USING ADMS MODELS FOR DERIVED EMISSION LIMITS COMPLIANCE WITH NUCLEAR REGULATIONS

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The present paper studies the accordance between the atmospheric dispersion models presently used by the National Commission for Nuclear Activities Control (CNCAN) and the more advanced ADMS code. The ADMS spread parameters calculation is based on the estimates of the boundary layer height and the Monin-Obukhov length scale as an atmospheric stability parameter, which presents several advantages over the older Pasquill-Gifford models (presented in the CNCAN procedures). It was conclude that the ADMS code is suitable for atmospheric dispersion studies because of the much greater complexity of the employed sub-models that consider the source and complex terrain characteristics.

Keywords: atmospheric dispersion, nuclear releases, derived emission limits, ADMS, Gaussian models

1. Introduction

Controlled release through a chimney of small amounts of radioactive effluents into the atmosphere under normal operation conditions is a characteristic of nuclear power plants. Also, in case of a nuclear accident with loss of all successive physical barriers could result in major radioactive release [1-3]. These effluents transported in the atmosphere forms a radioactive plume causing specific irradiation that could have adverse effects on population health. In order to evaluate the effects of radioactive discharges four steps are typically performed: (1) the amount of radioactive material to be released (for constant release) or that exists in all systems (for nuclear accidents) is evaluated; (2) determination of the way these effluents are released into the atmosphere (e.g. through a stack of certain characteristics); (3) study of radionuclides dispersion in the atmosphere considering meteorological characteristics of the site and the various means of reducing the concentrations (radioactive decay, wet and dry deposition, etc.); (4) population impact assessment by calculating the Derived Release Limits (DRL).

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Description of turbulent dispersion in the atmosphere is a problem for which has not been formulated a unique solution. None of the physical models that are currently used is able to fully describe the complex aspect of the dispersion problem. Atmospheric dispersion of radioactive materials into the air, released by a nuclear power plant depends on the weather conditions, terrain topology and effluent characteristics. Transport and distribution of material particles are functions of height source, air turbulence and air humidity. Surface roughness given by the local topography affects the degree of turbulence in the boundary layer. Also, the radionuclide concentrations in the environment are affected by radioactive decay and other forms of depletion like deposition to the ground. Although there is a large number of dispersion models developed today, not all of them are relevant for radiological releases from NPPs (Nuclear Power Plants). Suitable models for releases of radionuclides must take into account the following considerations [4, 5]:

- The emitters are typically point sources.
- The models developed to describe the behavior of conventional pollutants provide values for short-term concentrations (from several hours to several days). To describe the behavior of a radioactive effluent one must take into account the cumulative effect of radiation exposure, so the calculated quantity used to describe the exposure is the integrated concentration over time.
- The deposition on vegetation and other surfaces must be known because some radionuclides can endanger human health by food consumption from contaminated areas.

In this study we examine the potential of using the advanced ADMS (Atmospheric Dispersion Modeling System) code as a dispersion tool to estimate the derived release limits for a continuous release into the atmosphere from a nuclear power plant site. As a first step towards this we investigate how the ADMS code simulates the atmospheric boundary layer flows for neutrally stable and convective conditions. In addition, we simulate dispersion of a radioactive discharge from a 40m high stack, and compare the results with the generally accepted dispersion models in terms of spread parameters. The radioactive decay, wet and dry deposition, plume rise and buildings modules from ADMS 4 code are tested in order to assess the corresponding modification/depletion of the plume strength.

2. Theoretical basis of ADMS models

The physic-chemical, chemical, biochemical processes taking place inside the plume are hard to identify and some of them may be synergistic [6]. Important issues which arise consist of quantitative knowledge of these processes, determination of pollutant concentration at the ground surface level depending on effluent and dispersion medium characteristics: concentration of pollutants at the source, gas exit velocity, stack diameter and height, wind speed, temperature and density difference between air pollutants and atmosphere, boundary layer thermal gradient and other factors (see Fig. 1).

