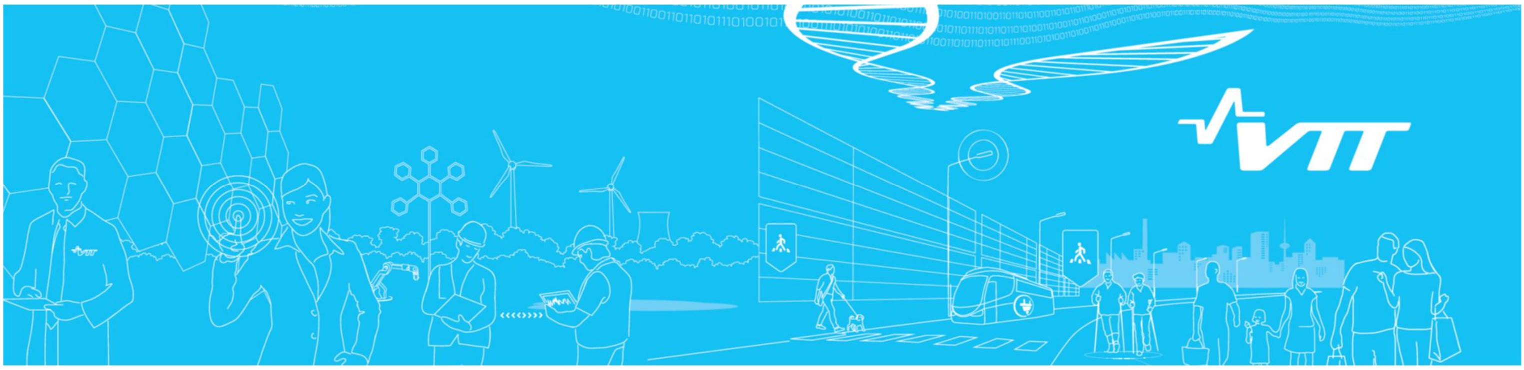

RESEARCH REPORT

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Dose assessment in level 3 PRA - a rewiew of recently used methods

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Summary

The assessment of ionizing radiation dose to the general public resulting from a nuclear accident is a central part of level 3 probabilistic risk analysis. This report reviews dose assessment methods used recently either in major studies (the SOARCA study by the Nuclear Regulatory Council, and the Fukushima accident study by the United Nations Scientific Committee on the Effects of Atomic Radiation), or in modern level 3 PRA analysis codes (VALMA, SILAM, RODOS).

After a brief introduction to dose assessment, the methods are introduced by study/code. The methods of the Finnish VALMA code relies on work done at VTT previously, and on international standards and guidelines. It takes into account cloudshine, groundshine, inhalation and ingestion. The dose assessment of SILAM handles the same pathways as VALMA, and also rests on guidelines of IAEA and others. The dose assessment of RODOS relies on simple methods, but is quite versatile. The dose assessment used in the SOARCA study is the one implemented in MACCS2, and reflects the American way of dose assessment analysis. The dose assessment used in the UNSCEAR study originates from Russia, considers cloudshine, grounshine and inhalation, and contains submodels for finding radiation intensity in free air, the effects of the locations of exposed people, the whereabouts of people as a function of time, and conversion of radiation intensity to absorbed doses.

It turns out that there has been relatively little progress in dose assessment methods in the last 20 years. Some suggestions on future research on improving the accuracy and plausibility of dose assessments are made. These rely on utilizing developments in modelling, simulation and computation in the last decades.

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Contents

1. Introduction

Within the context of nuclear safety, dose assessment means quantitatively estimating the amount of ionizing radiation received by an individual or a population. The source of the radiation is radioactive material for which the principles of isolation and distance have failed: it has entered close to humans, without fully protecting isolating barriers, for example as a result of a nuclear accident.

