6.4 Functional requirements for specialized models

6.4.1 General definition of conditions requiring specialized models

6.4.1.1

The use of specialized models shall be considered wherever the release occurs over rugged terrain, at a coastline, or in a region of large land-use variations.

Note: *In such cases, the assumptions of steady-state straight-line transport in time or space could be inappropriate (40 CFR 2011).*

6.4.1.2

Specialized models should be used if at least one of the following factors is present (see Clause 6.2.2):

a) complex terrain;
b) non-stationary conditions; and
c) shoreline dispersion conditions.

Notes:

1) *Other complex situations that could require specialized models include (see Clause 6.2.2):*
   a) *low wind speeds or calms;*
   b) *fog;*
   c) *conditions conducive to resuspension or re-emission;*
   d) *tritiated hydrogen gas (HT); and*
   e) *multiple point, area, or volume sources.*
2) *Criteria to determine the need for specialized models are given in Clauses 6.4.2 to 6.4.9. Acceptable approaches, their limitations, and their uncertainties are discussed in Clause B.2.*

6.4.2 Complex terrain

6.4.2.1

Complex terrain shall be defined as terrain where changes in elevation are greater than the height of the stack.

Notes:

1) *For further information regarding complex terrain, see 40 CFR 2011.*
2) *Alternative classifications of complex terrain [e.g., terrain exceeding 50% of the stack height (Deaves and Hebden 2007)] are not adopted, because they are excessively conservative.*

6.4.2.2

The definition of complex terrain should also include slopes in excess of 10%, mountain or valley winds, valley stagnation or recirculation airflow under persistent light wind conditions, and complex thermal structures driving cross-valley circulations, including the effects of differential heating.

6.4.2.3

Wherever the terrain is complex, an ADM with the corresponding capability shall be used.

Note: *Modelling approaches to handling complex terrain are discussed in Clause B.2.2.*

6.4.3 Non-stationary conditions

6.4.3.1

Non-stationary conditions shall be assumed to occur whenever the assumptions of steady-state straight-line transport in time or space are inappropriate.

Note: *Complex dispersion caused by non-stationary conditions includes the effect of wind meandering and complex thermal structures that affect plume dispersion.*

6.4.3.2

If non-stationary conditions happen more than 10% of the time at the site of interest (so that there is a possibility that the upper decile of doses will be affected), a non-steady-state model should be used.

Note: *Models designed to handle non-stationary conditions are presented in Clause B.2.3.*

6.4.4 Shoreline dispersion

A shoreline dispersion model should be used for handling the thermal effects that occur in the vicinity of the shoreline, including a dynamical description of the height and growth of the TIBL.

Notes:

1) *The TIBL height and growth depend on land-water temperature difference, strength and direction of the geostrophic wind, time of day, surface roughness, air humidity inland, and curvature of the shoreline.*
2) *Shoreline dispersion models are discussed in Clause B.2.4.*

6.4.5 Low wind speeds and calms

A specialized model capable of handling low wind speeds should be considered if low speeds occur for a significant fraction of the time (> 5%) at the site of interest.

Notes:

1) *Low wind speeds are defined as speeds less than* 2 m/s*. When the speed is this low, longitudinal dispersion becomes comparable to advection and should be included in the model. Also, light winds are often accompanied by large variability in direction, and meandering should be taken into account.*
2) *The Gaussian plume model cannot be used in calm conditions (u = 0) because the wind speed appears in the denominator of the Gaussian equation and division by zero would result.*
3) *Methods for handling low wind speed conditions are presented in Clause B.2.5.*

6.4.6 Fog effects

Radionuclide deposition in the presence of fog should be modelled as a dry deposition process with an enhanced deposition velocity that is a function of wind speed.

Notes:

1) *The primary effect of fog on atmospheric dispersion is to increase the rate of dry deposition.*
2) *Measurements of the deposition velocities for fog droplets have been published (e.g., Scheier 2009).*
3) *Modelling approaches that account for the effects of fog are discussed in Clause B.2.6.*

6.4.7 Resuspension and re-emission

6.4.7.1 Particulates

Inhalation and cloudshine doses due to resuspension of radionuclides in particulate form may usually be neglected.

6.4.7.2 Actinides

When the release contains a high proportion of actinides (uranium, plutonium, americium), the inhalation exposure from resuspension should be assessed using a model that predicts air concentrations in the resuspended plume.