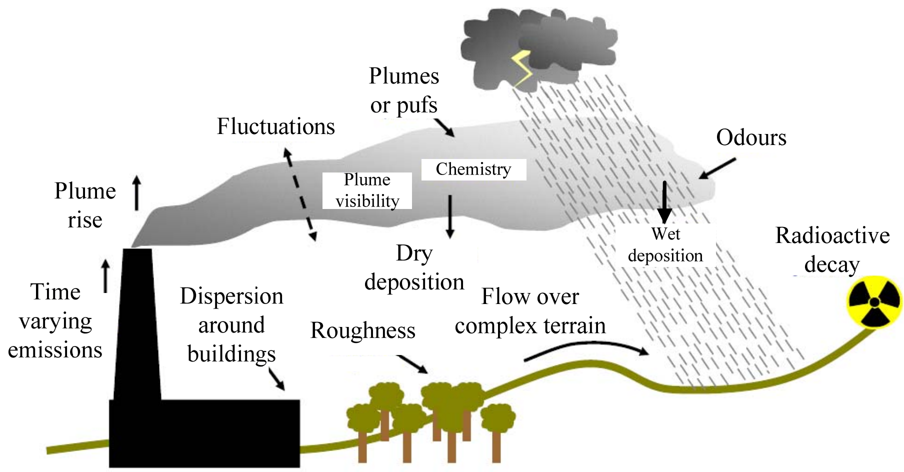

Fig. 1. The most important processes affecting the transport of radionuclides

All these intercorrelated aspects of the plume dispersion are considered in the ADMS modules:

- the effect of plume rise;
- the effect of buildings and hills (complex terrain) and spatial variation in surface roughness;
- the kinetics of the uptake of gases, and the thermodynamics and chemistry of the dissolution of gases in raindrops for wet deposition;
- dry deposition considering the deposition and terminal velocities;
- short-term fluctuations in concentration due to atmospheric turbulence;
- radioactive decay and gamma dose.

2.1. Simulation of boundary layer profiles

The atmospheric boundary layer can be evaluated using its height h and the characteristic Monin-Obukhov length L_{MO}, thus eliminating the need for a Pasquill-Gifford stability category [7]. In convective conditions, the Monin-Obukhov length used to account for the buoyancy on turbulent flows is negative. As a function of H/L_{MO} (where H is the boundary layer height), the Pasquill-Gifford unstable, neutral and stable categories can be formalized as:

- Neutral for -0.6 < H/L_{MO} < 2;
- Stable for H/L_{MO} > 2.
- Unstable for H/L_{MO} < -0.6;

The Monin Obukhov length is defined as:

$$L = -\frac{\rho C_p u_*^3 \theta}{kgH} \tag{1}$$

where u_* is friction velocity at the ground surface, k (=0.4) is the von Karman constant, g is the acceleration due to gravity, H is the surface heat flux, ρ and C_p are respectively the density and specific heat capacity of air and θ is the surface temperature.

The profile for the mean wind is calculated from [7]:

$$\begin{aligned} U(z) &= \frac{u^*}{k}\left\{ ln\left(\frac{z+z_0}{z_0}\right) - \Psi\left(\frac{z+z_0}{L_{MO}}, \frac{z_0}{L_{MO}}\right)\right\} \xrightarrow{for} z \le h \\ U(z) &= \frac{u^*}{k}\left\{ ln\left(\frac{z+z_0}{z_0}\right) - \Psi\left(\frac{h+z_0}{L_{MO}}, \frac{z_0}{L_{MO}}\right)\right\} \xrightarrow{for} z > h \end{aligned} \tag{2}$$

and where in convective conditions, $h/L_{MO} < 0$ [8],

$$\begin{aligned} \Psi &= ln\left(\frac{(1+x)^2}{(1+x_0)^2}\frac{(1+x^2)}{(1+x_0^2)}\right) - 2\left(tan^{-1}(x) - tan^{-1}(x_0)\right) \\ x &= \left(1 - \frac{16(z+z_0)}{|L_{MO}|}\right)^{1/4} \\ x_0 &= \left(1 - \frac{16z_0}{|L_{MO}|}\right)^{1/4} \end{aligned} \tag{3}$$

