer the exercise, probably since only very few data are known in this field, and the problem itself is complex. Two of the answers were near to the measured value of 2×10^{-5} m s^{-1} (although the stated uncertainty bands exceeded an order of magnitude), the other two were higher by a factor of more than ten (Fig. A-6). The authors agreed that there still remains a high degree of uncertainty in this field.

2.3.8. Elemental ^{131}I deposition on grass

In Table III the pre-accident value of 1.1×10^{-2} m s^{-1}, which includes consideration of data for meadows, is, as to be expected, close to the upper bound of the range of values measured on lawns after the Chernobyl accident of $1.8 \times 10^{-3} - 1.2 \times 10^{-2}$ m s^{-1} [24]. All answers of the respondents were within this range (Fig. A-7). The authors agree that the deposition velocity of elemental ^{131}I on grass is relatively well known.

2.3.9. Elemental ^{131}I deposition on roads

The pre-accident value of 2×10^{-3} m s^{-1} in Table III is about one order of magnitude larger than the range of values of $2.2 - 7.7 \times 10^{-4}$ m s^{-1}, measured after the Chernobyl accident by Roed [24]. Only five out of eight answers lay in the range of the pre- and post-accident data, namely $2.2 \times 10^{-4} - 2 \times 10^{-3}$ m s^{-1} (Fig. A-8). The authors agree that any justification for the other three answers is very small, but that the problem is far from being well understood.

2.3.10. Elemental ^{131}I deposition on roofs

The pre-accident assessment of 2×10^{-3} m s^{-1} in Table III is the lower bound of values measured after the accident, which were in the range of $2 - 4.3 \times 10^{-3}$ m s^{-1}. Five out of eight answers are very close to measured values (Fig. A-9). The other three answers are lower, two by a factor of more than ten. The authors agree that the justification for these three values is very low.

2.3.11. Elemental ^{131}I deposition on walls, trees and internal surfaces

For these surfaces, no pre-Chernobyl data were available and the authors agree that current knowledge is still too poor to give representative values with any certainty (Figs A-10, A-11, A-12).

3. WET DEPOSITION

The washout of particles and gases from the atmosphere in many cases can be a significant mechanism for the deposition of materials. This can be due to snow, fog, hail or more usually rain. The following discussion relates only to rain. In the case of fallout from the Chernobyl accident it gave rise to high activity concentrations on the ground at large distances from the damaged plant itself.

3.1.1. Washout

Washout is defined as the scavenging of particles and gases by precipitation from a cloud. The deposition from this process can be described by a *wet deposition velocity*, v_w analogous to the dry deposition velocity discussed in Section 2. The wet deposition velocity is defined as

$$v_w = \frac{W}{\bar{\chi}_0} \tag{23}$$

where W is the wet flux and $\bar{\chi}_0$ is the concentration in air at ground level.

The wet flux may be estimated from either the scavenging rate coefficient, Ψ_p, or the washout ratio, w_p. The scavenging rate coefficient, which is the more theoretical parameter, is usually defined as

$$\psi_p = \frac{K}{\bar{\chi}} \tag{24}$$

where K is the rate of removal of material from the air per unit volume and $\bar{\chi}$ the activity concentration in air.

The washout (or scavenging) ratio is defined as the ratio of the concentration in the precipitation to that in air, normally at ground level. This is

$$w_p = \frac{c_p}{\bar{\chi}_0} \tag{25}$$

where c_p = concentration in precipitation at ground level.

The washout ratio is much more easily measured than the scavenging rate coefficient. Essentially the washout ratio represents an integral of the scavenging rate coefficient and its corresponding air concentration:

$$w_p = \int_0^\infty \frac{\psi_p \cdot \bar{\chi}(z)}{p_0 \cdot \bar{\chi}_0} dz \tag{26}$$

where $\bar{\chi}(z)$ is the air concentration at height z and p_0 is the precipitation rate at the surface.

The wet flux W may be given as

$$W = p_0 \cdot w_p \cdot \bar{\chi}_0 \tag{27}$$

Then from Eqs (23) and (27), $v_w = w_p.p_0$

The wet removal of gases and particles is dependent on their chemical and physical properties, including solubility and particle size.

3.1.2. Run-off

Run-off is defined as that excess of deposited rainwater that is not retained on the area receiving the rainfall. As run-off water can carry away a part of the deposited radioactive material from roofs, roads and other hard surfaces through sewers, it clearly could be important for consequence assessments. The reason is that material deposited in urban areas may not all be retained there and in this case the dose to the urban population would be reduced.

The total run-off can consist of surface run-off and infiltration, i.e. the flow of water through the soil surface. Artificial surfaces in urban areas are mostly impervious. For these surfaces the following equation is valid:

$$Q_a = P - I_a \tag{28}$$

where Q_a is the actual direct run-off in mm, P the total rainfall in mm, and I_a the amount of precipitation in mm retained on the surface a. Ritchie et al. [39] assumed for an urban area that run-off from artificial surfaces would be essentially 100% for all rainfall exceeding 3 mm. If there has been rain within the previous hour the run-off is assumed to occur sooner.

In the model, Ritchie et al. [39] assumed that the concentration of radioactive material in the run-off water $c_{q,a}$ equals that in rainwater c_p. Experimental data on the retention of radionuclides on urban surfaces after wet deposition were not available before the accident at Chernobyl.

3.2. FIELD MEASUREMENTS

Roed [38] showed that the amount of run-off from roof material was very sensitive to the material used for the roofing. For a precipitation P = 9.2 mm just after the Chernobyl accident he found I_a values of 1.8 mm for cement tile, 4.2 mm for red tile, 1.4 mm for eternite (an asbestos type of material) and ~ 0 mm for silicon treated surfaces.

With the exception of iodine, the concentration of radioactive material in run-off water was found to be considerably less than that in the rainwater (Table IV).

TABLE IV. RELATION BETWEEN THE CONCENTRATION OF RADIOACTIVE MATERIAL IN RUN-OFF WATER TO THAT IN RAINWATER $(c_q / c_p)_a$, AS FOUND FOR A PRECIPITATION OF 9.2 mm [38]

Roof material	Cs	I [a]	Ru	Ba
Cement tile	0.49	1.24	0.56	0.40
Red tile	0.55	1.05	0.65	0.58
Eternite	0.14	1.18	0.3	0.37
Silicone treated eternite	0.74	1.00	0.52	0.67

[a] For iodine this ratio is greater than unity because dry deposited material was also washed off with the run-off water.

In more recent experiments at Risø, Roed [26] reports similar results for run-off of caesium on road surfaces. For a 6 mm artificial rainfall, he found the initially deposited rainfall for asphalt to be 3.8 mm and for concrete 3.4 mm. The ratio of the concentration of radioactive ^{137}Cs in run-off water to that in rainwater was 0.16 for asphalt and 0.21 for concrete. The bitumen content in new asphalt gives rise to greater run-off than for aged asphalt.

Thus it would seem reasonable to propose the following equation to describe the wet deposition of radioactive material:

$$u_w = c_p P - c_{q,a} Q_a \tag{29}$$

where u_w is the wet deposition density. We may expand this to incorporate the general result of Eq. (28) to derive an expression for the fraction of radioactive material retained by the surface, factored into components depending separately on the water retention and the concentration ratio of contaminant in run-off and precipitation:

$$\begin{aligned} \zeta &= \frac{u_w}{c_p P} = 1 - \frac{c_q Q}{c_p P} \\ &= 1 - \left(\frac{c_q}{c_p}\right)_{P,a} \cdot \left(1 - \frac{I_a}{P}\right) \end{aligned} \tag{30}$$

Roed and Sandalls [40] measured wet deposition on different surfaces in Gävle, Sweden, two years after the wet deposition from the Chernobyl accident; the results are given in Table V. The distribution of wet deposited material was found to be very dependent on the amount of run-off and on wall orientation. When considering walls the amount of rainwater deposited is dependent on the angle of the precipitation relative to the wall surface.

TABLE V. WET DEPOSITION MEASURED ON URBAN SURFACES IN GÄVLE, SWEDEN

Surface type	Location	Cs-137 (kBq m^{-2}) August 1988	Cs-134 (kBq m^{-2}) August 1988
Plain red brick wall in 5 storey building; south facing	Industrial rea	1.65 ± 9%	0.507 ± 16%
Plain red brick wall in 5 storey building; north facing		3.93 ± 7%	1.35 ± 10%
Yellow brick wall with roughened finish in single storey building; south facing		1.03 ± 11%	0.34 ± 24%
Yellow brick wall; north facing		0.42 ± 15%	0.15 ± 28%
Plastered wall; east facing		1.20 ± 10%	0.36 ± 18%
Grassed area		127 ± 5%	36.9 ± 6%
Plastered wall; south facing	Town centre	0.78 ± 11%	0.28 ± 20%
Plastered wall		0.55 ± 16%	0.19 ± 33%
Grassed area		85.2 ± 5%	24.1 ± 6%

The confidence limits given here refer to 2σ.

Together with measurements performed at Risø [23], in Munich [41], in Gävle [40], and very recent measurements at Risø [26], it is possible to state the distribution of deposited caesium and iodine just after deposition. These results are given in Table VI.

TABLE VI. RELATIVE DISTRIBUTION OF WET DEPOSITED CAESIUM (4–10 mm rainfall)

Surface	Activity retained per unit area of surface relative to that for grass	
	Cs-137	I-131
Grassed area	1	1
Paved areas	0.4–0.8	≈0–0.3
Roofs	0.3–0.9	≈0–0.4
Walls	0.003–0.03	0.01–0.03

3.3. DISCUSSION OF THE VAMP EXERCISE

3.3.1. Background of the exercise

The VAMP questionnaire dealt with the run-off of caesium and iodine for a wet deposition of 1 μm particles/aerosols. The very interesting problem of larger particles was excluded because of the lack of data. In addition only the problem of run-off from roofs was addressed, since these were the only available data that were not already published. The respondents to the VAMP questionnaire were asked to address the following problem:

A cloud of contaminated air arrives over an urban area just as it begins to rain. The rainfall has an intensity of 5 mm/h and lasts for two hours. The activity concentrations of ^{137}Cs and ^{131}I in the rainwater are 1000 Bq·L^{-1} and 10 000 Bq·L^{-1} respectively. The forms of ^{137}Cs and ^{131}I in the air are 1 μm AMAD aerosol and elemental iodine respectively.

