Order no. 360/2004

of 20/10/2004
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Approving the Norms on dispersion calculation of radioactive effluents discharged in the environment by nuclear installations

According to the provisions of:
• Law **no. 111/1996** on the safe deployment of nuclear activities, republished, with subsequent modifications and completions;
• Government Decision **no. 1.627**/2003 approving the internal rules of the National Commission for Nuclear Activities Control, with subsequent modifications,

The president of the National Commission for Nuclear Activities Control issues the following Order:

Art. 1. - The Norms on dispersion calculus of radioactive effluents discharged in the environment by nuclear instllations, provided in the annex which is integral part of this Order, are approved.
Art. 2. – This Order shall be published in the Official Law Bulletin of Romania, Part I.
Art. 3. – The Norms provided in art. 1shall enter into force on the date of their publishing in the Official Law Bulletin of Romania, Part I.
Art. 4. – The Division of Radiation Protection and Radioactive Waste within the National Commission for Nuclear Activities Control shall fulfil the provisions of this Order.

The President of the National Commission for Nuclear Activities Control,
dr. eng. Lucian Biro

Bucharest, 20 October 2004.
No. 360.

Annex to the Order

NORMS
ON
THE DISPERSION CALCULATION OF F RADIOACTIVE EFFLUENTS DISCHARGED IN THE ENVIRONMENT BY NUCLEAR INSTALLATIONS

Chapter I

General Considerations, Scope, Definitions

Article 1. – (1) These are applied to nuclear installations and establish general requirements and basic principles for calculating dispersion of radioactive materials released in the atmosphere and in aquatic environment by a nuclear power plant or any other nuclear installation during normal operation, transient or nuclear accident, according to the provisions set under the Law no. 111/1996 on the safe deployment of nuclear activities, with subsequent modifications and completions and of “Fundamental

Norms on Radiological Safety" approved by Order no. 14/2000 of the President of the National Commission for Nuclear Activities Control (CNCAN).
(2) These norms are also applied for radiological installations that can discharge radioactive effluents in the atmosphere or in near surface waters, under normal operating conditions or in case of an accident.
(3) Radiological installations stipulated under paragraph (2) are established by CNCAN within the authorization process.

Article 2. – The authorization holder and/or applicant shall permanently evaluate, starting from the design stage of the nuclear installation, the exposure to radiations of operating personnel, population and impact on environment as a result of the discharges of radioactive materials into the environment, during normal operation, in transient or in case of nuclear accident.

Article 3. – (1) Evaluation of radiation exposure for population and impact on environment in the influence area of the nuclear installation, in case of nuclear accident, transient and continuous operation is carried out on the basis of a mathematical pattern and it contains the following calculation stages:

a) Calculation of atmospheric or aquatic dilution of radioactive material discharged in the environment,
b) Calculation of integrated concentrations of radionuclides discharged in the environment, in relevant locations of receptive environments (hereinafter referred to as receptors);
c) Calculation of effective doses and equivalent doses, individual and collective.

(2) Calculation of atmospheric dilution factor requires knowledge of emission-specific characteristics, short-term and long-term local weather conditions, and specific characteristics of the location of nuclear installation.
(3) Calculation of the aquatic dilution factor requires a knowledge of emission-specific characteristics and hydro-geological characteristics or the receptor aquatic environment, both at local and at regional level in the influence area of the nuclear installation.
(4) Calculation of effective and equivalent doses, individual and collective, requires knowledge of integrated radionuclide concentration levels, calculated at paragraph (1), letter b), as well as dose conversion factors specific to each radionuclide, each separate irradiation method and depending upon the critical group the evaluation is performed for.

Article 4. – (1) These norms analyze the calculation of radioactive material dispersion in the environment during normal operation, in transient or nuclear accident. In the present norm, dispersion calculation means both the calculation of dilution factor and the calculation of integrated concentration levels of radionuclides discharged in the environment, at receptors located in the influence area of the nuclear installation.
(2) Calculation of effective doses and equivalent doses, individual and collective, are treated in the specific norm named "Norms on the dose calculation of supplementary radiations for population in the influence area of the nuclear power plant".

Article 5. During normal operation as well as in transient or nuclear accident situation, whenever possible, calculations shall be made in an iterative manner, input data of the mathematical pattern being corrected, as appropriate, on the basis of results of weather, hydrology and radioactivity measurements, as well as additional information regarding the nuclear installation status.

Article 6. For the purpose of applying these norms, besides the specialized terms and expressions defined in Law no. 111/1996 with subsequent modifications and completions and in “Fundamental Norms on Radiological Safety”, Appendix 1 defines the specialized terms specific to these norms.

Chapter II
General requirements for the calculation of radioactive effluents dispersion in the atmosphere

Article 7. Physical and chemical processes that must be taken into consideration in the calculation of atmospheric dispersion of radioactive effluents discharged from the nuclear installation with the purpose of obtaining radionuclide concentration levels at the receptors are as follows:

a) Transportation of the radioactive effluent in the atmosphere, by diffusion and advection processes,
b) Dry settling of radioactive material on the ground,
c) Wet settling as a result of the atmosphere wash by rainfall,
d) Radioactive disintegration of discharged radionuclides, taking into consideration all daughters, both before starting the discharge and after the material settles on the ground;
e) Re-suspension of radioactive material settled on the ground;
f) Special effects owed to the presence of buildings around the source.

Article 8. Calculation sequences in the estimation of integrated radioactive concentrations, at a receptor located in the influence area of the nuclear installation, as a result of the discharge of radioactive material in the atmosphere are as follows:

a) Calculation of atmospheric dilution factor;
b) Calculation of air concentration integrated in time, at the passage of the radioactive cloud above the receptor point, for each separate radionuclide issued at the source;
c) Calculation of concentration settled on the ground for each separate radionuclide discharged at the source.

Article 9. Input data for the mathematical model for the carrying out of calculation sequences presented under Article 8 must characterize:

a) The discharge of radioactive material at the source;
b) Weather conditions at the source;
c) Location of the nuclear installation;
d) Location of the receptor in respect of the discharge source.

Article 10. – (1) In order to calculate the dispersion of the radioactive material in the atmosphere, the data characterizing the discharge shall contain:

a) The source term, meaning the fraction in the radioactive inventory of the reactor discharged in the atmosphere, expressed in Bq/s or Bq of discharged radionuclide;
b) Physical and chemical characteristics of the gaseous radioactive effluents that influence the atmospheric dispersion and settlement processes;
c) Discharge geometry and mechanisms;

d) Effective discharge height for the radioactive material, meaning the discharge physical height ("0" level or height of the ventilation stack of the reactor), corrected by the consideration of the physical processes of progeny and overelevation of the pollutant track;
e) Total duration of the radioactive material discharge.

(2) During normal operation, the discharge of radioactive material in the atmosphere is considered as being continuous or on long term.
(3) Generally, during normal operation of the nuclear installation, the superelevation processes of the pollutant track are not important in the estimation of radionuclide concentration levels and doses for population and they can be neglected.
(4) The overelevation of the pollutant track mainly depends on the atmospheric stability class, wind speed at the chimney, heat content of the discharged material and exit speed of gaseous effluents on the chimney.
(5) Progeny effects will be considered only in case the discharge of radioactive material takes place at the reactor ventilation chimney.
(6) When calculating the effective discharge height, the overelevation corrections must be made at the end, after considering the progeny effects.
(7) In practice, the elevation process of the radioactive cloud can be stopped by the presence of a strong inversion layer.
(8) Overelevation of the radioactive pollutant track becomes significant in the situation of a fire or explosion, even for an emission at ground level; calculation of the overelevation will be considered in such situations only if the discharge characteristics details are known.
(9) The discharge duration represents the time period when the radioactive effluents are evacuated in the atmosphere; the type of emission is defined depending upon the discharge duration (Table 1).

Table 1. Discharge type, depending upon the duration of radioactive effluents discharge in the atmosphere.

Discharge type	**Discharge duration**
Instantaneous	$<$ 3 minutes
Short term	Between 3 minutes –1 hour
Prolonged duration	Between 1 hour – 24 hours
Long term	$>$ 24 hours

Article 11. – (1) Weather data characterizing the atmospheric dispersion shall include:
a) Wind direction at the source;
b) Wind direction at the dispersion height;
c) Dispersion parameters at various distances, depending upon atmospheric turbulence characterizing the mixture of radioactive material with air masses both in vertically and horizontally;
d) Atmospheric stability class;
e) Height of the mixture layer;
f) Type and intensity of rainfall.

(2) During normal operation or in case of a long-term accidental discharge, calculations must include the wind factor at ground level for the location of the nuclear installation, obtained by long-term local weather conditions.
(3) Wind direction is expressed in degrees and is established clockwise starting from "0" degrees, corresponding to wind direction from North to South.

(4) In case the wind speed at discharge height is not available by measurement, this shall be calculated on the basis of the wind speed measured at 10 m height from the ground level, or calculations shall even consider wind speed at 10 m above the ground level.
(5) Local dispersion parameters shall be determined directly by turbulence measurements or indirectly, first determining the atmospheric stability class.
(6) When evaluating the dispersion on vertical direction, presence of a limit layer or of thermal inversion layer must be considered.
(7) Discharge duration must be taken into consideration when evaluating the horizontal dispersion parameter.
(8) Dispersion parameters will be corrected, if necessary, for the effect of presence of buildings on the main wind direction.
(9) The atmospheric stability class shall be determined using Pasquill method or on the basis of atmospheric turbulence measurements carried out with equipment installed on the weather tower.
(10) The effect of presence of buildings upon the dispersion of radioactive material can be neglected if the effective discharge height is equal or higher than 2.5 times the height of the nearest building located in the close vicinity of the source.
(11) A building is considered as being in the close vicinity of the source if the distance between the source and the building is lower than 3 times the height of the building located on the main wind direction.

Article 12. Specific requirements for the weather measurement program that shall be carried out by the authorization holder for the nuclear installation with the purpose of obtaining weather data necessary to calculate the atmosphere dispersion of radioactive effluents are dealt with in the specific norm “Norms on weather and hydrological measurements for nuclear installations”.

Article 13. In order to calculate the dispersion of radioactive material discharged in the atmosphere, data characterizing the nuclear installation location must contain:
a) Aspects regarding the land orography;
b) Presence of buildings and the manner of arranging construction elements around the source, considered as an assembly.

Article 14. – (1) In order to calculate the dispersion of radioactive material discharged in the atmosphere by the nuclear installation, data characterizing the receptor are the geographical coordinates and the height from ground level where the receptor is located or the relative coordinates to the source.
(2) Generally, the origin of the relative coordinates system is selected as being the ground level point corresponding to the discharge.

Article 15. – (1) When evaluating radioactive fall-outs on the ground, both wet and dry fall-outs shall be taken into consideration.
(2) If applying a simplified procedure for the evaluation of radionuclide concentrations, care must be taken in order not to underestimate the air concentrations, ground settling or collective doses at high distance, especially under conditions of stabile stratification of the atmosphere.

Article 16. – (1) The calculation of the dispersion of radioactive material discharged in the atmosphere by the nuclear installation shall contain reliable mathematical patterns, tested in theory and validated on an experimental basis.

(2) Calculation codes that transpose mathematical patterns shall also be validated.
(3) The field and applicability limits of the utilized mathematical pattern shall correspond to the evaluated situation.
(4) The utilization of mathematical patterns for the calculation of atmospheric dispersion shall take into account the space & time variability of the weather conditions and the orography and topography of the land in the influence area of the nuclear installation.

Article 17. – (1) For distances smaller than 50 km between the discharge source and the receptors, for the calculation of radioactive effluent dispersion in the atmosphere, the Gaussian mathematical model described in Appendix 2 or other mathematical patterns that meet the general requirements presented in Articles 7-16 shall be utilized.
(2) The utilization of Gaussian-type pattern can be extended for distances between 50 – 100 km between the discharge source and the receptors.
(3) For distances longer than 100 km calculations utilize complex mathematical patterns for atmospheric transportation on long distances, meeting the general requirements set in Articles 7 – 16 or, in lack thereof, a Gaussian-type model can be utilized, with specific parameters for the transportation of the radioactive pollutant on long distances.
(4) The Gaussian mathematical pattern shall be utilized only for pollution sources with discharge heights lower than 200 m. For pollution sources discharging at heights higher than 200 m, mathematical patterns shall be utilized where dispersion parameters are estimated on the basis of physical parameters of the planetary limit layer.
(5) Selection of calculation models for the dispersion of the radioactive effluent in the atmosphere and the selection of model input parameters are the responsibility of the authorization holder.
(6) The utilization of mathematical patterns and specific codes in the calculation of atmosphere dispersion of radioactive effluents shall be approved by CNCAN beforehand.
(7) With the purpose of obtaining the approval stipulated under paragraph (6), the authorization holder shall justify the selection of the model, utilization of particular analytical techniques, simplifications and parameterizations carried out and the conservative degree of the selected model.

Article 18. – (1) Values of coefficients utilized in calculation of the dispersion parameters are obtained experimentally under different conditions and they are specific to the location where the experiment took place.
(2) In the absence of experimental coefficients specific to the location of nuclear installation, empiric coefficients can be utilized as taken from the specialized literature as those presented in Appendix 2.

