What if a ‘dirty bomb’ scenario involved a strong, not readily soluble beta-particle emitting contaminant ?

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Some important radionuclides of concern in connection with ‘dirty bombs’

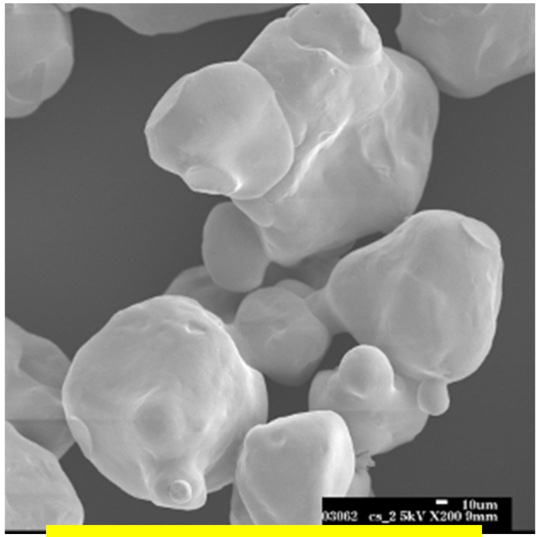
Radionuclide	Typical physicochemical form of large existing sources	Existing strong sources and their strengths
^{60}Co	Metal (can be dissolved in acid - liquid)	Sterilisation irradiator (up to 400,000 TBq). Teletherapy source (up to 1000 TBq)
^{90}Sr	Ceramic ($SrTiO_3$) - insoluble, brittle, soft (Mohs hardness: 5.5), can be powdered	Radioisotope thermoelectric generator (1000-10.000 TBq)
^{137}Cs	Salt (CsCl) (can be dissolved - liquid)	Sterilisation irradiator (up to 400,000 TBq). Teletherapy source (up to 1000 TBq)
^{192}Ir	Metal – soft - Mohs hardness 6.5 (can be powdered), insoluble in water	Industrial radiography source (up to 50 TBq)
^{226}Ra	Salt ($RaSO_4$) (can be powdered), very low solubility	Old therapy source (up to 5 TBq)
^{238}Pu	Ceramic (PuO_2) - insoluble, can be powdered	Radioisotope thermoelectric generator (up to 5,000 TBq)
^{241}Am	Pressed ceramic powder (AmO_2)	Well logging source (up to 1 TBq).
^{252}Cf	Ceramic (Cf_2O_3) - insoluble	Well logging source (up to 0.1 TBq).

(see, e.g., Harper et al., 2007; Ferguson et al., 2003)

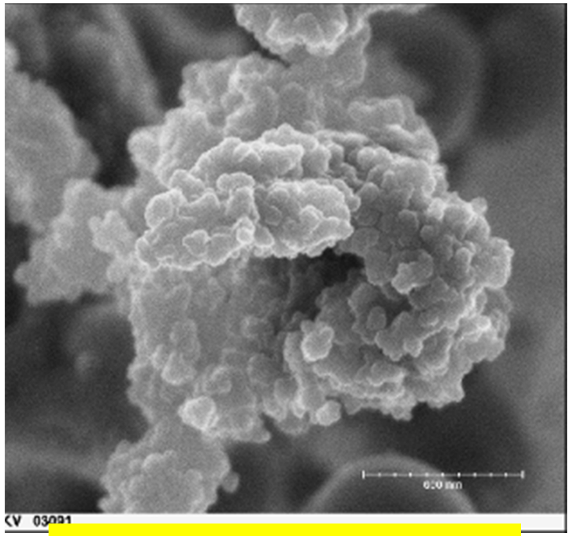
Suitability for aerosolisation and dispersion

Harper et al. (Sandia Natl. Lab.), 2007

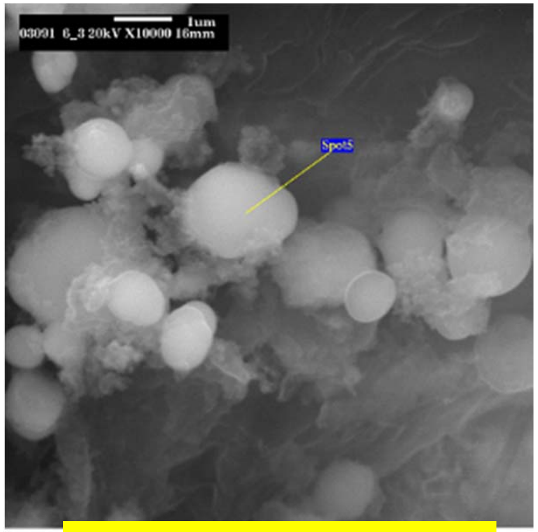
Powders: Depends on, e.g., original powder size and porosity
Phase transition possible at high pressure
Typically 20-80 % aerosolised



Initial salt grains (large)



Shock sublimation of salts (< 1 µm)



Shock melting of salts (< 10 µm)

Suitability for aerosolisation and dispersion

Harper et al. (Sandia Natl. Lab.), 2007

Powders:	Depends on, e.g., original powder size and porosity Phase transition possible at high pressure Typically 20-80 % aerosolised
Ceramics:	Typically 2-40 % aerosolised
Metals:	Very little cobalt (<0.2 %) aerosolised
Liquids:	Formation of (slightly) submicroneous particles after evaporation, depending on construction. Almost full aerosolisation is possible.

Debris of ^{60}Co after high explosion

’Orphaned’ ^{90}Sr sources


IAEA

Example of ’orphaned’ sources:
Two containers, each with 1300 TBq ^{90}Sr, found in a forest in Georgia in 2002.

For comparison, the total ^{90}Sr release from Chernobyl was estimated to ca. 8000 TBq (Sohier, 2002).

The US Dept. of Defense cooperative threat reduction program has expressed concern that material from RTG’s can be used by terrorists to construct a ‘dirty bomb’

Particle size spectrum for ceramics

Much of the mass in the 30-100 µm range, and smaller peak at a few microns (Harper et al., 2007)

In-line with measurements made after the Thule accident in 1968 (also a conventional explosion dispersing a solid, low solubility, radioactive material with a very high melting point).

In Thule, only 1.3 % of the particles were larger than ca. 18 µm, but these carried nearly 80 % of the activity.

Pinnick et al. (1983) consistently found similar spectra when conducting blast experiments impacting on different soils.

Relevant particle sizes and their pre and post deposition behaviour are not considered in current European decision support systems.

The near zone of a blast

Shrapnel and large particles will deposit within short distance

Example of gravitational settling of large particles

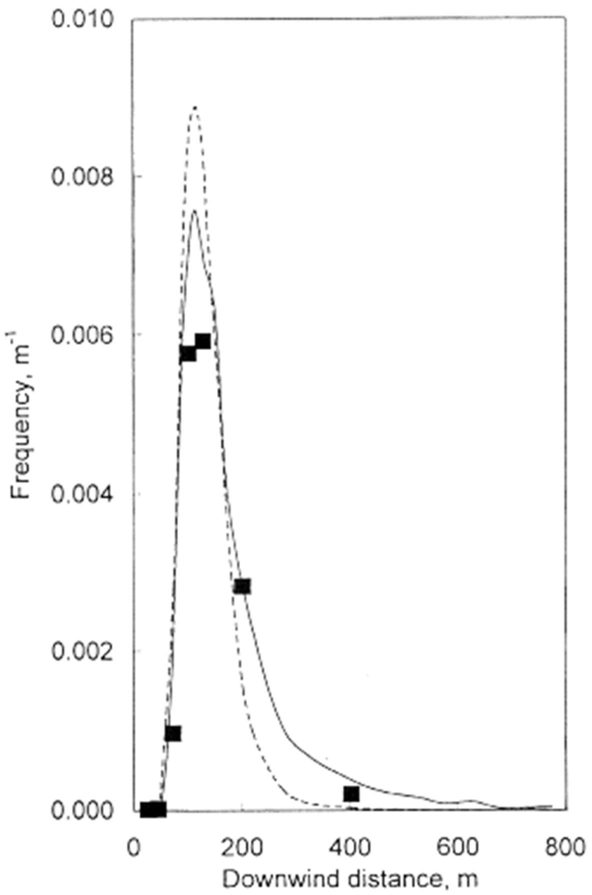


Fig. 1. Deposition curve for the conditions corresponding to those of the original Trial 5 (average wind speed at the release height, $u_{15\,\mathrm{m}} = 7.31\,\mathrm{m\,s^{-1}}$, $z_0 = 0.023\,\mathrm{m}$): (■ experimental data points (Hage, 1961); - - - - FDM; —— PTM).