Dose assessment presupposes that information is available on radionuclide concentrations in the released plume (or radionuclide concentrations in the aquatic systems considered), on people's amounts and locations, on demographics (mainly age), and on countermeasures implemented.

The results of dose assessment can be used in health effects (radiation sickness, cancers) assessment, and evaluation and comparison of countermeasures, their timing, organization etc.

This report concentrates on the assessment of individual and population doses resulting from a release from a nuclear facility. Such assessments may be a part of deterministic consequence analyses, or level 3 PRA (probabilistic risk analysis). The emphasis in this report is on methods that have been used recently, either in implementation of dose assessment software, major studies, or both.

2. Basics of dose assessment

The principles of dose assessment are covered in textbooks on PRA for the nuclear industry [4], [15], [16]. However, the treatment of the topic in the textbooks is rather unsystematic and even erratic. A more systematic treatment is provided by an IAEA guide [11].

There are different routes through which ionizing radiation can enter the human body. These routes are called pathways. These pathways are

- Cloudshine. The radioactive substance is in the air, and emits ionizing radiation that hits exposed humans.
- Groundshine. The radioactive substance is on the ground, for example as a result of rain washing it down from a radioactive plume. It emits ionizing radiation that hits exposed humans.
- Inhalation. The radioactive substances are in the air and enter exposed humans as they breathe. The substances may be contained in the passing plume, or they might be a result of resuspension of the ground deposit.
- Ingestion. The radioactive substances are in food (e.g. after having been absorbed from soil by edible plants) or drink (e.g. after being dissolved to drinking water), and enter exposed humans through eating or drinking.
- Skin contamination. Particles containing radioactive substances fall on the skins or clothes of exposed persons.

Cloudshine, groundshine and inhalation are considered to be the main pathways, and they are usually incorporated in consequence analyses. Ingestion is considered to affect humans in the long-term, and the risk of dose through ingestion is a basis of land use restrictions when the land is contaminated.

Different pathways dominate population dose in different time spans. During and shortly after plume passage (lasts up to a week, often called emergency phase), cloudshine and inhalation are the significant pathways. In the long term, when people return to their homes and agricultural lands are taken into use, the dose comes from groundshine, inhalation from resuspension and ingestion.

Several phenomena are at work in reducing population dose in the long run. Such phenomena include radioactive decay, wind transporting radionuclides away, water washing deposition from soil etc. The total effect of these phenomena causes that the long-run population dose does not grow much from the population dose of the first year. For example, in [22] it was reported that the effective ingestion dose in the 50 years following the Chernobyl accident is just about 1.3 times the first year dose.

For each pathway, a dosimetric model is used to convert the concentration of radionuclides to dose in humans. These are described in the following subsections.

Different consequence analysis codes use different dosimetric models. As an example, a relatively detailed description of the mathematical dosimetric models of the Dutch NUDOS code is given in [17].

Doses may be calculated for individuals (e.g. the most exposed individual of a population), and cohorts (groups of subjects with a common defining characteristic, usually age). The dose absorbed varies by age, because metabolism rate, breathing rate and certain other factors vary by age. Usually humans are divided in dose assessments into three age groups: infants, children and adults. In a more refined analysis, doses are calculated for each organ, because the health effects vary depending on what organ has received the dose. Cloudshine, groundshine and skin contamination affect skin, inhalation affects the respiratory system. The most complex pathway from a dose per organ point of view is ingestion, because ingestion dose depends on the radionuclides (and the chemical compounds they are parts of), and human metabolics (which are age-dependent); different radionuclides may accumulate in different organs (iodine in thyroid gland, metals in bone etc.).

Countermeasures taken during the course of the accident may greatly affect population doses, and they have to be taken into account in the assessment. The most important countermeasures in the short term are evacuation, sheltering to buildings, cars etc., and distribution of iodine tablets. Some sheltering is also provided by clothing, which reduces also exposure to skin contact. The most important countermeasures in the long run are relocation of population, food bans, land use restrictions, and agricultural actions such as selection of crops. The main inputs from countermeasure assessment to dose assessment are the locations of population by time, and their sheltering status (isolation of their skin from cloudshine by e.g. building structures, isolation of their breathing air from the plume, food and water intake from contaminated areas in the long run).