Chapter III
General requirements for the calculation of radioactive effluents dispersion in the aquatic environment

Article 19. – (1) This norm deals with the calculation of radioactive effluents dispersion in surface waters.
(2) Calculation of radioactive material dispersion in surface waters involves the utilization of a mathematical pattern of the type:

a) Numeric mathematical pattern, with the transformation of the fundamental dispersion equations in forms with finite differences or finite elements; such model provides a complex treatment of the physical-chemical processes of transportation and transfer that take place in the aquatic environment;

b) Compartmental model, where the aquatic environment is described by one or more compartments within which the distribution of radionuclides is presumed as homogenous; calculation of average concentrations for each compartment is carried out on the basis of transfer coefficients that connect the system compartments; mathematical patterns that consider the radionuclide-sediment interactions are generally of this type;
c) Simplified analytical model, for which analytical solutions of the fundamental transport equations are obtained; simplifications refer to the geometry of the aquatic environment, flow conditions and dispersion coefficients; this is the model most frequently utilized in analysis of dispersion for surface waters.

Article 20. – (1) Complex mathematical patterns shall be utilized in the calculation of the aquatic dispersion.
(2) The complexity of the mathematical pattern for the calculation of the aquatic dispersion depends on the specific character of the situation.
(3) Utilization of complex mathematical patterns involves detailed knowledge of aspects related to the local and regional hydro-geological description in the influence area of the nuclear installation.
(4) In case of lack of a detailed knowledge on local and regional hydro-geological characteristics, simplified mathematical calculation patterns can be utilized for the calculation of aquatic dispersion.
(5) The results of the simplified model shall be verified as much as possible by hydrological and radioactivity measurements in the aquatic environment.

Article 21. Selection of the mathematical calculation pattern for the radioactive effluents dispersion in surface waters shall be done by the consideration of the following factors:
a) Type of discharge (continuous, periodical, anticipated or accidental);
b) Aquatic environment where the discharge takes place (river, estuary, entrenchment/channel, lake/reservoir, sea, ocean);
c) Method of water utilization;
d) Magnitude of source term under normal operating conditions or in case of an accident;
e) Accuracy required in obtaining the pattern results.

Article 22. – (1) Physical-chemical processes that shall be taken into consideration when calculating dispersion in the aquatic environment of radioactive effluents discharged by the nuclear installation, with the purpose of obtaining radionuclides in the water, at different receptors, are as follows:
a) Transport of radioactive material in the aquatic environment by advection and diffusion processes,
b) Interaction of radioactive effluent with aquatic sediment and deposits on the bottom of the water (including transport processes of sediments suspended in the water, settling, re-suspension and erosion processes),
c) Interaction with biologic material present in the respective aquatic environment,
d) Radioactive disintegration, including consideration of occurrence of progeny products,
e) Interaction with underground waters,
f) Freezing effects at water surface.
(2) Interaction between radioactive material dispersed in the water and the aquatic sediment is treated by consideration of sorption-desorption processes.

(3) Concentration of a radionuclide in the sediment can be calculated on the basis of the concentration of the respective radionuclide in the water, utilizing a specific distribution coefficient.
(4) For simplification, it can be considered that the effect of the biological material and the effect of the sediment upon the value of radionuclide concentration in the aquatic environment are negligible, which will lead in many situations to an overestimation of the radionuclide concentration in the water.

Article 23. In the estimation of the aquatic dispersion of radioactive effluents, discharge data specific to the liquid radioactive effluent shall include:
a) The source term, meaning the discharge ratio for each separate radionuclide and total activity discharged within a particular period of time;
b) Chemical properties, including: concentrations of important anions and basic ions and their oxidation and complexion forms, organic contents, pH level, concentration of dissolved oxygen;
c) Physical properties, including: temperature, density and contents of suspended solid material and granulation of suspended solids;
d) Flow of liquid radioactive effluents, at continuous discharge or volume and frequency in case of series discharge;
e) Variation of source term during the discharge, necessary for the evaluation of radionuclide concentration, as a result of long-term discharges;
f) Discharge geometry and mechanisms.

Article 24. – (1) Within these norms, river and channel-type hydro-technical construction are considered aquatic environments.
(2) For a nuclear installation with discharge of radioactive effluents in a river, the hydrological information (including related data) shall include the following parameters:
a) River geometry, defined by average width, average transversal section and average slope of river sectors under analysis; in case there are major irregularities within the flowing sector that may influence the aquatic dispersion of the radioactive material, these shall be described; if necessary, measurements shall be made for the downstream river geometry of river sectors under analysis;
b) The river flowrate, as monthly average ratio calculated as being the inversion of the monthly arithmetic average of the opposites of daily flowrates; in the calculation of monthly average values the opposite of the flowrate is utilized because, in case the effects of sediment interaction are not considered, the concentration in water volume, at full mixture, is proportional to the opposite of the river flowrate;
c) Extreme values of the river flowrate, obtained throughout time;
d) Temporal variations of water level in the river sectors under analysis;
e) Data regarding possible interactions between the river water and the water in the phreatic layer; identification shall be carried out for any potential sectors of the river stream where the river water mixes with the underground water;
f) River water temperature, measured in different points during at least one year, expressed as monthly averages of daily values;
g) Surface layer thickness, in case of occurrence of the thermal stratification phenomenon;
h) Extreme temperatures of river water obtained throughout time;
i) Concentrations of sediment in suspension, measured in:
- Locations where the river is slowed, depleted or supplied with water,

- Samples taken from different points, with an adequately selected frequency,
- Periods characterized by different flowrates, in order to describe the sedimentation and/or erosion rate curve depending upon the river flow regime;

j) Characteristics of the settled sediments, including mineral and/or organic composition and dimensions of settled sediment particles;
k) Distribution coefficients in the bottom sediment and for sediments under suspension for each separate discharged radionuclide;
l) Level of basic natural and artificial radioactivity in water, sediment and in aquatic organisms;
m) Data regarding the occurrence and cyclic evolution of phytoplankton and zooplankton bio-mass;
n) Reproduction and feeding periods for main fish species in the respective aquatic environment.

(3) For a nuclear installation with discharge of radioactive effluents in a channel-type hydro-technical construction, hydrological information (including related data) must include:

a) Channel geometry, including length, width and depth, at different distances from the source;
b) The water flowrate in the channel, or flowrates at channel entries and exits of the receptor channel;
c) Predictable fluctuations at water level, as monthly averages;
d) Water quality at the entry point, including temperatures and solid particles in suspension;
e) Data regarding the thermal stratification and season variations of the thermal stratification;
f) Interaction with phreatic layer;
g) Characteristics of the sediment settled on the bottom of the channel;
h) Distribution coefficients in the sediment and for the material in suspension, for each separate discharged radionuclide;
i) Sedimentation rate;
j) Level of basic natural and artificial radioactivity in water, sediment and in aquatic organisms;
k) Data regarding the occurrence and cyclic evolution of phytoplankton and zooplankton bio-mass;
l) Reproduction and feeding periods for main fish species in the respective aquatic environment.

Article 25. – (1) When utilizing aquatic dispersion models, space and time variability shall be taken into account at local and regional level in the influence area of the nuclear installation as well as hydro-geological conditions of the receptor aquatic environment.
(2) Results of the mathematical pattern shall be tested and validated on the basis of results from hydrological and radioactivity measurements (carried out in the laboratory and on site) in the nuclear installation influence area.
(3) Calculation codes that transpose mathematical models shall also be validated.
(4) The applicability range and limits of the utilized mathematical pattern shall correspond to the evaluated situation.

Article 26. – (1) For the calculation of dispersion of radioactive effluents discharged in aquatic environment, mathematical pattern described in Appendix 3 or other

mathematical patterns meeting the general requirements presented in Articles 19 – 25 shall be utilized.
(2) Selection of calculation methods for the dispersion of liquid radioactive effluent and selection of entry parameters of the model are the authorization holder's responsibility.
(3) Utilization of mathematical patterns for calculation of aquatic dispersion of radioactive effluents and specific codes shall be previously approved by CNCAN.
(4) With the purpose of obtaining the approval stipulated under paragraph (3), the authorization holder shall justify the selection of the model, utilization of particular analytical techniques, simplifications and parameterizations carried out, as well as the conservative degree of the selected model.

Chapter IV
Dispersion analysis for authorization

IV.1. Normal operating conditions

Article 27. During the design, construction and authorization period of the nuclear installation, dispersion analysis shall utilize conservative estimations of the source term, based on the experience generated by the operation of other nuclear installations of the same type.

Article 28. – (1) Discharges of radioactive materials in the atmosphere during normal operation is considered as long-term discharge.
(2) In the dispersion equations it can be approximated that the distribution on horizontal direction, at a given distance from the source, of concentrations of discharged radionuclides is uniform in a considered wind sector.

Article 29. – (1) A weather measurement program shall be initiated even from the design stage in the influence area of the nuclear installation, for the evaluation of the atmospheric dispersion and to obtain the wind movement at ground level.
(2) The weather measurement program shall be issued according to the provisions of the specific norm named "Norms on weather and hydrological measurement at nuclear installations".
(3) Results of the own weather measurement program shall be completed whenever necessary with data obtained by the national weather and hydrology system.

Article 30. – (1) For the evaluation of aquatic dispersion in the influence area of the nuclear installation, a hydrological measurement program for surface and underground waters shall be initiated even from the design stage for the hydrological characterization of the area.
(2) The hydrological measurement program shall meet the requirements set under the specific norm named "Norms on weather and hydrological measurements at nuclear installations".
(3) Results of the own hydrological measurement program must be completed anytime whenever necessary with data obtained by the national weather and hydrology system.

IV.2. Situation of transient and anticipated accident

Article 31. – (1) During the design, construction and authorization stage of the nuclear installation, dispersion analyses in transient or anticipated accident situation shall utilize conservative estimations of the source term, based on different possible scenarios.

(2) Dispersion analyses shall be utilized in drawing up plans for intervention in case of nuclear emergency at the nuclear installation and real-time evaluation of radiological consequences of an accidental discharge of radioactive material in the environment.

Article 32. – (1) Dispersion analyses in transient or anticipated accident situations shall be carried out considering the discharge duration, the effective discharge height and the specific discharge parameters for each separate situation.
(2) Variation of each entry parameter shall be considered in the mathematical pattern and the most significant sizes and quantities will be estimated at different distances from the source.
(3) The situations with great occurrence probability and important radiological consequences will be selected from the total number of analyzed situations by statistical calculation methods.

Chapter V
Dispersion analyses during the NPP operation

Article 33. – (1) Radioactivity discharges shall be evaluated by measurement.
(2) Results of weather measurements on site shall be utilized in the atmospheric dispersion analyses, and the results of the hydrological measurements in the influence area shall be utilized in analyses of aquatic dispersion.
(3) The authorization holder shall have methods for the evaluation of dispersion for situations when results of weather and/or hydrological measurements on site are not available.

Article 34. Dispersion analyses during the operation of the nuclear installation shall utilize a statistical approach of the weather conditions, based on probabilities of occurrence of weather conditions.

Article 35. Dispersion analyses issued during the authorization period shall be completed throughout time, as new weather and hydrological data are gathered and calculation models are developed.

Article 36. Special discharge situations, predominant dispersion conditions during those special situations and resulting doses in such situations shall be analyzed separately and reported to CNCAN.

Chapter VI
Dispersion analyses in case of nuclear accident at the NPP

Article 37. – (1) The authorization holder shall have the capability to estimate by calculation, in real time, the dispersion of radioactive material in an accidental discharge in the environment.
(2) Calculations shall be carried out with mathematical patterns installed on computers with adequate technical performances.
(3) Moreover, the authorization holder shall have manual calculation procedures for the dispersion of radioactive material in case of an accidental discharge in the environment.

Article 38. (1) Evaluation of consequences of an imminent discharge of radioactive material in the atmosphere shall be done taking into consideration the predominant weather conditions during the accident.

(2) As necessary and possible, when evaluating the radiological consequences of an imminent discharge of radioactive material the forecast system for air pollution at local and regional scale available from the national weather system shall be utilized in addition.

Article 39. The control room of the nuclear installation shall have a screen displaying permanently the results of weather measurements and values calculated on the basis of measured parameters necessary for the calculation of atmospheric dispersion. In case of an accident, these data shall be transferred to the nuclear installation emergency response center in order to be utilized in dispersion calculations.

Article 40. When calculating the aquatic dispersion, consideration shall be given to the possibility of indirect contamination of surface waters as a result of radioactivity fall-outs, accidental discharge of radioactive effluents in the atmosphere, on the water surface.

Article 41. – (1) In case of accidental discharge of radioactive effluents in the environment, in case it is necessary, calculation of aquatic dispersion shall also consider the possibility of indirect contamination of underground water.
(2) Calculation of aquatic dispersion in underground water is not the subject of these norms.

Chapter VII
Regulatory inspection

Article 42. The preliminary safety analysis, the Preliminary Safety Analysis Report and the Final Safety Analysis Report for the nuclear installation shall indicate the manner of implementing the requirements set under this norm.

Article 43. – (1) Mathematical calculation patterns for the dispersion of radioactive effluents in the environment shall be reviewed periodically and modified as to reflect modern developments in respect of dispersion, conversion factors, parameterizations.
(2) After the review, the mathematical calculation pattern and specific codes shall be submitted to CNCAN for approval.

Chapter VIII
Transitory and final provisions

Article 44. This norm enters into force on the date of publishing in the Official Law Bulletin.

Article 45. Holders of authorization for nuclear installations, valid at the date of entry into force of this norm, shall meet the requirements thereof within maximum 12 months.

Article 46. Appendices 1, 2 and 3 represent an integral part of this norm.

Appendix 1.
Definitions

- **advection.** – movement or transfer of substance, heat, etc., induced by the movement of fluid (e.g. air or water) where it is located.
  - Transportation of a property by horizontal movement of air.