What are the activity densities, in Bq·m^{-2} roof area, after the rainfall has ceased, on:

(a) a 3 year old red tile roof with a slope of 45 degrees and without moss or algae growing on it?

(b) a 3 year old silicon-treated corrugated roof with a slope of 30 degrees and no moss or algae growing on it?

The replies received are summarized in the Annex and evaluated below. Five of the respondents described the assumptions they used for the assessment of the radionuclide retention on the roofs. These descriptions are compiled and recorded in the Annex. The evaluation is confined to a precipitation of 10 mm on dry roofs. As has been shown in Section 3.2, the simple model of Ritchie [39] is not generally applicable for the run-off of contaminant, and a satisfactory description of the processes is still needed.

3.3.2. ^{137}Cs activity on roofs after wet deposition

In the case of red tiles, a relatively large amount of the deposited caesium was retained on the roof (68% according to the measurement). This was also expected by all respondents with one exception (who predicted 20% retention) (Fig. A-13).

The retention on the silicon treated corrugated roof material is much lower than on red tiles (18% according to the measurement). Again, this was expected by all respondents with one exception (who estimated 100% retention) (Fig. A-14). The authors agreed that the experimental evidence for such a high value is low.

3.3.3. ^{131}I activity on roofs after wet deposition

Owing to the higher solubility of ^{131}I in rainwater compared to ^{137}Cs, the retention is expected to be less. In the case of red tiles the retention of the two radionuclides was not very different. According to the measurement 43% of the iodine was retained. Only five respondents ventured answers to this problem, for which only one measurement is generally known (Fig. A-15). Obviously three of the respondents knew this datum whilst the other two gave rough estimates (100% and 0–20%).

For the silicon treated corrugated roof material the iodine activity retained on the roof was below the detection level. Three respondents gave correspondingly low figures (Fig. A-16). The experimental evidence for the other two answers (26% and 100%) is small.

4. CONCLUSIONS

Since the VAMP project was dedicated to the validation of models with field measurements obtained after the Chernobyl accident, the questionnaire was confined to problems for which the Working Group could obtain reliable field results. This condition excluded several important topics:

- Very few data existed in the western countries on the larger particulates deposited in the vicinity of the Chernobyl power plant. It can also be expected that the size distribution of particles was very different in the western countries after transport over more than 1000 km, compared with that in the vicinity of the release point.

- The distribution of the radioactive cloud with height and the zones of formation and growth of cloud particles were not known well enough to enable wash out to be adequately treated in the validation exercise.

- Deposition by means of hail, snow or fog were not included in the VAMP exercise because no data existed for Chernobyl radionuclides

Most of the models tested with the exercise had been adapted following the experience of the Chernobyl accident, especially since not much was known on deposition in urban environments before the Chernobyl accident. Indeed the accident has increased interest in this topic for two reasons:

- It became evident that the external radiation field can contribute a major part of the radiation exposure of the public and that it is important to be able to quantify exposures in urban and semi-urban environments.

- Experience in the former USSR has shown that the countermeasures that may be taken against external exposure (evacuation, relocation, decontamination and resettlement) have large impacts.

The enhanced interest in assessing the external exposure in urban environments allowed the VAMP project to test both older and more recently developed models for deposition against several well defined scenarios. However, it appeared that, for some of the problems formulated in the VAMP questionnaire, there was often only one reliable source of information, and that one could not necessarily generalize the models to other situations.

It is probably true to say that it is not possible to fully validate models, only to invalidate them. The results from respondents given in the Annex indicate, with one or two exceptions, that most models were not invalidated by the exercise. By this we mean that the model predictions **together with their associated statements of confidence** were not proven to be erroneous for the cases investigated. From the exercise we cannot say whether one model is better than another, simply because it has expressed less uncertainty in its prediction. This is because the need for greater

confidence in the value of a model parameter depends on the question to which a model is to be applied. For example, great confidence in the dry deposition velocity to walls may not be of importance in assessing the population dose-rate following a deposit, whereas it may be much more critical in deciding where to allocate resources for decontamination. However, from the exercise it is possible to identify modellers who should re-examine the assumptions and parameters of their models — these are obvious from the results presented in the Annex.

The question of uncertainties is a key one throughout the VAMP exercise, and there are many types involved. In this exercise we have divided the uncertainites into those related to the measurement and those related to the model predictions. The uncertainties in the model predictions have been assumed to be due to lack of knowledge in the mechanisms and parameters in the models used to answer the appropriate question (possibly because some parameter values were not specified in the problem definition, such as detailed particle size distributions and biomass density of trees). We have assumed the upper and lower bounds given by the respondents to represent (2.5%, 97.5%) subjective confidence intervals in their predictions. The measurement uncertainty has been taken to include not only those associated with counting statistics, calibration uncertainty, standard errors associated with averaging over repeated measurements, etc., but also the uncertainty associated with the appropriateness of the problem definition to the measurement condition.

4.1. DRY DEPOSITION

In the VAMP exercise the respondents were asked to assess with their models the dry deposition of 1 μm ^{137}Cs aerosols and gaseous ^{131}I on different urban surfaces. The evaluation of the answers in Section 2.3 was confined to the situation of a windspeed of 5 m s^{-1} at a height of 5 m. Systematic field data on the dependence of the deposition velocity on wind speed are missing.

Caesium-137 deposition with 1 μm aerosols on grass in urban areas appeared to be well described by deposition velocities in the range of $2 \times 10^{-4} - 1 \times 10^{-3}$ m s^{-1}, depending on the grass biomass per unit area. The lower value corresponds to grass biomass per unit area in the range of 0.2 kg m^{-2}, the upper value to about 0.8 kg m^{-2}. Caesium-137 deposition on roads is consistent with deposition velocities in the order of 1×10^{-4} m s^{-1}, and deposition on roofs in the order of 3×10^{-4} m s^{-1}, although in both cases possible dependences on several parameters, such as physico-chemical forms of the radionuclides, atmospheric turbulence conditions and humidity of the surface, are not known. The current knowledge on caesium deposition on walls, trees and internal surfaces is still very poor. Concerning the dry deposition of elementary ^{131}I the situation is similar to that for ^{137}Cs, although in general even less is known, and the deposition on roads is also very unclear in this case.

It has been shown [41] that following dry deposition internal surfaces, trees, lawns and roofs are potentially important sources contributing to external exposures in urban environments. Paved areas and walls are only important in surroundings with negligible amounts of vegetation. For basements without windows above ground the deposition in light-shafts is important. It may be concluded that for a more comprehensive understanding of external exposures in urban environments, the dry deposition on indoor surfaces and on trees would have to be known more adequately.

4.2. WET DEPOSITION

Very few direct measurements of the retention of radionuclides on urban surfaces are available. In cases with high retention (e.g. caesium on roofs with clay or concrete tiles, or streets with asphalt or concrete pavements) indirect measurements [40, 42], taking into account the effect of weathering, can be used to assess the initial surface activity. It seems to be fairly clear that for rain events of about 5–10 mm precipitation, about 30–80% of the deposited activity is retained on the surfaces. In cases where these indirect measurements cannot be used, due to a small fraction being initially retained or due to the short half-life of the radionuclide, the situation is much more unclear.

Almost nothing is known for wet deposition with precipitation below 5 mm and above 10 mm. To predict run-off for these conditions, modellers would have to make extrapolations for which no data exist. An exception is caesium on well retaining surfaces (see above) for small amounts of precipitation, for which a retention of 50–100% can be assumed.

Since roofs and paved areas are potentially important radiation sources in urban environments after wet deposition [41], it can be concluded that for a more comprehensive understanding of external exposures in urban environments, the run-off from these surfaces needs to be known more adequately, particularly if deposition of iodine or of large particles plays an important role.

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Annex

SUMMARY OF RESPONSES TO QUESTIONNAIRE No. 1

A-1. INTRODUCTION

This is a summary of the results of the first questionnaire circulated by the VAMP Urban Working Group to its participants.

The Group received a total of 19 replies from 8 countries and one international organization. To all of these participants, the Group would like to express its appreciation of their time and effort. A list of the respondents together with abbreviations used in the tables and figures of this summary is given in Table A-I.

The questionnaire comprised four technical sections, addressing **Data**, **Concepts** relating to deposition in the urban environment, **Models** for simulating deposition processes and Calculational **Problems** to test the concepts and models. The response to each of these sections is now discussed in turn.

A-2. DATA

Ten respondents reported that they had data that could be used to formulate scenarios for model validation purposes. The questionnaire asked respondents to indicate which of eleven key questions their data could be used to address. Table A-II indicates the replies received and the categories of data. The eleven key questions are listed below:

1. Do we understand the processes involving the dry deposition of caesium, tellurium, ruthenium and iodine on to trees, lawns and gardens, roofs and internal surfaces of buildings?

2. Are the processes of wet deposition onto and subsequent run off from trees, lawns and gardens, and roofs of buildings, of caesium, tellurium, ruthenium and iodine sufficiently well understood for purposes of dose assessment and assessment of the effectiveness of countermeasures?

3. Are the Chernobyl data consistent with our understanding of the mechanisms by which caesium and ruthenium concentrations change as a function of time on trees, roofs of buildings, internal surfaces of buildings and at various depths under lawns and gardens?

4. To what extent is the Chernobyl release unique in terms of the behaviour of the radioactive material in the urban environment?

5. Do current models correctly predict the absorbed dose rate in air above a contaminated area of lawn/soil/garden of known activity profile as a function of time?

6. Do current shielding models correctly predict the absorbed dose-rate inside a building, given knowledge of the activity configuration, building geometry and construction?

7. Are the processes by which contaminants are fixed to urban surfaces adequately understood, and can the removal factor likely to be achievable by various different treatments be estimated?

8. Can models correctly predict the reduction in dose rate obtained by various means of decontamination (e.g. ploughing of lawns and gardens, hosing of streets, roofs and walls - removal of soil, removal of trees, etc.)?

