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A SIMPLIFIED MODEL FOR CALCULATING ATMOSPHERIC RADIONUCLIDE TRANSPORT AND EARLY HEALTH EFFECTS FROM NUCLEAR REACTOR ACCIDENTS

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ABSTRACT

During certain hypothetical severe accidents in a nuclear power plant, radionuclides could be released to the environment as a plume. Prediction of the atmospheric dispersion and transport of these radionuclides is important for assessment of the risk to the public from such accidents. A simplified PC-based model was developed that predicts time-integrated air concentration of each radionuclide at any location from release as a function of time-integrated source strength using the Gaussian plume model. The solution procedure involves direct analytic integration of air concentration equations over time and position, using simplified meteorology. The formulation allows for dry and wet deposition, radioactive decay and daughter buildup, reactor building wake effects, the inversion lid effect, plume rise due to buoyancy or momentum, release duration, and grass height. Based on air and ground concentrations of the radionuclides, the early dose to an individual is calculated via cloudshine, groundshine, and inhalation. The model also calculates early health effects based on the doses. This paper presents aspects of the model that would be of interest to the prediction of environmental flows and their public consequences.

INTRODUCTION

During certain hypothetical severe accidents in a nuclear power plant, radionuclides could be released to the environment as a plume. Prediction of the atmospheric dispersion and transport of these radionuclides is important for assessment of the risk to the public from such highly unlikely accidents. The Reactor Safety Study (1975) presented the first comprehensive assessment of the risk to society from potential accidents at nuclear power plants. The CRAC model was developed as part of this study to calculate the public consequences of accidental releases of radionuclides to the atmosphere (Wall et al., 1977). Following this, several other consequence models were developed (OECD, 1984), including an improved version of CRAC, CRAC2 (Ritchie et al., 1983). This was followed by the development of the MELCOR Accident Consequence Code System (MACCS), which is currently used as the basis for severe accident risk assessments by the U. S. Nuclear Regulatory Commission (Chanin et al., 1987). More recently, an international probabilistic consequence assessment (PCA) code comparison exercise was carried out under the joint auspices of the European Communities and the OECD Nuclear Energy Agency (OECD, 1994).

In 1988, a simplified PC-based model, called SMART, was developed that used an integral approach for calculating early offsite consequences from nuclear reactor accidents (Madni et al., 1988). The model predicts time-integrated air concentration of each radionuclide at any location from release as a function of time-integrated source strength using the Gaussian plume model. The solution procedure involves direct analytic integration of air concentration equations over time and position, using simplified meteorology. This is different from the discretization approach used in codes, such as CRAC and MACCS. The formulation allows for dry and wet deposition, radioactive decay and daughter buildup, reactor building wake effects, the inversion lid effect, plume rise due to buoyancy or momentum, release duration, and grass height. Based on air and ground concentrations of the radionuclides, the early dose to an individual is calculated via cloudshine, groundshine, and inhalation. The model also calculates early health effects based on the doses. The SMART code is fast-running, about two orders of magnitude faster than codes, such as MACCS and CRAC2, thereby providing a valuable tool for sensitivity and uncertainty studies. Detailed sensitivity and uncertainty analyses were carried out using the code (Madni et al., 1989). The code has also been benchmarked against both MACCS and CRAC2. This paper presents aspects of the model that would be of interest to the prediction of environmental flows and their public consequences.

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DESCRIPTION OF MODELS

Atmospheric Dispersion

Diffusion Equation and Air Concentration. When released into the atmosphere, radioactive gases and aerosols follow prevailing winds and are diffused due to the cumulative effects of atmospheric turbulence. Predictions of dispersion in the lower atmosphere are most commonly made from the semiempirical "Gaussian plume" model. This model has been and still is widely used to analyze the dispersion of atmospheric pollutants, due to its short computing time, simplified input requirements, and reasonable agreement with the average of many observations (Hanna et al., 1982).

