MATHEMATICAL SIMULATION OF "SHELTER" OBJECT RELEASES IMPACTS

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Methods of mathematical modeling of radiological human impacts are described. Calculation of admissible releases at different exploitation stages of New Safe Confinement at the existing ChNPP "Shelter" object are given.

PACS: 28.41Te

1. INTRODUCTION

During practical activities aimed at operation of New Safe Confinement (NSC) of ChNPP "Shelter" object, diverse works are planned to carry out (dismantle of unstable structures, subsequent retrieval of fuel-containing materials, et al.), which can be resulted in radiation impacts to public and environment. In force of the fact that the NSC will contain a huge amount of nuclear and radioactive materials, it can be referred to radiation hazardous facilities.

In conformity with NRBU-97, limitation of public exposure is implemented by way of regulating and monitoring of aerosol releases and water discharges in the course of operating radiation and nuclear facilities.

To reduce the releases, admissible release (AR) of radioactive substances into environment must be established, which refers to radiation and hygienic regulations of first group.

To solve that task, NSC release modeling must be conducted and impact of these releases to the public should be estimated. Besides, one should identify the critical group of public (i.e. groups, impact on which will be maximal), as well as impact ways that are most intensive in influencing a critical group.

AR was evaluated from the condition of non-exceeding relevant release quotes due to all the ways of dose formation (40 μSv/year) at 10 km distance from NSC.

2. PROCEDURE FOR RELEASE IMPACT ESTIMATE

To identify release impacts to public, one should estimate effective dose of human exposure with considering all dose formation ways.

There are the following main release impacts to a man:

- internal exposure conditioned by radioactive substance intake to human organism with food;
- internal exposure due to radioactive substance inhalation;
- external exposure from radionuclides precipitated on the earth;
- external exposure conditioned by staying in radioactive cloud.

The following foodstuff makes the basis for man's food allowance: potable water; bread; potato; cabbage; fruits and berries; leaf vegetables; meat and its processing produce; milk; fish.

3. RADIOACTIVE SUBSTANCE CONCENTRATIONS IN THE AIR AND SOIL. CONTINUOUS RELEASES

As release cloud moves, radioactive aerosol precipitate on earth surface. Surface source of external exposure is formed. Radionuclide precipitation density on the soil after release Q (Bq/s) is defined from the formula [1]:

$$\dot{A}_s = Q(v_g G + \Lambda G^Z), \tag{1}$$

where Q – release intensity, Bq/s; v_g – dry precipitation velocity, m/s; G – meteorological dilution factor, s/m^3, under which is implied the ratio of volumetric activity of radionuclide in atmosphere to a release per time unit; Λ – wash-out constant, s^{-1}, depending on precipitation type, raindrop spectrum, precipitation intensity; G^z – integral of dilution factor G along vertical coordinate z, s/m^3,

$$\Lambda = k_r k_0 I, \tag{2}$$

where I – precipitation intensity, mm/hour; $k_r = 10^{-5}$ hour/(mm · s) – standard value of absolute rain washing-out ability (for all nuclides beside inert gases), specific for rain intensity I = 1 mm/hour; k_0 – relative washing-out ability for diverse precipitation types (see Table 1).

$$G^z(x,y) = \int_0^{H_z} G(x,y,z)\,dz, \tag{3}$$

where H_z – height of cloud lower boundary – precipitation source (m).

Table 1. *Relative washing-out ability for diverse precipitation types [1]*

Precipitation type	k_0
Rain	1,0
Rain with thunderstorm	1,1
Snow with thunderstorm	2,4
Rainfall	2,8
Snow	3,0
Drizzle	4,5
Mist	5,0

PROBLEMS OF ATOMIC SCIENCE AND TECHNOLOGY. 2004, № 5.
Series: Nuclear Physics Investigations (44), p. 96-100.