9. Does ^{7}Be act as an analogue for caesium in all situations that might be of interest?

10. Can models estimate the radiological hazard associated with air conditioning filters?

11. Are the processes of resuspension in the urban environment sufficiently understood?

Of the 11 questions, it was felt that data were available for considering ten of them. It is recognized that it would be useful if respondents could provide references for the data if they had

TABLE A-I. RESPONSES TO QUESTIONNAIRE No. 1

No.	Abbreviation	Respondent
1.	-	Brian Y. Underwood, UK Atomic Energy Authority, United Kingdom
2.	Sandia	Hong-Nian Jow, Sandia National Laboratories, United States of America
3.	AEA1	K. W. Nicholson, UK Atomic Energy Authority, Harwell, United Kingdom
4.	Ups	Allan Rodhe, University of Uppsala, Sweden
5.	AEA2	F. J. Sandalls, UK Atomic Energy Authority, Harwell, United Kingdom
6.	-	B. T. Wilkins, National Radiological Protection Board, United Kingdom
7.	IC	A. J. H. Goddard, Imperial College, United Kingdom
8.	IFE	Ulf Tveten, Institutt for Energiteknikk, Norway
9.	LSK	H. Bonka, Lehrgebiet Strahlenschutz in der Kerntechnik, Germany
10.	-	K. B. Stadie, OECD/NEA, France
11.	GSF	Peter Jacob, Gesellschaft für Strahlen- und Umweltforschung[a], Germany
12.	NRPB	Joanne Brown, National Radiological Protection Board, United Kingdom
13.	-	Ulf Bäverstam, Statens Stralskyddsinstitutt, Sweden
14.	CRNL	Peter Barry, Chalk River Nuclear Laboratories, Canada
15.	SSI	Olof Karlberg, National Institute of Radiation Protection, Sweden
16.	BS	H. de Witt, Brenk Systemplanung, Germany
17.	JAERI	Hideo Matsuzuru, Japan Atomic Energy Research Institute, Tokai-mura, Naka-gun, Ibaraki-ken, Japan
18.	NRI	Jan Hornya, Nuclear Research Institute, Czech Republic[b]
19.	RISØ	Jorn Roed, Risø National Laboratory, Denmark (measurement)

[a] Now the GSF - Forschungszentrum für Umwelt und Gesundheit.

[b] Formerly Czechoslovakia.

TABLE A-II. KEY QUESTIONS OF SECTION A-2 FOR WHICH RESPONDENTS CONSIDERED THEIR DATA COULD BE USEFUL

Respondent	Country	1	2	3	4	5	6	7	8	9	10	11
AEA1	UK	*		*								*
Ups	Sweden	*	*	*	*							
AEA2	UK		*	*		*		*	*			
IC	UK						*	*	*			*
IFE	Norway			*	*	*	*	*	*			
GSF	Germany		*	*		*	*					
BS	Germany			*				*	*			
SSI	Sweden	*	*	*		*			*			
NRI	Czech Republic					*	*					
RISØ	Denmark	*	*	*		*		*	*	*		

been published. The Working Group recommends that those respondents who indicated that they had valuable data for testing models and/or clarifying some of the topics addressed in Questionnaire No. 1 be asked to consider providing their data for examination by the Group. On the other hand there were no data identified that could be used for assessing the radiological hazard of air conditioning filters. This was disappointing as such information must surely exist.

In addition to the eleven key questions elucidated at the previous VAMP meeting, respondents were asked whether there were any other issues to which the Working Group should devote attention. These issues have been considered by the members of the Working Group and their responses are reproduced here alongside the original proposals.

Several respondents had suggested that the group look further into physico-chemical forms of the pollutants. In particular, the National Radiological Protection Board (NRPB) suggested consideration of their solubility, Sandia National Laboratories recommended addressing dry deposition as a function of particle size and Imperial College suggested trying to understand such aspects in the indoor environment. Also with regard to the indoor environment, Imperial College London expressed a wish that the group consider the mechanical transport of particulate material into buildings and infiltration processes. The Working Group decided that these subjects should be addressed in future questionnaires, not as a separate subject, but integrated into the other problems raised. Indeed, the questions of particle size and infiltration have already been incorporated into Questionnaire No. 2.

Relating to deposition, Tveten (IFE, Norway) suggested that there was a need to consider the non-uniform distribution of deposited activity as a function of small to moderate differences in slope (such as over ditches, hillocks, etc.). The Group considered this to be interesting, but because it was so complex and data were apparently so poor, considered that these problems should not be addressed specifically within the VAMP programme.

Moving on to questions of retention of activity on building surfaces, NRPB wanted the group to consider the mechanisms of fixation of radioactive material to urban surfaces, whilst Brenk Systemplanung, in a related way, suggested gaining understanding of the main parameters influencing the decontamination of urban surfaces. These topics will be given consideration in the Group's Questionnaire No. 3.

Two respondents suggested consideration of the fate of radionuclides entering drainage and sewerage systems, Sandalls for reasons of understanding, Tveten for use as an indicator of levels of urban contamination. The Working Group decided to extend the objectives of the work and to include these topics in Questionnaire No. 3.

Additionally, it was agreed that the concept of using the ^{7}Be analogy for caesium be extended to other nuclides.

A-3. CONCEPTS

The section of the questionnaire relating to concepts asked for a description of the deposition processes of relevance to the urban environment. To a large degree, the responses were in agreement about the key processes. A summary of the responses is given in the following:

- In dry conditions airborne pollutant material is brought into the vicinity of the surface by atmospheric turbulence, by a process which is a function of both 'external' meteorology and the micrometeorology amongst the surface projections. If the material is gaseous, it then diffuses across the boundary layer in the immediate vicinity of surfaces and their projecting elements, and is absorbed by physical and chemical mechanisms. If particulate in nature, it may make its final transfer to the surface via turbulent impaction (with interception) or Brownian diffusion depending on particle size.

- During rain, pollutant is taken up by drops as they fall (or as they are formed) and deposited directly onto surfaces, some of which will be pervious and some impervious. In the latter case, runoff will be especially important, with subsequent transfer to sewers. The degree of initial retention of the pollutant will depend on the nature of the surface and on the physicochemical form of the pollutant.

- Within urban areas there are ranges of both natural and man-made surface types, geometries and configurations. There are inherent difficulties in ascribing dry deposition rates for given surface types. The dry deposition rate will certainly depend on prevailing meteorological conditions and also on topographical features that could influence the meteorological or atmospheric conditions within a locality. A better description of urban areas would be needed to assess these effects.

- Precipitation (i.e. rain or snow) in urban areas is most likely to be intercepted by upwards facing surfaces, such as pavements, roads, roofs, lawns, etc. The degree of run-off will be dependent on the porosity of the surface and the affinity of the surface for the deposited chemical species, as well as orientation (ie. slope or camber).

- Snow will contaminate all horizontal and sloping surfaces, but leave little material on vertical surfaces. The material deposited with snow is likely to be left on the surface as the snow melts. If the snow melts forming standing water, then the interception factors are probably similar to those for rain. What happens when snow melts without the ground becoming wet is not clear.

- With regard to fog, the urban heat island will alter the frequency and characteristics of fog. If fog penetrates into the city, pollutant may become incorporated into droplets (or new droplets may form on it) enchancing the local rate of deposition compared to that in dry conditions.

- Deposition to internal surfaces reflects the effects of the lower air concentration indoors than outdoors (typically a factor of 0.3) due to the filtering effects of buildings. We would expect deposition to all internal surfaces, with roughly equal deposition to the ceiling and walls of a room. Other surfaces would have different depositions because of the different surface properties. Thus, deposition to carpets would be larger than that to walls. All surfaces in the room would be contaminated to a greater or lesser extent.

A-4. MODELS

This section presents the models described by the respondents. The questions are listed along with a compilation of the corresponding answers.

Models are developed in order that certain problems or questions can be answered to an adequate degree of accuracy. Do you have models that include the simulation of the deposition of contaminants in an urban environment?

Yes: **7, 9, 11a, 11b** under development, **12, 14, 15, 16, 17.**
No: **1, 2, 3, 4, 5, 6, 7, 8, 10, 13.**

If yes, what is the name of the model?

7: DHOMO
11a: ECOSYS.
12: EXPURT
14: CURB
15: OSCAAR
17: UNIDOSE

Do you have a report or publication on the model?

Yes: **7, 8, 9 in press, 11a, 12, 17.**
No: **11b, 14, 15.**

Please give a summary of the model that you use for deposition of contaminants in the urban environment, listing the independent variables and parameters for the model, the processes simulated and the output of the model.

1. We do not have a model specific to deposition in an urban environment. Perceived differences would be handled via an adjustment of parameters in the model currently used.

3. None other than conceptual models.

7. The DHOMO model has been developed to incorporate the research results as they are acquired at Imperial College and elsewhere. The model addresses indoor exposure primarily.

8. Only the possibility of modifying models really valid for rural condition and even those simplified.

11a. ECOSYS.

11b. Model under development.

Input: different possibilities, for example:

- activity in air and precipitation, amount of precipitation;
- contamination of different urban surfaces;
- decontamination factors;
- resident time.

Output: external exposure as a function of time.

12. Dry and wet (rain) deposition are modelled. Deposition onto roofs, external walls, interior surfaces (dry deposition only) paved areas/roads and grass/soil is considered.

Parameters which describe deposition processes in the model:

(1) Ratio of dry deposition on each urban surface to that on grass/soil (element dependent).

(2) Fraction of dry deposition that is mobile compared to fixed.

(3) Interception of wet deposited material by each relevant surface. Rest of activity is in the runoff water from the surface.

The principal independent variables are the magnitude of wet and dry deposition for given weather conditions.

The output of this part of the model is the mobile and fixed activity on each surface, and, for wet deposition, the activity in the runoff water. In general, EXPURT has not been used in the past for element dependent calculations of deposition although it is flexible enough to take into account element dependent parameter values if necessary.

14. The model allows for both wet and dry deposition with time and precipitation dependent rates of fixation and runoff. Five surface categories include roofs, walls, paving, grass and trees. Within each category the model permits several types of each surface material to be defined, e.g. roads may be asphalt or concrete. Suburban and downtown environments are defined by areas of each type of surface. To be added later are runoff effects to receiving bodies (lakes, rivers, etc.), especially after snowmelt. Also to be added is precipitation as snow with accumulation during the winter.

15. **Dry deposition**

Deposition velocity concept is used in the puff dispersion model with variable trajectories.

Wet deposition

Washout coefficient approach is used with time and spatial variable rainfall distributions.

Output

Ground contamination.
Groundshine dose (short term and long term)

17. It is similar to the CRAC code with a gaussian dispersion model and cloudshine, groundshine, inhalation and ingestion dose pathways. A grid area could be denoted urban or rural and different parameter values could be assigned. Model output are CCDF curves of doses, health-effects, etc. or detailed information at single meteorological situations. The model works with the PRISM code for uncertainty analysis.