- **distribution coefficient.** Concentration ratio of a radionuclide in two stages in contact, being under balance conditions. Multiple distribution coefficients can be defined for a radionuclide, depending on the stages in which it is distributed.

- **National Commission for Nuclear Activities Control (CNCAN).** National competent authority in the nuclear field exercising regulatory, authorization and control attributions according to Law 111/1996 on the safe deployment of nuclear activities, with subsequent modifications and completions.

- **convection**. – Slow vertical movement of air caused by the non-homogenous heating of air in its lower layers. Due to temperature gradients, hot air rises and the cold air lowers, replacing the hot air.
  - Transport of heat or other properties by (generally vertical) movement of air.

- **diffusion.** – Travel movement of atoms or molecules of a substance from a high concentration region to a low concentration region, as a result of the concentration gradient action.
  - Transport of matter only by random movement of molecules, not by coherent movement of molecule groups.
  - Mixing process of fluid properties by turbulent and molecular movements.

- **dispersion.** – Particle tendency (e.g. radioactive particles) to spread in the respective fluid due to low scale variations of fluid speed.
  - spreading of air constituents such as atmospheric pollutants.

  It can be the result of molecular diffusion, turbulent mixture or average shearing of wind.

- **radioactive discharge.** The process of radioactive effluent discharge in the environment.

- **atmospheric / aquatic dilution factor.** The ratio between the concentration of radioactive material at the receptor point (located in the air or in aquatic environment) and total activity of radioactive material issued at the source.

- **temperature gradient.** A vector that characterizes the decrease of atmosphere temperature per distance unit, oriented in the normal direction at the thermal insulation surface.

- **thermal inversion.** Increase of temperature with height, apart from regular conditions, when temperature decreases with height; inversions can occur at ground level and in the free atmosphere.

- **turbulent movement.** Fluid movement where each particle, besides a given speed of the current also has an additional speed. For this reason, the fluid movement seems chaotic. Air movement in the atmosphere is always turbulent.

- **planetary limit layer.** That particular portion of the troposphere where the airflow is strongly influenced directly by the interaction with the Earth surface. The height of the limit layer is variable in time and space, being contained between several hundred meters and a few kilometers. For average conditions at medium latitudes, the planetary limit layer extends on the first kilometer of atmosphere from the Earth surface and thus contains approximately 10% of the atmosphere mass.

- **receptor.** A person exposed to radiations as a result of the discharge of radioactive material in the atmosphere or aquatic environment.

- **wind rose.** A graphical representation of wind frequency on different directions; synonym: ground level wind regime.

- **sorption/desorption.** Interaction processes of an atom, molecule or particle with the surface of a solid; they are interaction processes in dynamical balance, directed in one way (sorption) or another (desorption), by a modification of the concentration of balanced components; the term of sorption includes both adsorption processes (surface processes, at the interaction with a non-porous solid) and absorption processes (sorption processes taking place inside the chemical structure of a porous solid); processes take place under the influence of physical or chemical nature forces.

- **transport of radionuclides.** Movement (migration) of radionuclides in the environment; it can include processes as advection, diffusion, sorption and incorporation.

- **atmosphere turbulence.** Fluid (air) status characterized by a turbulent movement.

- **wind.** Movement of air compared to the ground surface; the horizontal component of this movement is usually taken into consideration; it is defined by two elements: the direction of movement and speed, both very variable in time and space; wind, as horizontal movement, is created under the action of the baric gradient, then being deviated by the friction force, Coriolis force and centrifugal force.

Appendix 2.
Calculation of atmospheric dispersion of radioactive material with Gaussian model

Stages in the calculation of atmospheric dispersion are as follows:
i) calculation of atmospheric dilution factor,
ii) calculation of air concentration integrated in time, Bq·s/m^3,
iii) calculation of concentration of radionuclides settled on the ground.

i). Calculation of atmospheric dilution factor, $\chi(x,y,z)/Q$

In the equations for the determination of atmospheric dilution factor, the origin of the Cartesian system of axis is considered as being at the basis of the discharge point (projection of discharge at ground level) and the direction of wind is parallel to axis x. The deviation of the receptor point on horizontal level, perpendicular to the wind direction, is given by coordinate y. The height where the receptor is located compared to the ground level is represented by coordinate z. Distances x, y, z are expressed in m.

1. Instantaneous or short-term discharge

- For an instantaneous or short-term discharge, the dilution factor at the receptor point of coordinates (x, y, z) is calculated in the Gaussian model with the formula:

$$\frac{\chi(x,y,z)}{Q} = \frac{1}{2\pi\Sigma_y\Sigma_z\bar{u}}\exp(-\frac{y^2}{2\Sigma^2{}_y})\left[\exp(-\frac{(z-H)^2}{2\Sigma_z^2}) + \exp(-\frac{(z+H)^2}{2\Sigma_z^2})\right] f(\Sigma_z, H, h_i),\ (\mathrm{s/m^3}) \quad (1)$$

where

$\chi(x,y,z)$ = is the air concentration integrated in time (Bq·s/m^3) at the receptor point of coordinates (x, y, z); the period when the concentration is integrated is at least equal to the discharge duration;

Q = is the effective activity of the source (Bq), total quantity of radioactive material discharged by the source, corrected with factors that characterize the radioactive disintegration phenomena, occurrence of progeny products and settlement on ground;

Σ_y = is the dispersion parameters on direction y (σ_y), expressed in m, corrected with factors that characterize the effect of presence of buildings around the source and the duration of discharge;

Σ_z = is the dispersion parameter on direction z (σ_z), expressed in m, corrected with factors that characterize the effect of presence of buildings around the source;

H = is the effective source height (m), meaning the physical height of the discharge corrected by consideration of overelevation phenomena of the pollutant track;

$\bar{u}$ = is the average wind speed (m/s) at the height corresponding to the discharge, H; calculations can utilize the wind speed measured at 10 m height from

the ground level or the average wind speed at various heights can be calculated depending upon the wind speed at 10 m above the ground level (equation 18.c);
h_i = is the height where the inversion layer is formed (distance from the ground level to the basis of the inversion layer), expressed in m,
$f(\Sigma_z, H, h_i)$ = correction function for thermal inversion.

- In case the receptor is located at ground level, meaning z = 0,

$$\frac{\chi(x,y,0)}{Q} = \frac{1}{\pi \Sigma_y \Sigma_z \bar{u}} \exp\left[-\frac{1}{2}\left(\frac{y^2}{\Sigma_y^2} + \frac{H^2}{\Sigma_z^2}\right)\right] f(\Sigma_z, H, h_i), \text{ (s/m}^3\text{)} \quad (2)$$

Equation (2) represents the most often utilized form of Gaussian model.

- For discharge at ground level (H=0) and supposing that h_i is a lot higher than H, the dilution factor on the wind direction (y=0) is

$$\frac{\chi(x,0,0)}{Q} = \frac{1}{\pi \Sigma_y \Sigma_z \bar{u}}, \quad \text{(s/m}^3\text{)} \quad (3)$$

- In the situation of an instantaneous discharge, the dilution factor at the receptor point of coordinates (x, y, z) is calculated with one of the equations (1), (2) or (3). Due to the fact that the discharge duration is very short, the dispersion parameters must be corrected only considering the effect of presence of buildings around the source.
- In the situation that the wind speed at the discharge point is lower than 2 m/s, equations (2) and (3) cannot apply, because the wind direction and speed can modify in an uncontrolled manner, even for a period of a few minutes, which may lead to an increased atmospheric dispersion. The utilization of equations (2) and (3) could produce in such situations an overestimation of the concentration of radioactive material in the air. For short discharges associated with low wind speeds, it is recommended to utilize the equations presented for the situation of a discharge with long duration (equation (4)).

2. Discharges with extended duration

- For a discharge with extended duration, it is supposed that due to the sinuous wind movement, the radioactive effluent is spread in an uniform manner in an angle circle sector θ radians. The atmospheric dilution factor at ground level is given by the equation:

$$\frac{\chi(x, \text{orice } y \text{ in sectorul determinat de } \theta_L, 0)}{Q} = \left(\frac{2}{\pi}\right)^{1/2} \frac{1}{\Sigma_z \bar{u} x \theta_L} \exp\left[-\frac{H^2}{2\Sigma_z^2}\right] f(\Sigma_z, H, h_i), \quad \text{(s/m}^3\text{)} \quad (4)$$

where

θ_L is the angle (in radians) underneath which the pollutant track is visible from the discharge point.

- θ_L can be calculated as being $2\pi/n$ radians, where n represents the number of equal sectors the wind rose is divided into. Long-term observations upon the wind variation indicated that, generally, angle θ_L varies between 30 - 60° in case of discharges with extended duration, under different conditions of atmospheric stability. It is recommended to conservatively select a value of 22.5° for angle θ_L (n=16) for any atmospheric situation.

3. Long-term discharges

- For a long-term discharge it is supposed that both weather conditions and the wind direction are changed for the duration of the discharge. For the consideration of such a situation, equation (4) is modified by inputting factors F_k and F_{ki}, where

- F_k is the frequency (expressed in time percents, in equation (5)) with which the wind blows in sector k from the wind rose,
- F_{ki} is the time fraction where a particular class of stability i is predominant while the wind blows in sector k of the wind rose.

For a considered wind sector k, summing the contributions from all Pasquill stability classes (i=1÷6, in equation (5)). The atmospheric dilution factor for long-term discharges, χ_k/Q_{med} at a receptor point in sector k, of coordinates (x, any y in sector determined by angle θ_L, 0) is calculated with the equation:

$$\frac{\chi_k}{Q_{med}} = \left(\frac{2}{\pi}\right)^{1/2} \frac{0.01F_k}{x\theta_L} \sum_i \left[\frac{F_{ki}}{\Sigma_z \bar{u}} f(\Sigma_z, H, h_i) \exp\left(-\frac{H^2}{2\Sigma_z^2}\right)\right], \quad (\text{s/m}^3) \qquad (5)$$

where summing is carried out considering all Pasquill stability classes (A - F) and Σ_z, $\bar{u}$ and Q_{med} are values averaged on long period of time, and Q_{med} is calculated with the formula:

$$Q_{med} = \frac{\sum_i \chi_i}{\sum_i \frac{\chi_i}{Q_i}}, \qquad (5.a)$$

where summing is carried out considering all Pasquill stability classes (A - F).

- F_k *and* F_{ki} must be determined by local weather measurements (at the discharge points) carried out during a long time period (e.g., weather conditions averaged for the duration of one year).

- Equation (5) is utilized both in continuous discharge situations, under normal operation, and in case of long-term accidental discharge.

4. Dispersion parameters σ_z , σ_y

- The Gaussian model considers that the radioactive material discharged in the atmosphere presents a Gaussian distribution both in horizontal and in vertical level. σ_y and σ_z represent standard deviations of the distribution of concentration on horizontal level and vertical level, respectively, with approximately 96% of the effluent concentration contained in element $2\sigma_y 2\sigma_z$.
- Vertical dispersion parameter, σ_z, depending upon the distance x on the wind blow direction is calculated with the formula:

$$\sigma_z = g(x)F(z_0, x), \text{ (m)} \tag{6}$$

where

$$g(x) = \frac{a_1 x^{b_1}}{1 + a_2 x^{b_2}}, \tag{6a}$$

$$F(z_0, x) = \ln\{c_1 x^{d_1}[1 + (c_2 x^{d_2})^{-1}]\}, \text{ dacă } z_0 > 0.1\text{m} \tag{6b}$$

$$F(z_0, x) = \ln\left(\frac{c_1 x^{d_1}}{1 + c_2 x^{d_2}}\right), \text{ dacă } z_0 \leq 0.1\text{m}. \tag{6c}$$

Parameters a_1, b_1, a_2, b_2 depend upon the atmospheric stability class, regular values being given in table 1.
Parameters c_1, d_1, c_2, d_2 depend upon the roughness weather parameter, z_0, that takes into account the roughness degree of the ground surface (regular values presented in table 2).

Table 1. Usual values of coefficients a_1, b_1, a_2, b_2 utilized in the calculation of vertical dispersion parameter [7], [11].

Pasquill stability class	a_1	b_1	a_2	b_2
A	0.112	1.060	5.38×10^{-4}	0.815
B	0.130	0.950	6.52×10^{-4}	0.750
C	0.112	0.920	9.05×10^{-4}	0.718
D	0.098	0.889	1.35×10^{-3}	0.688
E	0.0609	0.895	1.96×10^{-3}	0.684
F	0.0638	0.783	1.36×10^{-3}	0.672

Table 2. Usual values of coefficients c_1, d_1, c_2, d_2 utilized within calculation of vertical dispersion parameter [7], [11].

Surface type	**Roughness parameter z_0, m**	c_1	d_1	c_2	d_2
Lawn, water reservoirs	0.01	1.58	0.048	6.25×10^{-4}	0.45
Tilled surfaces	0.04	2.08	0.0269	7.76×10^{-4}	0.37
Open lawn	0.1	2.72	0	0	0
Rural area	0.4	5.16	-0.098	18.6	-0.225
Forest or urban area	1.0	7.37	-0.0957	$4.29\times10^{+3}$	-0.60
City with tall buildings	4.0	11.7	-0.128	$4.59\times10^{+4}$	-0.78

- Horizontal dispersion parameter σ_y, depending upon the distance x on the wind blow direction, is calculated with the formula:

$$\sigma_y = \frac{c_3 x}{(1+0.0001x)^{1/2}}, \text{ (m)} \qquad (7)$$

where parameter c_3 depends on the stability class, as given in table 3.