In this model, the governing equations are derived by starting with the classical Fick's law diffusion equations. These equations are solved assuming that the coefficients of diffusivity are constants. In the resulting expressions, the diffusivity coefficients are then allowed to become dependent on both space and atmospheric stability conditions in order to fit the plume model to experimental data. For an ideal, nonisotropic, infinite atmosphere, the diffusion equation in Cartesian coordinates is (see Nomenclature):

$$\frac{D\chi}{Dt} = K_x\frac{\partial^2\chi}{\partial x^2} + K_y\frac{\partial^2\chi}{\partial y^2} + K_z\frac{\partial^2\chi}{\partial z^2} \qquad (1)$$

where

D/Dt = particle derivative operator

χ = concentration (Ci/m^3) of a particular radionuclide.

With an average wind speed $\bar{u}$ in the x direction, Eq. (1) reduces to

$$\frac{\partial\chi}{\partial t} + \bar{u}\frac{\partial\chi}{\partial\chi} = K_x\frac{\partial^2\chi}{\partial x^2} + K_y\frac{\partial^2\chi}{\partial y^2} + K_z\frac{\partial^2\chi}{\partial z^2} \qquad (2)$$

If we consider the concentration to be caused by a point source emitting contaminant at a constant rate Q', then $\partial\chi/\partial t = 0$. Furthermore, diffusion in the direction of the wind is neglected, or $K_x = 0$. Equation (2) then reduces to

$$\bar{u}\frac{\partial\chi}{\partial x} = K_y\frac{\partial^2\chi}{\partial y^2} + K_z\frac{\partial^2\chi}{\partial z^2} \qquad (3)$$

with boundary conditions corresponding to the source term at the release point, and $\partial\chi/\partial y = \partial\chi/\partial z = 0$ (due to symmetry) at the plume centerline.

The solution of this equation is (Lamarsh, 1966)

$$\chi = \frac{Q'}{2\pi\bar{u}\sigma_y\sigma_z}\exp\left[-\left(\frac{y^2}{2\sigma_y^2} + \frac{z^2}{2\sigma_z^2}\right)\right] \qquad (4)$$

where σ_y and σ_z are defined by

$$\sigma_y = \frac{(2xK_y)^{1/2}}{\bar{u}} \quad and \quad \sigma_z = \frac{(2xK_z)^{1/2}}{\bar{u}} \qquad (5)$$

Postulated releases from reactor accidents would be at some altitude h above ground level; hence, the earth's surface would be a barrier to downward diffusion and expansion of the plume. A conservative estimate of this effect can be made by assuming the ground to be a perfect reflector of the contaminants. An image source is placed at an altitude of $-h$, and the solution is obtained as

$$\chi = \frac{Q'}{2\pi\bar{u}\sigma_y\sigma_z}\exp\left[-y^2/2\sigma_y^2\right]$$
$$x\left(\exp\left[-\frac{(z+h)^2}{2\sigma_z^2}\right] + \exp\left[-\frac{(z-h)^2}{2\sigma_z^2}\right]\right) \qquad (6)$$

The concentration at z = 0 (i.e., for a receptor or observer at ground level) is

$$\chi = \frac{Q'}{\pi\bar{u}\sigma_y\sigma_z}\exp\left[-\left(\frac{y^2}{2\sigma_y^2} + \frac{h^2}{2\sigma_z^2}\right)\right] \qquad (7)$$

For a release of finite duration τ, the time-integrated source strength Q is given by

$$Q = \int_0^\tau Q'\,dt \qquad (8)$$

and the time-integrated (total, cumulative) concentration χ_T is similarly defined as

$$\chi_T = \int_0^\tau \chi\,dt \qquad (9)$$

Equation (7) then becomes

$$\chi_T = \frac{Q}{\pi \bar{u} \sigma_y \sigma_z} \exp\left[-\left(\frac{y^2}{2\sigma_y^2} + \frac{h^2}{2\sigma_z^2} \right) \right] \qquad (10)$$

In Eqs. (7) and (10), note that a ground-level release *($h = 0$)* gives a conservative estimate of concentration and hence should be used if the height of release is not known. In the rest of this paper, χ is used instead of χ_T to denote time-integrated air concentration.