2.1 Cloudshine

Ionizing radiation from a passing plume consists of β and γ radiation. However, the contribution of β particles is often omitted because of their short range in the air (a few meters), and limited penetration (does not penetrate skin).

In principle, the calculation of the γ dose involves three-dimensional integration of radiation over the whole plume, taking into account scattering and absorption in the air, for the duration of the exposure. However, since this is very tedious and time-consuming, approximate methods are usually used. For low γ ray energies and large cloud dimensions, tabulated results for a semi-infinite plume have been used ever since the WASH-1400 study [29] in the 1970's. The dose rate in the air for γ radiation is

$$\frac{dD_\gamma}{dt} = 0.507\,\chi \overline{E}_\gamma$$

Where χ is the radionuclide concentration in the plume (assumed to be constant), and $\overline{E}_\gamma$ is the average energy of γ radiation.

For people indoors, the building attenuates radiation. This shielding is usually taken into account by using a shielding factor, the ratio of the dose indoors divided by the dose outdoors. This factor depends on the building (thickness and materials of outer and inner walls, floors and roofs) and ranges from 0.01 to 0.7.

2.2 Groundshine

The contribution of β particles is usually omitted due to reasons outlined in section 2.1, and dose is estimated only for γ radiation.

Exposure to groundshine occurs usually over long periods of time. Therefore, in addition to the length of exposure time, also decay of radionuclides has to be taken into account. Furthermore, weathering processes may remove deposit from the exposed surfaces: wind may carry it away, and rainfall may wash it away. Dose from groundshine is often calculated by multiplying the deposit radiation by a dose per unit deposit conversion factor, and integrating over an appropriate time period. The conversion factor takes into account the long-term removal mechanisms (decay, weathering). Usually it is also taken into account that people spend a certain proportion of their time indoors, and for that proportion radiation is reduced by the shielding factor (see section 2.1).

2.3 Inhalation

The inhalation dose is obtained as the product of breathing rate, time integrated concentration of radionuclides in air, and a precalculated dose per unit conversion factor. The breathing rate depends on the age of the person and on the level of physical activity; a typical value for adults is 2.66×10^{-4} m^3/s. The conversion factors are age-dependent and obtained from metabolic models. Metabolic models track the radioactive material as it moves through the body after inhalation, and calculate individual organ doses. In practical calculations, conversion factors are obtained from a database where the results of metabolic models have been tabulated.

Buildings provide sheltering also against radionuclides entering through the inhalation pathway. This can be taken into account by using a filtering factor, which is less than 1.

Inhalation dose may also be obtained over a longer period of time due to resuspension of the radionuclides from the ground by winds or human activities (e.g. driving vehicles or ploughing). In consequence analysis codes, the relationship between the concentration of radionuclides in air and the amount of material deposited is generally described by a time-dependent resuspension factor, defined as the ratio of the air concentration due to resuspension and the initial surface concentration. This factor is generally determined from measurements made in the environment [10].

2.4 Ingestion

All three kinds of ionizing radiation - α, β and γ - need to be considered when assessing ingestion doses. Ingestion doses are calculated from the total amount of radionuclides deposited in foodstuffs, the activity concentration of particular radionuclides in food per unit deposition, the consumption rate of the food products and the dose per unit activity ingested. Of these, consumption rate and dose per unit activity ingested depend on the age of the exposed person.