Table 3. Usual values of coefficient c_3, utilized in the calculation of horizontal dispersion parameter [7].

Pasquill stability class	c_3
A	0.22
B	0.16
C	0.11
D	0.08
E	0.06
F	0.04

- Values of σ_y, calculated with the equation (7), are representative for the roughness parameter z_0 = 0.03 m. It is generally considered that σ_y does not depend on the land roughness degree.

5. Dependence of dispersion parameters depending upon the duration of discharge and effect of presence of buildings around the source

- The vertical dispersion parameter generally does not depend on average time durations or on the discharge duration. It is not recommended to have corrections for σ_z in this respect.
- The horizontal dispersion parameter depends largely on the average duration when weather data are obtained and must be corrected depending upon the discharge duration, t_R, if there are considerable differences between the time intervals. Values

for σ_y obtained with equation (7) are representative for 10-minute time intervals and for discharges with a duration of less than 10 minutes: $\sigma_{y,t_R} = \sigma_y$, dacă $t_R \le 600$ s.

For discharges with duration contained in the interval 10 minutes – 1 hour, σ_y must be corrected following the relation:

$$\sigma_{y,t_R} = \sigma_y \left(\frac{t_R}{600} \right)^{0.2}, \text{ dacă } 600\,\text{s} < t_R \le 3600\,\text{s}, \tag{8}$$

where t_R is the discharge duration, expressed in seconds.

- For extended duration or long-term discharges, the widening of pollutant track on horizontal level is already taken into consideration in equations (4) and (5).
- Dispersion of radioactive material discharged from a source is strongly influenced by the presence of buildings around the source, on the main wind direction. The effect of presence of buildings can be neglected completely if the effective discharge height, H, equals or is higher than 2.5 times the height of the nearest building located in the vicinity of the source. In this situation, ($H \ge 2.5 \times H_{building}$), dispersion parameters are calculated with equations (6) and (8):

  $\Sigma_z = \sigma_z$,

  $\Sigma_y = \sigma_{y,t_R}$
- A building is considered as being located in the vicinity of the source if the distance from the source to the building is smaller than 3 times the height of the building located on the main wind direction.
- For situations where $H < H_{building}$, dispersion parameters must be corrected for the effect of transversal section area of the building upon the dispersion:

$$\begin{aligned} \Sigma_y &= \Sigma_y \max = \left(\sigma_{y,t_R}^2 + \frac{CA_{cladire}}{\pi} \right)^{1/2}, \text{ (m)} \\ \Sigma_z &= \Sigma_z \max = \left(\sigma_z^2 + \frac{CA_{cladire}}{\pi} \right)^{1/2}, \quad \text{(m)} \end{aligned} \tag{9}$$

where

$A_{building}$ = area of the transversal section of the building located in the vicinity of the source, perpendicular on the main direction of the wind, expressed in sq. m.;

C = factor that connects area $A_{building}$ to the pressure wave noticed experimentally, with values contained between the interval 0.5 - 2.0. It is also recommended that the value of C is selected in the interval 0.5 - 2.0, in order to give the greatest possible value to the calculated dilution factor.

- For situations where $H_{building} \le H < 2.5 H_{building}$, the following equations are recommended for the calculation of dispersion parameters:

$$\begin{aligned} \Sigma_y &= \Sigma_y \max - \left(\frac{H - H_{cladire}}{1.5 H_{cladire}} \right) (\Sigma_y \max - \sigma_{y,t_R}), \text{ (m)} \\ \Sigma_z &= \Sigma_z \max - \left(\frac{H - H_{cladire}}{1.5 H_{cladire}} \right) (\Sigma_z \max - \sigma_z), \quad \text{(m)} \end{aligned} \tag{10}$$

- Utilization of modified dispersion parameters Σ_y, Σ_z in equations (1) - (5) may lead to a significant reduction of the value of concentration in the air integrated in time at the source, in case of a discharge at the ground level, in the vicinity of a building. It is recommended that the decrease factor is not higher than 3 in the calculations or it shall be disregarded.

6. Effective discharge height, H

6.1. Correction for effect due to descending air currents (Δh_d)

- When the discharge of radioactive material is carried out at the reactor ventilation chimney, part of the discharged material can be directed downwards, in the low pressure portion of the protected part of the chimney, a situation in which the discharge height corrected for this effect will be lower than the physical chimney height, $h_{chimney}$, with a quantity Δh_d:

$$H_1 = h_{coş} - \Delta h_d, \text{ (m)} \quad (11)$$

- The decrease effect of the effective discharge height due to descending air currents is manifested when the chimney exit gas speed, w_0, is comparable or less than the average speed of wind in the chimney area, $\bar{u}$. Generally, the effect occurs and must be considered when $w_0 < 1.5\ \bar{u}$. The correction in such situations will be:

$$\Delta h_d = 2(1.5 - w_0/\bar{u})D, \text{ (m)} \quad (12)$$

  where D = inner diameter of the ventilation chimney.
- In case the discharge does not take place at the chimney, the effect must be disregarded.

6.2. Correction for the effect of picking-up material in the aerodynamic cavity of the protected part of the building located in the close vicinity of the ventilation chimney (Δh_{en})

- The discharge height, corrected for the effect due to descending air currents (equations (11) and (12)), can be reduced with a quantity Δh_{en} by the picking-up effect upon radioactive material in the aerodynamic cavity of the protected part o the building located in the close vicinity of the ventilation chimney, a situation in which the effective discharge height becomes:

$$H_2 = H_1 - \Delta h_{en} = h_{coş} - \Delta h_d - \Delta h_{en}, \text{ (m)} \quad (13)$$

- When H_1 is lower than the height of the buildings located in the vicinity of the source, practically the chimney height must be disregarded, meaning $H_2=0$.
- If $H_1 > 2.5\ H_{building}$, it can be considered that the picking-up effect does not occur and Δh_{en}=0.
- If $H_{building} \le H_1 \le 2.5\ H_{building}$, the correction for the picking-up effect depends on the average wind speed at the chimney, $\bar{u}$. For low speeds ($\bar{u} <$ 5 m/s), the picking-up

effect does not occur and Δh_{en}=0. For high speeds ($\bar{u} \geq$ 5 m/s), the correction due to the picking-up effect of radioactive material in the protected area of the building located in the vicinity of the source must be calculated according to the equation:

$$\Delta h_{en} = 1.5 H_{cladire} - 0.6 H_1, \text{ (m).} \quad (14)$$

6.3. Overelevation corrections of the radioactive pollutant track

- The discharge height, corrected for the effects stipulated under points 6.1 and 6.2, can suffer an increase with a quantity $\Delta h_{m,b}$, as a result of the exit speed of radioactive material on the chimney (impulse effect) and/or as a result of the heat content of the pollutant (lift effect):

$$H = h_{cos} - \Delta h_d - \Delta h_{en} + \Delta h_{m,b}, \text{ (m).} \quad (15)$$

- Overelevation of the pollutant track mainly depends on the atmospheric stability class, wind speed, heat content of the discharged material and exit speed of gaseous effluents on the chimney.
- When the radioactive material is subjected to both overelevation effects (impulse effect, with Δh_m, and lift effect, with Δh_b), but one of the effects is predominant, the predominant effect will be considered only:

$$\Delta h_{m,b} = \Delta h_m, \text{ dacă } \Delta h_m >> \Delta h_b \text{ (m)}$$
$$\Delta h_{m,b} = \Delta h_b, \text{ dacă } \Delta h_b >> \Delta h_m \text{ (m).} \quad (16)$$

- In case of a “cold” discharge (a discharge where the gas temperature is only 5 - 10 °C above the ambient temperature), the impulse of the discharged material is the main overelevation factor. For “hot” discharges (with temperatures of the discharged gases more than 50 °C higher than the ambient temperature), the lift effect becomes predominant.
- Overelevation of the radioactive pollutant track involves two stages: transition stage and final stage, both depending on atmospheric stability and wind speed.

a) Predominant lift effect, transition stage of the pollutant track overelevation

- Under unstable, neutral and slightly stable atmospheric conditions, at a distance x on the wind direction, the overelevation of the pollutant track in the transition stage is calculated with the formula ("2/3" law):

$$\Delta h_b = \frac{1.6 F^{1/3} x^{2/3}}{\bar{u}}, \text{ dacă } x < 3.5\, x^o \text{ (m)} \quad (17)$$

where

$\bar{u}$ = average wind speed at discharge height (m/s),

F = lift flow parameter (m^4/s^3),

x^o = distance where the atmospheric trubulence starts to dominate the development of the pollutant track (m), defined by relations:

$x^o = 14F^{5/8}$, dacă $F < 55$ m^4/s^3,
$x^o = 34F^{2/5}$, dacă $F \geq 55$ m^4/s^3. (17.a)

- The value of F parameter is calculated with the equation:

1) $$F = \frac{\rho_a - \rho_0}{\rho_a} g w_0 \left(\frac{D}{2}\right)^2, \ (\text{m}^4/\text{s}^3) \quad (17.b)$$

where
ρ_0 = density of discharged radioactive gasses (kg/m^3),
ρ_a = average density of ambient air (1.293 kg/m^3 under standard conditions of temperature and pressure),
g = gravitational acceleration (9.8 m/s^2),
w_0 = gas exit speed (m/s),
D = inner diameter of the ventilation chimney (m).

2) For a material of molecular mass and specific heat similar to air, the equation (17.b) becomes:

$$F = \frac{T_0 - T}{T_0} g w_0 \left(\frac{D}{2}\right)^2, \ (\text{m}^4/\text{s}^3) \quad (17.c)$$

where
T_0 = temperature of discharged gases (K),
T = average temperature of ambient air (293 K).

- For a hot source, a calculation alternative good enough for F parameter is:

$$F = \frac{g Q_H}{\pi C_p \rho_a T}, \ (\text{m}^4/\text{s}^3) \quad (17.d)$$

where
Q_H = heat discharge ratio due to flow of gas discharged on the chimney, cal/s, with the supposition that the water vapors do not condensate,
C_p = air specific heat at constant pressure, cal/kg/K.
Under standard conditions of pressure and temperature, $F = 3.7 \times 10^{-5}$ m^4/s^3.

b) Predominant lift effect, final stage of pollutant track overelevation

- Final overelevation of radioactive pollutant track under atmospheric stability conditions is calculated with the equation:

$$\Delta h_b = 2.6 \left(\frac{F}{\bar{u} S}\right)^{1/3}, \ (\text{m}) \quad (18)$$

where

S = stability parameter, calculated with the equation $S = \frac{g}{T}\left(\frac{\partial\theta}{\partial z}\right)$, ($s^{-2}$), (18.a)

and $\left(\frac{\partial\theta}{\partial z}\right)$ = vertical gradient of potential temperature in the atmosphere, (K/m), calculated with the formula:

$$\left(\frac{\partial\theta}{\partial z}\right) = g / C_p + \frac{\partial T}{\partial z}, \quad \text{(K/m)}. \tag{18.b}$$

Where C_p must be expressed in J/kg/K.

It is recommended that the average wind speed and the vertical temperature gradient to be evaluated at the height corresponding to the discharge point. Wind speed at any height z, $u(z)$, can be calculated depending upon the wind speed measured at a height of 10 m above the ground $u(10)$, with the formula:

$$u(z) = u(10)\left(\frac{z}{10\,\text{m}}\right)^m, \tag{18.c}$$

where m is a coefficient that depends on the atmospheric stability class and the nature of the land in the vicinity of the source. Table 4 indicates values of the m coefficient.

Table 4. values for coefficient characterizing the vertical wind profile, m [3].

m / Land surface nature	Stability class					
	A	B	C	D	E	F
Water surfaces	0.03	0.05	0.06	0.08	0.10	0.12
Agricultural surfaces	0.10	0.15	0.20	0.25	0.35	0.40
Towns, forested areas	0.16	0.24	0.32	0.40	0.56	0.64

- It is recommended that for heights higher than 200 m, to utilize the wind speed measured or calculated at 200 m.

- Under neutral stability conditions, the final overelevation of the pollutant track can be estimated with the equation:

$$\Delta h_b = \frac{1.6F^{1/3}(3.5\,x^o)^{2/3}}{\bar{u}}, \quad \text{(m)} \tag{19}$$

where distance x^o has been defined in equation (17.a).