Rough estimate of meteorological dilution factor in vicinity and at up to 10-km distance behind the zone of near-surface concentration maximum can be made using the procedure of envelope:

$$G = \frac{2}{(2\pi)^{3/2}} \cdot \frac{\eta F(x)}{\sqrt{e} h \bar{u} x}, \tag{4}$$

where η – wind rose oblongness in specified direction; $F(x)$ – cloud exhaustion function; h – release source height, m; $\bar{u}$ – wind average velocity, m/s; x – distance from a man to release source.

This formula gives maximum (conservative) estimates in the sense, that under any law of vertical dispersion factor change and any reiteration of weather conditions, no high concentration values can be obtained.

Wind rose oblongness in specified direction is defined by the following formula:

$$\eta = n / n_0, \tag{5}$$

where n and n_0 – wind direction reiteration in a given azimuth sector under real wind rose and under round wind rose, accordingly.

Function of radioactive cloud exhaustion as result of dry precipitation is defined by the following formula:

$$F(x) = \exp\left[-A \cdot \int_0^x \left(\frac{1}{\sigma_z}\right) \cdot \exp\left(-\frac{h^2}{2\sigma_z^2}\right) dx\right], \tag{6}$$

where $A = \sqrt{(2/\pi)} \cdot (v_g / u(h))$; $u(h)$ – horizontal constituent of wind velocity in dependence of effective release height, m/s; σ_z – mean-square deflection of admixture distribution in release cloud due to turbulent diffusion in vertical direction, m;

$$u(h) = u(2) \cdot (h/2)^p, \tag{7}$$

where $u(2)$ – wind velocity at 2 m height, m/s; p – factor from Table 2.

Table 2. *Exponential factor values p for wind velocity estimate*

	Air stability category using Pasquill					
	A	B	C	D	E	F
Standard conditions	0,07	0,07	0,10	0,15	0,35	0,55
Urban conditions	0,15	0,15	0,20	0,25	0,40	0,60

Dispersion factors σ_z are defined in dependence of weather conditions using Smith-Hosker formula:

$$\sigma_z(x) = \begin{cases} f(z_0,x)g(x), & f(z_0,x)g(x) \le \sigma_z^{max}; \\ \sigma_z^{max}, & f(z_0,x)g(x) > \sigma_z^{max}, \end{cases} \tag{8}$$

where $\sigma_z^{\max}$ – limiting value σ_z for given category of atmospheric stability; z_0 – height of underlying surface roughness, cm; x – distance from release source, m.

Functions $g(x)$ and $f(z_0, x)$ are estimated depending of atmosphere stability category due to the following formulae:

$$g(x) = a_1 x^{b_1} / (1 + a_2 x^{b_2}), \tag{9}$$

$$f(z_0, x) = \begin{cases} ln\left[c_1 x^{d_1}(1 + c_2 x^{d_2})\right], z_0 > 10 \text{ cm}; \\ ln\left[c_1 x^{d_1} / (1 + c_2 x^{d_2})\right], z_0 \le 10 \text{ cm}. \end{cases} \tag{10}$$

The main factors needed for estimates are shown in Tables 3-5.

Table 3. *Factors applicable for estimates of jet lateral dispersion σ_y and function $g(x)$*

Atmosphere stability category by Pasquill	$\sigma_z^{\max}$, m	a_1	b_1	a_2	b_2
A	1600	0,112	1,06	$5{,}38 \cdot 10^{-4}$	0,815
B	920	0,130	0,950	$6{,}52 \cdot 10^{-4}$	0,750
C	640	0,112	0,920	$9{,}05 \cdot 10^{-4}$	0,718
D	400	0,098	0,889	$1{,}35 \cdot 10^{-3}$	0,688
E	220	0,0609	0,895	$1{,}96 \cdot 10^{-3}$	0,684
F	100	0,0638	0,783	$1{,}36 \cdot 10^{-3}$	0,672

Table 4. *Factors of function $f(z_0, x)$ modifying σ_z for diverse roughness height z_0*