Please mark below for what types of problem the model is used:

7,9,12,16: Scientific purpose to research mechanisms.

1,2,11a,12,14,15,16,17,18:

Prediction of external radiation doses in risk assessment situations.

2,15: Prediction of resuspension doses.

1,2,11a,11b,12,15:

Assessment of effectiveness of different countermeasure options.

1,11a,11b: Sheltering.

1: Evacuation.

1,11b,12: Decontamination.

1,11a: Predictions of external radiation doses in real emergency situations.

11b: Scientific purpose to research influence of different parameters on external exposure and to improve models.

Does your model distinguish between deposition in different meteorological conditions?

Yes: **1, 2, 9, 11a and 11b, 12, 15, 17(?).**

If yes, can your model simulate deposition by:

Fog: **1 and 9.**

Snow: **2, 9, and 15.**

Rain: **1, 2, 9, 11a, 11b, 12, 14, 15, 17.**

Does your model/parameters distinguish between different physico-chemical forms of contaminants?

Yes: **2, 9, 11a, 12, 14, 15, 17, 18.**

If yes, please indicate which:

Form of iodine: **9, 11a, 12, 14, 15.**

Particle size: **2 and 15.**

Does your model/parameters distinguish between the different surfaces in an urban environment? If so, please list the surfaces considered.

1: Has surface categories.

9: Vegetation and other surfaces.

11b: Windows, walls, roofs, basement windows, light shafts, paved areas, trees, lawns, indoor surfaces.

12: Roofs, walls, interior building surfaces, paved areas/roads, grass/soil.

14: Roofs, walls, pavements, grass, trees, clay, asphalt, asphalt shingles, concrete, brick, aluminum and vinyl siding.

18: Plants (grass, trees), soil, artificial surfaces (roads, roofs), house walls.

When rain occurs, part of the rainwater is lost rapidly from the surface onto which the rain has fallen into the sewer system. In hydrology this phenomenon is called runoff. Does your model explicitly take into account runoff in predicting deposition to an urban environment?

Yes: **2, 11b, 12, 14, 17.**
No: **1, 9, 11a (only implicitly), 15.**

Is your model capable of explicitly predicting the quantities of radionuclides that are lost to the drainage system and subsequently into the aquatic environment?

Yes: **2, 12, 14.**
No: **1, 9, 11a, 11b, 15, 17.**

If all the parameters in your model were known exactly, how uncertain, in your opinion, would the results of your model then be?

9: factor 2.
12: outdoors 5, indoors 10.
15: factor 3.
17: factor 5.

Please list the key references on which your model/parameters for deposition in an urban environment is based.

2: NUREG/CR-2300, "PRA Procedure Guide", Appendix D, 1982.

11a: Schwarz, G., Deposition and Post-Deposition Behaviour of Radionuclides in Urban Environment, IN Proc. CEC Workshop on Methods for Processing the Off-Site Radiological Consequences of Nuclear Accidents, Luxembourg, 15-19 April 1985, pp. 533-599 and references therein (1986). Edts, F. Luykx and J. Sinnaeve. Commission of the European Communities. Directorate-General Information Market and Innovation, Bâtiment Jean Monnet, Luxembourg.

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TABLE A-III BEST ESTIMATES OF DRY DEPOSITION PER UNIT AREA (Bq m^{-2}) OF DIFFERENT URBAN SURFACES

Responses to Problem 1

	Respondent No										
Nuclide	SURFACE	2*	3*	5	9	11*	12	14*	17	18	Measurement
Cs-137	- grass	$3\ 10^{5}$	$2\ 5\ 10^{5}$	$1\ 10^{5}$	$4\ 10^{4}$	$1\ 8\ 10^{5}$	$3\ 6\ 10^{5}$	$2\ 1\ 10^{5}$	$1\ 1\ 10^{6}$	$1\ 8\ 10^{5}$	$2\ 10^{5}$
	- roads	$3\ 10^{4}$	$1\ 8\ 10^{5}$	$4\ 10^{4}$	$2\ 10^{4}$	$3\ 6\ 10^{4}$	$3\ 6\ 10^{4}$	$2\ 6\ 10^{4}$	-	$7\ 2\ 10^{4}$	$2\ 4\ 10^{4}$
	- walls	-	$3\ 6\ 10^{3}$	$4\ 10^{3}$	10^{4}	$9\ 0\ 10^{3}$	$3\ 6\ 10^{4}$	$6\ 2\ 10^{4}$	-	$8\ 0\ 10^{3}$	$3\ 10^{3}$
	- roofs	$3\ 10^{4}$	$1\ 4\ 10^{5}$	$7\ 10^{4}$	$4\ 10^{4}$	$9\ 0\ 10^{4}$	$3\ 6\ 10^{4}$	$2\ 5\ 10^{5}$	-	$7\ 2\ 10^{4}$	$1\ 10^{5}$
	- trees	$3\ 10^{6}$	$5\ 4\ 10^{5}$	$2\ 10^{5}$	$2\ 10^{5}$	$9\ 0\ 10^{5}$	$3\ 6\ 10^{6}$	$2\ 6\ 10^{5}$	-	$1\ 8\ 10^{5}$	$2\ 5\ 10^{5}$
	- indoor	$3\ 10^{5}$	-	$4\ 10^{3}$	-	-	$3\ 6\ 10^{3}$	-	-	$7\ 2\ 10^{4}$	$6\ 10^{3}$
I-131	- grass	$1\ 10^{6}$	$2\ 10^{6}$	$7\ 10^{5}$	$3\ 10^{6}$	$1\ 8\ 10^{6}$	$3\ 6\ 10^{6}$	$2\ 5\ 10^{6}$	$3\ 6\ 10^{6}$	$9\ 0\ 10^{5}$	$2\ 4\ 10^{6}$
	- roads	$1\ 10^{5}$	$2\ 10^{6}$	$2\ 10^{5}$	$1\ 10^{6}$	$3\ 6\ 10^{5}$	$3\ 6\ 10^{4}$	$1\ 7\ 10^{5}$	-	$3\ 6\ 10^{5}$	$1\ 4\ 10^{5}$
	- walls	-	$1\ 10^{6}$	$1\ 10^{5}$	$1\ 10^{6}$	$9\ 0\ 10^{4}$	$3\ 6\ 10^{4}$	$1\ 1\ 10^{5}$	-	$4\ 0\ 10^{4}$	$1\ 1\ 10^{5}$
	- roofs	$1\ 10^{5}$	$1\ 10^{6}$	$7\ 10^{5}$	$1\ 10^{6}$	$9\ 0\ 10^{5}$	$3\ 6\ 10^{4}$	$1\ 1\ 10^{6}$	-	$3\ 6\ 10^{5}$	$1\ 1\ 10^{6}$
	- trees	$1\ 10^{7}$	$3\ 10^{6}$	$4\ 10^{6}$	$1\ 5\ 10^{7}$	$9\ 0\ 10^{6}$	$3\ 6\ 10^{7}$	$3\ 0\ 10^{6}$	-	$9\ 0\ 10^{5}$	$2\ 9\ 10^{6}$
	- indoor	$1\ 10^{6}$	-	$4\ 10^{3}$	$1\ 10^{6}$	-	$3\ 6\ 10^{3}$	-	-	$3\ 6\ 10^{5}$	$5\ 10^{4}$

* Figures were changed to these values by the participant after a first review

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A-5. PROBLEMS

A-5.1. Problem 1

A radioactive cloud arrives over an urban area in dry conditions, the wind speed at 5 m height is 5 m/s and the integrated concentration of activity in air of ^{137}Cs particles of 1 μm AMAD is 100 000 Bq.h/m^3, whilst that of ^{131}I in elemental form is also 100 000 Bq.h/m^3. What is the deposition density, in Bq/m^2, on a grass area in a town park, on the roads and pavements, on the external wall of a house, on the roof of a house, on trees in an urban area and on indoor surfaces? Please describe any assumptions you make.

(Respondents were asked to provide best estimates and lower and upper bounds of uncertainty.)

TABLE A-IV. LOWEST AND HIGHEST RESULTS FOR THE BEST ESTIMATES ON RADIONUCLIDES DRY DEPOSITED ON DIFFERENT URBAN SURFACES (Bq m^{-2})

Responses to Problem 1

Radionuclide	Deposition density (Bq m^{-2})				
	Lowest value		Highest value		Number of
Surface	Respondent	Deposition (Bq m^{-2})	Respondent	Deposition (Bq m^{-2})	responses
Cs-137					
Grass	9	$4\ 10^4$	17	$1.1\ 10^6$	10
Roads	9	$2\ 10^4$	3	$1.8\ 10^5$	9
Walls	19 (meas.)	$3\ 10^3$	14	$6.2\ 10^4$	8
Roofs	2	$3\ 10^4$	14	$2.5\ 10^5$	9
Trees	18	$1.8\ 10^5$	12	$3.6\ 10^6$	9
Indoor	12	$3.6\ 10^3$	2	$3\ 10^5$	5
I-131					
Grass	5	$7\ 10^5$	12, 17	$3.6\ 10^6$	10
Roads	12	$3.6\ 10^4$	3	$2\ 10^6$	9
Walls	12	$3.6\ 10^4$	3, 9	$1\ 10^6$	8
Roofs	12	$3.6\ 10^4$	14, 19 (meas.)	$1.1\ 10^6$	9
Trees	18	$9\ 10^5$	12	$3.6\ 10^7$	9
Indoor	12	$3.6\ 10^3$	2, 9	$1\ 10^6$	6

Problem 1 was addressed by 10 of 18 respondents on the questionnaire other than RISØ who provided the scenario. In one case (response No. 15) the deposition on all surfaces was assumed to be the same. This response was not included in the following summary. Table A-III lists the best estimates reported by the respondents. Deposition values measured in a situation like the one described in the problem are also included in the table. Some participants have been asked to reconsider their values because of apparent errors. Any subsequent change of the results has been marked by an asterisk in Table A-III. Best estimates together with error bars based on the expression of upper and lower bounds are summarized in Figs A-1 to A-12.