Radionuclide concentrations are usually estimated using a dynamic food-chain transport model normalized to unit deposit, taking time-dependency (decay rate) into account. These models describe the transport of radionuclides in the environment (with water, sedimentation etc.), and in food chains (uptake by crops, accumulation in fish etc.). An example of such models is the Finnish Detra code [26]. These models are rather complex and computationally intensive, and therefore consequence analysis codes usually use a database where model results (activity concentrations in foodstuffs) for more important foodstuffs and accidents occurring at different times of year have been tabulated. In principle, each foodstuff represents a different food-chain for the intake of radionuclides, and therefore each foodstuff that is consumed in significant amounts should have a model of its own.

Consumption is usually treated under one of two alternative assumptions:

- Foodstuff is both produced and consumed locally. Then, individual consumption rates and the number of people in the area considered are used to estimate individual and collective doses.

- All food produced in the contaminated area is consumed somewhere, but not necessarily locally (affecting the dose of the local population only). Spatial distributions of foodstuff production are used to estimate the collective ingestion dose, under the assumption that all food produced is consumed and contributes to the collective intake. No information is obtained on individual doses; more realistic estimates would require data on the distribution of food between the point of production and the point of consumption.

Both food processing and culinary techniques can reduce the amount of radionuclides in foodstuffs.

Doses per unit activity ingested (ingestion dose conversion factors) are obtained from the same metabolic models used to assess inhalation doses (section 2.3), and the results of these models are usually tabulated in databases for ingestion, too.

2.5 Skin contamination

Due to the close distance, both β and γ emitters contribute to individual external exposure when radioactive material has deposited on skin and clothing. The dose received is generally evaluated by multiplying the amount of radioactive material deposited by a precalculated dose per unit activity of particular radionuclides. The amount of radionuclides deposited on the skin and clothing is often calculated as a fraction of the amount deposited on the ground.

3. Methods used in recent assessments and assessments in the Nordic countries

In this section, dose assessment methods used in the recent years in notable studies or generally used software are described.

3.1 Valma

VALMA [9] is an atmospheric dispersion and dose assessment code developed at VTT. It was originally developed for emergency preparedness applications. It uses the Lagrangian (tracking of particle trajectories) method for dispersion, and can take changes in weather, e.g. in wind direction, into account.

Valma's dose assessment has been developed since the 1990's. It is based on dose assessment methods recommended in international guidelines, and on methods developed at VTT. In 2016, the ingestion pathway was added to Valma. Valma's dose assessment is described in [19], [20] and [21].

VALMA's dose assessment considers four pathways: cloudshine, groundshine, inhalation and ingestion. Cloudshine is calculated by assuming that the plume is semi-infinite. The dose rate calculation for this pathway is otherwise quite conventional, except that for the γ dose rate, first the energy flux density of γ radiation at a given time instance is calculated first as an integral over an infinitesimally small volume in the target (skin) divided by the respective exposed area, and then the dose rate as an integral over time of the energy flux density multiplied by certain constants. Doses through groundshine and inhalation are calculated using methods described in section 2 of this report. Inhalation dose factors are from [25]. The ingestion pathway is calculated using the AGRID model developed for ARANO [14].

3.2 SILAM

SILAM (System for Integrated modeLling of Atmospheric composition) [23] is a general-purpose atmospheric dispersion model with a spatial range from beta-mesoscale (element size 1 kilometer) to global. It was originally developed by VTT, but the Finnish Meteorological Institute has taken over its development. SILAM is freely available and open source. It has Eulerian (partial differential equations) and Lagrangian (particle trajectories) models for the dispersion computations. It contains modules for atmospheric physics and chemistry. It can be used e.g. for calculating the dispersion of pollen or smoke from forest fires.

One of the applications of SILAM is transport of radionuclides by atmospheric dispersion. Its dose assessment model is described in [24]. The pathways considered are cloudshine, groundshine, inhalation and ingestion. The age groups considered are infant and adult. The calculation aims at obtaining complementary cumulative distribution functions for individual doses - that is, the individual dose that is exceeded by probability of less than e.g. 2 %. A momentary (or short-period) dose is obtained by multiplying radionuclide concentration with a dose conversion factor (and similarly for deposition). Total doses are obtained by integrating momentary doses over time, taking into account the migration of population over the contaminated territory, decay of radionuclides and environmental self-cleaning processes.