Dispersion of 50-100 µm glass particles

Release height 15 m

The air is clean within one minute.

Scenario specific assumptions

Focus on atmospheric dispersion of particles outside ’blast zone’

Ceramic: 10 % of activity in 5-10 µm particles (the rest large)

^{90}Sr particles not readily soluble (prior application)

Fraction of time spent outdoors over long periods is 15 %

People are outdoors during plume passage

Weather is dry on day of attack

Ventilation rate is 0.4 h^{-1}

Contaminants washed 1 cm down in soil after 10 days

Time spent outdoors for simplicity assumed to be in large open soil areas (dose contributions from other surface types excluded here)

Deposition velocities, filter factor, inhalation rate, dose conversion factors, weathering/clearance rates, etc. from new ARGOS data libraries

Simplified dose estimates from a ’dirty bomb’

External dose from contamination on outdoor surfaces

External dose from contamination on indoor surfaces

External dose from contamination on human skin

Committed dose from inhalation during plume passage

- all described relative to contamination level on grassed reference surface

Generally of less importance in this context:

External dose from the passing contaminated plume

Committed dose from inhalation of resuspended contaminated dust

External dose from contamination on outdoor surfaces

Only dose to skin calculated. Dose to inner organs would typically be 3 orders of magnitude lower (Eckerman & Ryman, 1993)

External dose calculated using a probably highly conservative factor of 4 10^{-11} Sv h^{-1} per Bq m^{-2} on the ground surface (suggested by HPA-RPD, 2005, for decision support).

Contamination assumed to be washed 1 cm down in soil after 10 days (heavy rain). This will reduce dose rate by 3 orders of magnitude (Eckerman & Ryman, 1993).

Skin dose estimate:
15 % · $4 \cdot 10^{-11}$ Sv h^{-1} per Bq m^{-2} · 10 days · 24 h day^{-1} ~ $1 \cdot 10^{-9}$ Sv per Bq m^{-2}.

Much smaller dose to skin protected by even thin layers of clothing.

Dose contributions from contamination on other surfaces are not included in this simplified example, but should be included for decision support.

External dose from contamination on indoor surfaces

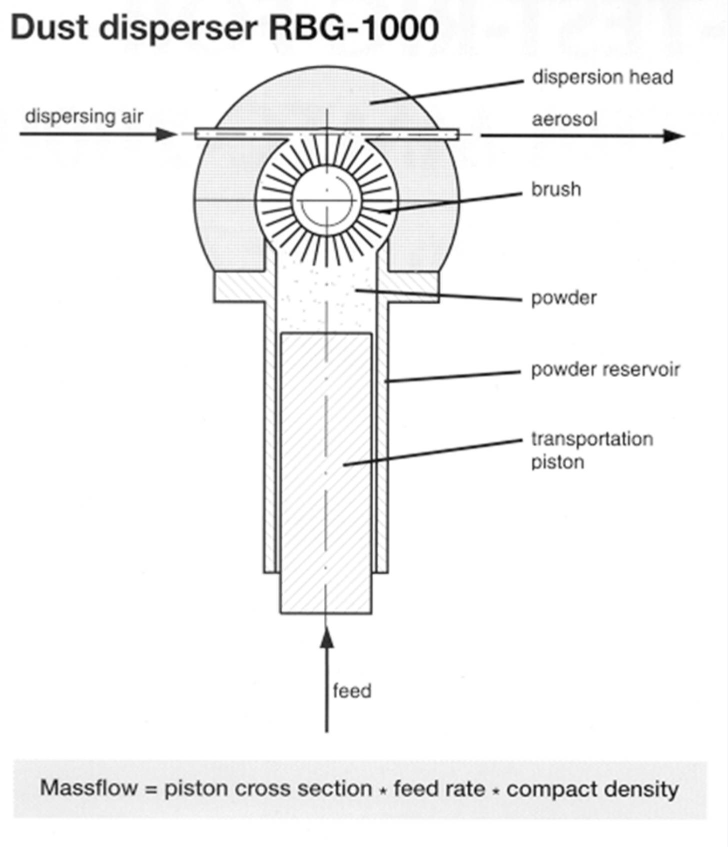
Again, only dose to skin calculated. Dose to inner organs would typically be 3 orders of magnitude lower (Eckerman & Ryman, 1993)

Deposition on indoor surfaces (floor):
$D_i \sim (D_0/ v_{d,0})\ h\ f\ \lambda_d\ \lambda_v / (\lambda_d + \lambda_v)$, where D_0 is the corresponding deposition on the grassed reference surface, $v_{d,0}$ is the deposition velocity to the reference surface, h is the room height, f is the filtering factor, λ_d is the rate coefficient of deposition indoors, and λ_v is the rate coefficient of ventilation of the dwelling. With typical values, $D_i / D_0 \sim 0.1$.

Assuming an indoor natural clearance half-life of 60 days and 85 % time spent indoors, the dose becomes (60 d/10 d) · 0.1 · 0.85/0.15 = 3 times that from contaminants deposited on outdoor surfaces, or in other words, $3 \cdot 10^{-9}$ Sv per Bq m^{-2} on the horizontal outdoor reference surface.

Dy and In particle emission in a test room

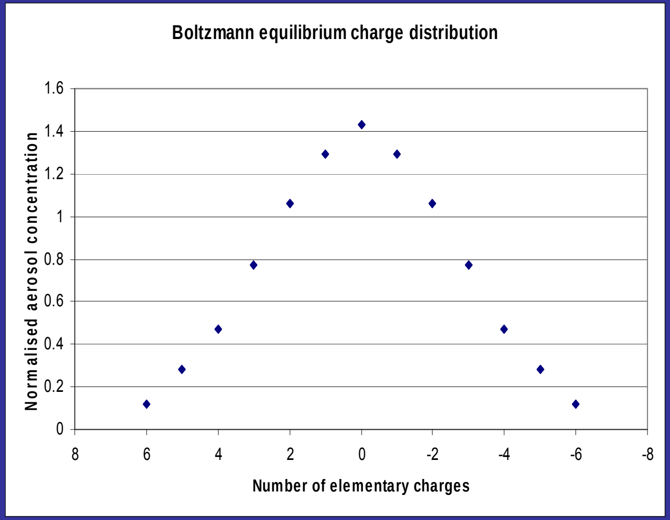
Palas RBG 1000 powder dispersion generator