Dispersion Parameters and Weather Data. The dispersion parameters σ_y and σ_z given by Eq. (5) are functions of constant diffusivities K_y and ${}_zK$, respectively, and would, therefore, vary as χ from the point of release for a given wind speed. However, these dispersion parameters are found to also depend on the atmospheric stability conditions. A more realistic model of dispersion would, therefore, use experimental values of σ_y and σ_z to calculate radionuclide concentrations.

Pasquill (1961) proposed a simple scheme in which he presented information on lateral and vertical spreading of a plume as functions of six atmospheric stability classes designated A to F. Gifford (1976) converted the plume spreading data into families of curves of the standard deviations σ_y and σ_z of the plume concentration distribution. These curves are frequently called the Pasquill-Gifford (P-G) curves. For the simplified model, they were fitted by

$$\sigma_y(x) = \exp\left[sy_0 + sy_1 \ln(x) + sy_2 \ln(x)^2\right] \qquad (11)$$

and

$$\sigma_z(x) = \exp\left[sz_0 + sz_1 \ln(x) + sz_2 \ln(x)^2\right] \qquad (12)$$

The coefficients in these curve-fit equations are listed in Table 1. The seventh stability condition, type G (extremely stable), has been approximated by the following relations (Lamarsh, 1983) and are in accordance with Regulatory Guide 1.145 (1982):

$$\sigma_z(G) = \frac{3}{5}\sigma_z(F)$$

and

$$\sigma_y(G) = \frac{2}{3}\sigma_y(F) \qquad (13)$$

The P-G curves were also fitted by Martin and Tikvart and were used by the consequence code CRAC2 (Ritchie et al., 1983). Several other investigators have also proposed parameterization of σ_y and σ_z to match the measured data of plume dispersion. Most of these have been reviewed by Gifford (1976). The work of Rogers and Gamertsfelder has also been referred to by Wilson et al. (1985).

Corrections to Air Concentration

The basic Guassian plume model is modified to take into account dry and wet deposition, radioactive decay and daughter buildup, reactor building wake effects on plume mixing, the inversion lid effect, plume rise due to buoyancy, release duration, and grass height. These modifications are based on approaches available in the literature and are similar in approach to the MACCS model.

Dry Deposition. The standard way of dealing with dry deposition is to assume that if $\chi(x,y,0)$ is the ground-level, time-integrated concentration, the total activity deposited by the passing cloud is given by

$$\chi_D(x,y) = v_d \chi(x,y,0) \qquad (14)$$

where v_d is a proportionality constant, called the "deposition velocity." Deposition can occur by gravitational settling, turbulent and molecular diffusion, and inertial impaction (Horst, 1977) and depends on several factors, including the size and shape of the particles, their chemical properties, ground roughness, nature of vegetation, and atmospheric stability. Values of v_d can range from 10^{-6} to 0.2 m/s (Hosker, 1974). For release from reactor accidents, v_d can be expected to be in the range 0.001 to 0.1 m/s. The value of 0.01 m/s was chosen for use in the Reactor Safety Study (1975). In the SMART code, it is left as a user input value for each radionuclide, defaulting to 0.01 m/s. Deposition velocities for noble gases are taken to be zero.