Roughness height z_0, cm	c_1	d_1	c_2	d_2
1	1,56	0,0480	$6{,}25 \cdot 10^{-4}$	0,45
4	2,02	0,0269	$7{,}76 \cdot 10^{-4}$	0,37
10	2,73	0	0	0
40	5,16	-0,098	$5{,}38 \cdot 10^{-2}$	0,225
100	7,37	-0,00957	$2{,}33 \cdot 10^{-4}$	0,6
400	11,7	-0,128	$2{,}18 \cdot 10^{-5}$	0,78

Table 5. *Roughness height z_0 for diverse types of surface microrelief*

Microrelief	z_0, cm
Snow, 1 cm high lawn	0,1
Mown and low grass to 15 cm	0,6…2
High grass to 6 cm	4…9
Heterogenous surface with alternate grass areas, shrubs etc.	10…20
Park, forest to 10 m height	20…100

4. RELEASES OF RADIOACTIVE AEROSOL ADMIXTURES INTO ATMOSPHERE

According to [1], individual average annual dose rate is conditioned by intake of radioactive substances in human organism with foodstuff, is defined as follows:

$$\dot{H} = \dot{A}_s \cdot K_{FD}, \tag{11}$$

where – individual average annual dose rate, Sv/s; $\dot{A}_s$ – contamination intensity, Bq/(m^2·c).

$$K_{FD} = K_{FI} \cdot B_{ig}, \tag{12}$$

where K_{FI} – factor linking contamination level with radionuclide intake into organism, m^2; B_{ig} – factor linking activity coming with foodstuff with effective dose (depends on age) [3], Sv/Bq.

Effective dose rate of external exposure $\dot{H}_v$ (Sv/s) due to each nuclide for a man staying on earth surface conditioned by a radioactive aerosol cloud, which was produced as result of release, is defined from the formula:

$$\dot{H}_v = A_V \cdot \widetilde{B}_{ay} , \tag{13}$$

where A_V – radionuclide volumetric activity, Bq/m^3; $\widetilde{B}_{a\gamma}$ – transient dosimetric multiplier (depending on age) characterizing effective dose rate created by a radioactive aerosol cloud of single concentration at open earth surface [3], Sv m^3/(s·Bq).

Effective dose H_{int} (Sv) conditioned by inhalation intake of radioactive aerosol, is estimated by the formula:

$$H_{int} = V_{age} T e_{\tau age} A_V , \tag{14}$$

where V_{age} – breathing rate (depends on age) [4], m^3/hour; T – stay time in aerosol cloud, hour; $e_{\tau age}$ – dose per unit of activity intake by inhalation way (depends on age) [3], Sv/Bq.

Effective dose H_{int_r} (Sv) conditioned by inhalation intake of resuspended dust is estimated by the formula:

$$H_{int\_r} = V T e_{\tau age} A_V^* , \tag{15}$$

where A_V^* – volumetric activity due to resuspended dust, Bq/m^3.

Ratio of volumetric activity produced due to resuspended dust and nuclide volumetric activity under absence of wind rise, is defined as follows:

$$\frac{A_V^*}{A_V} = \left(v_g + \frac{\Lambda}{H_Z^{\max}}\right)\left[\frac{K_{\alpha 1}}{\lambda_1 + \lambda_2} + \frac{K_{\alpha 2}}{\lambda_2}\right], \tag{16}$$

where $K_{\alpha 1} = 10^{-5}\ \text{m}^{-1}$; $K_{\alpha 2} = 10^{-9}\ \text{m}^{-1}$; λ_1 – constant of deflation factor reduction for rapid phase, $\lambda_1 = 1{,}46 \cdot 10^{-7}\ \text{c}^{-1}$; λ_2 – constant of its more prolonged reduction, $\lambda_2 = 2{,}2 \cdot 10^{-10}\ \text{s}^{-1}$; $H_Z^{\max}$ – mixing layer height, m, which is defined by formula:

$$H_Z^{\max} = \sqrt{(\pi / 2)} \cdot \sigma_z^{\max} . \tag{17}$$

Dose conditioned by radiation of soil contaminated surface, is defined from the formula:

$$\dot{H}_{surf} = \dot{A}_s B_{S\gamma} \tau_{eff} , \tag{18}$$

where $\dot{H}_{surf}$ – expectable dose, Sv/s; $B_{S\gamma}\tau_{eff}$ – expectable dose per contamination unit (depends on age), Sv m^2/Bq.