Dy and In particle emission in a test room

Palas RBG 1000 powder dispersion generator

Ni-63 source in outlet



Dy and In particle emission in a test room

Palas RBG 1000 powder dispersion generator

Ni-63 source in outlet

Nebulisation of indium acetyl-acetonate powder dispersed in alcohol

Medical nebuliser

Dy and In particle emission in a test room

Palas RBG 1000 powder dispersion generator

Ni-63 source in outlet

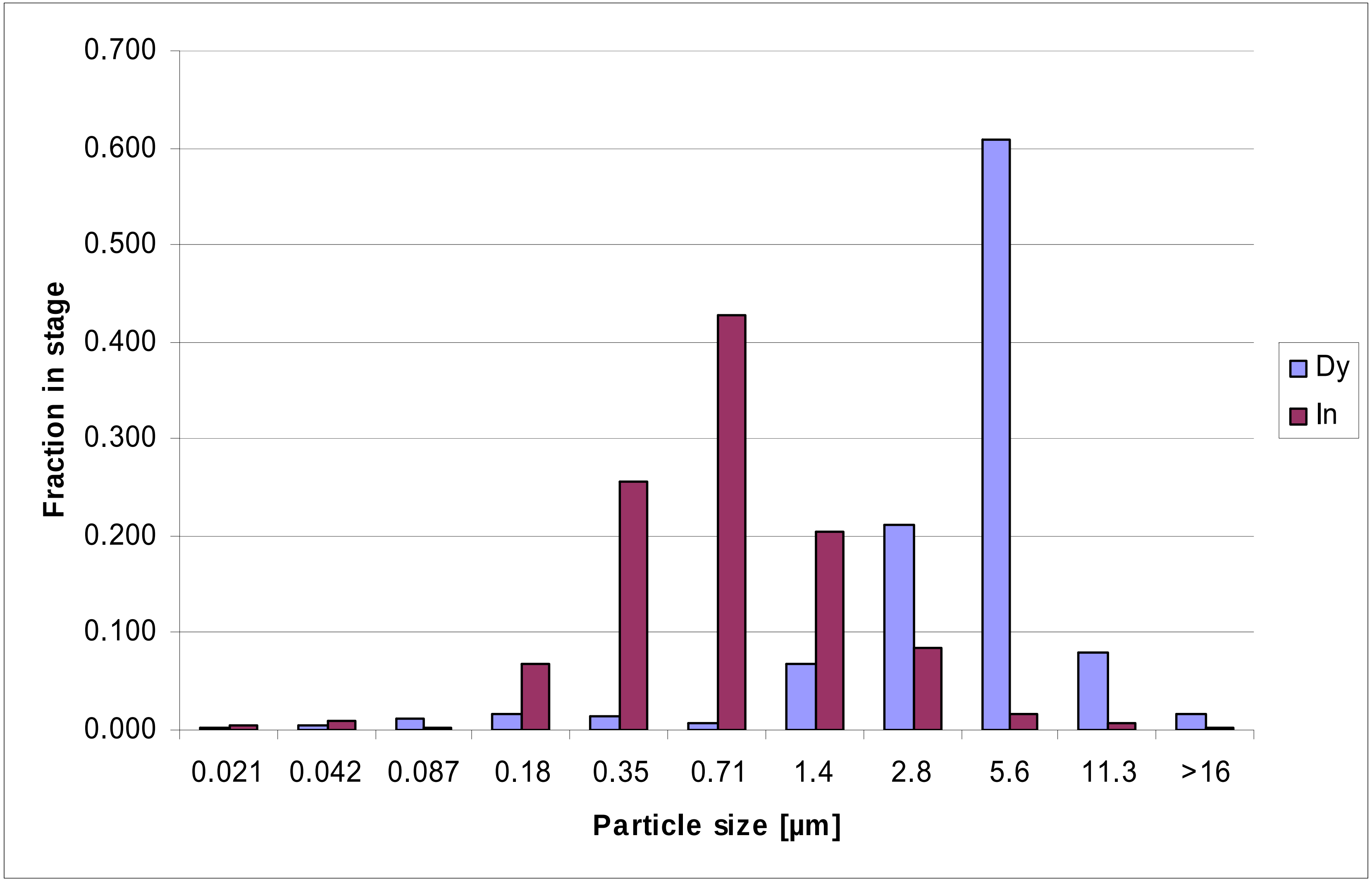
Nebulisation of indium acetyl-acetonate powder dispersed in alcohol

Ventilator

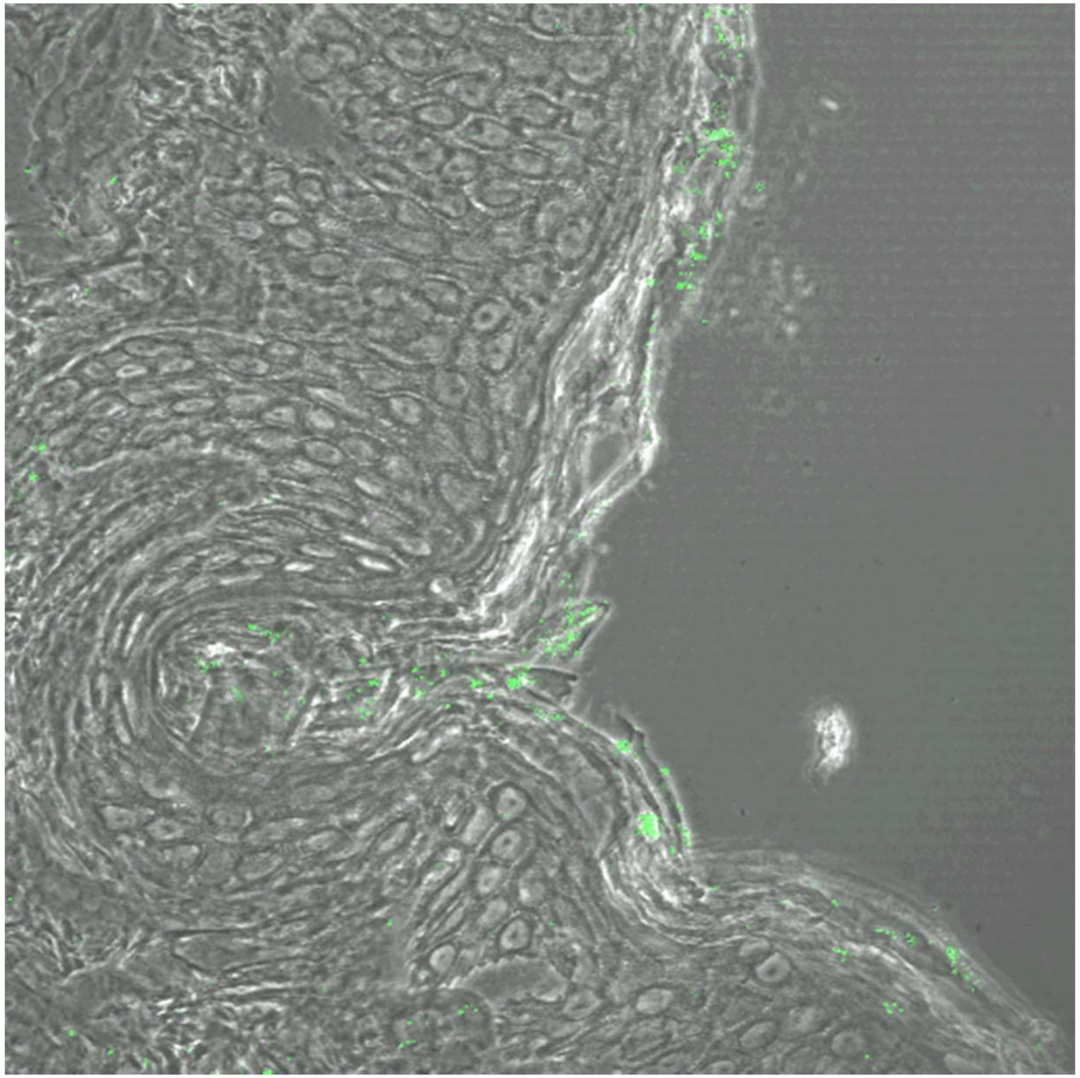
Total-filters

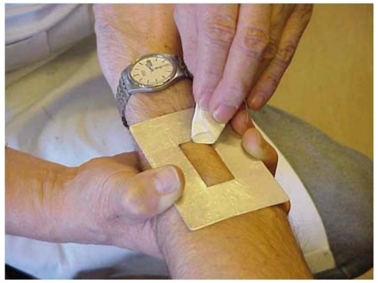
Pump and gasmeter

Dy and In particles measured with Berner LP impactor



Human contamination model





Skin wipes with ethanol soaked filter paper after deposition of Dy / In particles on skin