and in stable-neutral conditions, $h/L_{MO} \ge 0$ [9],

$$\Psi = a\frac{z_0}{L_{MO}} + b\left(\frac{z_0}{L_{MO}} - \frac{c}{d}\right)e^{-dz_0/L_{MO}} - \left\{ a\frac{(z+z_0)}{L_{MO}} + b\left(\frac{(z+z_0)}{L_{MO}} - \frac{c}{d}\right)e^{-d(z+z_0)/L_{MO}}\right\} \tag{4}$$

where the constants a = 0.7, b = 0.75, c = 5.0 and d = 0.35.

2.2. Plume rise model specification

The increase of the plume centerline vertical coordinate as the plume moves downwind is considered using an integral model, depending upon the solution of conservation equations for mass, momentum and energy. This plume rise model takes into consideration three effects: the buoyancy of the releases given by a higher temperature than the ambient air, the stack exit momentum, and also the atmospheric thermal inversions.

The velocity field in the downwind region of a building can affect the plume rise of the release by decreasing the mean height of the plume. This influence occurs only for small vertical exit velocities, since all other emissions rise rapidly away from the zone of influence. In case of a small emission velocity ratio, w_S/U_H, less than 1.5, the release height is modified by Δz_s:

$$\Delta z_s = \begin{cases} 2\left(\frac{w_s}{U_H} - 1.5\right) D_s \xrightarrow{for} \frac{w_s}{U_H} < 1.5 \\ 0 \xrightarrow{for} \frac{w_s}{U_H} > 1.5 \end{cases} \tag{5}$$

where D_s represents the release stack diameter, U_H is the air velocity at the height of the stack, w_s is the gas exit velocity trough the stack, and Δz_s represents the height correction of the source.

2.3. Plume depletion methods

The ADMS code can include three depletion phenomena: dry deposition by gravitational and diffusive terms, wet deposition through washout in clouds or by rain drops and radioactive decay. All these depletion aspects are responsible for concentration variation with downwind distance of the plume strength P:

$$P(x) = \int_{-\infty}^{\infty} dy \int_{0}^{\infty} C(x, y, z) U dz \tag{6}$$

The dry deposition rate is considered to be proportional to the ground-level concentration:

$$F_{dry} = v_d C(x, y, 0) \tag{7}$$

where F_{dry} represents the deposition rate per unit area and unit time, $C(x, y, 0)$ is the radionuclide concentration near the Earth's surface and v_d represents the deposition velocity. This velocity contains a diffusive part commonly referred to as the deposition velocity itself, and an element due to the gravitational settling, namely the terminal velocity of a particle.

The uptake of gases in clouds and rain, and their subsequent deposition at the ground in solution, is a complex kinetic process that must be simplified for application in practical models of wet deposition. Using a washout coefficient to model wet deposition is a significant simplification of the processes involved, but the predicted values are relatively accurate when the uptake of pollutants is irreversible. However, when a pollutant is subject to significant 'out-gassing' (i.e. where the pollutant passes back from the droplet to the atmosphere due to relatively low air concentrations of the pollutant in the local vicinity), wet deposition predicted by the washout coefficient methodology may be significantly over-estimated. In such cases, where possible, the user can use the ‘falling drop’ method.

The radioactive decay module solves the coupled ordinary differential equations governing the transformation of radioactive isotopes:

$$\frac{dN_i}{dt} = -\lambda_i N_i + \sum_{j \neq i} f_{ij} \lambda_j N_j \qquad (8)$$

3. Stack dispersion

3.1. Model input parameters and stack discharge conditions

A number of input variables related to meteorological data and discharge conditions are required by the ADMS preprocessing unit, in order to further perform the calculations. The air properties and discharge gas characteristics are presented in Table 1. The air molecular weight and specific heat are taken for an ambient temperature of 20 ^{o}C. Because the modeling procedure concerns the radiological emission, an additional input requirement is necessary, i.e. the tritiated water activity emission rate (presented in Table 1).