The lowest and the highest best estimate for each radionuclide and deposition area are summarized in Table A-IV. The range of these results is about one order of magnitude for ^{137}Cs on grass, roads, walls, roofs and trees and for elementary (gaseous) ^{131}I on grass. In the case of grass, the mass area density (E) of grass was not stated in the problem, although it is considered an important parameter for the deposition velocity (v_d). It has been agreed that the Working Group should consider whether a representative value of E (e.g. 0.4 kg m^{-2}) should be assumed for urban areas. It has been suggested that the problem should perhaps be reconsidered for a fixed mass density of grass. Different models for the dependence of the deposition velocity on the mass area density have been proposed for discussion at the next session of the Working Group. For example:

$$v_d = v_0 \left(\frac{E}{E_0} \right)$$

$$v_d = v_0 \left(\frac{E}{E_0} \right)^{0.67}$$

$$v_d = v_{max} \left(1 - e^{-E/E_0} \right)$$

where E_0 = 1 kg m^{-2}, v_0 is the corresponding deposition velocity, and v_{max} is the limiting deposition velocity as $E \rightarrow \infty$.

TABLE A-V. BEST ESTIMATES OF DRY DEPOSITION PER UNIT AREA ON DIFFERENT URBAN SURFACES RELATIVE TO THE DEPOSITION ON GRASS

Responses to Problem 1

Ratio of deposition density on urban surface to that on grass by Respondent No.

	2	3	5	9	11	12	14	18	Measurement
Cs-137									
Grass	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Roads	0.1	0.7	0.4	0.5	0.2	0.1	0.1	0.4	0.12
Walls	-	0.01	0.04	0.25	0.05	0.1	0.3	0.04	0.015
Roofs	0.1	0.6	0.7	1.0	0.5	0.1	1.2	0.4	0.5
Trees	10	2	2	5	5	10	1.2	1.0	1.3
Indoor	1.0	-	0.04	-	-	0.01	-	0.4	0.03
I-131									
Grass	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Roads	0.1	1.0	0.3	0.3	0.2	0.01	0.07	0.4	0.06
Walls	-	0.5	0.1	0.3	0.05	0.01	0.04	0.04	0.05
Roofs	0.1	0.5	1.0	0.3	0.5	0.01	0.4	0.4	0.5
Trees	10	1.5	6	5	5	10	1.2	1.0	1.2
Indoor	1.0	-	0.006	0.3	-	0.001	-	0.4	0.02

For depositions on urban surfaces other than grass, the database is small. For some surfaces the lowest and highest values for the best estimates reported on the questionnaires differ by more than two orders of magnitude. The Working Group should consider whether these values could be inferred from existing knowledge and should try to identify the most important fields of uncertainties.

Table A-V summarizes the deposition on the various urban surfaces relative to grass as deduced from Table A-III. In most cases, with the exception of ^{131}I on trees, the range is the same as for the absolute depositions. As mentioned earlier, it would be of interest to have responses on the same problem with a well defined mass density of grass. The remarks of the participants indicate that the nature of the roofs, the size of the trees, and the ventilation rate in the houses should have been defined in the problem.

A-5.2. Problem 2

A cloud of contaminated air arrives over an urban area just as it begins to rain. The rainfall has an intensity of 5 mm/h and lasts for two hours. The activity concentrations of ^{137}Cs and ^{131}I in the rainwater are 1000 Bq/L and 10 000 Bq/L respectively. The forms of ^{137}Cs and ^{131}I in the air are 1 μm AMAD aerosol and elementary iodine respectively.

What are the activity densities, in Bq/m^2 of roof area, after the rainfall has ceased on:

(a) A 3 year old red tile roof with a slope of 45° and without moss or algae growing on it?
(b) A 3 year old silicon treated corrugated roof material with a slope of 30° and no moss or algae growing on it?

Please give best estimates, as well as lower and upper bounds of uncertainty.

(Text cont. on p. 49)

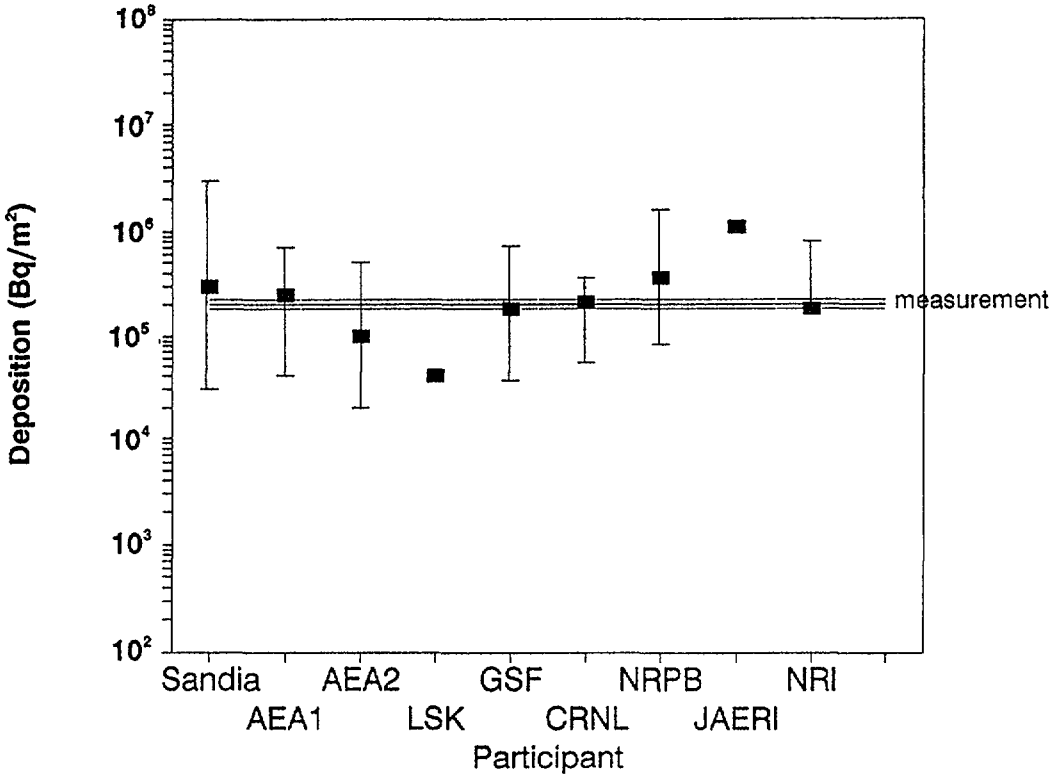

FIG. A-1. Estimates of ^{137}Cs dry deposition on grass.

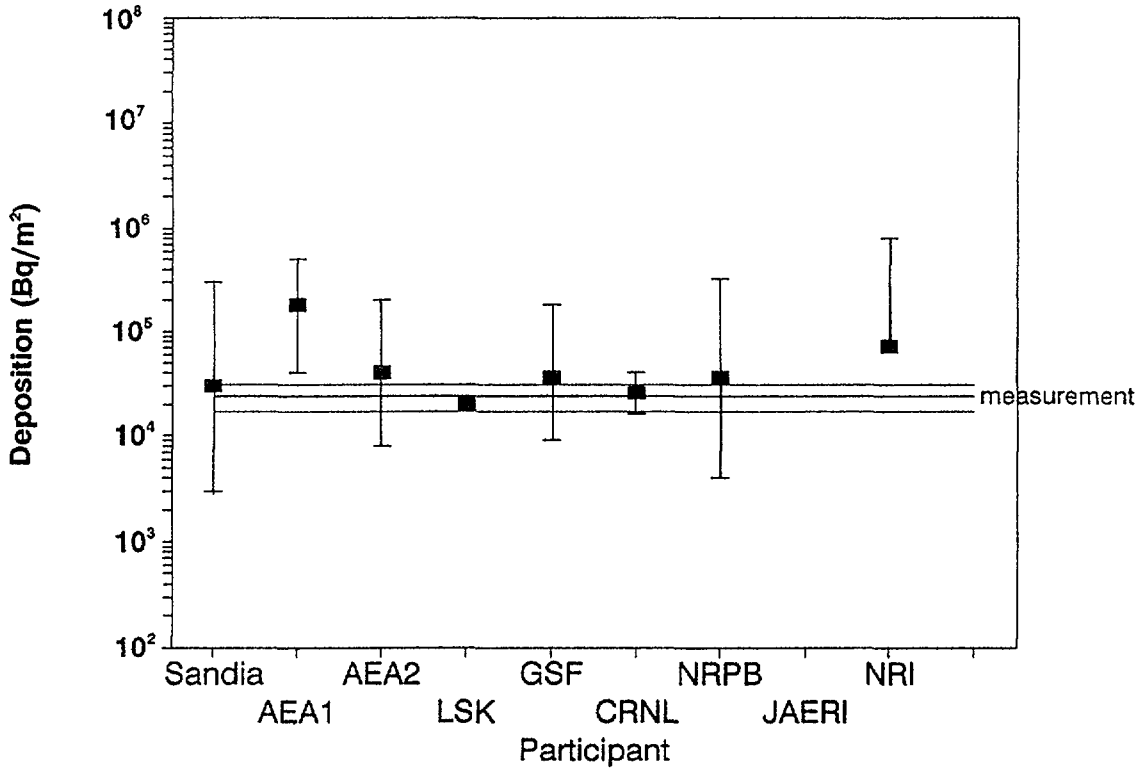

FIG. A-2. Estimates of ^{137}Cs dry deposition on roads.