The SILAM models for the ingestion pathway take the transport of radionuclides from deposition to soil to plants and animals, and also removal of radionuclides due to e.g. radioactive decay, washout, resuspension etc., explicitly into account. The parameters used in the models are mostly from [12].

As an example, consider the amount of radioactivity entering the human body via ingestion:

$$E_{ing} = \left(F_{ing} \sum_{foodstuff} C_{foodstuff} Q_{foodstuff} \right)$$

Here $Q_{foodstuff}$ (kg/day) is the consumption of the type of foodstuff, $C_{foodstuff}$ (Bq/kg) is the radionuclide concentration of the foodstuff, and F_{ing} (Sv/Bq) is the ingestion dose coefficient for the given nuclide.

3.3 RODOS and JRODOS

RODOS [3] is an accident management and decision support code developed in several EU projects over the 1990’s and 2000’s. It is meant for several users in distributed locations. JRODOS [18] is a version of RODOS written in the Java programming language and released in 2009. The functionality of RODOS reflects its purpose. In data management, it contains functionality for data acquisition and quality checking of radiological data, using a distributed database and decentralized data management, and a geographic information system called RoGIS. In assessment of radiological situation, it contains analysis and prediction of release transport in the air, based on monitoring data, meteorological data and models. In countermeasures, it contains simulation and determination of their feasibility, quantification of their benefits and disadvantages, and evaluation and ranking of countermeasure strategies (costs, residual dose, reduction of stress and anxiety, socio-psychological aspects, political acceptability etc.), taking into account the judgements and preferences of decision makers. Comparison and evaluation of countermeasure strategies has been implemented by integrating into RODOS the Web-HIPRE package developed by the Systems Analysis Laboratory of Aalto University. It also contains functionalities for communication and cooperation between different participants in accident management (e.g. radiation protection officials in different countries, police, emergency services), and visual presentation of results. It is in use in several European countries; for example, in Finland it is used by STUK.

Due to its intended purpose, compromises have been made in RODOS concerning analysis accuracy for speed. Therefore, RODOS is of limited use in level 3 analyses, but is still relevant.

For dose assessment, RODOS has four modules:

- Terrestial Food Chain and Dose Module, which consists of a terrestrial food chain module and a terrestrial dose module. It assesses the transport of radionuclides in soil and the resulting doses from agricultural products. RODOS considers all major pathways (see section 2).
- Hydrological module consists of aquatic food chain module and aquatic dose module. It assesses the transport of radionuclides in water systems and the dose resulting from fish and other sea products, and from drinking water.
- Forest food chain and dose module considers transport of radionuclides to mushrooms, wild berries and game, and also quantifies the internal and external exposure from contaminated forests.
- Tritium food chain and dose module is a simple module for assessing transport of tritium through food chains.

Dose combination module combines the results of these modules to an assessment of the total dose.

RODOS can handle all ordinary countermeasures (sheltering, distribution of iodine tablets, evacuation, decontamination of land, temporary and permanent delocation), and an extensive set of countermeasures related to agriculture:

- Food bans
- Food processing and storage
- Changes in the feed composition of animals (supplying clean feed for a certain period after deposition, changes in the proportion of contaminated feed in the diet, and the use of different feedstuffs)
- Administration of sorbents and boluses
- Soil treatment (e.g. addition of fertilizer)
- Change of crop varieties or species grown
- Change in land use from agriculture to forestry
- Decontamination of agricultural land by plowing and soil removal

3.4 MACCS2: SOARCA study

The biggest undertaking in accident consequence analysis study in recent years has been the State-of-the-Art Reactor Consequence Analyses (SOARCA) project initiated by NRC. It began in 2007 and ended in 2012. Its scope was accident progression, effects of countermeasures, and health consequences. It developed best estimates of the offsite radiological health consequences for potential severe reactor accidents, using the Surry and Peach Bottom power stations as case study objects. The main results are reported in [1].