At significant distances downwind, the equation for air concentration must be modified to account for the loss of deposited contaminants. This effect can be incorporated by multiplying the source terms of χ by (Lamarsh, 1983)

$$f_d = \exp\left(\frac{-v_d x}{\bar{u}\,\bar{z}} \right) \qquad (15)$$

where $\bar{z}$ is the effective height of the plume given by

$$\bar{z} = \left(\frac{\pi}{2} \right)^{1/2} \sigma_z \exp\left(\frac{h^2}{2\sigma_z^2} \right) \qquad (16)$$

Wet Deposition. If it rains during atmospheric transport of the plume, the radioactive particles are deposited onto the ground by a process called washout or wet deposition. A number of techniques have been suggested in the literature. The approach

TABLE 1

Curve Fitting Coefficients for Atmospheric Stability Classes A Through F

Stability Class	sy_0	sy_1	sy_2	sz_0	sz_1	sz_2
F (moderately stable)	-3.559	1.160	-1.719×10^{-2}	-4.539	1.412	-5.45×10^{-2}
E (slightly stable)	-2.817	1.066	-1.147×10^{-2}	-4.213	1.443	-5.471×10^{-2}
D (neutral)	-2.546	1.077	-1.252×10^{-2}	-3.162	1.197	-3.459×10^{-2}
C (slightly unstable)	-1.969	1.022	-8.377×10^{-3}	-2.981	1.212	-2.538×10^{-2}
B (moderately unstable)	-1.961	1.111	-1.405×10^{-2}	2.693	-0.781	0.158
A (extremely unstable)	-1.790	1.151	-1.733×10^{-2}	9.430	-3.393	0.425

used here is the one discussed in Appendix 6 of the Reactor Safey Study (1975) and in the PRA Procedures Guide (1983). The fractional rate of material removed from the plume Λ is expressed empirically (Ritchie, et al., 1976) in the form

$$\Lambda = CR \tag{17}$$

where

R = rainfall rate
C = proportionality constant.

For stable and neutral atmospheric conditions, C is set to 10^{-4}h/mm·s while for unstable conditions C is set to $^{-3}$10 h/mm·s (Ritchie et al., 1981). The value of Λ can vary from 10^{-5} to 10^{-2} s $^{-1}$. This effect is incorporated into the SMART model via a correction factor for the air concentration:

$$f_w = \exp\left(-\Lambda\ \Delta t\right) \tag{18}$$

where $\Delta t = t\text{-}t_0$ is the duration of rain from its onset time t. Combining both dry and wet deposition, Eq. (10) becomes

$$\chi = \frac{Q}{\pi \bar{u} \sigma_y \sigma_z} \exp\left[-\left(\frac{v_d x}{\bar{u}\ \bar{z}} + \Lambda\ \Delta t + \frac{y^2}{2\sigma_y^2} + \frac{h^2}{2\sigma_z^2}\right)\right] \tag{19}$$

The total activity deposited on the ground due to both dry and wet deposition can be calculated from

$$\chi_D = (v_d + v_w)\ \chi \tag{20}$$

where v_w is an equivalent "wet" deposition velocity given by

$$v_w = \frac{\Lambda\ \Delta t\ \bar{u}\ \bar{z}}{x} \tag{21}$$

Radioactive Decay and Daughter Buildup. At any distance x downwind of the plume release, the strength of nuclide I is

$$Q_I = f_I\ Q_I^0 \exp\left[-\lambda_I\ (t_c + x/\bar{u})\right] \tag{22}$$

If the decay of a radionuclide (parent) leads to the buildup of a daughter product D, then at any distance x downwind of the plume release, the strength of the daughter nuclide D is determined by

$$\begin{aligned} Q_D &= f_D\ Q_D^0 \exp\left[-\lambda_D\ (t_c + x/u)\right] \\ &+ \frac{\lambda_p f_p Q_p^0}{\lambda p - \lambda_D}\left(\exp[-\lambda_D\ (t_c + x/u)] - \exp\ [-\lambda_p\ (t_c + x/u)]\right) \\ &+ \frac{\lambda_p f_p Q_p^0\ \exp(-\lambda_p t_c)}{\lambda_p - \lambda_D}\ x\ \left[\exp(-\lambda_D x/u) - \exp(-\lambda_p x/u)\right] \end{aligned} \tag{23}$$

The first two terms in Eq. (23) are the source at x from decay of initial daughter release into the environment, and the last term is the additional source at x due to parent decay during plume travel.