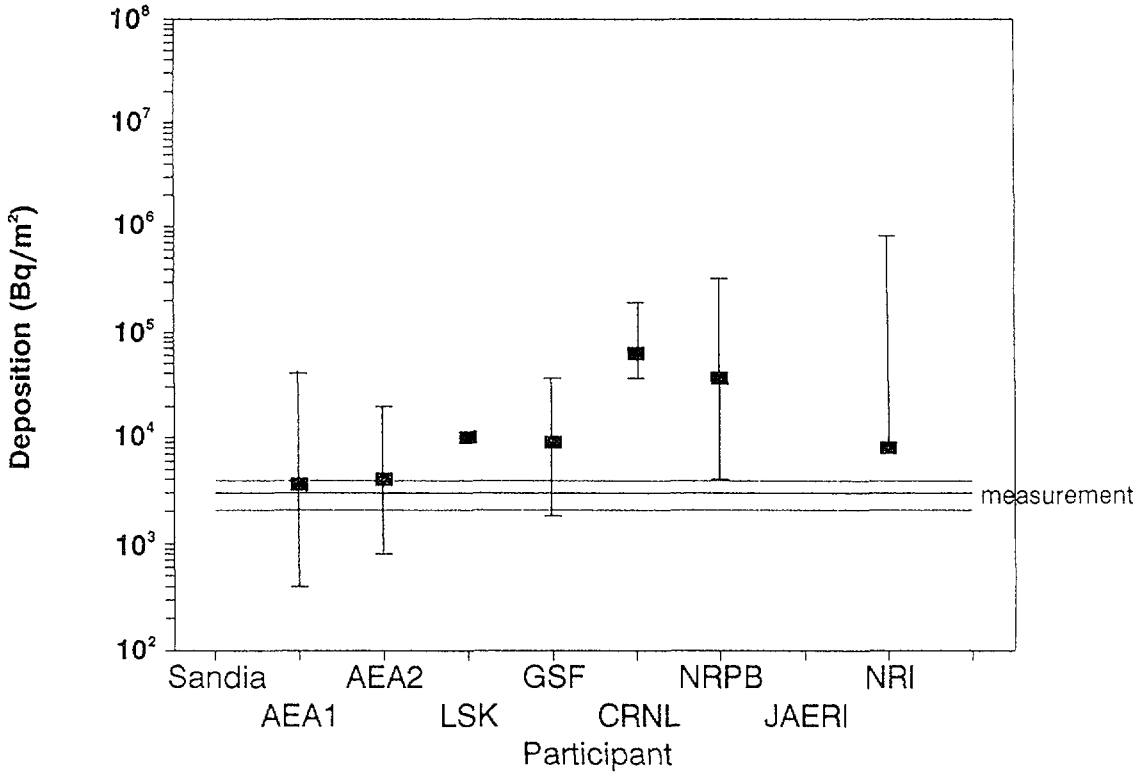

FIG. A-3. Estimates of ^{137}Cs dry deposition on walls.

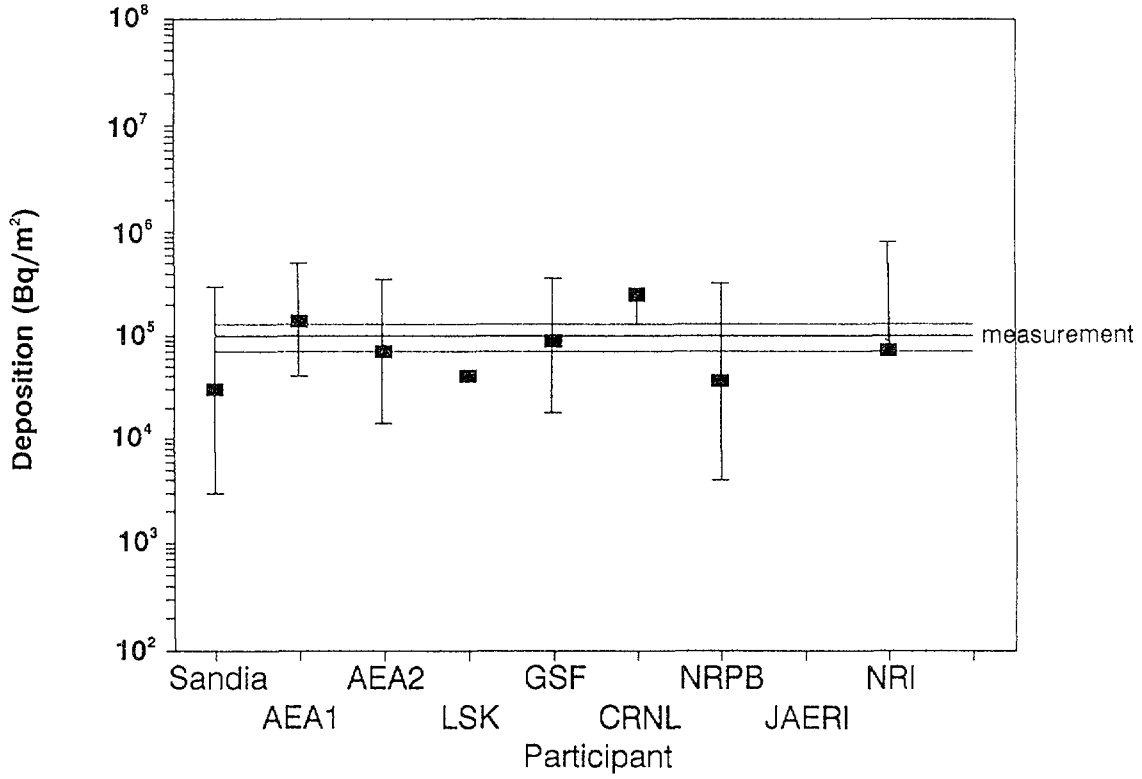

FIG. A-4. Estimates of ^{137}Cs dry deposition on roofs.

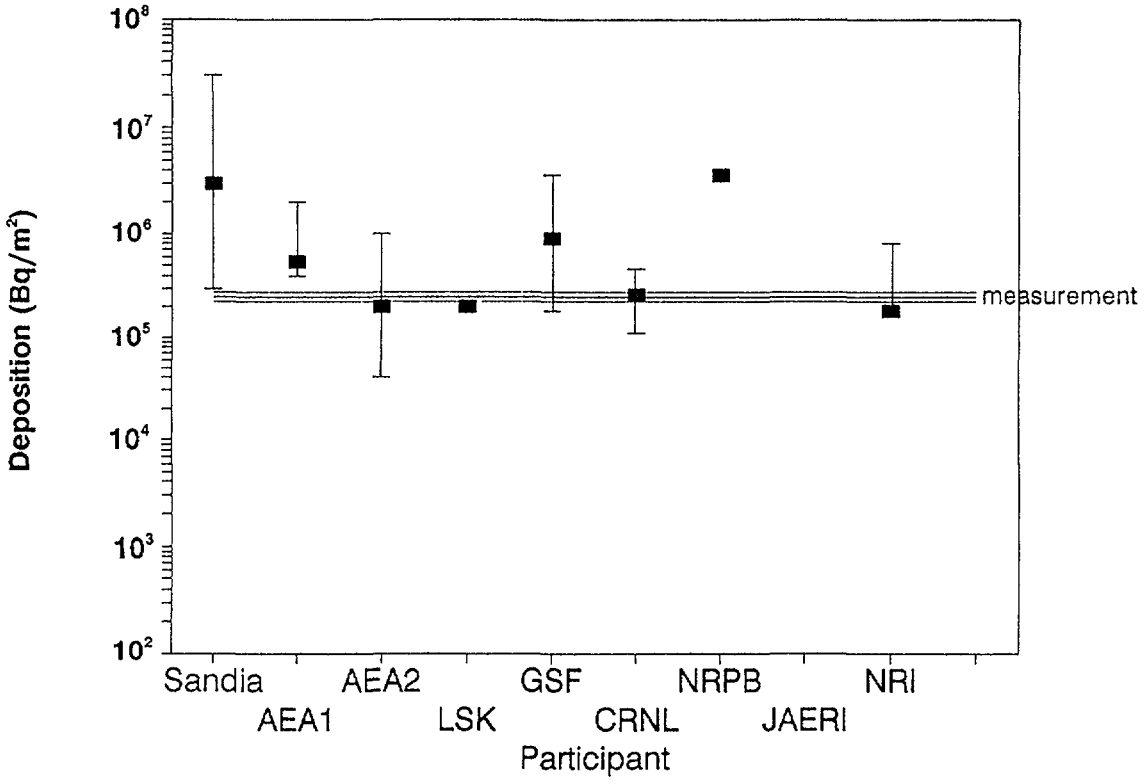

FIG. A-5. Estimates of ^{137}Cs dry deposition on trees.

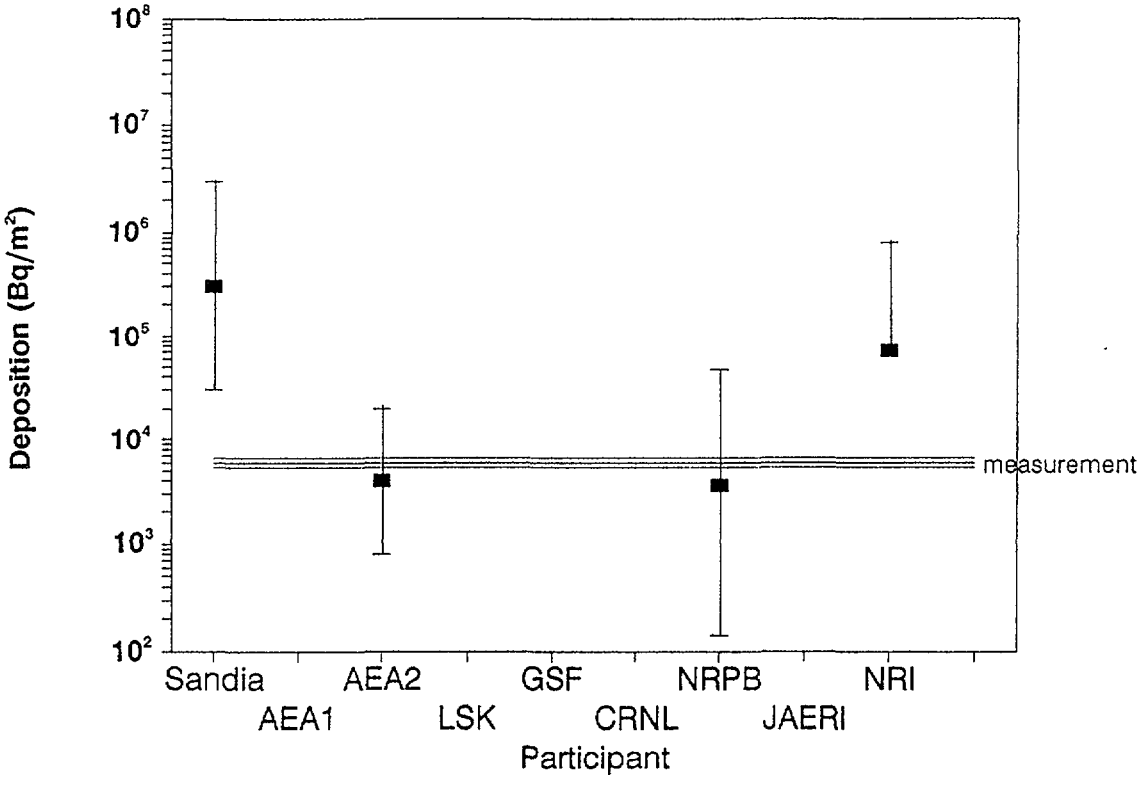

FIG. A-6. Estimates of ^{137}Cs dry deposition on internal surfaces.