- Under calm situations (stable or neutral), final overelevation of the pollutant track can be estimated with the equation:

$$\Delta h_b = 5.0F^{1/4}S^{-3/8} \quad \text{(m)}. \tag{20}$$

- Under neutral or stable conditions with low-intensity wind, it is recommended to utilize equation (20), in case the calculated overelevation is smaller than the one calculated with equations (18) or (19).
- Equation (19) applies with good results under atmospheric instability conditions also, for the calculation of the average overelevation.
- Equation (19) also applies for slightly stable atmosphere conditions, if the overelevation calculated value is smaller than the value calculated with equation (18).

c) Predominant impulse effect, transition stage of pollutant track overelevation

- For a radioactive material where the lift effect is insignificant, transition overelevation is calculated with equation ("1/3" law):

$$\Delta h_m = 1.89\left[\frac{w_0^2 D}{\bar{u}(w_0 + 3\bar{u})}\right]^{2/3} x^{1/3}, \quad \text{(m)}. \tag{21}$$

d) Predominant impulse effect, final stage of pollutant track overelevation

- For the calculation of final overelevation of the radioactive material mainly characterized by the initial impulse at exit on the chimney, it is recommended to utilize one of the equations (22) – (24), the one that indicates the lowest value for Δh_m, even if each of the equations describe better a particular set of atmospheric conditions, as found out during experiments.
- Under conditions of neutral stability with strong winds, Δh_m is calculated with the equation:

$$\Delta h_m = \frac{1.5 w_0 D}{\bar{u}}, \quad \text{(m)}. \tag{22}$$

- Under conditions of calm (neutral or stable), Δh_m is calculated with the equation:

$$\Delta h_m = 4\left(\frac{F_m}{S}\right)^{1/4}, \quad \text{(m)} \tag{23}$$

where

F_m is the flow parameter of the impulse, $F_m = \frac{\rho_0}{\rho} w_0^2 \left(\frac{D}{2}\right)^2$, (m^4/s^2). (23.a)

For a material of molecular mass and specific heat similar to air, equation (23.a) becomes:

$$F_m = \frac{T}{T_0} w_0^2 \left(\frac{D}{2}\right)^2, \quad (\text{m}^4/\text{s}^2). \tag{23.b}$$

- For stable conditions with strong wind,

$$\Delta h_m = 1.5 \left(\frac{F_m}{\bar{u}}\right)^{1/3} S^{-1/6}, \quad (\text{m}). \tag{24}$$

e) Both effects, with similar contributions

- Generally, contributions to the overelevation of the pollutant track must not be summed up, but only consider the predominant effect. For the special situation where the two contributions are significant and approximately equal, the transition semi-empiric formula from equation (17) shall be utilized at equation (21).

$$\Delta h_{m,b} = 3^{1/3} \times \left[\frac{F_m x}{\left(\frac{1}{3} + \frac{\bar{u}}{w_0}\right)^2 (\bar{u})^2} + \frac{F x^2}{0.5(\bar{u})^3} \right]^{1/3} \quad (\text{m}). \tag{25}$$

- Overelevation of the radioactive material can be stopped by the presence of an inversion atmospheric layer. In such situations, the overelevation corresponding to the transition stage shall be utilized in the prediction of the final overelevation, $\Delta h_{m,b}$. It is considered that the overelevation is finished when 10% of the contour of the pollutant track intersects the inversion layer in a vertical direction. This happens for the value of x at which the vertical dispersion parameter satisfies the relation: $\Sigma_z = (h_i - H)/2.15$.

  It is recommended that during the calculation of the effective discharge height, the overelevation corrections as a result of lift and momentum effects to be carried out at the end, after considering other picking-up effects.

7. Influences of the inversion layer presence upon the atmospheric dispersion of radioactive material

- The temperature increase with height, as opposed to normal situations where the temperature decreases with height, produces the occurrence of an inversion layer on the ground or at a particular height in the atmosphere.
- The effects of presence of inversion layer upon the dilution factor depends on the effective height where the discharge occurs, H, the height where the inversion layer is formed, h_I, coordinates of the receptor point in relation to the coordinates system of the source and ther value of vertical dispersion parameter at receptor point, Σ_z.
- The formation of the inversion layer and the stable stratification in the inversion layer limit the development of the pollutant track in vertical direction. At a particular

distance from the source, on the main direction of the wind occurs the uniform mixture in vertical direction of radioactive material in the air mass located beneath the inversion layer and the vertical dilution process stops. The radioactive material will be found, on vertical direction, in the mixture layer with a height equal to h_i. The development of the radioactive cloud on horizontal direction will continue, in the absence of any major obstacles (a hill, for example).

- When the radioactive material remains trapped underneath the inversion layer and if the inversion is maintained for a long while, concentrations on ground level in a receptor point will be high.

7.1. Discharge under the lower limit of the inversion layer, $H < h_I$

- In case that the discharge takes place in a layer less stable than the layer above, somewhere under the inferior limit of the inversion layer, supposedly exists a double reflexion of the radioactive cloud on the surface of the limit layer and on the surface of the ground. The dilution factor can be calculated in such situations with the formula:

$$\frac{\chi(x,y,0)}{Q} = \frac{1}{\pi\Sigma_y\Sigma_z\bar{u}}\left\{\exp\left(-\frac{H^2}{2\Sigma_z^2}\right)+\exp\left[-\frac{(2h_i-H)^2}{2\Sigma_z^2}\right]+\exp\left[-\frac{(-2h_i-H)^2}{2\Sigma_z^2}\right]\right\}, (\text{s/m}^3) \quad (26)$$

- Equation (26) is a simplification of the general formula containing infinite series of exponential terms corresponding to the multiple reflexions of the radioactive cloud on the surface of the ground and inversion layer:

$$f(\Sigma_z,H,h_i) = \frac{\sum_{n=-\infty}^{+\infty}\exp\left(\frac{-(z+H+2nh_i)^2}{2\Sigma_z^2}\right)+\exp\left(\frac{-(z-H+2nh_i)^2}{2\Sigma_z^2}\right)}{\exp\left(\frac{-(z-H)^2}{2\Sigma_z^2}\right)+\exp\left(\frac{-(z+H)^2}{2\Sigma_z^2}\right)}. \quad (26.a)$$

- For $z=0$ or $z << H$, equation (26.a) becomes:

$$f(\Sigma_z,H,h_i) = \frac{\sum_{n=-\infty}^{+\infty}\exp\left(\frac{-(H+2nh_i)^2}{2\Sigma_z^2}\right)}{\exp\left(\frac{-H^2}{2\Sigma_z^2}\right)}. \quad (26.b)$$

- In case that the vertical dispersion of the radioactive material is limited by the presence of the inversion layer created at height h_I, the dilution factor can also be calculated with equations (1) – (5), considering $f(\Sigma_z, H, h_I) = 1$ and considering that the value of the vertical dispersion parameter remains constant at distances beyond the point where $\Sigma_z = \frac{h_i}{2.15} \cong h_i/2$.

- It is considered that the uniform mixture of radioactive material in the upper limited layer from the basis of the inversion layer that occurs when the radioactive cloud traveled the double of distance at which $\Sigma_z = \frac{h_i}{2.15} \cong h_i / 2$.
- In case that the discharge takes place in a layer more stable than the superior one, somewhere under the inferior limit of the inversion layer, it is conservatively recommended to utilize equations (1) – (5) for the calculation of dilution factor, considering $f(\Sigma_z, H, h_I) = 1$.

7.2. Discharge above the inferior limit of the inversion layer

- In case the discharge of radioactive material takes place somewhere above the superior limit of the inversion layer, in a layer higher and more stable than the layer underneath, the dilution factor for the region underneath the inversion layer may have the following formula:

$$\frac{\chi(x, y, 0 \le z < h_i)}{Q} = \frac{1}{(2\pi)^{1/2}\Sigma_y h_i \bar{u}} \exp\left(-\frac{y^2}{2\Sigma_y^2}\right), \text{ (s/m}^3\text{)}. \qquad (27)$$

  where $\bar{u}$ and Σ_z are considered for the less stable layer.
- In case that the discharge takes place in a less stable layer than the layer underneath, it is recommended to utilize equations (1) – (5) for the calculation of dilution factor with the consideration $f(\Sigma_z, H, h_I) = 1$, where dispersion parameters have values according to corresponding meteorological conditions existing in the top layer.
- In equations (26) – (27) it is considered that the formation height of the inversion layer is constant per distance, per main direction of wind, but this supposition is not observed in coastal areas and in particular positions located inside the continent. This is why, in situations like this, the formation height of the inversion layer depends on the distance, wind speed, friction forces between the different masses of air, vertical temperature gradients, temperature differences between the ocean and dry land.

8. Pasquill method for determination of stability class depending upon the weather conditions at the source

- Characterization of the dispersion is accomplished by describing the degree of atmosphere instability.
- Atmospheric stability is classified in five up to seven different classes, from very turbulent atmosphere to very stable atmosphere, depending upon the weather conditions.
- Pasquill created a system where stability is classified on the basis of data regarding wind speed, nebulosity and solar radiation. The relationship between Pasquill stability classes and weather conditions is presented under table 5.

Table 5. Pasquill stability classes depending upon the weather conditions [3].

A – extremely unstable
B – moderately unstable
C – slightly unstable
D – neutral*
E – slightly stable
F – slightly moderate; **G** – very stable

Wind speed at 10 m, m/s	**Sun shine**			**Sky coverage during nighttime**	
	Strong	**Moderate**	**Light**	**Cloudiness ≥ 4/8**	**Cloudiness ≤ 3/8**
< 2	A	A-B	B	-	-
2 - 3	A-B	B	C	E	F
3 - 5	B	B-C	C	D	E
5 - 6	C	C-D	D	D	D
> 6	D	D	D	D	D

- The atmospheric stability degree is strongly influenced by the vertical temperature gradient and the horizontal component of the wind: high-value negative gradients generally lead to atmospheric instability, neutral conditions correspond to low-value negative gradients and positive temperature gradients lead to atmospheric stability. There are methods to determine atmospheric stability utilizing vertical temperature gradients and wind speed.

ii). Calculation of air concentration integrated in time

- Effective activity on wind direction, somewhere at a receptor point, is changed depending upon the time lapsed from the moment of discharged until the radioactive cloud reaches above the receptor point. This is why the initial source term, meaning the total activity discharged by the source, Q_0, (Bq), must be corrected with factors that take into account radioactive disintegration phenomena, occurrence of progeny products, dry and wet deposit of radioactive material on the ground. Effective activity at a receptor point is calculated with the formula:

$$Q = Q_0 (DEC)(DEP), \quad \text{(Bq)} \tag{28}$$

where
Q_0 = initial activity discharged by the source, (Bq),
(DEC) = correction factor for radioactive disintegration and occurrence of progeny products, without any dimensions,
(DEP) = correction factor for wet and dry settling, without any dimensions.

- Effective activity is calculated for each separate radionuclide discharged in the atmosphere.

- Total contribution at a receptor during the passage of the radioactive cloud is expressed in the concentration integrated in time for a particular radionuclide (Bq·s/m^3), χ.
- Air concentration integrated in time, obtained at the passage of the radioactive cloud above a receptor point is calculated by multiplying the effective activity discharged by the source with the factor of atmospheric dilution:

$$\chi = \left(\frac{\chi}{Q}\right) Q_0 (DEC)(DEP), \quad (\text{Bq} \cdot \text{s/m}^3) \tag{29}$$

where

$\frac{\chi}{Q}$ = the atmospheric dilution factor at the coordinates receptor point (x, y, z), calculated with equations (1) - (5) from paragraph i).

1. Correction factor for radioactive disintegration and occurrence of progeny products, (DEC)

- For the radioactive material discharged in the atmosphere, the activity in the radioactive cloud decreases according to the law of radioactive disintegration, meaning

$$(DEC) = \exp(-\lambda_i t) = \exp(-\lambda_i \frac{x}{\bar{u}}), \tag{30}$$

where

t = time lapsed for the radioactive cloud from the source to the receptor point, $t = \frac{x}{\bar{u}}$,

x = distance traveled by the radioactive cloud on the wind direction,

$\bar{u}$ = wind speed at the source = travel speed for radioactive material on the wind direction,

λ_i = disintegration constant for radionuclide i.

- Progeny products of some radioactive elements can be formed in the radioactive cloud, especially at long distances from the source, simultaneously with the increase of time spent by radioactive cloud from the source to the receptor point, t. In this situation, the correction factor is of the form:

$$(DEC) = \frac{\lambda_d}{\lambda_i - \lambda_d} \left[\exp(-\lambda_d \frac{x}{\bar{u}}) - \exp(-\lambda_i \frac{x}{\bar{u}}) \right], \tag{31}$$

where

λ_d = disintegration constant for daughter d.

- For radioactive discharges in case of nuclear accident, occurrence of daughters Rb-88, Rb-89, Xe-135m, Xe-135 and Cs-138 by the disintegration of Kr-88, Kr-89, I-135 and Xe-138 must be especially taken into consideration.

- Corrections of equation (31) type in the situation of long-life daughters resulted from short-life progenitors are generally insignificant in atmospheric discharges.

2. Correction factors for wet and dry settling

- Settling processes that can contribute to the decrease of radionuclide concentrations from the radioactive cloud are as follows:
  - Gravitational settling,
  - Dry settling,
  - Wet settling.

2.1. Gravitational settling

- Radioactive material discharged in the atmosphere during the normal operation of a nuclear reactor or in case of an accident is mainly found under gaseous shape or as some drops or particles of very small dimensions (a few microns diameter). The effect of gravitational settling is thus negligible in comparison with dry and wet settling effects and it can be ignored in the calculations.

2.2. Dry settling

- Radioactive material can be removed from the radioactive cloud as a result of the dry settling, result of turbulent diffusion, Brownian movement, electrostatic attraction processes, adsorption, surface impact and chemical interactions. Dry settling ratio depends on the nature of the radioactive material (particle dimensions, physical and chemical properties), the surface it settles on, but also on the weather conditions and can be estimated with the concept of settling speed.
- Settling speed is defined as the ratio between quantity of material settled on the ground in the time unit and the material concentration in the air, at ground level.
- Results of experimental settling speed determinations are very varied, depending on all factors mentioned above. Recommended values for any stability class are given in table 6.
- The following values can be utilized in the absence of specific data for different chemical forms of Iodine and other radionuclides [6]:
  - particles (most radionuclides) 1×10^{-3} m/s,
  - reactive gas, e.g. anorganic Iodine vapors 1×10^{-2} m/s,
  - Iodine gaseous organic form 1×10^{-5} m/s.
- Rare gases do not settle. Rare gases settling speed is zero.