Micrograph of particle-exposed skin, showing green-fluorescent 0.5 µm beads after 18 hours. Beads are evident at the stratum corneum surface, but also in deeper regions in a hair follicle (from Andersson et al., 2004).

External dose from contamination on human skin

Deposition velocities to human skin, hair and clothing measured in numerous experiments employing, e.g., monodisperse silica particles labelled with neutron activatable rare earth tracers (Andersson et al., 2004).

Natural clearance of contaminants from human skin, hair and clothing measured in numerous experiments scanning fluorescein labelled particles (Andersson et al., 2004).

The dose from contamination with these ^{90}Sr particles on freely exposed skin would here amount to $8 \cdot 10^{-6}$ Sv per Bq cm^{-2} (Andersson et al., 2004).

Multiplied by the relationship between deposition velocities to skin and the grassed reference surface gives: $4 \cdot 10^{-9}$ Sv per Bq m^{-2} on the ref. surface

Doses from contamination on hair and clothes will be much smaller, although clearance half-lives have been found to be longer (Andersson et al., 2004).

Committed dose from inhalation during plume passage

Time-integrated air concentration leading to 1 Bq m^{-2} on the ref. surface can be found by dividing 1 Bq m^{-2} by v_d (ca. 2 10^{-3} m s^{-1} for these particles)

Multiplied by standard inhalation rate (ICRP, 1993), the total amount inhaled can be found: 1.7 10^{-2} Bq.

By multiplying with the dose conversion factor (ICRP, 1995) for slow absorption, this gives a committed dose of $3 \cdot 10^{-9}$ Sv per Bq m^{-2} on the reference surface.

This dose contribution would be much less if people stayed indoors, and if the aerosol had been more readily soluble.

Also, rain would have depleted plume concentrations, while enhancing deposition on outdoor surfaces.

An other aspect: atmospheric dispersion modelling

In atmospheric dispersion models so far applied in European decision support systems, inhabited areas are simply modelled as areas with enhanced surface roughness and different deposition rates compared with open areas.

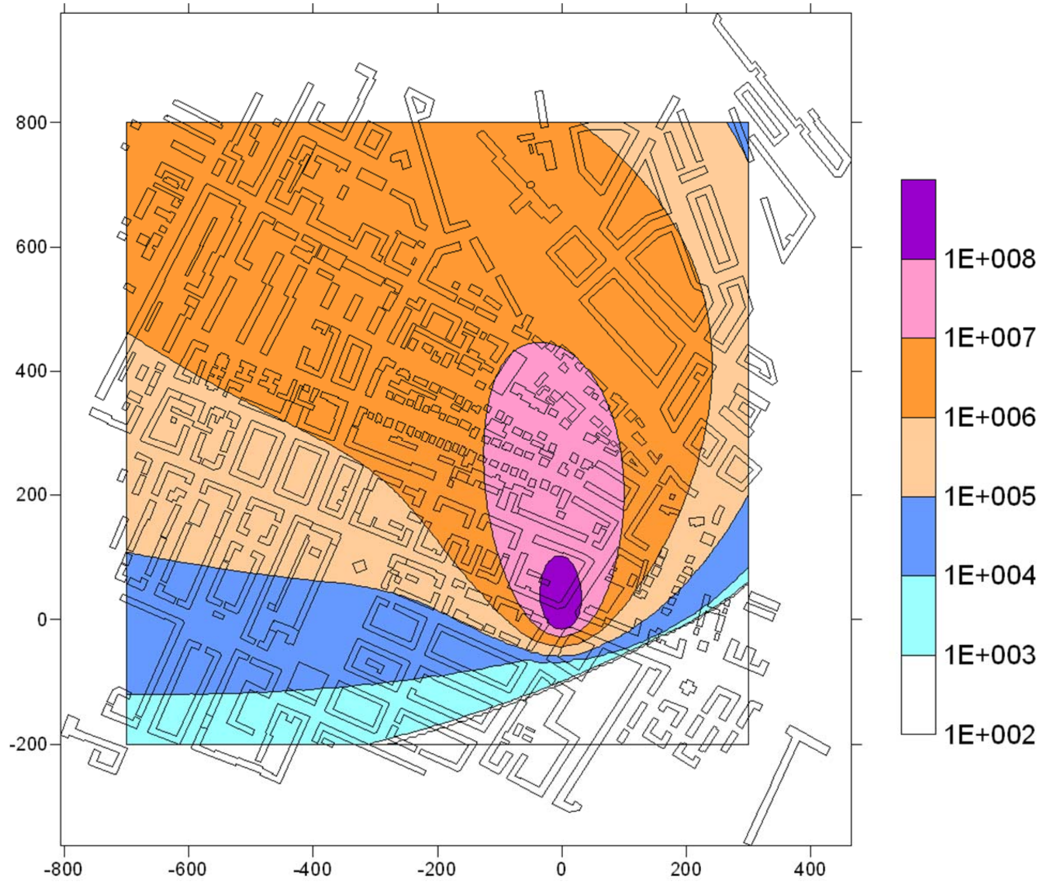
Presence of buildings has three effects modelled in the new high resolution urban dispersion model, URD, for implementation in ARGOS:

1) It limits the size of the horizontal eddies present in the atmosphere and thereby limits the large scale horizontal dispersion.

2) It enhances the smaller scale dispersion by creating more small scale turbulence.