Considering the fact that main contribution into external exposure from soil contaminated surface induces ^{137}Cs, $B_{S\gamma}\tau_{eff} = 1{,}01 \cdot 10^{-7}$ Sv m^2/Bq [1].

5. PROCEDURE FOR ADMISSIBLE RELEASE ESTIMATE

To estimate admissible release, PRC-1 program was created, which allows estimating AR with considering all described ways of dose formation from NSC releases. The program features permit working with all initial data, changing them with the help of MS Excel, as well as displaying any needed information in graphic, or table form.

For more pictorial view and facilitation of work with the software, it was compiled as follows. First, single release impact to public is estimated, thereafter by way of iterations with indicated accuracy the set of releases is made to achieve required dose quote.

In estimating AR, radionuclide content of NSC release is considered. Based on the fact that projected NSC existing time – 100 years, radionuclide content of releases through each 10 years of NSC operation was estimated as an assumption that radionuclide content correspond to SO fuel content [2] in the same year.

6. ADMISSIBLE RELEASE VALUES

Based on above procedure, estimate of admissible release for total NSC operational life time for critical group of public was made. Besides, an estimate of admissible release for β- and α-emitting nuclides and dust fuel release from the NSC was made. Estimate results are shown in Table 6. Estimates were made for five reference ages of man (new-born, 1 year, 5 years, 10 years, 15 years, adult), and for the two sexes.

Reduction with time of summary AR and β-emitting radionuclide AR is conditioned by influence of different chains of radioactive decay. Simultaneously, the main β-emitting radionuclides decay with half-life being 30 years and less. At the same time, total alpha-activity even increases due to ^{241}Am accumulation resulted by ^{241}Pu β-decay (maximum value will be reached approximately to the year of 2050). Because of it, contribution to dose from α-emitting radionuclides will increase, and their AR will grow. Naturally, total amount of dust fuel will also increase, whose release will lead to dose for public of 40 μSv/year at 10 km zone border.

Contributions to quote due to diverse dose formation ways in the beginning (for 2010 year) and in the end of NSC operation (2110 year) are submitted in Tables 7 and 8.

In the beginning of NSC operation (Table 7), dose will be, mainly, defined by internal exposure (around 34 μSv/year), in addition due to radionuclide intake through food chains (around 28 μSv/year).

Under external exposure, dose due to immersion in cloud is negligible one and relatively low dose (1,1 μ Sv/year) is mainly defined by ^{137}Cs radiation from contaminated ground surface.

In estimating doses under inhalation intake of radionuclides, two mechanisms were considered too – direct exposure in radioactive cloud due to exposure release occurred and from resuspension of dust precipitated on surface. Beginning from, approximately, the third year of operation, relative contribution to inhalation intake dose directly from a cloud remains, practically, constant one, and makes around 2/3 of all inhalation doses.

Ingest dose is, mainly, defined by dose conditioned by aerial way of contamination of agricultural produce (around 24 μSv/year). There are less, at a significant rate, of doses (2,2 μSv/year) due to contamination of water medium resulted by releases. Around 5,4 μ Sv/year – dose due to root way of contamination.

To NSC operation end, the situation can somehow change (Table 8). Determining contribution to dose will induce ingestion intake of alpha-emitting nuclides. Dose due to that mechanism may total around 28 μSv/year, some 6 μSv/year will be defined by intake through food chains, mainly, due to alpha-emitting nuclides.