Note: *For a given level of activity on the ground, actinides give very small doses from external exposure and comparatively large doses from inhalation of resuspended material.*

6.4.7.3 Volatiles

The inhalation dose of volatile radionuclides such as tritium, C-14, S-35, and radioiodine should be considered when these radionuclides are re-emitted to the atmosphere following deposition.

Notes:

1) *When the release stops, the partial pressure gradient and the diffusive flux of volatile radionuclides are directed upward and the radionuclides are lost from soil and plants to the atmosphere.*
2) *Of the volatile radionuclides, tritium is very susceptible to re-emission. Tritium deposited from the atmosphere to soil and plants is readily recycled back to the atmosphere via evapotranspiration.*
3) *More information on resuspension and re-emission is provided in Clause B.2.7.*

6.4.8 Tritiated hydrogen gas (HT)

In estimating doses due to the release of tritiated hydrogen gas (HT), models should take into account the dry deposition of HT from air to soil, the oxidation of HT to HTO in soil, and the re-emission of the HTO from soil and plants to the air.

Notes:

1) *HT is taken up very slowly by the environment and humans. Direct exposure to HT results in very low doses and can be neglected.*
2) *HT can diffuse into the soil and be converted to HTO, which is subject to the same processes and pathways as the HTO deposited during an HTO release. In particular, some of the converted HTO is re-emitted to the atmosphere from soil and plants. HT releases can be adequately addressed if the concentration of the converted HTO in air can be reliably estimated.*
3) *Approaches to modelling HT releases are discussed in Clause B.2.8.*

6.4.9 Multiple point, area, and volume sources

Dispersion from multiple point, area, and volume sources shall be treated using the methods discussed in Clause 5.7.

6.5 Justification of the model choice

6.5.1 General requirements

6.5.1.1 Justification

Justification of the chosen model should be provided for each application. In particular, the model shall produce results that meet the goals of the safety assessment.

6.5.1.2 Selection principles and criteria

6.5.1.2.1

Selection of a model shall be based on established scientific principles and criteria.

Note: *Examples are available in EPA Guidance (EPA 1992, 2005, 2008) and ADMLC Guidelines (Deaves and Hebden 2007, and Ireland et al. 2004).*

6.5.1.2.2
The model should have received a scientific peer review.

6.5.1.2.2
The model shall be applicable to the problem in that it accounts for all important phenomena.

6.5.1.2.3
The data required by the model shall be available.

6.5.1.2.4
The model should demonstrably not be biased towards underestimates of the consequence.

6.5.1.2.5
The use of the model should be based on a documented protocol of methods and procedures to be followed.

6.5.2 Model validation

6.5.2.1
Model validation (performance evaluation) should cover all default phenomena and all special phenomena occurring more than 10% of the time at the site of application.

Notes:

1) *Validation means comparison of predicted data against field data.*
2) *In Canada, codes used for compliance with the AHJ might be subject to the requirements of CSA N286.7.*

6.5.2.2
In cases where field data are not available, validation may be demonstrated by benchmarking against a validated model of greater sophistication and more elaborate capacities (see Annex C).

Note: *Atmospheric turbulence is stochastic in nature and varies in time and space. It is not possible, given current understanding and measurement capabilities, to capture the local variations in atmospheric conditions that result in differences in downwind concentrations over short timeframes. This irreducible uncertainty places a practical limit on the accuracy that can be expected of model predictions and provides a benchmark against which to judge model performance and acceptability. Gaussian dispersion models are generally believed to predict atmospheric concentrations averaged over long times to within about a factor of 2 under ideal conditions (neutral stability, flat terrain) (40 CFR 2011, Part 51-W), but can be significantly less accurate for shorter averaging times or more extreme conditions.*

7 Calculation of consequences

7.1 Quantities
The calculation of consequences shall include one or more of the following quantities:

a) doses and health effects (deterministic effects and stochastic effects) associated with human receptors; and
b) airborne and ground concentrations.

Notes:

1) *For design basis accidents, deterministic effects are unlikely, and the analysis should focus on the calculation of doses and stochastic health effects. For severe accidents in nuclear power plants, deterministic effects in*

the population are possible within a distance of a few kilometres from the point of release. In those instances, a better measure of the consequences of an accident consists of summing fatalities from deterministic effects and stochastic health effects, since fatalities are not necessarily a linear function of the dose. Non-fatal deterministic health effects can be calculated separately for each syndrome.

2) *The individual risk of fatalities is the sum of the risk of stochastic health effects (see Clause 7.12) and deterministic health effects (see Clause 7.13).*
3) *Airborne and ground concentration end points are used in emergency planning to determine the type of radiation detection to acquire and to identify zones where food bans may be necessary.*

7.2 Receptors

7.2.1

The choice of receptor shall be based on the safety objectives of the calculation.