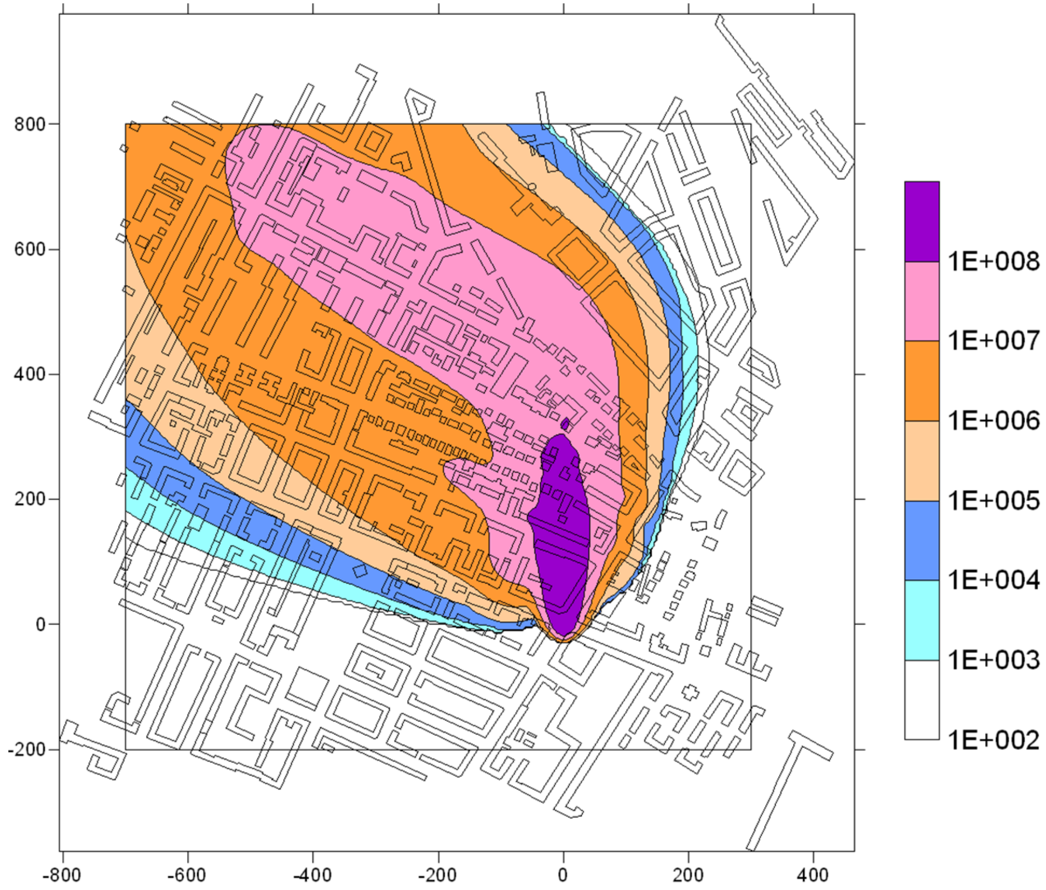
3) It delays part of the dispersion by retaining aerosols in more or less stationary recirculation zones on the downstream side of the buildings.

Frederiksberg (Copenhagen) model case study (1)



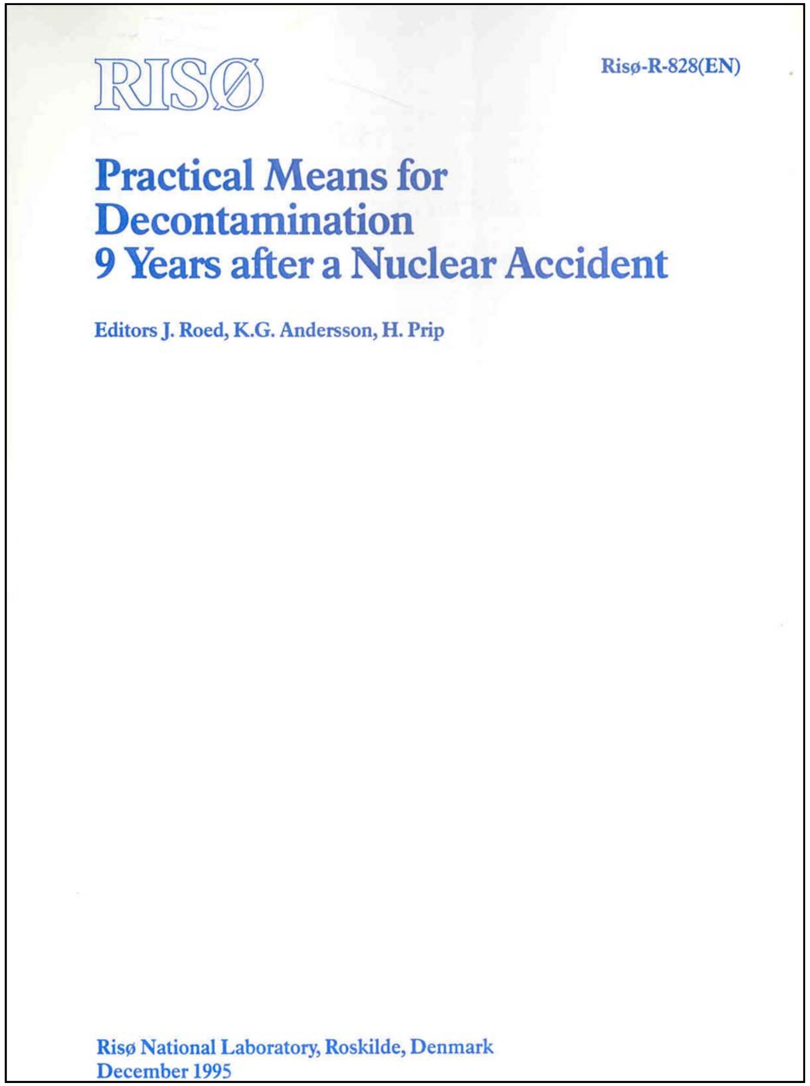
RIMPUFF estimate of the time air integrated concentration [Bq s/m^3] at ground level. No building influence.

Frederiksberg (Copenhagen) model case study (2)



URD estimate of the time integrated air concentration [Bq s/m^3] at ground level, with all three building effects modelled.

Countermeasure descriptions (NPP accidents)



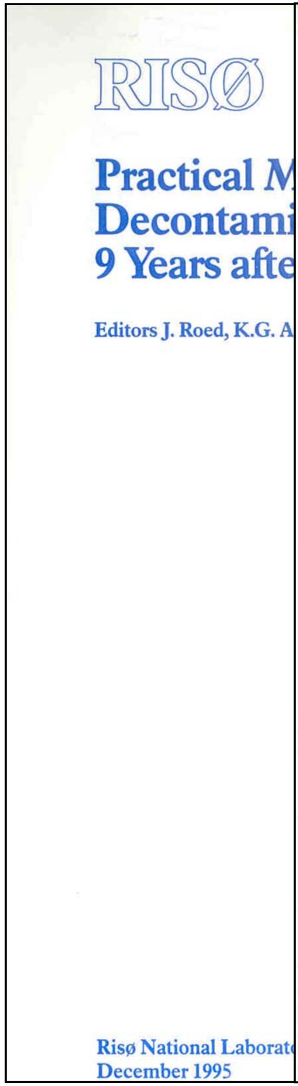
Risø-R-828(EN)

Practical Means for Decontamination 9 Years after a Nuclear Accident

Editors J. Roed, K.G. Andersson, H. Prip

Risø National Laboratory, Roskilde, Denmark
December 1995

Countermeasure descriptions (NPP accidents)