MACCS (MELCOR Accident Consequence Code Systems) is a computer code for consequence analyses and level 3 PSA analyses developed by the U.S. Nuclear Regulatory Commission. Its currently used version is MACCS2 [2], and this version was used in the SOARCA study, utilizing its WinMACCS front end. However, it seems that there has been little substantial development in its dose assessment computation since the original MACCS was released in 1990 (some notable exceptions are that the treatment of variations in emergency response is more fine-grained regarding population segments, and enhancements in the treatment of evacuation speed and direction to better reflect the spatial and temporal response of individual cohorts). Therefore we concentrate on the original dose assessment model as described in [13].

MACCS divides dose assessment into two domains: early exposure during and shortly after plume passage (emergency phase), and long-term exposure.

In the emergency phase, cloudshine, groundshine, inhalation (both from plume and resuspension), and skin contamination are the pathways considered. The dose is calculated per spatial element for individuals in it, and the dose equations are products of radionuclide concentration, dose conversion factor, duration of exposure, and a shielding factor.

As an example, consider doses from cloudshine:

$$DC_k = \left(\sum_i AC_i^c * DFC_{\infty ik} \right) * C * F * SFC$$

Where

- DC_k is the cloudshine dose (Sv) to organ k

- AC_i^c is the time-integrated air concentration (Bq*s/m^3) of radionuclide i, from atmospheric dispersion calculations
- $DFC_{\infty ik}$ is the semi-infinite cloud dose conversion factor (Sv*m^3/Bq*s) to organ k from nucleotide i, from a dose conversion factors file
- C is an off-centerline correction factor that corrects the dose if the spatial element considered is not in the centreline of the plume
- F is the fraction of exposure duration during the plume passage
- SFC is the cloudshine shielding factor specified by the user. They take into account the protection provided by e.g. sheltering

For long-term exposure, three pathways are taken into account: groundshine, resuspension inhalation, and ingestion (both from food and drinking water). The handling of groundshine and inhalation resemble the corresponding short-term models. The long-term ingestion doses are calculated as the product of the gound concentration of the radionuclide, an integrated transfer factor for the nuclide to human intake, and an ingestion dose conversion factor. As an example, consider food ingestion population dose:

$$D_{ijk} = GC_i * DF_{ik} * FA * FAC_j * TF_{ij}$$

Where

- D_{ijk} is the food ingestion population dose from radionuclide i via crop category j to organ k
- GC_i is the initial ground concentration (Bq / m^2) of radionuclide i in the spatial element
- DF_{ik} is an ingestion dose conversion factor for nuclide i to organ k (Sv / Bq), where off-centerline correction has been taken into account
- FA is the area (m^2) in the grid element which is devoted to farming
- FAC_j is the fraction of the farmland area in the spatial element that is used to cultivate crop j
- TF_{ij} is an overall transfer factor from soil to population for nuclide i via crop j

3.5 UNSCEAR study of the Fukushima Daiichi nuclear accident

The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) has created a study on the effects of the Fukushima nuclear accident on the general public in Japan [27]. The dose assessment methodology used in it is described in [28]. The study contains an assessment of doses to the general public for the 80 years following the accident. Three pathways are taken into account: cloudshine, groundshine and inhalation (though inhalation from resuspension was omitted). The target organs considered are the thyroid gland, red bone marrow and female breast.

Estimates of groundshine from deposition were based on an extensive set of measurements of deposition density: in June and July 2011, soil was sampled on a grid of 2 by 2 km squares up to distance of 80 km, and on a grid of 10 by 10 km squares up to distance 100 km, and over the remaining area of the Fukushima prefecture - all in all, 2 200 measurements. Furthermore, results of more than 1 000 measurements from Fukushima and neighboring prefectures from late 2011 were used. Also, a limited number of measurements of radionuclide concentrations in the air were available.