7.2.2

For the safety assessment to verify compliance with individual dose limits, the representative person shall include, as a minimum, a hypothetical adult individual located at the site boundary in the downwind direction at the time of the event.

Note: *Safety assessments generally apply to off-site receptors (members of the public). In addition, on-site non-nuclear energy workers that are not covered under the facility's radiation protection program and health and safety program may be evaluated.*

7.2.3

For safety assessments involving collective doses and for probabilistic safety assessment (PSA), the population distribution around the reactor, projected if necessary to the time period of interest, shall be used.

7.2.4

For dose calculation for site-specific emergency planning evaluations the representative individual for the general population should be an adult.

Note: *Dose calculations for emergency planning can inform other urgent public protective actions such as decontamination of the public and longer term protective actions such as temporary relocation and decontamination of land and buildings.*

7.2.5

Where appropriate and as outlined by the AHJ, protective measures should be assessed on the basis of the doses calculated for the vulnerable population.

Note: *Vulnerable populations can be defined as members of the population who have higher radiation sensitivity or additional needs before, during, and after a radiological release.*

7.2.6

Local atmospheric dispersion models should not be used for calculating the dose to the representative person at distances greater than 50 km, as the models have limited accuracy beyond 20 km and are unreliable beyond 50 km.

Note: *For greater distances, see Clause 4.6.4.*

7.3 Concentrations

7.3.1
Concentrations in air should be calculated using the methods discussed in Clause B.1.16.

7.3.2
Concentrations on the ground should be calculated using the methods discussed in Clauses 6.3.12.1, 6.3.13.1, and B.1.16.

7.4 Doses

7.4.1 General
The choice of a specific dose quantity shall depend on the safety objectives (see Clause 7.2) and the magnitude of the release (see Clause 7.4.3).

7.4.2 Compliance with dose limits
Note: *Dose limits are established by the AHJ.*

7.4.2.1
Both stochastic and deterministic end points shall be considered in a manner consistent with the requirements of the AHJ.

7.4.2.2
For demonstration of compliance with dose limits, the evaluation of the consequences shall include calculation of the committed effective dose.

7.4.2.3
When required for demonstration of compliance, the equivalent dose to an organ shall be calculated.

Note: *For example, in reactor accidents, inhalation of radioactive iodine is an important exposure pathway for the thyroid. In this instance, the evaluation of the consequences can include the calculation of the equivalent dose to the thyroid.*

7.4.3 Severe accident assessment
For releases of large magnitude, an evaluation of the health effects shall include the calculation of the effective dose and the absorbed dose.

Notes:

1) *Stochastic health effects (such as cancer) are calculated from the committed effective dose, multiplied by an appropriate risk factor (see Clause 7.12).*
2) *Deterministic health effects (such as mortality or morbidity associated with acute radiation exposure as presented in Table D.1) are calculated from the absorbed dose to the whole body or to specific organs, multiplied by a relative biological effectiveness (RBE) factor (see Clause 7.13).*

7.4.4 Dose intervention levels and emergency reference levels

7.4.4.1

For the preparation of emergency plans, the evaluation of the consequences should include calculation of the projected effective dose and the projected equivalent dose to the thyroid.

Notes:

1) *In Canada, current national guidelines for the preparation of emergency plans require a comparison of consequences with dose intervention levels.*
2) *For further guidance, see Health Canada (2003).*
3) *The guidance from ICRP-103 and IAEA GSR Part 7 makes a distinction between optimized triggers for urgent protective actions, expressed as dose intervention levels, and absolute triggers for protective actions, expressed as dose emergency reference levels.*
4) *The calculation of dose for comparison to dose intervention levels or reference levels might not include all exposure pathways. As an example, the reduction of the equivalent dose to the thyroid associated with the administration of stable iodine tablets is solely a function of the inhalation of radioactive iodine, because stable iodine substantially reduces the contribution of the inhalation pathway for radioactive iodine, but has no effect on the inhalation exposure from other radionuclides or the external exposure pathways from the cloud or the ground.*

7.4.4.2

Intervention levels or reference levels used to plan countermeasures in an emergency exposure situation shall meet the requirements of the AHJ.