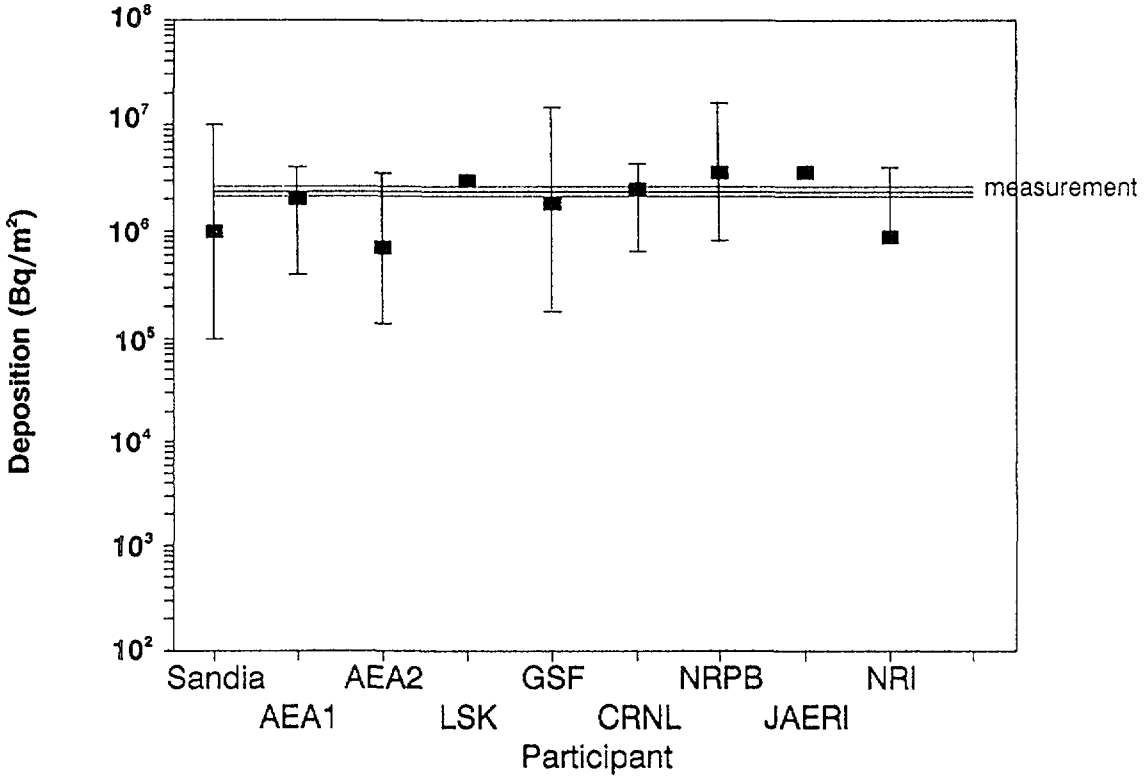

FIG. A-7. Estimates of elemental ^{131}I dry deposition on grass.

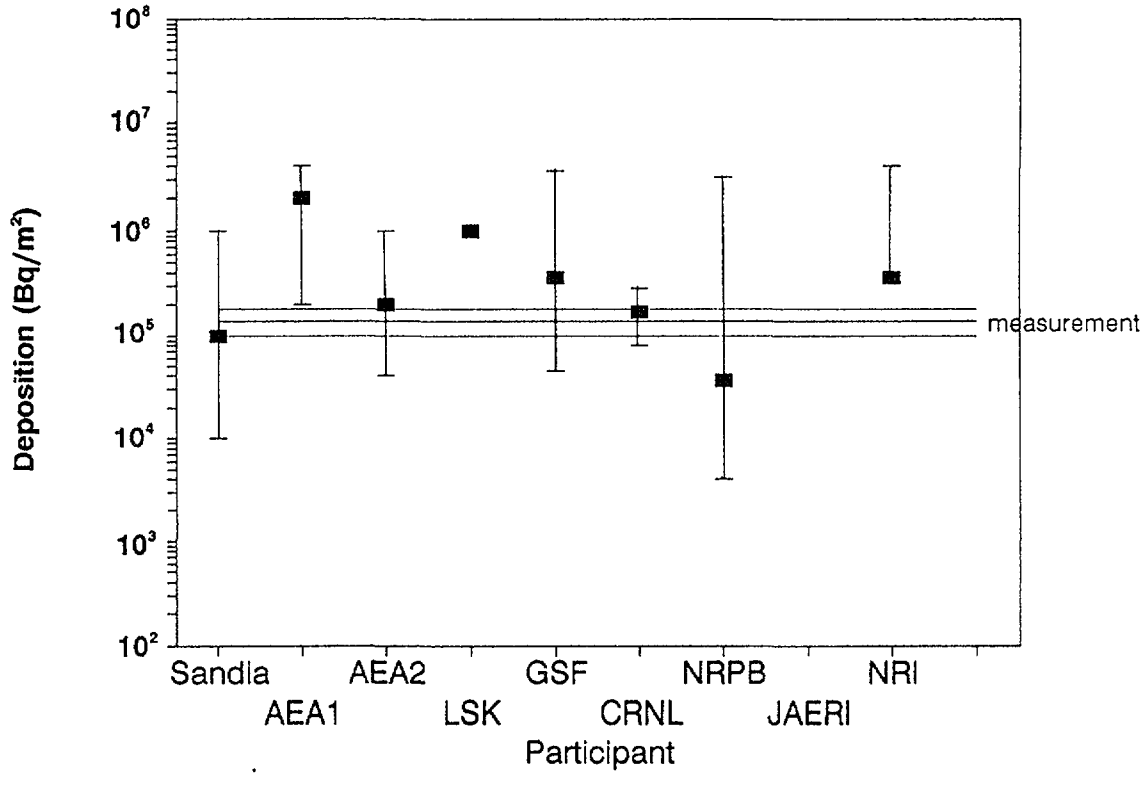

FIG. A-8. Estimates of elemental ^{131}I dry deposition on roads.

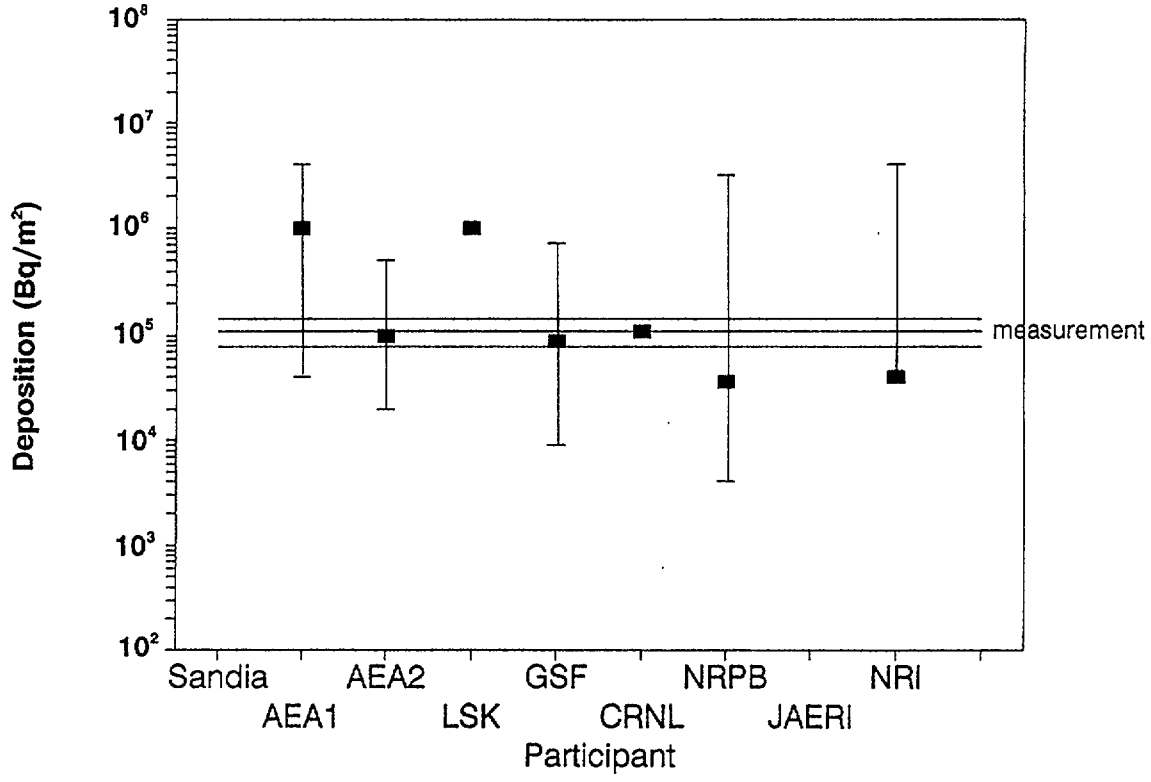

FIG. A-9. Estimates of elemental ^{131}I dry deposition on walls.