Table 1

Stack discharge conditions and model input parameters

Parameter	***Value***
Surface roughness (z_0)	0.3m
Wind direction	From West to East
Air specific Heat, Cp	1012 J/kgC
Stack height	40; 60; 80; 100m
Stack diameter	2m
Exit temperature	40 C
Exit velocity	9m/s
Wind velocity	10m/s
Boundary layer height	1000m
Tritiated water deposition velocity	0.015m/s
Tritiated water washout coefficient	1e-4
Terminal velocity	0m/s
Tritiated water source activity	0.25e+14Bq/s

3.1. Results and discussions

In general, the semi-empirical dispersion models do not take into account the source or boundary layer height characteristics. The models implemented in ADMS consider the influence of the source height on the horizontal and vertical spread parameters. Figs. 2 - 4 presents various parameters for different heights of the source.

In order to compare the plume rise modeling in ADMS, the results from Fig. 2(left) were compared with the CNCAN (National Commission for Nuclear Activities Control) procedures for evaluation of the atmospheric dispersion on nuclear sites [10]. The plume rise effect is due to two phenomena: buoyancy forces and releases momentum. For the final phase of the plume rise the buoyancy and momentum consequences are evaluated as:

$$\Delta h_b = \frac{1.6F^{1/3}(3.5x_0)^{2/3}}{\bar{u}} \tag{9}$$

$$\Delta h_m = \frac{1.5w_0 D}{\bar{u}} \tag{10}$$

where:

$$F = \frac{T_0 - T}{T_0} g w_0 \left(\frac{D}{2}\right)^2 \tag{11}$$

$$x_0 = 14F^{5/8} \tag{12}$$

and $\bar{u}$ is the wind velocity, w_0 is the exit velocity of the releases, D is the stack diameter, T_0 is the releases temperature, T represents the ambient air temperature and g is gravitational constant.

Using the formulas above (eqs. 9 -12) the late phase plume rise is almost 10.5m, which is relatively close to the 40m release height. Increasing the stack height, the CNCAN provisions over predicts the plume rise, mainly because the empirical procedure given in [10] do not consider the release height.

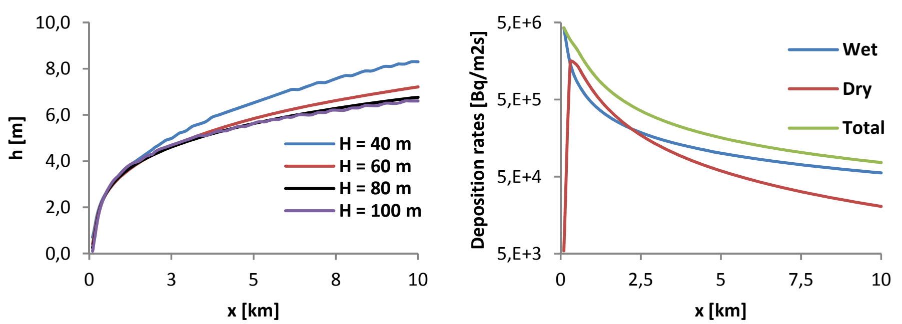

Fig. 2. The plume rise (left) and deposition rates (right) variations with downwind distance