Table 6. Recommended values for settling speed (m/s), for any stability class and different types of surfaces [7].

Radionuclide	Type of surface where the radioactive material is settled on				
	Water	Soil	Snow	Grass	Forest
Iodine					

	v_{dL}	0.2×10^{-2}	0.07×10^{-2}	0.07×10^{-2}	0.2×10^{-2}	1.0×10^{-2}
	v_{dH}	2.0×10^{-2}	1.0×10^{-2}	0.7×10^{-2}	3.0×10^{-2}	10.0×10^{-2}
Ruthenium						
	v_{dL}	0.2×10^{-2}	0.06×10^{-2}	0.2×10^{-2}	0.1×10^{-2}	0.5×10^{-2}
	v_{dH}	3.0×10^{-2}	0.3×10^{-2}	1.0×10^{-2}	1.0×10^{-2}	5.0×10^{-2}
Cesium						
	v_{dL}	0.1×10^{-2}	0.03×10^{-2}	0.1×10^{-2}	0.07×10^{-2}	0.4×10^{-2}
	v_{dH}	1.0×10^{-2}	0.1×10^{-2}	0.3×10^{-2}	0.3×10^{-2}	2.0×10^{-2}
Other radionuclides						
	v_{dL}	0.2×10^{-2}	0.2×10^{-2}	0.2×10^{-2}	0.2×10^{-2}	1.0×10^{-2}
	v_{dH}	3.0×10^{-2}	3.0×10^{-2}	3.0×10^{-2}	3.0×10^{-2}	10.0×10^{-2}

v_{dL} – relatively low value (inferior limit), utilized generally for the calculation of radioactive concentration in the air;

v_{dH} – relatively high value (superior limit), utilized generally in the calculation of dry settling on the ground.

- The dry settling speed depends on the aerodynamic diameter of the settled particles. Particles with aerodynamic diameter between 0.1 and 1 μm have a settling speed of approximately 0.02×10^{-2} m/s, and those with aerodynamic diameter between 1 and 10 μm have settling speeds between 0.02×10^{-2} m/s and 5×10^{-2} m/s [11].
- Tritium released in the atmosphere presents mainly two chemical forms: tritium water vapors (HTO) and tritium hydrogen (HT). Experimental measures produced an estimation regarding the HTO settling speed between 0.4×10^{-2} m/s and 0.8×10^{-2} m/s, if the height of the tropopause is considered as being 12 – 15 km. Under the same circumstances, the HT settling speed was estimated as a small-size order, meaning 0.04×10^{-2} m/s – 0.05×10^{-2} m/s [5].

- The correction factor for dry settling, instantaneous or short-term discharge is calculated with formula:

$$(DEP)_d = \exp\left[-\left(\frac{2}{\pi}\right)^{1/2}\left(\frac{v_{dL}}{\overline{u}}\right)\cdot\int_0^x \frac{\exp(-H^2/2\sigma_z{}^2(x'))}{\sigma_z(x')}dx'\right]. \quad (32)$$

- The correction factor for dry settling, for long-term or extended term discharge is calculated with the formula:

$$(DEP)_d = \sum_i \exp\left(-\alpha\int_0^x \frac{\exp(-H_i{}^2/2\sigma_{zi}{}^2(x'))}{\sigma_{zi}(x')}dx'\right),$$

unde . (33)

$$\alpha = 0.01F_kF_{ki}\left[\frac{\tan\theta/2}{\theta}\right]\left[\frac{2\sqrt{2}}{\sqrt{\pi}}\right]\left[\frac{v_{dL}}{\overline{u_i}}\right],$$

with summing following all Pasquill stability classes (A - F).

- In equations (32) and (33) v_{dL} represents the average settling speed during the travel of the radioactoive cloud.
- Settling radioactive material on the ground is calculated with the equation:

  $$\omega = v_{dH}\chi(x, y, 0), \quad (\text{Bq/m}^2), \tag{34}$$

  where v_{dH} represents the settling speed on a particular surface and in a particular receptor.
- It is recommended that in the calculation of settling of radioactive material on the ground to consider values v_{dH} (superior limit) from table 6 for settling speeds.
- For the quick and conservative estimation of total settling process (dry and wet), aerosols and reactive gases is recommended to utilize a total settling speed of 1000 m/day, meaning 1.16×10^{-2} m/s. For H-3, C-14 and rare gases, total settling speed is considered as being zero [2].

2.3. Wet settling

- Wet settling is the process with which the radoioactive material is removed by mean of precipitations (rain or snow) from the radioactive cloud and settled on the ground.
- There are two mechanisms considered in the description of atmosphere wash process and that produce wet settling of radioactive material on the ground: wash in the rain cloud and wash underneath the basis of the rain cloud.
- The correction factor for wet settling is calculated with the equation:

  $$(DEP)_w = \exp(-\Lambda t), \tag{35}$$

  where

  Λ = atmosphere wash coefficient (s^{-1}),

  t = period of time during which the radioactive material is subjected to process.
- The wash coefficient is a function of multiple parameters, such as chemical and physical status of the radioactive material, dimension of raindrops or snow crystals, intensity and rate of precipitations. The recommended values of the wash coefficient (inferior and superior limits), taken from the specialized literature, are presented in table 7.
- It is recommended in equation (35) to utilize the inferior limits of the wash coefficients
- It is recommended that in calculation of the wet settling of radioactive material on the ground to take into consideration the superior limits of the wash coefficient.

Table 7. Values recommended for the wash coefficient, (s^{-1}) [7].

Radionuclide	Rain, mm/h				Snow, mm/h (equiv. water)			
	0.5	1	3	5	0.5	1	3	5
Tritium and Iodine								
Λ_L	5×10^{-6}	1×10^{-5}	2×10^{-5}	3×10^{-5}	$<10^{-7}$	1×10^{-7}	2×10^{-7}	3×10^{-7}

	Λ_H	1×10^{-4}	2×10^{-4}	4×10^{-4}	6×10^{-4}	2×10^{-7}	4×10^{-7}	8×10^{-7}	1×10^{-6}
Other radionuclides									
	Λ_L	1×10^{-5}	2×10^{-5}	3×10^{-5}	5×10^{-5}	3×10^{-4}	5×10^{-4}	8×10^{-4}	1×10^{-3}
	Λ_H	2×10^{-4}	3×10^{-4}	7×10^{-4}	1×10^{-3}	1×10^{-2}	2×10^{-2}	4×10^{-2}	5×10^{-2}

Λ_L – relatively low value (inferior limit), utilized generally for the calculation of radioactive concentrations in the air;

Λ_H – relatively high increased value (superior limit), utilized generally for the calculation of wet settling on the ground.

iii). Calculation of radioactive concentration settled on the ground

1. Dry settling

- Radioactive concentration settled on the ground in the absence of rainfall at a receptor point located on the wind direction, is calculated by multiplying the air concentration integrated in time (equation (29)) with the dry settling speed, v_d:

$$\omega_d = v_d\left(\frac{\chi}{Q}\right)Q_0(DEC)(DEP), \quad (\text{Bq/m}^2). \tag{36}$$

- For conservatory reasons, it is recommended to utilize in equation (36), superior values of settling speed presented in table 6.

2. Wet settling

- The activity settled on the surface unit in rainfall conditions is calculated for a coordinate receptor point (x, y, z), with the equation:

$$\omega_w = \int_0^{\xi}\Lambda\chi(x,y,z)dz, \quad (\text{Bq/m}^2). \tag{37}$$

where

ξ = height (in m) from the radioactive cloud subjected to washing process.

- Maximum value for wet settling on ground is obtained when it is considered that the entire radioactive cloud is subjected to the washing process, meaning $\xi\rightarrow\infty$ and for Λ superior limits are taken from table 7.
- Wet settling on ground, for an instantaneous or short-term discharge, for any effective discharge height, is calculated with the formula:

$$\omega_w = \frac{\Lambda_H Q_0(DEC)\exp(-\Lambda_L t)}{\sqrt{2}\pi\bar{u}\Sigma_y}\exp(-\frac{y^2}{2\Sigma_y^2}) \quad (\text{Bq/m}^2). \tag{38}$$

- Wet settling on ground for an extended duration or long-term discharge, for any effective discharge height, is calculated with the formula:

$$\omega_w = \frac{\Lambda_H Q_0 (DEC) \exp(-\Lambda_L t)}{\bar{u}\theta_L x} \quad (\text{Bq/m}^2). \tag{39}$$

- In a conservative manner it is considered that once settled, the radioactive material is not removed from the ground with mechanical processes or other physical processes.

3. Calculation of re-suspension

- Once settled on the ground, the radioactive material can be picked-up back in the air (re-suspended), as a result of the wind on ground level or human activities. Inhalation of radioactive material re-suspended from the ground level can become under particular circumstances an important way of exposing the human body.
- The relationship between the concentration settled on the ground and the concentration of radioactive material re-suspended in the air is given by the re-suspension factor K,

$$K\,(\text{m}^{-1}) = \frac{\text{Concentration in the air of re-suspended material (Bq/m}^3)}{\text{Settlling on ground (Bq/m}^2)}. \tag{40}$$

- The temporal dependency of the re-suspension factor K can be described by two exponential components:

$$K = A\exp(-\lambda_1 t) + B\exp(-\lambda_2 t), \tag{41}$$

where
A and B are constant,
A – values taken from specialized literature are within the interval 10^{-4} - 10^{-6} m^{-1},
B – values taken from specialized literature are within the interval 10^{-8} - 10^{-10} m^{-1},
λ_1 represents an effective removal rate on short-term, with halving time in weeks,
λ_2 represents an effective removal rate on long-term, with halving time in the interval of 50 – 100 years.

- Reference values for constants in equation (41) are as follows:
$A = 10^{-5}$ m^{-1}, $B = 10^{-9}$ m^{-1}, $\lambda_1 = 1\times10^{-2}$ $days^{-1}$ şi $\lambda_2 = 2\times10^{-5}$ $days^{-1}$.

vi). Prediction accuracy for Gaussian model

- Gaussian model presented above has certain limitations and its predictions feature an inherent level of uncertainty.
- For distances shorter than 1 km, under ideal conditions of flat and uniform terrain and stable weather conditions, the air concentration integrated in time, maximum,

on the wind direction, at ground level, calculated with Gaussian model is correct in a percentage of only 20% for a discharge at ground level and 40% for a chimney discharge. The uncertainty related to the model predictions in the interval $\pm$ 2 Σ_y compared to the main wind direction is estimated to vary up to a factor 2.

- When the Gaussian model is applied under weather and terrain conditions close to ideal conditions, for distances smaller than 10 km, spreading of estimated values also increases and the uncertainty related to predictions varies with a factor 2.
- When the Gaussian model is applied for long distances up to 100 km, under real weather conditions, the uncertainty related to predictions varies with a factor 4 up to 10.
- Under weather conditions of slow wind ($<$ 2 m/s), the movement of the radioactive cloud and quick direction changes of the wind can be a lot underestimated by he Gaussian model, leading to the overestimation of air concentrations integrated in time.
- Uncertainties associated to predictions of the Gaussian model at different distances from the source, for discharges with effective discharge height $<$ 100 m and under weather conditions of wind $>$ 2 m/s are indicated in table 8.

Table 8. Uncertainties related to the Gaussian model predictions of radioactive material dispersions in the atmosphere [7].

Discharge type	100 m $<$ x $<$ 1 km	1 km $<$ x $<$ 10 km	10 km $<$ x $<$ 100 km
Short term discharge	with a factor 2	with a factor 5	with a factor 10
Extended duration or long-term discharge	with a factor 1.4	with a factor 2	with a factor 4

v). Special considerations regarding the dispersion of radioactive material discharged in the atmosphere as a result of a fire or non-nuclear explosion

1. Fire [*1*]

- In a special situation of a fire that involves the discharge or radioactive material in the atmosphere, such as a plane crashed in the fuel pool of a nuclear reactor, dispersion of radioactive material in the atmosphere is simulated with the equations of the Gaussian model described above, with a few special remarks.
- Overelevation of the radioactive pollutant track is owed to the heat power of the discharged material, so that the main effect producing the elevation of the material is the lift effect. Impulse effect is insignificant in such situations.
- Important parameters in calculating the effective discharge height are the heat power of the material discharged during the fire, Q, cal/s, and the lift flow parameter, F, m^4/s^3.

- For a fuel fire, the heat power of the material discharged in the atmosphere is calculated with the equation:

$$Q = VdH(1-f)/t, \quad (42)$$

where

Q = heat power of the material discharged during the fire, cal/s,
V = volume of fuel spent during time t, m^3,
d = density of spent fuel, kg/m^3,
H = burning heat, cal/kg,
f = fraction of discharged burning heat,
t = fire duration, s.

- The volume of fuel spent during time t determines the overelevation of radioactive material in the atmosphere. Experiments have shown that burning rates, expressed in pool depth rates, generally come within the interval of 1 - 5 mm per minute.
- Values recommended for terms in equation (42) are as follows: f = 30%, d = 0.810 g/cm^3, H=1.2×10^4 cal/kg.
- Lift flow parameter, F, m^4/s^3 is calculated, depending on the heat power of the discharged material, with the equation:

$$F = \frac{gQ}{\pi C \rho T}, \quad (43)$$

where

g = gravitational acceleration (9.8 m/s^2),
C = specific heat of discharged gases (cal/(kg·K)),
ρ = air density, (kg/m^3),
T = temperature of ambient air (K).