Notes:

1) *The guidance from ICRP 103 recommends that emergency reference levels between 20 and 100 mSv/year should be used to plan countermeasures in an emergency exposure situation. In practice, the specific requirements of national and local authorities should be used.*
2) *The emergency reference levels correspond to the residual dose received by representative persons of the public, after all countermeasures combined in an overall protection strategy have been implemented. The guidance from ICRP 103 further states that limiting the effective doses below 1000 mSv should avoid serious deterministic effects; below 500 mSv should avoid other less serious deterministic effects.*
3) *Health Canada (2018) provides recommended generic criteria for taking protective actions where the reference level is set towards the upper range of the IAEA's recommended 20-100 mSv.*

7.5 Pathways

The radiation exposure pathways shall include

a) external exposure from radioactive material in both primary and re-emitted airborne plumes;
b) external exposure from radioactive material deposited on the ground; and
c) internal exposure resulting from inhalation of radioactive material in both primary and re-emitted airborne plumes and from absorption through the skin in the case of HTO.

Note: *In this Standard, it is assumed that countermeasures put in place after an accident will avoid exposure from ingestion of contaminated foodstuffs and water.*

7.6 Dose from external exposure to the cloud

7.6.1 Definition

The dose from external exposure to the cloud shall be defined as the external dose due to photons (gamma and x-ray) and electrons (beta emission, Auger, and internal conversion) that an individual receives when immersed in a cloud containing radioactive material.

7.6.2 Semi-infinite cloud approximation

For situations where the representative person is on the centreline of a plume released at ground level, the external immersion dose should be calculated by multiplying the time-integrated concentration of the radionuclide at the receptor location by the respective dose conversion factor for a semi-infinite uniform cloud.

Note: *In this situation, the semi-infinite cloud approximation tends to overestimate the external dose and is conservative.*

7.6.3 Finite cloud effects

7.5.6.1 Finite cloud corrections

To obtain more accurate dose estimates for the situation discussed in Clause 7.6.2, the external dose calculated by the semi-infinite cloud approximation should be multiplied by a correction factor to account for the finite size of the cloud.

Notes:

1) *The actual dimensions of a plume or a puff are finite and the distribution of radioactive material within the cloud is usually non-uniform.*
2) *Acceptable finite cloud correction factors are a function of the type of radioactive emission (whether an electron or a photon), the emission energy, the size of the plume, and the distribution of radioactive material in the plume and are available in tabulated form or as interpolation curves (Stocki et al. 2007; Stocki et al. 2009).*

7.6.3.2 Finite cloud calculations

If the human receptor is located some distance from the plume centreline (as in the case of an elevated release or when the representative person is at some transverse distance from the centreline), the dose estimation based on the time-integrated concentration at the receptor location can seriously underestimate the dose from external exposure. More sophisticated methods of calculations should be used to correctly handle the full range of potential receptor locations relative to the plume centre line.

Note: *For these situations, acceptable methods of calculations include*

a) *full numerical integration of the three-dimensional equation representing the dose (as in ADDAM), (Scheier 2009; Tarasov 1993; Gorshkov et al. 1995); and*
b) *look-up tables of values for the pre-calculated three-dimensional integral representing the dose (as in COSYMA and MACCS2).*

7.6.4 Dose conversion factors for external exposure to the cloud

An appropriate set of dose conversion factors consistent with the requirements of the AHJ shall be used.

Notes:

1) *For the purposes of this Clause, the AHJ is the CNSC and the specific requirements are those identified in the Government of Canada's Radiation Protection Regulations.*
2) *ADDAM, COSYMA, and MACCS2 include a set of acceptable dose conversion factors that are based on the recommendations of ICRP 60. Acceptable dose conversion factors available in the Dose Coefficient File Package 3 (DCFPAK3) (Eckerman and Leggett 2012) and AcuteDose (Eckerman 2012) codes may be used for calculating the following doses:*
   a) *effective dose;*
   b) *equivalent dose to organs (such as the thyroid); and*
   c) *absorbed dose to organs for calculation of deterministic health effects.*
3) *Acceptable dose conversion factors may be different from those above if Canadian regulations are amended. The user of this Standard should check current regulations before adopting a set of dose conversion factors.*

7.7 Dose from internal exposure to the cloud

7.7.1 Definition

The dose from internal exposure to the cloud shall be defined as the internal dose due to the intake of radioactive material into the body by inhalation (and, in the case of tritiated water vapour (HTO), by absorption through the skin) by a person immersed in the cloud.

7.7.2 Inhalation rates

7.7.2.1

For conservative safety assessments, such as deterministic calculations used to demonstrate compliance, the 95th percentile of the breathing rate for the representative person should be used.