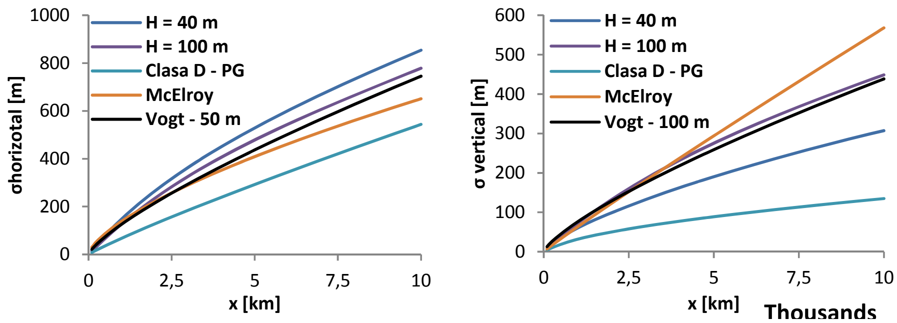

Fig. 3. The spread parameters variations with downwind distance

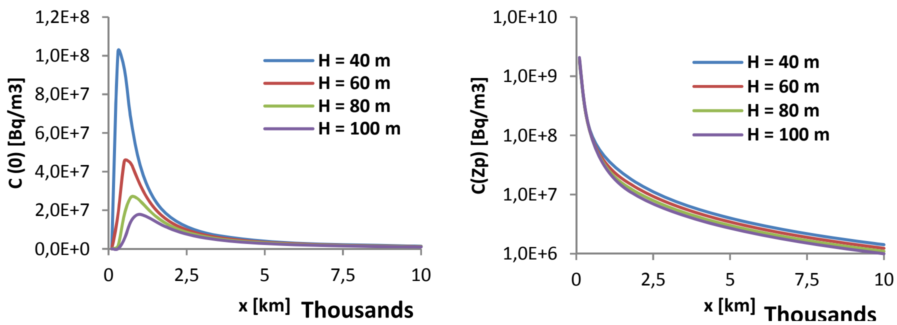

Fig. 4. The tritiated water concentration variations with downwind distance (left – ground level, right – plume centerline)

Dispersion parameters obtained from ADMS code (Fig. 3) are compared with those calculated using semi-empirical models: Pasquill - Gifford, McElroy and Vogt, all considering the atmospheric stability class D. As shown the Vogt model is the closest to the results obtained by running ADMS. Also, the spread parameters obtained with the Pasquill-Gifford model greatly underestimates the ADMS results.

4. Building effects on plume spread

In general, the plume release take place from elevated stack on buildings, the entrainment of plumes in building wakes being of major interest and represents a major factor in obtaining acceptable derived release limits. The most important feature of building effect upon the dispersion studies is the plume entrainment in the building wake or its rapid downwash from elevated sources, since this generates higher near-field concentrations at the ground level.

For evaluation of this behavior, we used a 40m height stack with a neutrally buoyant discharge, adjacent to buildings of 40m, 70m and 130m heights.

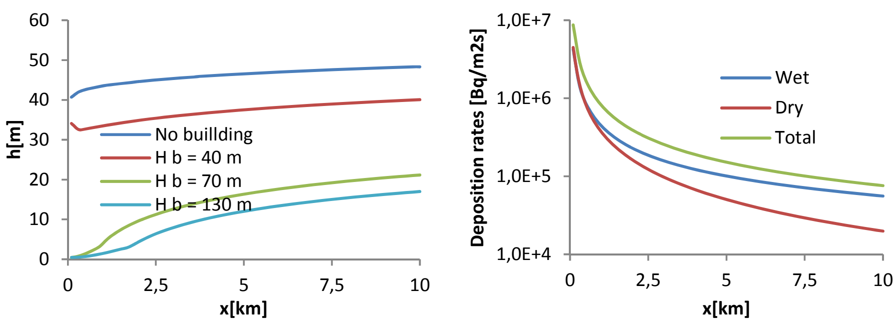

Fig. 5. The plume rise (left) and deposition rates (right – H_b =70m) variations with downwind distance