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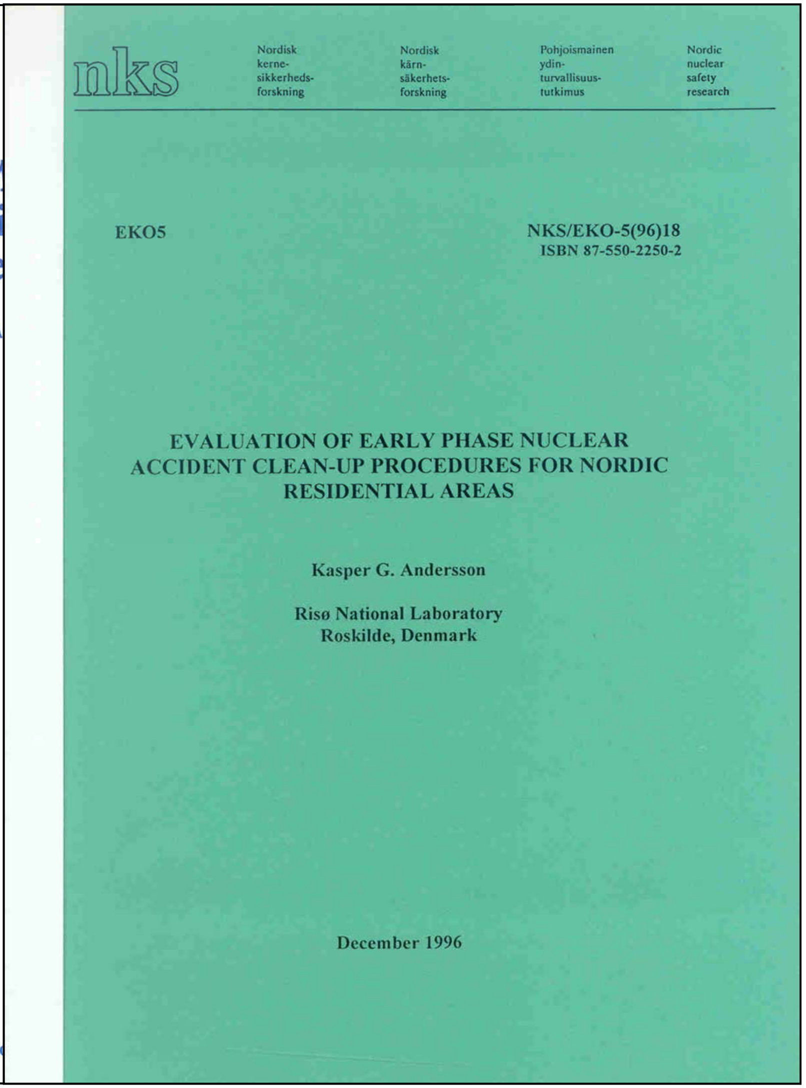

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NKS/EKO-5(96)18
ISBN 87-550-2250-2

EVALUATION OF EARLY PHASE NUCLEAR
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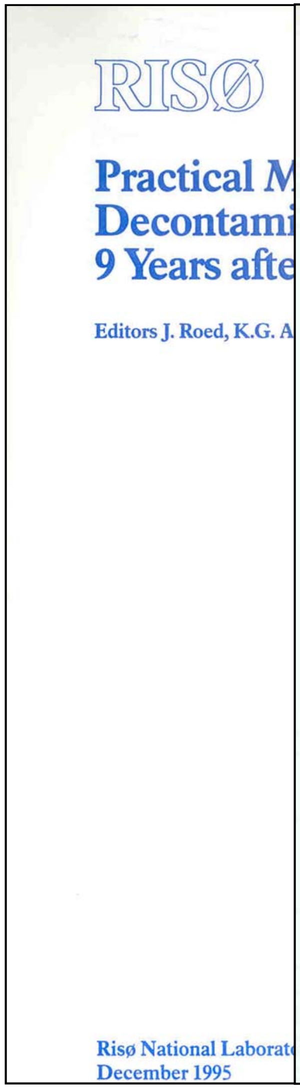
RESIDENTIAL AREAS

Kasper G. Andersson

Risø National Laboratory
Roskilde, Denmark

December 1996

Countermeasure descriptions (NPP accidents)



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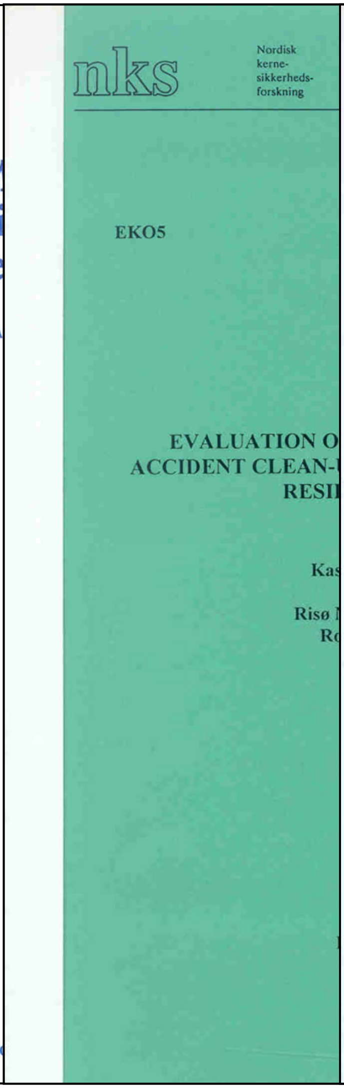

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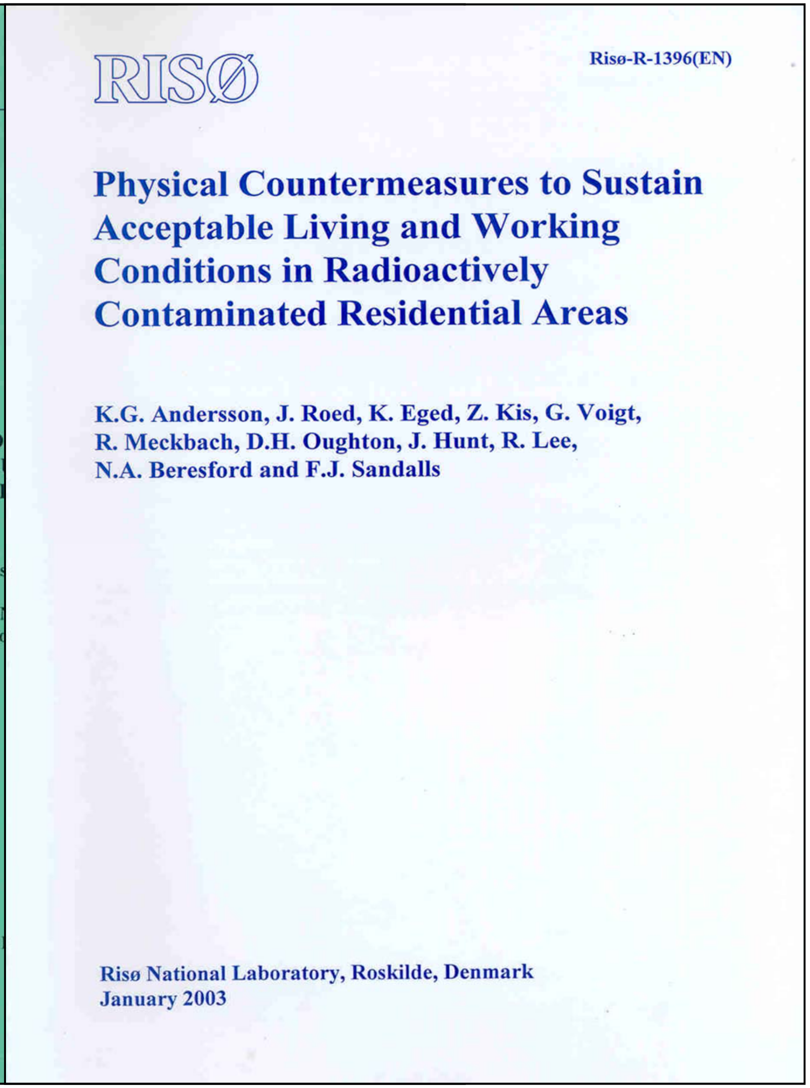