7.7.2.2

For best-estimate safety assessments, such as in a probabilistic safety assessment, a realistic breathing rate averaged over daily activities should be used.

Notes:

1) *Allan and Richardson (1998) combined distributions of short-term inhalation rates and activity frequencies in a Monte Carlo analysis to obtain distributions of long-term inhalation rates for six age groups (0.25, 2.5, 8, 15.5, 39.5, and 65 years). Interpolation of these results provides 95th percentile inhalation rates for an infant of 0.31 m^3/h, for a child of 0.90 m^3/h, and for an adult of 0.96 m^3/h.*
2) *ICRP 89 published male adult breathing rates corresponding to heavy exercise (3 m^3/h) and light exercise (1.5 m^3/h) and breathing rates averaged over daily activities (sleep, sitting, light exercise and heavy exercise) of 0.93 m^3/h.*

7.7.3 Committed dose conversion factors for inhalation

An appropriate set of dose conversion factors based on the recommendations of the ICRP (ICRP 103 or ICRP 119) and consistent with the requirements of the authority having jurisdiction shall be used.

Notes:

1) *Within Canada, the AHJ is the CNSC and the specific requirements are those identified in the* Government of Canada's Radiation Protection Regulations*.*
2) *ADDAM, COSYMA, and MACCS2 include a set of acceptable dose conversion factors that are based on the recommendations of ICRP 60. DCFPAK3 (Eckerman and Leggett 2012) and AcuteDose (Eckerman 2012) contain acceptable tables of dose conversion factors that may be used for calculating the following doses:*
   a) *effective dose;*
   b) *equivalent dose to organs (such as the thyroid); and*
   c) *absorbed dose to organs for calculation of deterministic health effects.*
3) *The relative biological effectiveness (RBE) for deterministic effects (also known as tissue effects) is different from the radiation weighting factor (w_R) used in the calculation of the effective dose and equivalent dose (ICRP 92).*
4) *Acceptable dose conversion factors may be different from those above if Canadian regulations are amended. The user of this Standard should check current regulations before adopting a set of dose conversion factors.*

7.7.4 Period of integration

7.7.4.1

The period of integration for the committed dose shall depend on the type of dose.

7.7.4.2

The committed effective dose and committed equivalent dose to organs should be integrated to age 70.

7.7.4.3

The absorbed dose to the whole body or to specific organs for assessment of deterministic health effects should be integrated over a few days to a few weeks.

7.7.5 Chemical form of particulates

Where a particulate radionuclide can have more than one chemical or physical form (ICRP 66), the form corresponding to the maximum value of the committed dose conversion factor shall be used.

Note: *The current compilation from ICRP 68, ICRP 72, and ICRP 74 of effective and equivalent dose coefficients for inhalation and ingestion is ICRP 119. For members of the public, the dose coefficients are based on particles of 1.0 µm activity median aerodynamic diameter (AMAD) (ICRP 72). These dose coefficients must be multiplied by an inhalation rate (see Clause 7.7.2) to obtain dose conversion factors relating the effective dose or equivalent dose to an organ to the time-integrated activity concentration in the cloud (Bq•s•m^{-3}). Most current codes contain at least one set of dose conversion factors compatible with ICRP 60 recommendations.*

7.7.6 Noble gases

The dose conversion factors for inhalation of all krypton and xenon radionuclides should be zero.

Notes:

1) *Noble gases are not absorbed by the human body.*
2) *When the half-life of a noble gas radionuclide is short, some compilations of dose conversion coefficients add the contribution from their progeny to the inhalation dose conversion factor. In such cases, the noble gases dose conversion coefficients are not zero. It is the responsibility of the user of such a compilation to identify these assumptions.*

7.7.7 HTO absorption through skin

The inhalation dose conversion factor for HTO should be multiplied by 1.5 to account for tritium uptake by absorption through the skin.

7.8 Dose from external exposure to ground deposition

7.8.1 Definition

The dose from external exposure to ground deposition shall be defined as the external dose due to photons (gamma and x-ray) and electrons (beta emission, Auger, and internal conversion) that a person receives when standing on ground contaminated with radioactive material (Bq/m^2).

Notes:

1) *During the passing of the cloud, radioactive material from the cloud will deposit on the ground.*
2) *After the cloud passes, the surface activity will decrease due to natural radioactive decay. Physical removal processes such as weathering may be neglected for simplicity and conservatism.*

7.8.2 Period of exposure

7.8.2.1

The period of exposure to ground deposition shall depend on the purpose of the safety assessment.