Equation (19) is modified to account for this effect and becomes

$$\chi = \frac{Q(x)}{\pi \bar{u} \sigma_y \sigma_z} \exp\left[-\left(\frac{V_d x}{\bar{u}\ \bar{z}} + \Lambda\ \Delta t + \frac{y^2}{2\sigma_y^2} + \frac{h^2}{2\sigma_z^2}\right)\right] \tag{24}$$

where $Q(x)$ is given by Eq. (22) for any nuclide, including parent, and by Eq. (23) for a daughter product.

Equation (24) is solved directly for χ at any distance x from the source, instead of marching over mesh intervals. This is in contrast to the approach in CRAC2 and MACCS, which is based on discretization of the distance coordinate into mesh intervals over which meteorological changes are allowed.

Building Wake Effects. When the effluent plume emerges from the reactor building, its dispersion into the atmosphere is increased by the turbulence in the wake region. This effect needs to be incorporated in calculating potential exposures. The default correction used in the SMART model is the one presented in Sec. 3 of TID-24190 (Slade, 1968). According to this, an adjustment is made to the dispersion coefficients in Eq. (24) as follows:

$$\sigma_y^{\prime} = \left(\sigma_y^2 + \frac{cA}{\pi}\right)^{1/2} \tag{25}$$

and

$$\sigma_z^{\prime} = \left(\sigma_z^2 + \frac{cA}{\pi}\right)^{1/2} \tag{26}$$

where

σ'_y, σ'_z = corrected horizontal and vertical standard deviations of plume material

A = cross-sectional area of the building perpendicular to the wind

c = shape factor, which is in the range of 0.5 to 2.

Regulatory Guide 1.145 (1982) indicates that the building wake correction should be used in the first 8 h following release, with a shape factor c of 0.5 and the minimum cross-sectional area of the reactor building only.

Alternately, as was proposed by Holland (1953), a virtual point source can be assumed, which would produce a Guassian plume having dimensions comparable to those of the reactor building.

Any modification proposed to date is only an approximation and cannot be expected to be valid within the wake region of the reactor building. However, the adjustments presented here are a simple and economical approximation to account for this very complicated effect in calculating air concentrations further downwind. For complex building shapes, no reliable simple guidelines are presently available.

Plume Rise. The release height h in Eq. (24) is adjusted to account for plume rise on release, due to buoyancy (Ritchie et al., 1983; Briggs, 1975).

Grass Height. The vertical dispersion parameter from the P-G curves, $\sigma_z(x)$, is adjusted for surface roughness as recommended by the American Meteorological Society Workshop (1977) and implemented in CRAC2 and MACCS, to be more appropriate for a roughness of 10 cm, as follows:

$$\sigma_z = \sigma_{zP\text{-}G}\left(\frac{10cm}{3cm}\right)^{0.2} = 1.27\sigma_{zP\text{-}G} \tag{27}$$

Alternatively, $\sigma_z(x)$ can be obtained from fits to Smith's curves (Hosker, 1974) with correction factors for various roughnesses ranging from 1 to 400 cm.

Release Duration. For a release of longer duration T with the wind direction nominally constant, the time-averaged plume will probably be wider due to increased horizontal dispersion than it would be for a release of shorter duration T_E. This effect has been included simply by

$$\sigma_y = \sigma_{yP\text{-}G}\left(\frac{T}{T_E}\right)^n \tag{28}$$

The horizontal dispersions from the P-G curves are based on experiments where the release duration is a few minutes.

In CRAC2, T_E is taken to be 3 min; $n = 0.2$ for $3 < T \leq 60$ min and $n = 0.25$ for $60 < T \leq 600$ min. The same scheme is used in the SMART model.

Inversion Lid. The atmospheric boundary layer is capped by a very stable layer, whose base forms an effective barrier to the upward growth of a plume. This is called the inversion lid. Estimates of the height of this lid H can be obtained from Holzworth (1972). In the present model, σ_z is allowed to grow to a maximum of $0.8H$, where H is a user-input value.