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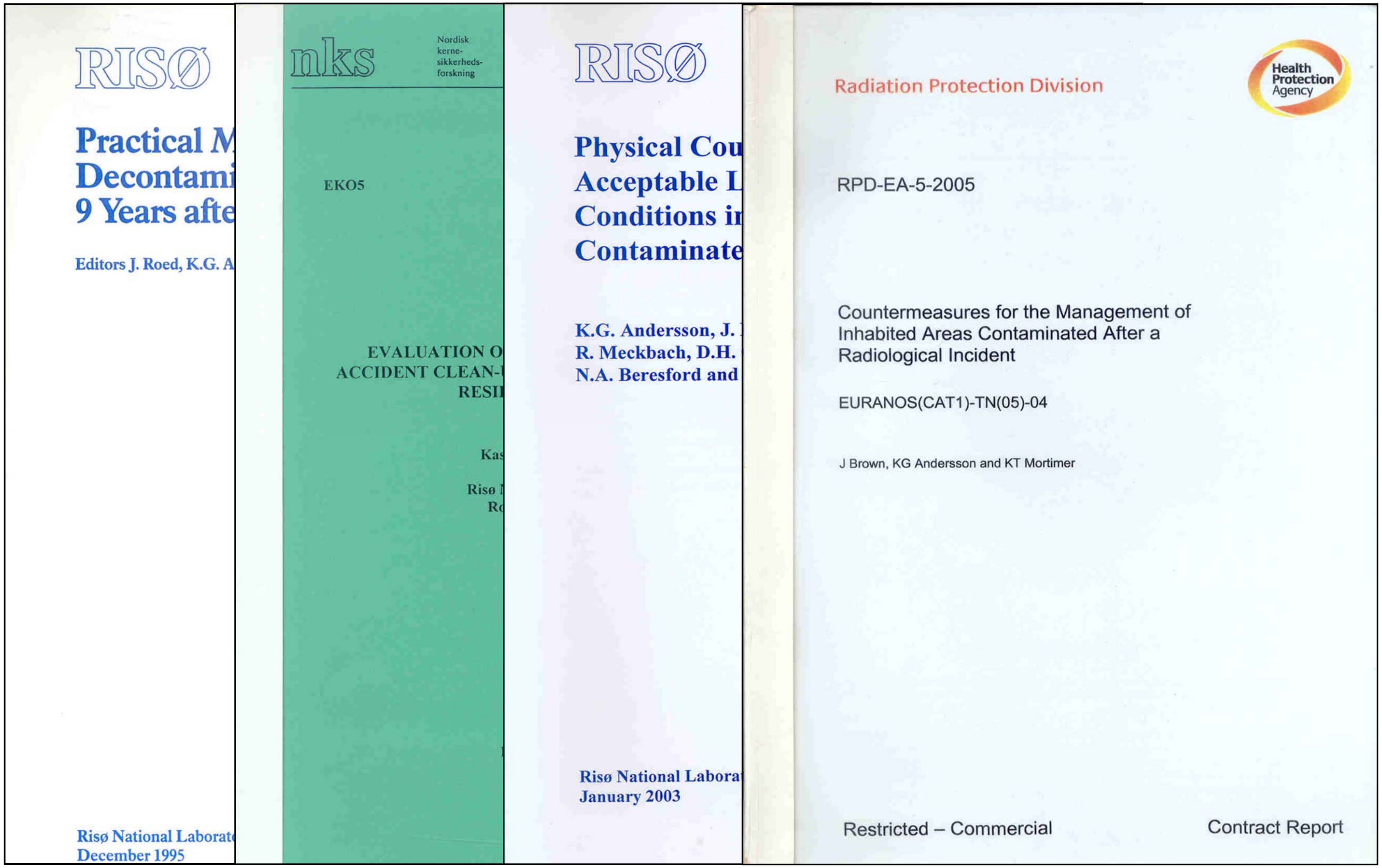
Risø-R-1396(EN)

Physical Countermeasures to Sustain Acceptable Living and Working Conditions in Radioactively Contaminated Residential Areas

K.G. Andersson, J. Roed, K. Eged, Z. Kis, G. Voigt,
R. Meckbach, D.H. Oughton, J. Hunt, R. Lee,
N.A. Beresford and F.J. Sandalls

Risø National Laboratory, Roskilde, Denmark
January 2003

Countermeasure descriptions (NPP accidents)



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Editors J. Roed, K.G. A

Risø National Laborat
December 1995

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K.G. Andersson, J.
R. Meckbach, D.H.
N.A. Beresford and

Risø National Labora
January 2003

Radiation Protection Division

Health Protection Agency

RPD-EA-5-2005

Countermeasures for the Management of
Inhabited Areas Contaminated After a
Radiological Incident

EURANOS(CAT1)-TN(05)-04

J Brown, KG Andersson and KT Mortimer

Restricted – Commercial

Contract Report

The EURANOS datasheets

ID: 30 **- Roads and paved areas -**

Vacuum sweeping

Objective	**To reduce external gamma and beta doses from contamination on roads, paved and other outdoor areas with ‘hard’ surfaces within inhabited areas, and reduce inhalation doses from material resuspended from these surfaces.**
Other benefits	Will remove contamination from roads, paved and other outdoor areas with ‘hard’ surfaces.
Countermeasure description	Municipal vacuum sweepers can be used to clean paved areas. Different types of vacuum sweeper are used for large surface areas, such as roads, and for small surface areas, such as pavements. It is recommended that machines with the ability to dampen the surface with water sprays are used to reduce dust and hence the resuspension hazard. Some road sweepers can operate in wet weather conditions. The aqueous waste can be disposed to drains either directly or can be collected. Segregation of the contaminated dust from the water may be possible. Dust creation during implementation is unlikely to be a problem and so methods are not required to reduce the resuspension hazard to workers. Recontamination of surface by resuspended contaminants will be insignificant, so repeated action is not called for.
Target surface or population	Paved surfaces (roads, pavements, paths, yards, playgrounds etc.)
Target radionuclides	All radionuclides. Suitable for removing short-lived radionuclides if implemented quickly. See Part III, Section 3 for information on radionuclides.
Scale of application	Any size. Suitable for small surface areas (e.g. pavements, playgrounds) and large surface areas (e.g. roads). Unlikely to be used around peoples’ houses.
Timing of implementation	Maximum benefit if carried within 1 week of deposition as option relies on removing dust from surface.
Constraints on implementation	

Countermeasure template format: main categories of data

Objective – primary aim, other benefits

Countermeasure description – what happens and how is it done

Target, targeted radionuclides, scale of application, timing

Constraints on implementation – legal, environmental/technical

Effectiveness - DF, surface dose rate reduction, resuspension reduction, extra dose

Factors influencing effectiveness – technical (e.g., evenness), social (e.g., behaviour)

Requirements – equipment, consumables, worker skills, safety precautions

Intervention costs – equipment, consumables, operator time, factors influencing costs

Waste – amount and type

Side effects / Impact – environmental (e.g., land use), social (e.g., on behaviour)

Practical experience – extent of trials, scale of testing, etc.

Key references – for further reading

Countermeasure differences (RDD incidents)

Different range of relevant countermeasures (considering new range of contaminants, different time-scale, size of contaminated area, and possibly different intervention criteria).