The dose assessment model used in the study is described in [5], [6], [7] and [8]. The main results of the model are

- The time-dependent kerma rate $\dot{K}_{air}(t)$ (nGy/h) (radiation intensity at time t) at a reference site for each settlement;
- Location factors $f_j(t)$, or the ratios of kerma rates in air at the locations considered to the kerma rates at the closest reference point;
- Occupancy factors p_{ij} that give the time population group i spends at location j;
- Conversion coefficients $\dot{E}_i^{dep}(t)$ that give the conversion from kerma rate in the air to effective dose rate, or absorbed dose rate to the particular organ, for population group i

The model consists of four submodels. The first one calculates the time-dependent kerma rate $\dot{K}_{air}(t)$ in free air, at 1 m above an undisturbed open field, lawn or meadow, as

$$\dot{K}_{air}(t) = r(t)A_{Cs-137}\sum_{m}\frac{A_m}{A_{Cs-137}}k_m^{dep}e^{-\lambda_m t}$$

Where $r(t)$ is the ratio of the kerma rate in air above undisturbed open ground to that for a reference depth distribution of a radionuclide concentration in soil (accounts for the penetration of radionuclides in soil), A_m is the deposition density of radionuclide m on the ground (kBq/m^2), k_m^{dep} is the kerma rate conversion coefficient for a reference depth distribution of radionuclide m in soil (the ratio of the kerma rate in free air at 1 m to the deposition density of the radionuclide in soil), and λ_m is the decay constant of radionuclide m (t^{-1}).

In the second submodel, the kerma rate in air at location j is assessed by multiplying $\dot{K}_{air}(t)$ by the time-dependent dimensionless location factor $f_j(t)$.

In the third submodel, the dose rate in air for the representative person of population group i is calculated taking into account human behaviour. This is done by weighting $\dot{K}_{air}(t)$ at location j by occupancy factor p_{ij}, and summing the product over the locations of interest.

In the fourth submodel, the effective dose rate $\dot{E}_i^{dep}(t)$ to the representative of population group i (or absorbed dose rate to the particular organ of these individuals) is calculated by

$$\dot{E}_i^{dep}(t) = \dot{K}_{air}(t)k_i\sum_{m} f_i(t)p_{ij}$$

4. Discussion and conclusions

Dose assessment is a central activity in assessing health consequences resulting from a nuclear accident with a release of radionuclides. It seems that only little progress in dose assessment methodology has been made within the latest 30 years. The progress that has been made has been made in connection with studies on the Chernobyl and Fukushima accidents.

There are several ways that the dose assessment methods and models could be improved upon. In assessing the dose from cloudshine, more accurate modelling would better take into account the effect of the various objects in the human environment that shield humans from direct radiation, such as buildings and trees. It is unclear how well the impact of clothing as a shielding factor has been taken into account in the existing models, and this should be studied, too. Concerning groundshine, more attention should be given to the fact that all survaces are not alike in absorbing radionuclide compounds, or in acting as a source of ionizing radiation. For example, it is likely that soil radiates less per unit of radionuclides than concrete, due to its greater porosity. Accounting for this would involve both the physical study of different surfaces, and assessment of how large portions of different surfaces there are in human environments.

The success of countermeasures is a central determinant of population doses, and therefore exploiting improvements in behavioural simulation and crowd models gained within the last 20 years could greatly improve the accuracy of the results. Taking external events and seasonal factors would also improve accuracy: for example, bad weather may hamper evacuation, and snow cover is known to reduce dose significantly.

Advances in computational power, and computational methods developed recently, have not been much utilized in dose assessments for level 3 PRA. For example, it would be worthwhile considering whether Monte Carlo methods for dose assessment developed for medical physics [30] could be taken into use in consequence analyses.

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