Dose Calculations

Once the atmospheric and ground-level concentrations χ and χ_D for each radionuclide are determined, the radiation dose accumulated by individuals can be considered in two phases: the initial or acute phase during and shortly after passage of the radioactive cloud, and the latent phase sometime after the cloud passage.

Radiation doses in the early phase can be received via the following pathways:

1. direct external exposure to radiation emitted by radionuclides in the passing cloud (cloudshine)
2. early external exposure to radiation from radionuclides deposited on the ground (short-term groundshine)
3. internal exposure due to inhalation of radionuclides from the cloud (inhalation).

Doses in the latent phase can be received via ingestion of contaminated food and drink by deposited radionuclides and inhalation of resuspended radionuclides, as well as long-term exposure to groundshine. Early effects are more significant for determining the necessary emergency response actions and are the only effects included in the current version of SMART.

The dose calculations are performed in the same manner as CRAC2 or MACCS depending on which health effect model is chosen as the input option. Values of dose conversion factors for both CRAC2 and MACCS are included (Madni et al., 1988).

Health Effects

The health effects models of both MACCS and CRAC2 are included in SMART for early health effects only. These effects are early deaths and injuries modeled for organ-specific doses from the three pathways.

MACCS uses the hazard function approach to calculate early fatalities as discussed in Evans et al. (1985). First, the cumulative hazard is calculated as

$$H = \ln(2)\ (D/D_{50})^{v} \tag{29}$$

where

D = dose

D_{50}= dose required for producing an effect in 50 percent of the exposed individuals

and v determines the steepness of the dose effect curve. That fatality risk is then given as

$$Risk = 1 - \exp\left[-(H_1 + H_2 + H_3 + H_4)\right] \tag{30}$$

where H_1 is for red marrow, H_2 is for lungs, and H_3 and H_4 are for the lower large and small intestines. The risk is assigned a threshold of 0.005.

In CRAC2, the dose response is piecewise linear due to irradiation of the bone marrow, lung, and gastrointestinal tract. The total risk is then

$$R = R_1 + (1-R_1)R_2 + (1-R_1)(1-R_2)\ R_3 \tag{31}$$

where R_1, R_2, and R_3 are the risks to the three organs, respectively. MACCS gives somewhat higher risk, principally because the lung dose is now considered more effective in producing fatalities and also because the hazard function gives some risk at lower doses.

The effect of the model differences is that MACCS predicts a higher probability for small numbers of deaths, while CRAC2 predicts a higher proability for large numbers of deaths.

Early injuries in MACCS are also calculated using the hazard function except that the cumulative hazard is not summed as in Eq. (30). Rather, the risk of lung impairment, prodromal vomiting, hypothyroidism, and thyroid ablation are calculated separately. Several other injuries can be defined, although only persons who did not suffer early death are considered.

Early injuries in the CRAC2 model are calculated as in Eq. (31) using doses to the whole body, lungs, and lower large intestinal wall. The dose response is discussed in Appendix VI of the Reactor Safety Study (1975). The risk of death is subtracted from the risk of injury.

BENCHMARKING COMPARISONS

The SMART code was benchmarked by comparing results for ^{137}Cs air concentration, total dose to organs, and health effects, with single-weather calculations performed by CRAC2 and MACCS version 1.4. Note that the most recent version of MACCS is 1.5.11. However, there are no signficiant differences in the models of the two versions except for late health effects, which are beyond the scope of the current SMART code models. The radiological releases correspond to the largest release cluster for an early containment failure due to direct heating. The core inventory selected was for a pressurized water reactor operating at 3412-MW (thermal) power. For the remainder of the input, CRAC2 and MACCS default values were chosen (Ritchie et al., 1983; Chanin et al., 1987). Six separate calculations were performed with each computer code, for atmospheric stability classes A, D, and F, and wind speeds of 1 and 5 m/s. Each case was labeled with the corresponding weather condition (A1, A5, D1, D5, F1, F5). Test D1 was also performed with dry deposition velocity equal to zero.