One should consider that the releases from NSC operation will not be uniform in the course of a year, and will depend on type and intensity of works being implemented. In case of conduct of dust-producing works in pre-harvest period, which will be accompanied by intensive release during a short time period, annual dose can essentially increase. That fact should be considered when planning the works in NSC.

The main conclusions of carried out modeling are:

- before 2080, critical group is 15 year teenagers of male sex, after 2080 – adults of male sex;
- during all NSC operation period is expected that most ingestion dose will be from bread consumption;
- in NSC operation start, ingestion dose is mainly defined by dose conditioned by aerial way of contamination of agricultural produce;
- in NSC operation end, determining contribution to dose will be induced by inhalation intake of alpha-emitting nuclides.

***Table 6**. Main results of admissible release estimate*

Year	Radionuclide mix AR, Ci	Radionuclide mix AR, Bq	Beta-emitting radionuclide AR, Ci	Beta-emitting radionuclide AR, Bq	Alpha-emitting radionuclide AR, Ci	Alpha-emitting radionuclide AR, Ci	Fuel dust AR, g
2010	8,3	3,07E+11	8,1101	3,00E+11	0,1899	7,03E+09	167,71
2020	7,6	2,81E+11	7,3581	2,72E+11	0,2419	8,95E+09	200,52
2030	7	2,59E+11	6,7033	2,48E+11	0,2967	1,10E+10	238,77
2040	6,4	2,37E+11	6,0485	2,24E+11	0,3515	1,30E+10	279,75
2050	5,85	2,16E+11	5,4415	2,01E+11	0,4085	1,51E+10	325,06
2060	5,3	1,96E+11	4,8359	1,79E+11	0,4641	1,72E+10	371,54
2070	4,8	1,78E+11	4,2789	1,58E+11	0,5211	1,93E+10	421,36
2080	4,35	1,61E+11	3,7702	1,39E+11	0,5798	2,15E+10	474,57
2090	3,9	1,44E+11	3,2676	1,21E+11	0,6324	2,34E+10	524,61
2100	3,4	1,26E+11	2,7354	1,01E+11	0,6646	2,46E+10	559,17
2110	2,95	1,09E+11	2,2613	8,37E+10	0,6887	2,55E+10	587,79

***Table 7.** Contribution into effective dose from admissible release of diverse nuclides and diverse ways of impact at NSC operation start*

<table>
<tr><th rowspan="3"></th><th rowspan="3">Dose due to intake through vegetative and meat chains for individual radionuclides, μSv</th><th colspan="4">Internal exposure</th><th colspan="2">External exposure</th></tr>
<tr><th colspan="3">Dose due to intake through alimentary chains, μSv</th><th rowspan="2">Dose due to RS inhalation, μ Sv</th><th rowspan="2">Dose due to immersion in cloud, μSv</th><th rowspan="2">External dose from surface contamination ^{137}Cs, μSv</th></tr>
<tr><th>Contamination aerial way</th><th>Contamination root way</th><th>Dose due to consumption of fish and water, μ Sv</th></tr>
<tr><td>^{137}Cs</td><td>9,26</td><td rowspan="4">24,34</td><td rowspan="4">3,65</td><td rowspan="4">5,4</td><td>0,08</td><td>2,05E-07</td><td rowspan="2">1.1</td></tr>
<tr><td>^{90}Sr</td><td>16,14</td><td>0,13</td><td>1,81E-07</td></tr>
<tr><td>Alpha-emitting nuclides</td><td>2,28</td><td>5,3</td><td>4,13E-08</td><td></td></tr>
<tr><td>^{241}Pu</td><td>0,36</td><td>1,85E-03</td><td>2,25E-11</td><td></td></tr>
<tr><td>Sum</td><td>28,04</td><td colspan="3">33,39</td><td>5,51</td><td></td><td></td></tr>
<tr><td></td><td></td><td colspan="3">Dose sum of internal exposure</td><td>38,9</td><td>Dose sum of external exposure</td><td>1,1</td></tr>
</table>