- Calculation equations of the above-mentioned overelevation (Briggs' formula) apply in case of a chimney discharge, considered of a negligible interior diameter.
- For a burning pool of radius R, overelevation is calculated with the formula:

$$H_1 = \left[H^3 + \left(\frac{R}{\gamma} \right)^3 \right]^{1/3} - \frac{R}{\gamma}, \quad (44)$$

where

H = effective discharge height calculated with Briggs methodology, m,
R = radius of ground fire (radius of burning pool), m,
γ = picking-up coefficient = 0.6.

- Once the effective height is calculated for lifting the radioactive material, the dispersion radius of material at height H_1 is considered as:

$$R_{nor} = 0.6H_1. \quad (45)$$

- In order to model the final distribution of radioactive material at height H_1, a virtual source term is supposed to exist on the wind direction, positioned at distance -x

compared to the discharge point. The virtual source term creates above the discharge point, at height H1, dispersion parameters:

$$\sigma_y(x=0) = \sigma_z(x=0) = \max(0.5R_{nor}, 0.5R_{piscina}). \quad (46)$$

2. Non-nuclear explosion [*1*]

- Five source terms shape the initial distribution of radioactive material in case of an explosion. For each real source, two virtual source terms are supposed to exist, on the wind direction, positioned at distance *–dy*, and *–dz*, respectively, from the explosion point, these virtual source terms generating in the emission point, at final height, with dispersion parameters σ_y and σ_z.
- The source distribution is considered as having:
  4% at ground level (h1=0),
  16% at h2=0.2 from the height of the cloud formed after the explosion,
  25% la h3=0.4 from the height of the cloud formed after the explosion,
  35% la h4=0.6 from the height of the cloud formed after the explosion,
  20% la h5=0.8 from the height of the cloud formed after the explosion.

- Characteristic parameters of the cloud formed after the explosion are calculated with equations:

$$H_{nor} = 76w^{0.25}, \quad \text{(m)}$$
$$R_{nor} = 0.20H_{nor}, \quad \text{(m)} \quad (47)$$

  where
  H_{nor} = height of the cloud formed after the explosion,
  R_{nor} = radius of the cloud formed after the explosion
  w = the explosive quantity utilized for the explosion.

- The effective discharge height is considered as being: $H_{eff} = 0.8H_{nor}$.
- Dispersion parameters σ_y and σ_z are calculated above with the equations:

$$\sigma_y(x=0) = 0.5R_{nor},$$
$$\sigma_z(x=0) = 0.2H_{nor}. \quad (48)$$

Appendix 3.
Calculation of aquatic dispersion of radioactive material

Dispersion models of the radioactive material in the aquatic environment suppose the resolution of equation:

$$\frac{\partial C}{\partial t} = A + D - R + P - \lambda C, \quad (1)$$

where
C = water concentration of the considered radionuclide, (Bq/m^3);

t = average time necessary to move the radionuclide to the receptor point, (s).;
A = advection term;
D = diffusion term;
R = term referring to the capture of radionuclides by the sediment in suspension;
P = term that considers the external sources or radionuclide absorbents (system eliminations) at the limits, sedimentation, biological settling but not transfer to or from suspended sediments;
λ = radionuclide disintegration constant.

Equation (1) terms, under balance conditions, write:

$$A = u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} + w\frac{\partial C}{\partial z}$$

$$D = \frac{\partial}{\partial x}\left(K_x \frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial C}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial C}{\partial z}\right) \quad (2)$$

$$R = K_d S \frac{\partial C}{\partial t} \quad ,$$

where
u, v, w = components of water speed along the x, y and z coordinate axis;
K_x, K_y, K_z = coefficients of turbulent diffusion on x, y and z directions;
S = concentration of sediments suspended in the water;
K_d = balance distribution coefficient between solid and liquid states.

- Due to the complexity of considered interactions, equation (1) can be solved only by numerical techniques. In order to obtain analytical solutions, simplifying solutions must be issued. Hypotheses must present the real situation in an adequate manner.
- Mathematical modeling of aquatic dispersion generally involves three stages:
- Stage 1: initial mixture,
- Stage 2: extended from stage 1 up to distances for obtaining the complete mixture on the entire transversal section of the aquatic environment,
- Stage 3: extends in continuation of stage 2 and it generally involves consideration of interactions with the sediment.
- Initial mixture of liquid radioactive effluents with water volume of the receptor environment depends on factors such as: discharge geometry (discharge point, at surface or submerged, with one or multiple discharge points, width and depth of discharge flow), temperature and exit speed of effluents, geometry of receptor aquatic environment, characteristics of flow currents, including flow speeds, directions and temperatures.
- Direct determination of the diffusion coefficients is carried out by different measurement methods with tracers, such as fluorescent colorants, radioactive substances or stable elements.
- It is recommended to use as tracers neutral elements in relation to the environment in order to avoid secondary effects and interpretation complications.

1. Transport of radionuclides in rivers

- In order to simulate the dispersion of liquid radioactive effluents in aquatic environment, this environment is divided into four categories: rivers, lakes, estuaries and coastal sea areas.
- This appendix will contain a description of the mathematical pattern of the transport and dilution of radioactive material in rivers or channel-type hydrotechnical constructions.
- Calculation methodology presented hereinafter is based on analytical solutions of the transport equations that describe the migration of radionuclides in surface waters, obtained in certain simplifying hypotheses:

- stationary flow regime (flow characteristics of the aquatic environment, e.g. flow speed and water depth do not change significantly in relation to distance),
- simple determination processes for dispersion coefficients and river-specific parameters,
- river geometry (transversal section) is not modified significantly with the distance,
- radionuclides in water and sediment, under the conditions of a continuous routine discharge, are balanced.

1.1. Characteristics specific to the river where the discharge shall take place

- For the calculation of radionuclide concentration in the river water, river-specific characteristics must be determined:

a) River width B, (m),
b) River depth d, (m),
c) Total river flowrate, Q (m^3/s).

- Characteristics of the water course must be determined on the basis of hydrological studies carried out in the influence area of the nuclear installation.
- In the absence of experimental results, the following relations can be utilized:

$$d = 0.163 \cdot Q^{0.447}, \quad (3)$$

$$B = 10 \cdot Q^{0.460}, \quad (4)$$

where
B = river width (m),
d = river depth (m),
Q = river flowrate (m^3/s).

- In order to estimate the flowrate, width and depth of the river as minimum values obtained in the past 30 years, the following actions will be taken:

- Estimate the river width by notes or by means of a map, B;
- With the value obtained for B, estimate the yearly average flowrate Q with formula (4) or utilizing values in table 1;

- Calculate the minimum multi-year flowrate (for a period of 30 years), as 1/3 from the yearly flowrate;
- With the value of the minimum multi-year flowrate and formulas (3) and (4) or utilizing the values calculated in table 1, B and d corresponding to the minimum level of the river flowrate, calculated for a period of 30 years.

Table 1. Relations between Q, B and d [*2*]. (*)

Q (m^3/s)	B (m)	d (m)	Q (m^3/s)	B (m)	d (m)
0.1	3.47	0.058	100	83.2	1.28
0.2	4.77	0.079	200	114	1.74
0.3	5.75	0.095	300	138	2.09
0.4	6.56	0.108	400	157	2.37
0.5	7.27	0.120	500	174	2.62
0.6	7.91	0.130	600	190	2.84
0.7	8.49	0.139	700	204	3.05
0.8	9.02	0.148	800	216	3.24
0.9	9.53	0.156	900	229	3.41
1	10.0	0.16	1 000	240	3.57
2	13.8	0.22	2 000	330	4.87
3	16.6	0.27	3 000	398	5.84
4	18.9	0.30	4 000	454	6.64
5	21.0	0.34	5 000	503	7.34
6	22.8	0.36	6 000	547	7.96
7	24.5	0.39	7 000	587	8.53
8	26.0	0.41	8 000	624	9.05
9	27.5	0.44	9 000	659	9.54
10	28.8	0.48	10 000	692	10.0
20	39.7	0.63	20 000	952	13.6
30	47.8	0.75	30 000	1150	16.3
40	54.6	0.85	40 000	1310	18.6
50	60.5	0.94	50 000	1450	20.5
60	65.8	1.02	60 000	1580	22.3
70	70.6	1.09	70 000	1690	23.9
80	75.1	1.16	80 000	1800	25.3
90	79.2	1.22	90 000	1900	26.7
			100 000	2000	28.0

(*) – linear interpolation between the values.

- River flow speed, u (m/s), corresponding to the minimum multi-year flowrate is calculated with the formula:

$$u = \frac{Q}{dB}.$$

(5)

1.2. Empiric calculation formulas for turbulent coefficient diffusion

- The turbulent diffusion coefficients vary significantly from one river to another and even within the same river.
- The longitudinal (K_x) and lateral (K_y) diffusion coefficients vary with a few sizes depending upon the river dimensions.
- The following empiric calculation expressions offer predictions in a pretty good relation to reality for a wide range of variation of river characteristics:
  - vertical diffusion coefficient is calculated with the equation:

$$K_z = 0.067 \cdot u_* \cdot d, \tag{6}$$

where
u_* = tangential speed (m/s) = 0.1u.

- longitudinal and lateral dispersion coefficients are calculated with the equations:

$$K_x = \frac{u^2 B^2}{30 u_* d}, \tag{7}$$

$$K_y = \alpha \cdot d \cdot u_*, \tag{8}$$

where
α = a proportionality coefficient varying between 0.1 – 0.2 for small rivers and irrigation channels and between 0.6 – 2.0 for rivers; as reference value consider α = 0.6.

- Equations (6) – (8) are written, considering u_*=0.1u and α = 0.6:

$$K_z = 0.0067 \cdot u \cdot d, \tag{9}$$

$$K_x = \frac{u B^2}{3d}, \tag{10}$$

$$K_y = 0.06 \cdot d \cdot u. \tag{11}$$

1.3. Partial / complete mixture conditions

- In order to obtain distances along the flowing direction of the river when the mixture of radioactive effluent with receptor environment is complete, it is supposed that the mixture, both on horizontal and on vertical direction is accomplished when the minimum concentration is at least equal to half of the maximum concentration level on horizontal level and vertical level, respectively.
- Supposing that the radioactive effluent is discharged from one of the river banks at depth d/2, longitudinal distances where mixture occurs on horizontal direction and vertical direction, respectively, are as follows:

$$L_y = 0.18\frac{uB^2}{K_y} = 3\frac{B^2}{d}, \quad (12)$$

$$L_z = 0.045\frac{ud^2}{K_z} = 7d. \quad (13)$$

- Given that almost any river has a width larger than the depth, distance L_y is larger than L_z, so that at distances larger than L_y, along the flow direction of the river, the radioactive effluent is completely mixed both on horizontal and on vertical direction.
- In the area where $x<L_z$, distribution of radionuclides is treated in three dimensions. For this region it can be considered that there is no dilution of radioactive effluent with river water. This type of approach is practically independent of the aquatic environment where the discharge takes place and the radioactive concentration in the water is calculated with the equation:

$$C_{w,i} = C_0 = \frac{W_i}{Q}, \quad (14)$$

where

$C_{w,i}$ = radionuclide concentration i in water, Bq/m^3,

C_0 = radionuclide concentration in liquid effluent at the discharge in aquatic environment, Bq/m^3,

W_i = yearly average of the discharge ratio for radionuclide i, Bq/s,

Q = flowrate of liquid effluent, m^3/s.

1.4. Transport equations and analytical solutions in case of long-term discharge and considering the complete mixture between the radioactive effluent and the river water

- After obtaining the complete mixture, the transport equation of radionuclides in the river water can be described as bi-dimensional. Considering only the radioactive disintegration phenomenon, the equation is written:

$$ud\frac{\partial C}{\partial x} = \frac{\partial}{\partial y}(K_y d\frac{\partial C}{\partial y}) - (\lambda d)C, \quad (15)$$

where the terms have been defined with priority.

- Whereas, in real situations, u and d are variable functions of y, equation (15) will not have analytical solutions, in general. For the modification of the equation form, independent variable q is input and defined as:

$$q = \int_0^y (ud)dy. \quad (16)$$

Quantity q expresses the flow cumulated between y = 0 and any given y, on the perpendicular flow direction. When $y \to B$, results that $q \to Q$, where B is the width of the river and Q is the total flowrate.

Replacing equation (16) in equation (15), the following transport equation results:

$$\frac{\partial C}{\partial x} = \frac{\partial}{\partial q}\left[(K_y u d^2)\frac{\partial C}{\partial q}\right] - \frac{\lambda}{u}C. \tag{17}$$

In the disintegration term, u can be replaced with average speed $\bar{u}$. In this circumstance, the following can be written:

$$C(x,q) = \chi(x,q)\exp(-\frac{\lambda x}{\bar{u}}). \tag{18}$$

The result is the following transport equation for concentration χ:

$$\frac{\partial \chi}{\partial x} = \frac{\partial}{\partial q}\left[(K_y u d^2)\frac{\partial \chi}{\partial q}\right]. \tag{19}$$

Quantity $D=K_y u d^2$ is known as diffusion factor. Diffusion factor D, variable, can be replaced by a constant factor defined as:

$$\overline{K_y u d^2} = \frac{1}{Q}\int_0^Q K_y u d^2 dq. \tag{20}$$

Equation (19) can now be written:

$$\frac{\partial \chi}{\partial x} = D\frac{\partial^2 \chi}{\partial q^2}, \tag{21}$$

where D means the constant diffusion factor.