For the benchmarking study, all the above cases were calculated using dispersion models of CRAC2 or MACCS, both of which are built into the SMART code for purposes of benchmarking and sensitivity calculations. These models are incorporated as options into SMART and do not require separate executions of CRAC2 or MACCS codes. Figure 1 illustrates results of a benchmark comparison of total bone marrow dose versus distance for test D5 as calculated with the present model versus the CRAC2 and MACCS codes. Similar results were obtained for all other weather conditions and doses to different organs. Calculations from the present model are seen to agree to within 3 percent or better with both CRAC2 and MACCS for all distances (Madni et al., 1988).

SUMMARY AND CONCLUSIONS

A personal computer-based interactive approach has been developed that uses an integral approach and simplified meteorology for calculating early offsite consequences from nuclear reactor accidents. The computing time requirements for a typical calculation using the SMART consequence model are more than two orders of magnitude lower than the MACCS code, thus providing a valuable tool for sensitivity and uncertainty studies. The model predicts the time-integrated air concentration of each radionuclide at any distance from the point of release as a function of the time-integrated source strength using the Guassian plume model. The solution procedure involves direct analytic integration of air concentration equations over time and position. This is different from the discretization approach currently used in the MACCS code. The model includes dry and wet deposition, radioactive decay and daughter buildup, and the effects of reactor building wake, inversion lid, plume rise, release duration, and grass height. Early dose to an individual is calculated via cloudshine, short-term groundshine, and inhalation. The model also calculates early health effects based on the doses. The SMART code was benchmarked against both MACCS version 1.4 and CRAC2.

There are large uncertainties in the initial and boundary conditions to a consequence assessment code, aside from uncertainties in the models themselves, that can result in up to several orders of magnitude deviation in the calculated results of radiation dose and health effects. The consequence calculations have, therefore, to be performed in a probabilistic context. This makes the fast-running SMART code an especially useful tool to provide insights into accident management and siting strategies and their risk reduction benefits to the public in the vicinity of a nuclear facility.

NOMENCLATURE

A = building cross-sectional area (m^2)
Br = breathing rate of receptor (m^3/s)
c = shape factor
D_c = cloudshine dose (rem)
D_g = groundshine dose (rem)
D_i = total inhalation dose (rem)
$F_{c\infty}$ = cloud dose conversion factor (rem·m^3/Ci·s)
F_g = integral ground dose conversion factor (rem·m^2/Ci)
F_{in} = inhalation dose conversion factor (rem/Ci)
f_d = correction factor to air concentration due to dry deposition
f_I = fraction of nuclide I in containment available for environmental release
f_w = correction factor to air concentration due to wet deposition
h = height of release (m)
K_x, K_y, K_z = diffusivities in the x, y, and z directions, respectively (m_2/s)
Q = time-integrated source strength (Ci)
Q^0 = radionuclide inventory in core (Ci)
Q' = release rate of radionuclides from source (Ci/s)
R = rainfall rate (mm/h)
t = time (s)
t_c = time of containment failure (s)
$\bar{u}$ = mean wind speed in the x direction (m/s)
v_d = dry deposition velocity (m/s)
v_w = equivalent wet deposition velocity (m/s)
x = horizontal coordinate along the wind (m)
y = horizontal cross-wind coordinate (m)
z = vertical coordinate (m)
$\bar{z}$ = effective height of the plume (m)

Greek

Δt = duration of rain (s)
λ = radioactive decay rate (s^{-1})
Λ = fractional rate of material removed due to rain (s^{-1})
σ_y = horizontal dispersion coefficient (m)
σ_z = vertical dispersion coefficient (m)
χ, χ_T = time integrated air concentration of a radionuclide (Ci·s/m^3)
χ_D = total ground concentration of a radionuclide (Ci/m^2)

Subscripts

D = daughter product
I, I = radionuclide I
p = parent

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