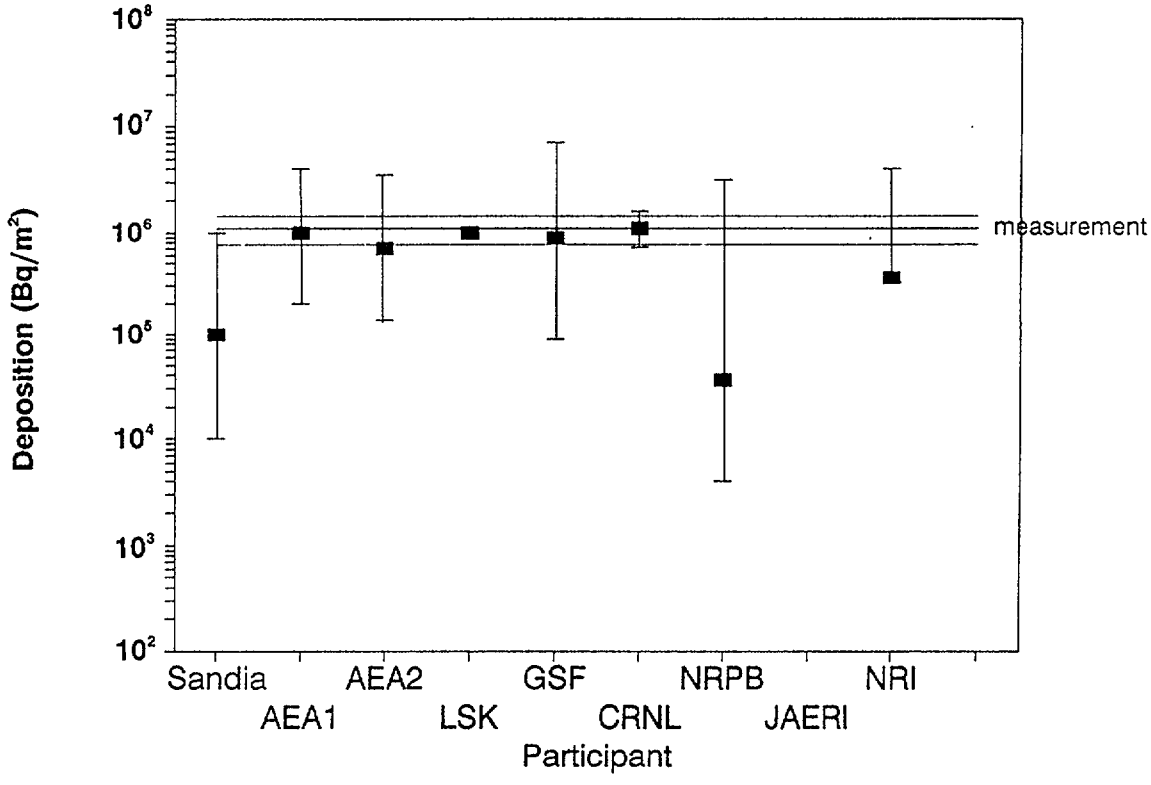

FIG. A-10. Estimates of elemental ^{131}I dry deposition on roofs.

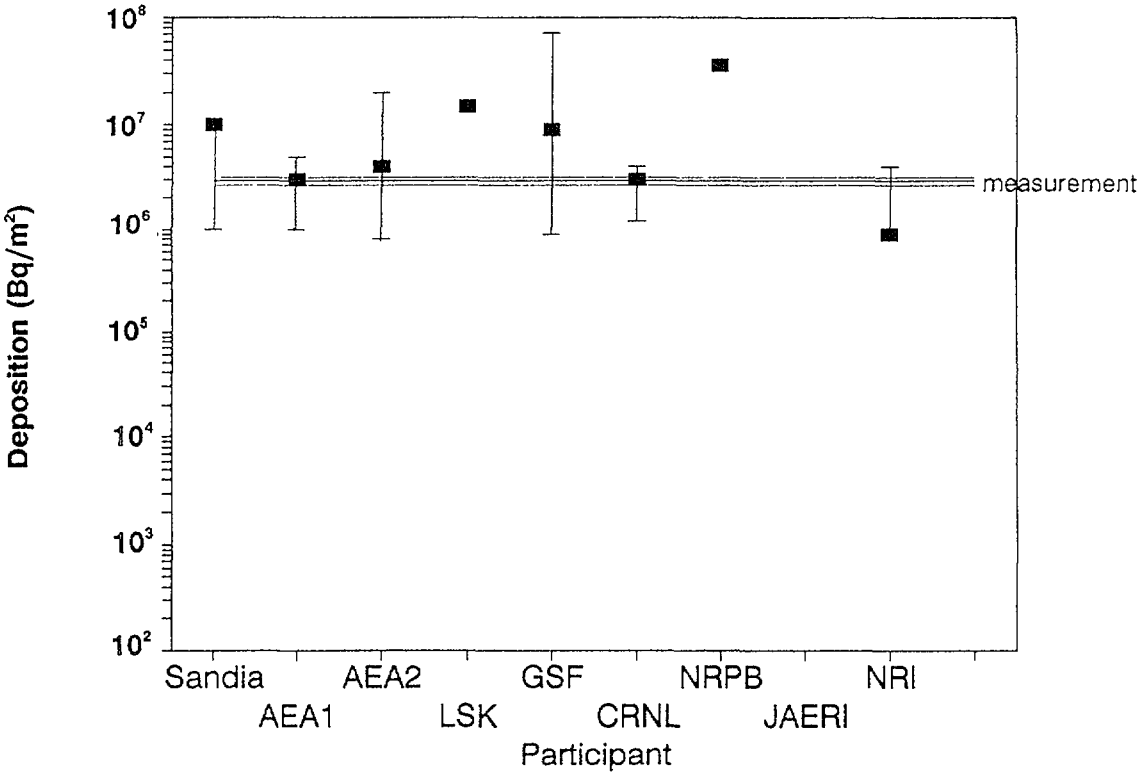

FIG. A-11. Estimates of elemental ^{131}I dry deposition on trees.

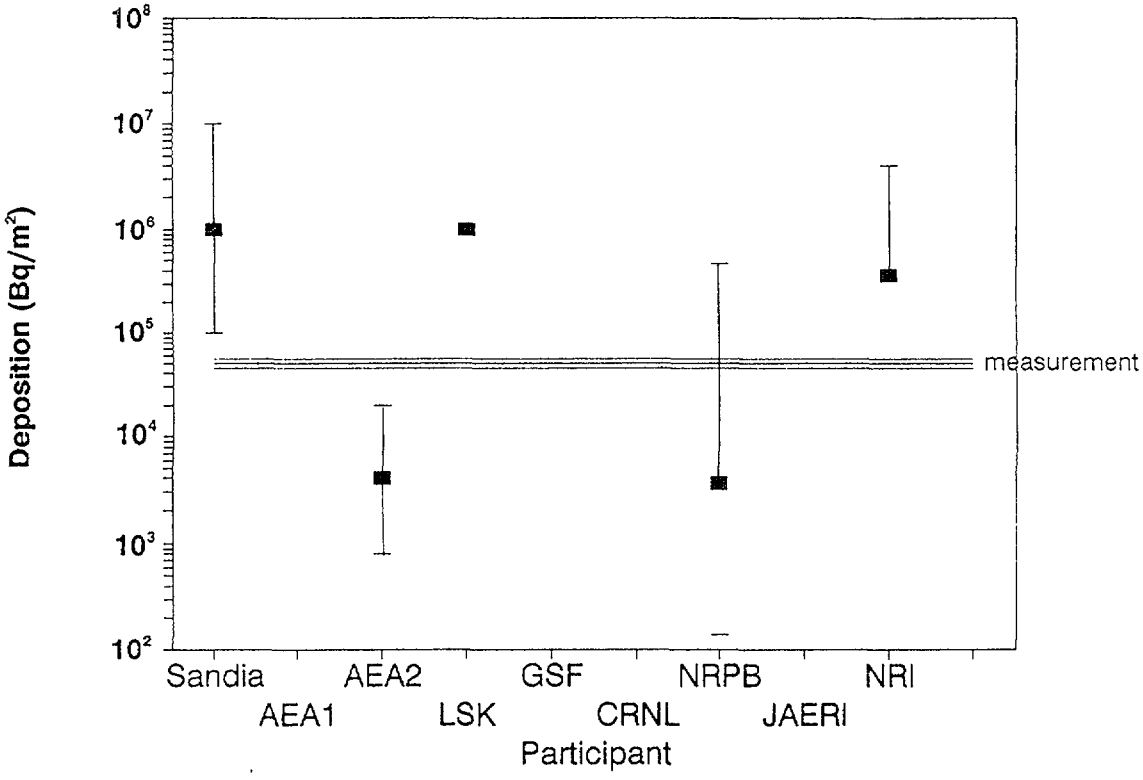

FIG. A-12. Estimates of elemental ^{131}I dry deposition on internal surfaces.

TABLE A-VI. ACTIVITY DENSITY ON ROOF AREA AFTER A WET DEPOSITION EVENT

Responses to Problem 2

	Activity density by Respondent No. (kBq m^{-2})									
	3	5	8[a]	11[b]	12	14*	15	17	18	Measurement
Red tile										
Cs-137	5	6.8	-	6.5	3.5	6.8	2	10	2-7	6.8
I-131	-	43	-	-	35	43	-	100	0-20	43
Silicon treated corregated roof material										
Cs-137	3.5	1.8	3	-	2.6	1.8	2	10	0-2	1.8
I-131	-	5	-	-	26	0	-	100	0-20	0

[a] After some months.
[b] Figures were changed to these values by the participant after a first review.
* Measurement.

Table A-VI and Figs A-13 to A-16 summarize the results given by nine respondents and results of a measurement after the reactor accident of Chernobyl. Compared to Problem 1 on dry deposition, the results show smaller variation (exception: ^{131}I on silicon treated corregated roof material). One participant assumed that all of the activity deposited was retained on the roof. The lowest estimates for ^{137}Cs were for an interception of 20% for the red tile and of 18% for the silicon treated tile. For iodine only five of the participants gave results, reflecting the very small database.

The following comments were given by the participants on their models for the calculation:

Number	Comment	
3	Cs:	Interception = cos (angle of slope)assessed retention, Retention = 70% for red tile, Retention = 40% for silicon treated roof.
5	I:	0.5mm of rain remains on the silicon treated roof to dry after cessation of rainfall.
11	Cs:	Runoff after 3mm of rain with 50% of initial concentration for the red tile.
12	I & Cs:	50% interception for red tile and 30% interception for silicon treated roof.
17	Cs:	80% runoff.

Some authors used the cosine of the angle of slope of the roof to calculate the activity density per unit roof area. This implies that the deposition per projected unit area is independent of the slope in these models.

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Research Co-ordination Meetings
Vienna, Austria: 2–6 May 1988, 5–8 December 1989,
4–8 March 1991, 2–6 March 1992, 5–9 July 1993

Consultants Meetings
Vienna, Austria: 13–14 October 1988, 14–16 August 1989,
25–29 June 1990, 10–14 December 1990,
8–12 July 1991, 9–13 December 1991,
18–22 January 1993

RECENT IAEA PUBLICATIONS ON DOSE ASSESSMENT MODEL VALIDATION

1989 Evaluating the Reliability of Predictions Made Using Environmental Transfer Models (Safety Series No. 100)

1992 Modelling of Resuspension, Seasonality and Losses during Food Processing. First report of the VAMP Terrestrial Working Group (IAEA-TECDOC-647)

1994 Assessing the Radiological Impact of Past Nuclear Activities and Events (IAEA-TECDOC-755)