***Table 8**. Contribution into effective dose from admissible release of diverse nuclides and different impact ways at NSC operation end*

<table>
<tr><td rowspan="3"></td><td rowspan="3">Dose due to intake through vegetative and meat chains for individual radionuclides, μSv</td><td colspan="4">Internal exposure</td><td colspan="2">External exposure</td></tr>
<tr><td colspan="3">Dose due to intake through alimentary chains, μSv</td><td rowspan="2">Dose due to RS inhalation, μSv</td><td rowspan="2">Dose due to immersion in cloud, μSv</td><td rowspan="2">External dose from surface contamination ^{137}Cs, μSv</td></tr>
<tr><td>Contamination aerial way</td><td>Contamination root way</td><td>Dose due to consumption of fish and water, μ Sv</td></tr>
<tr><td>^{137}Cs</td><td>1,19</td><td rowspan="5">31,03</td><td rowspan="5">1,10</td><td rowspan="5">2,21</td><td>6,79E-03</td><td>8,66E-08</td><td rowspan="2">0,5</td></tr>
<tr><td>^{90}Sr</td><td>3,35</td><td>2,00E-02</td><td>6,74E-08</td></tr>
<tr><td rowspan="2">Alpha-emitting nuclides</td><td rowspan="2">27,56</td><td>5,14E+00</td><td>1,74E-07</td><td></td></tr>
<tr><td rowspan="2">1,35E-04</td><td rowspan="2">2,30E-12</td><td rowspan="2"></td></tr>
<tr><td>^{241}Pu</td><td>0,04</td></tr>
<tr><td>Sum</td><td>32,13</td><td colspan="3">34,34</td><td>5,17E+00</td><td></td><td></td></tr>
<tr><td></td><td></td><td colspan="3">Dose sum of internal exposure</td><td>39,5</td><td>Dose sum of external exposure</td><td>0,5</td></tr>
</table>

Thus, when planning activities for protection of public and environment during NSC operation, radiation monitoring must be provided of NSC releases, of radionuclide concentrations in air (in first turn of ^{90}Sr, ^{137}Cs and ^{241}Am), of surface contamination levels, of radionuclide content in foodstuff.

It seems as inexpedient to grow cereals (except feed-preparing works), near exclusion zone borders, especially in case of reduction of its dimensions. Besides, one should consider the fact that in case of reduction of borders of 30 km exclusion zone to 10 km, practical implementation of all agricultural works must be provided on the basis of recommendations for agricultural activities on the territories that are contaminated with radionuclides. It implies that a complex of measures (counter-measures) should be implemented to minimize radionuclide intake into the products of agricultural industry and conduct of continuous radioecological monitoring.

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МАТЕМАТИЧЕСКОЕ МОДЕЛИРОВАНИЕ ВОЗДЕЙСТВИЙ ПРИ ВЫБРОСАХ ИЗ ОБЪЕКТА “УКРЫТИЕ”

В.Г. Батий, С.А. Паскевич, В.М. Рудько, А.А. Сизов, В.Н. Щербин

Описана методика математического моделирования воздействий на население по всем возможным путям в результате возможного выброса радиоактивных веществ. Приведены результаты расчета допустимых выбросов на различных этапах эксплуатации нового безопасного конфайнмента над существующим объектом “Укрытие” Чернобыльской АЭС.

МАТЕМАТИЧНЕ МОДЕЛЮВАННЯ ВПЛИВІВ ПРИ ВИКИДАХ З ОБ’ЄКТУ “УКРИТТЯ”

В.Г. Батій, С.А. Паскевич, В.М. Рудько, А.О. Сізов, В.М. Щєрбін

Описано методику математичного моделювання впливів на населення за всіма можливими шляхами у результаті можливого викиду радіоактивних речовин. Надано результати розрахунку допустимих викидів на різних етапах експлуатації нового безпечного конфайнменту над існуючим об’єктом “Укриття” Чорнобильської АЕС.