Equation (21) is a typical diffusion equation that allows analytical solutions.
Supposing that the discharge of radioactive effluents is accomplished with a constant rate W (Bq/s) and considering the source coordinates as being x=0 and $y=y_s$ and corresponding to y_s as being the cumulative flow q_s, the analytical solution of equation (21) is:

$$\chi = \frac{W}{Q}\left[1 + 2\sum_{n=1}^{\infty}\exp(-\frac{n^2\pi^2 Dx}{Q^2})\cos(\frac{n\pi q_s}{Q})\cos(\frac{n\pi q}{Q})\right]. \tag{22}$$

Supposing that the effluent dispersion takes place in a uniform, rectangular, straight-edged channel with constant speed U, in equation (22) transformations can be made as in the following parentheses :

$$\begin{Bmatrix} D/Q^2 \\ q \\ Q \end{Bmatrix} \rightarrow \begin{Bmatrix} K_y/UB^2 \\ y \\ B \end{Bmatrix}.$$

The general form presented in (22) is preferable, however, in the situation of irregular water courses.

1.5. Accidental discharges

- There are a lot of situations where the discharge of radioactive effluents is carried out continuously, with interruptions, in series of effluents. This situation is found out in the case of accidental discharges of liquid effluents.
- In such situations, radionuclides concentration must be calculated as a function depending on time and space.
- Radionuclide concentration in a rectangular channel with straight edges corresponding to an instantaneous discharge of a finite quantity of material, at a source of coordinates x=0 and y=y_s the following equation is calculated:

$$C = \frac{M}{(4\pi K_x t)^{1/2} A} \exp\left\{ -\frac{[x-ut]^2}{4K_x t} - \lambda t \right\} \left[1 + 2\sum_{n=1}^{\infty} \exp\left(-\frac{n^2\pi^2 K_y t}{B^2}\right) \cos\left(n\pi \frac{y_s}{B}\right) \cos\left(n\pi \frac{y}{B}\right), \right] \quad (23)$$

A = transversal section area,
M = discharged activity (in Bq),
t = time elapsed from the discharge,
and the rest of terms have been defined previously.

- Utility of equation (23) is that it allows the calculation of radionuclide concentration in real situations of evacuation. In case of a short-term evacuation, spreading of radionuclides along the water flow direction (considering K_x) can be an important dispersion mechanism that is not considered in the long-term discharge model.

1.6. Simplified equations for the calculation of radionuclide concentrations

- General equations presented in paragraph 1.4 can be simplified on the basis of considerents issued in paragraphs 1.1 – 1.3, as follows: considering the mixture ratio, average time when the radionuclides reach from the source to the receptor, radioactive disintegration phenomenon, equation (14) becomes:

$$C_{w,i} = P \frac{W_i}{Q} M_p \exp(-\lambda_i t_p), \quad (24)$$

where
P = conversion factor connecting discharge rate units and river flow with water concentration,
M_p = mixture ratio, the opposite of dilution factor, no dimensions,
λ_i = radioactive disintegration constant (s^{-1}),
t_p = necessary mean time for the movement of the radionuclide i at receptor point (s).

- Mixture rate M_p in equation (24) has value 1 for undiluted effluent and has value Q/R in total mixture situation, where R is the yearly mean value of the river flowrate.
- In order to find out the radionuclide concentration at a receptor point located on the bank opposite to the discharge point, the following equation is utilized:

$$C_{w,i} = \frac{W_i}{Q}\exp(-\frac{\lambda_i x}{U}) = C_t, \quad (25)$$

where

x is the distance between the discharge point and the receptor point.

- In order to find out the radionuclide concentration at a receptor point located on the same bank with the discharge point, two situations are considered:

a) $x < L_z$, situation when it is supposed that the radioactive material is not diluted and radionuclide concentration in the river water is calculated with equation (14) and

b) $x > L_z$, situation when it is supposed that the complete mixture is accomplished on vertical direction of the radioactive material with river water; the concentration of radioactive material in the river water must be corrected with a partial mixture coefficient P_r, that considers that the mixture in horizontal direction can be incomplete at distance x corresponding to the receptor point: $C_{w,i} = C_t P_{r,}$ (26)

where P_r is obtained from Table 2, depending upon the partial mixture index A, calculate with equation: $A = \frac{1.5dx}{B^2}$; for $x > 3B^2/d$, $P_r \cong 1$.

Table 2. Values recommended for the correction factor for partial mixture, P_r [*2*]. (*)

A	P_r	A	P_r	A	P_r	A	P_r
1×10^{-6}	31.0	1×10^{-4}	20.9	1×10^{-2}	10.7	1	2.6
2	29.8	2	19.4	2	9.3	2	2.0
3	28.9	3	18.5	3	8.5	3	1.7
4	28.2	4	17.8	4	7.9	4	1.5
5	27.6	5	17.4	5	7.5	5	1.4
6	27.2	6	17.1	6	7.2	6	1.3
7	26.9	7	16.7	7	6.9	7	1.3
8	26.7	8	16.4	8	6.6	8	1.2
9	26.4	9	16.1	9	6.3	9	1.1
1×10^{-5}	26.1	1×10^{-3}	15.9	1×10^{-1}	6.0	10	1.0
2	24.8	2	14.2	2	4.8	20	1.0
3	23.6	3	13.3	3	4.2	30	1.0
4	22.9	4	12.8	4	3.7	40	1.0
5	22.5	5	12.2	5	3.4	50	1.0
6	22.1	6	11.8	6	3.2	60	1.0
7	21.6	7	11.5	7	3.0	70	1.0
8	21.3	8	11.2	8	2.8	80	1.0
9	21.1	9	11.0	9	2.7	≥ 90	1.0

(*) – linear interpolation between values.

2. Transport of radionuclides in discharge channels

- There are two types of discharge basins utilized for the evacuation of liquid effluents from the nuclear installation:

- basins with almost closed circuit for discharged effluents, where the effluents are cooled and recirculated in the nuclear installation; a certain quantity of the basin water must be evacuated from the system as purging water in order to maintain the concentration level of solids dissolved under a particular limit level; fresh water is added to the system in order to compensate the effect of processes of evaporation and evacuation as purging water;
- discharge channels with open circulation where the effluents are not recirculated or they are partially recirculated in the nuclear installation; the effluent is evacuated in the discharge channel and then into a receptor environment (river) of larger dimensions.

- Simple calculation models can be utilized for the determination of radionuclide concentration in discharge basins.

- The present appendix describes a situation regarding the discharge channels with pen circulation.

- Radionuclide concentration levels in the discharge channels, assuming there is no recirculation of the effluent is calculated with the equation:

$$C = C_0 \exp(-\lambda V_T / q_b), \quad (1)$$

where

C_0 = radionuclide concentration in the liquid effluent, Bq/m^3

V_T = volume of the discharge channel,

q_b = effluent flowrate through the discharge channel.

- When there occurs a partial recirculation of the liquid effluent and the influences of the purging water and the nuclear installation pumps influence the flowrate in a significant amount, the mathematical calculation pattern must be modified as to consider both the installation pumping ratio, q_p, and the system loss ratio through purging waters, q_b.
- The recirculation factor, R, is defined as being:

$$R = \frac{q_b}{q_p}.$$

- Concentration of radionuclides in the discharge channel, in stationary regime, is calculated with the equation:

$$\frac{C}{C_0} = \frac{R}{(R+1)\exp\left[\frac{R}{\tau(R+1)}\ln 2\right]-1}, \quad (2)$$

where

$$\tau = \frac{T_{1/2} q_b}{V_T} = \frac{\ln 2 \cdot q_b}{\lambda \cdot V_T}.$$

- Assuming that the effluent is not recirculated, , R $\rightarrow\infty$ and equation (2) is reduced to the form presented in equation (1).

3. Interaction of radioactive effluent with aquatic sediments

3.1. Distribution coefficient, Kd

- When sediments interact with radionuclides in the water, radionuclide concentration in the dissolved stage may drop as a result of the sorption processes on the sediment particles.
- A radionuclide in dissolved status in the water can be adsorbed/absorbed by suspension particles and vice versa, the adsorbed/absorbed radionuclides can pass to dissolved status in the water. Neglecting the term describing the radioactive disintegration, equations describing interaction processes are as follows:

$$\frac{\partial \chi}{\partial t} = -K_1 \chi + K_2 \chi_s \ ,$$
$$\frac{\partial \chi_s}{\partial t} = K_1 \chi - K_2 \chi_s \qquad (1)$$

where

χ = concentration of radionuclides in dissolved status in the considered volume of water, V

χ_s = concentration of radionuclides adsorbed/absorbed by the particles in suspension,

K_1 = adsorbtion/absorption of radionuclides from dissolved status,

K_2 = transfer ratio from adsorbed/absorbed status into dissolved status.

- Under balance conditions,

$$\frac{\partial \chi}{\partial t} = \frac{\partial \chi_s}{\partial t}, \qquad (2)$$

resulting

$$\frac{\chi_s}{\chi} = \frac{K_1}{K_2} \equiv K_d \qquad (3)$$

where K_d is the distribution of repartition coefficient.

- The distribution coefficient K_d (L/kg) is defined as the ratio of radionuclide concentration levels in two stages under contact, in balance. Multiple distribution coefficients can be defined for a radionuclide depending upon the sdtages where it is distributed. The distribution coefficient of a radionuclide for sediment in suspension and water is obtained with the relation:

$$K_d = \frac{\text{radionuclide concentration / kg of sediment in suspension}}{\text{radionuclide concentration / litre of water}}. \quad (4)$$

- K_d depends on the sediment type, water quality and other factors and it may vary with size order for each separate radionuclide. This is why the selection of K_d is very important depending upon the specific of the evaluated situation.
- In the absence of experimentally determined data at local level, usual value for K_d can be utilized, similar to those given in table 3.
- Generally, the finer the sediment, the greater K_d value, for the same water quality.

Table 3. Usual values of the distribution coefficient for fresh water. [*2*]

Radionuclide	**K_d (L/kg)**
Am	5×10^3
C	5
Ce	1×10^4
Cm	5×10^3
Co	5×10^3
Cr	1×10^4
Cs	1×10^3
Eu	5×10^2
Fe	5×10^3
H	0
I	10
Mn	1×10^3
Np	10
P	50
Pm	5×10^3
Pu	1×10^5
Ra	500
Ru	500
Sb	50
Sr	1×10^3
Tc	5
Th	1×10^4

U	50
Zn	500
Zr	1×10^3

3.2. Concentration of radionuclides in Radion filtered water

Radionuclide concentration in the dissolved stage (filtered water) is calculated with the equation:

$$C_{w,s} = \frac{C_{w,tot}}{1+0.001K_d S_s}, \quad (5)$$

where

S_s = concentration of the sediment suspended in the water, kg/m^3 or g/L;

0.001 = conversion coefficient of K_d from L/kg into m^3/kg.

- In the calculation for public supplementary doses as a result of ingestion of water and fish, it is recommended to utilize the concentration of radionuclide in unfiltered water, without considering the sediment interaction processes.
- Sediment interaction shall be considered only in the evaluation of doses received as a result of exposure to sediment.
- Concentration in unfiltered water is calculated with the equations presented in the previous paragraphs.
- Concentration of suspended sediment varies significantly with the characteristics of the aquatic environment.
- This is why it is recommended to utilize experimentally determined values for the evaluated situation. In the absence of experimental data, for fresh water of river can utilize the value $S_s = 5\times10^{-2}$ kg/m^3.

3.3. Concentration of radionuclides in suspended sediments

Concentration of adsorbed/absorbed radionuclides on the suspended sediment, $C_{s,w}$ (Bq/kg) is calculated with the equation:

$$C_{s,w} = \frac{0.001K_d C_{w,tot}}{1+0.001S_s K_d} = 0.001K_d C_{w,s}. \quad (6)$$

- Concentration of radionuclides in sediments suspended in the water can be important in situations when the sediment is utilized as a superficial soil source (surface).

3.4. Concentration of radionuclides in bottom sediments

- Bottom sediments will contain radionuclides as a result of the direct sorption processes with radionculides present in the water and by settling processes of the suspended sediments (radioactive) on the bottom of the water.
- Experimental data obtained indicate that the distribution coefficient values are a lot lower than for the suspended sediments. It can be stated that for bottom sediments, K_d represents one tenth of K_d value for the suspended sediment, in the same aquatic environment. The assumption represents an overevaluation of K_d for the bottom sediment leading to a conservative evaluation of the exposure dose at the contaminated bottom sediment, for special situations when such sediment is dredged and brought to surface in special works of establishment for some soils.
- Radionuclide concentration in the bottom sediment in bottom sediments, $C_{s,b}$ (Bq/kg) is calculated with the equation:

$$C_{s,w} = \frac{(0.1)(0.001)K_d C_{w,tot}}{1+0.001 S_s K_d} \times \frac{1-\exp(-\lambda_i T_e)}{\lambda_i T_e} = 0.1 C_{s,w} \times \frac{1-\exp(-\lambda_i T_e)}{\lambda_i T_e}, \quad (7)$$

where

T_e = effective accumulation time for the radionuclide in the bottom sediment, (s); a typical value recommended for the effective accumulation time is $T_e = 3.15 \times 10^7$ s.

4. Related uncertainties

- Uncertainties related to predictions of equations presented under this appendix are generated by the failure to observe the proposals and by the extent of the real situation separation from the assumptions of the original model.
- In order not to implement greater uncertainties, in the partial mixture area the river geometry and flow characteristics must be relatively constant. After obtaining complete mixture, these requirements are not as critical.
- Interaction with sediments and utilization of some distribution coefficient taken from the specialized literature instead of values determined on a local basis, may alos implement significant errors in the final evaluation result.

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