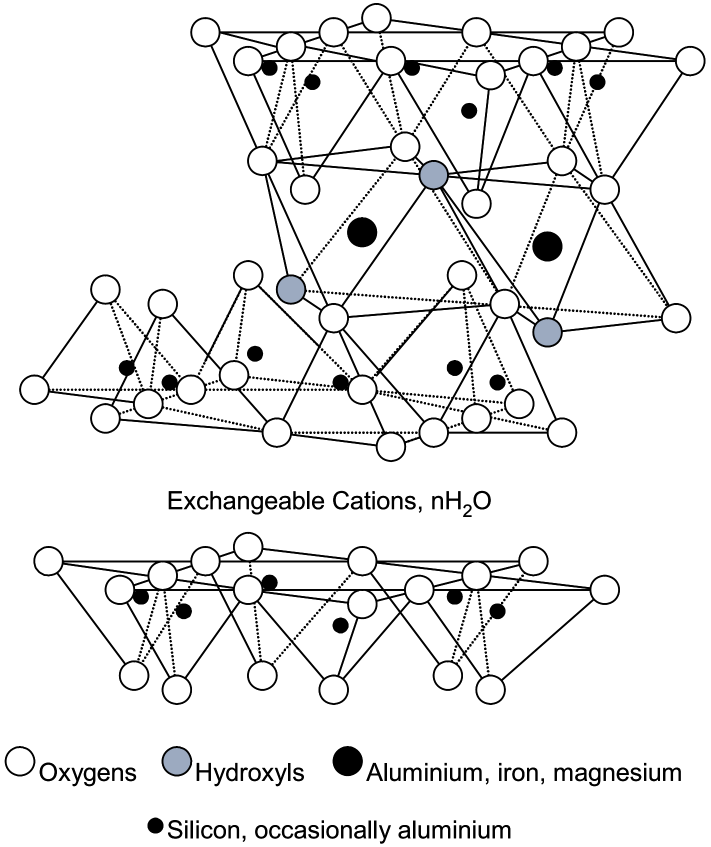
Revision of countermeasure efficiency factors (’new’ contaminants). Depends on, e.g., dispersion process, physicochemical forms.

Different deposition and natural weathering mechanisms for the ’new’ contaminants will change the relative importance of cleaning surfaces.

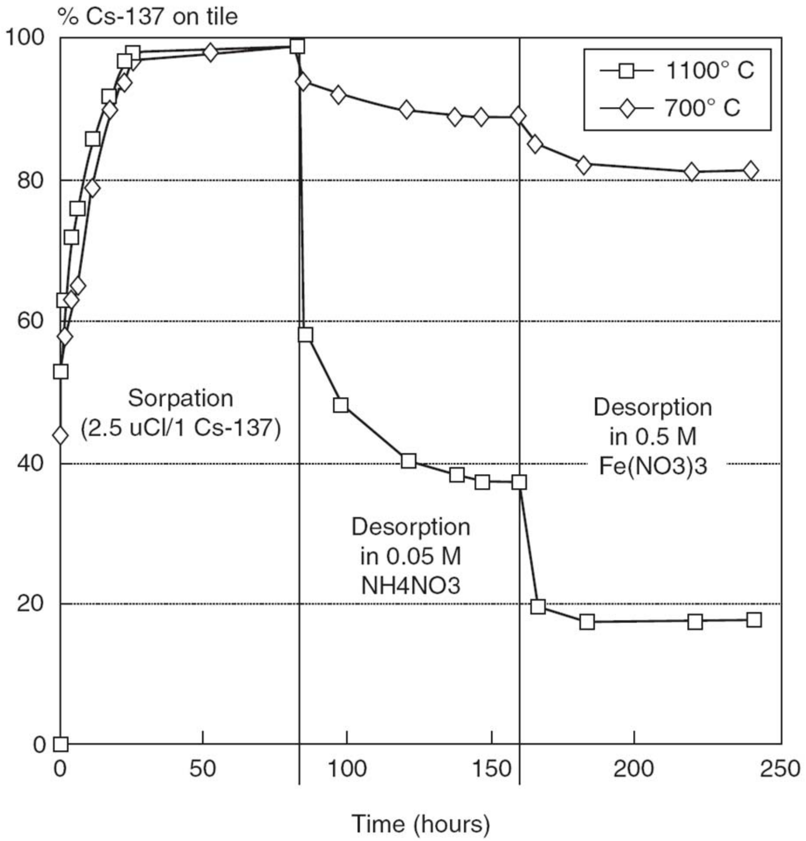
Justification and optimisation of countermeasures requires trustworthy dose prognoses (Re ICRP residual dose concept). *All* dose contributions/ pathways must be included. Not only migration processes need parameterisation, but also dose conversion factors for complex urban geometries.

Societal, ethical and legal aspects would be different, due to the different public perception, size of affected area, radionuclides, timing.

Cation fixation in micaceous minerals

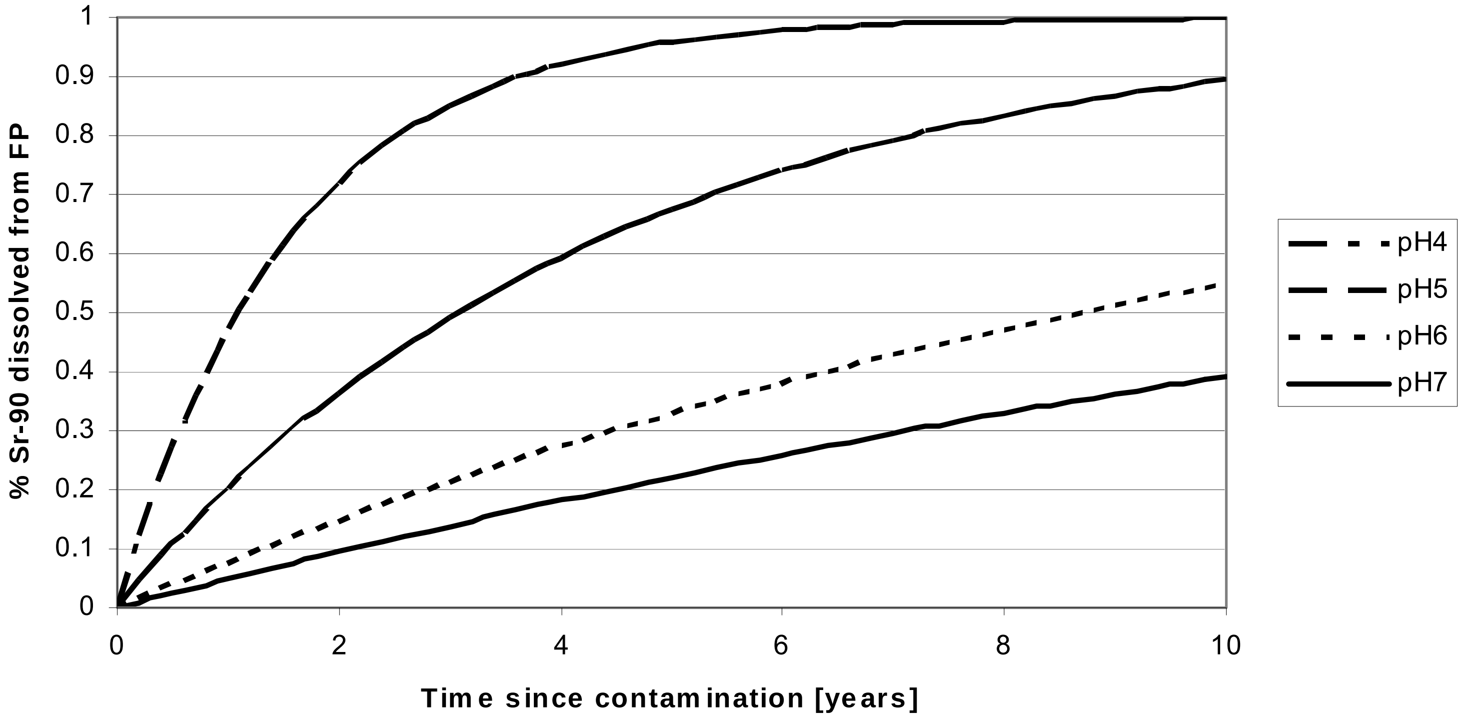


Influence of firing of micaceous construction materials



Desorption of ^{137}Cs on clay roof tile pieces fired at different temperatures.

Slow dissolution of strontium particles after Chernobyl



Time-dependence of the fraction of ^{90}Sr dissolved from fuel particles in the areas contaminated by the Chernobyl accident