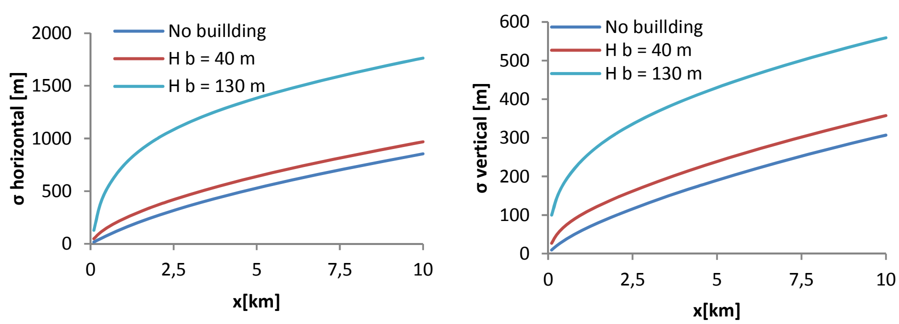

Fig. 6. The spread parameters variations with downwind distance for various building heights

As one can observe from Fig. 5(left) the plume rise effect is strongly dependent on the building height. For H_b greater than 70m the induced downwash takes place, so a recirculation area is created downwind the building. The deposition rates have similar profiles along the wind direction (Figs. 2 and 5 – right), but for the building test cases the rates are higher mainly because of the increased concentration at the ground level. Also, the spread parameters (Fig. 6) are strongly decreased relatively to the no building cases.

5. Conclusions

In this paper a numerical methodology using the ADMS4 code for evaluation of atmospheric dispersion and for calculation of radionuclides concentrations released from a specific nuclear power plant site was proposed. Compared to other existing codes and to CNCAN procedures it was made clear that the ADMS code is superior, allowing the evaluation of wet and dry deposition rates, the disintegration of radioactive products and the building effects near the source.

The results of this paper will be further used for:

1. Evaluation of Derived Release Limits (DRL) for the detritiation facility (Cernavoda Tritium Removal Facility - CTRF) including the continuous release from the Cernavoda units 1&2. The atmospheric conditions from the Cernavoda site obtained from the meteorological stations will be used for calculation of maximum and mean concentration at the ground level at the critical group location.

2. Using the Gaussian puff model implemented in ADMS, an atmospheric dispersion transient for an accidental release on Cernavoda site will be studied.

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R E F E R E N C E S

[1] *** Site Evaluation for Nuclear Installations – IAEA Safety Standards Series, No. NS-R-3, November 2003

[2] *** Dispersion of radioactive material in air and water and consideration of population distribution in site evaluation for Nuclear Power Plants – IAEA Safety Standards Series, No. NS-G-3.2, March 2002

[3] *** Generic assessment procedures for determining protective actions during a reactor accident – IAEA-TECDOC-955, ISSN 1011-4289, August 1997

[4] *H.R. Olesen,* Ten years of harmonisation activities: Past, present, and future. In: Proceedings of the Seventh International Conference on Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes, 2001

[5] *W. Scheuermann, A. Piater, A. Lurk, T. Ionescu, C. Krass, T. Wilbois,* Modelling and simulation of the radioactive release during the Fukushima Accident, 14th International Conference on Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes, Kos, Greece, October 2011

[6] *D.B.Turner*, Workbook of Atmospheric Dispersion Estimates. PHS Publication No. 999 - AP-26. U.S. Department of Health, Education and Welfare, Bureau of Disease Prevention and Environmental Control for Air Pollution Control Administration, Cincinnati, Ohio, 1967

[7] ***CERC, ADMS 4 Technical Specification, 2010

[8] *H.A. Panofsky, J.A. Dutton*, Atmospheric Turbulence, New York: Johm Wiley, 1984

[9] *A.P. van Ulden, A.A. Holtslag*, Estimation of atmospheric layer parameters for diffusion applications, Journal of Climate and Applied Meteorology, 1985

[10]***Normele privind calculul dispersiei efluentilor radioactivi evacuati in mediu de instalatiile nucleare (NSR-23), aprobate prin Ordinul Presedintelui CNCAN nr. 360 din 20.10.2004 si publicate in Monitorul Oficial al Romaniei, Partea I nr. 1.159 bis / 08.12.2004