ESTIMATION OF RADIOLOGICAL CONSEQUENCES FROM ACCIDENTAL IODINE RELEASES AT NUCLEAR POWER PLANTS

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ABSTRACT

The radiological consequences of a beyond design-basis accident at an NPP for a VVER-1000 reactor are evaluated. Using the software code COSYMA and accounting for radioiodine activity release to the atmosphere at the early stage of the accident, the radionuclide concentration in air and ground deposition densities were estimated. Inhalation and ingestion thyroid doses to different population sub-groups have been calculated. Using modern knowledge about the risk of radiation-induced cancer, the radiological danger of radionuclides released is evaluated for different exposure pathways. Thyroid doses and risk was estimated for populations living at different distances from the NPP. The comparative analysis of exposure pathways and radiological danger of the radionuclides in release during early and intermediate stage of accident has conducted.

INTRODUCTION

Radiation protection of the population is one of the key problems in nuclear power engineering. The Republic of Belarus has no nuclear power engineering, however NPPs are located in close vicinity to the Republic's borders in Lithuania, the Russian Federation and the Ukraine. The territory of Belarus enters a 30-km or 100-km zone of the Ignalinskaya, Rovenskaya, Smolenskaya and Chernobylskaya NPPs. Accidents at one of these NPPs can lead to wide-scale radioactive contamination of the territory and potential exposure of the population of Belarus living tens to hundreds of kilometers from the site.

Thyroid exposure from accidental iodine releases from an NPP is one of the main concerns of radiation danger for the population. The Chernobyl accident has demonstrated how harmful is a "beyond design-basis" accident when all protective barriers against radioactive releases are destroyed. The early stage of the accident is the most dangerous. It is characterized by the incidence, absence of complete information on the accident type, characteristics of the radioactive release, and time deficit for decision-making.

For preliminary development of the radiation protection plans for a population and of the decision-making required in case of an accident at an NPP, it is necessary to simulate the different accidental scenarios and to obtain information about radionuclide releases, contamination of territories, population exposures, and radiation risks. The given problem has a large scientific and practical significance, as the simulation of the different accidental scenarios allows the prediction of radiological consequences of the accidental release of radionuclides, the evaluation of radiation danger from the accident, and the justification of necessary countermeasures. Such a simulation also allows the prognosis of population exposure and risk of exposure with consideration of countermeasures.

METHODS

Environmental contamination

To evaluate the radiological consequences of a beyond design-basis accident at an NPP for a VVER-1000 reactor, an investigation was conducted. The scenario of the hypothetical accident was a fast loss of coolant as a result of a rupture in the primary circuit pipeline with diameter of 850mm and minimum radiation consequences when containment integrity is preserved. The radioiodine content in cores and accidental release to atmosphere according to the (Grishmanovsky et al., 1989; Savushkin et al., 1999) is given in Table 1. As can be seen from Table 1 the activity of radioiodine in release within considered scenario is less than 0,1 per cent of build up activity in cores.

TABLE 1. Accidental iodine release to atmosphere from VVER-1000 reactor (Grishmanovsky et al., 1989; Savushkin et al., 1999)

Radio-nuclide	Half-time	Radionuclides content, Bq	
		in cores	in release
^{131}I	8,04 d	$3,15 \cdot 10^{18}$	$1,44 \cdot 10^{15}$
^{132}I	2,30 h	$4,45 \cdot 10^{18}$	$1,26 \cdot 10^{15}$
^{133}I	20,8 h	$6,30 \cdot 10^{18}$	$2,33 \cdot 10^{15}$
^{134}I	52,6 m	$6,67 \cdot 10^{18}$	$1,37 \cdot 10^{15}$
^{135}I	6,61 h	$5,93 \cdot 10^{18}$	$2,18 \cdot 10^{15}$

To estimate atmospheric transport and deposition on the ground surface the following initial conditions have been defined:

- Accident occurs in summer;
- Pasquill stability category is F, and wind speed is 2 $m \cdot s^{-1}$;
- Surface roughness parameter is $0,1<z<1,0$ m that corresponds to sites in rural areas;
- Effective release height is 100 m;
- Released radionuclides are in aerosol form;
- Three scenarios: dry deposition and wet deposition with rainfall amount of R=1 and R=3mm·h^{-1} are considered;
- Dry deposition velocity of aerosols $v_g=8\cdot10^{-3}$ $m\cdot s^{-1}$ (Gusev et al., 1993);
- Washout of radionuclides from cloud by rainfall is estimated as:

$$f_w = \exp\left(-\Lambda \cdot x/u\right), \qquad (1)$$

where

$\Lambda = \alpha \cdot R$ – washout coefficient, s^{-1}; $\alpha = 8\cdot10^{-5}$ $h\cdot mm^{-1}\cdot s^{-1}$ (Romanov, 1990);

x – distance from the source, m;

u – wind speed, $m\cdot s^{-1}$.

Thyroid exposure

Thyroid exposure has been estimated for the two pathways: inhalation of radionuclides during passage of the cloud, and ingestion of contaminated foodstuffs.

Thyroid dose due to inhalation for different distance from source x (m) is calculated as:

$$D_{i,k}^{inh}(x) = A_{v,k}(x) \cdot V_i \cdot DF_{i,k}^{inh}, \qquad (2)$$

where

$D_{i,k}^{inh}(x)$ – thyroid dose from inhalation of k-th radionuclide to i-th age group of population, Gy;

$A_{v,k}(x)$ – time integrated activity concentration of k-th radionuclide in air, $Bq\cdot m^{-3}\cdot s$;

V_i – inhalation rate for i-th age group of population, $m^3\cdot s$;

$DF_{i,k}^{inh}$ – thyroid dose from inhalation of unit k-th radionuclide to i-th age group of population, $Gy\cdot Bq^{-1}$.

Thyroid dose due to ingestion of contaminated food within time T after deposition to population living on the different distance from source x (m) is calculated as:

$$D_{i,k}^{ing}(x) = DF_{i,k}^{ing} \cdot \int_0^T I_{i,k}(x,t)\,dt, \qquad (3)$$

where

$D_{i,k}^{ing}(x)$ – thyroid dose from ingestion of k-th radionuclide to i-th age group of population, Gy;

$DF_{i,k}^{ing}$ – thyroid dose from ingestion of unit k-th radionuclide to i-th age group of population, $Gy\cdot Bq^{-1}$;

$I_{i,k}(x,t)$ – intake function of k-th radionuclide to i-th age group of population, $Bq\cdot d^{-1}$.

Intake function has been estimated using radioecological model adapted to the local Belarusian condition. Take into account post Chernobyl experience two pathways were considered: intake of radionuclides with milk and leafy vegetable. Detail description of model could be found elsewhere (Drozdovitch et al., 1997; Drozdovitch, 1999). The following values of main parameters have been used in calculations:

- Vegetation yield 1,5 $kg\cdot m^{-2}$ (fresh weight);
- Dry deposition velocity of aerosols to vegetation $1,2\cdot10^{-2}$ $m\cdot s^{-1}$;
- Initial interception factor of iodine by vegetation for wet deposition f=0,18 for wet deposition with rainfall R=3 mm·h^{-1};
- Feed-to-milk transfer factor $2,3\cdot10^{-3}$ $d\cdot L^{-1}$.

Thyroid doses have been calculated for five age groups of population: 1, 5, 10, 15 year and adults. Inhalation dose estimates are based on an activity median aerodynamic diameter (AMAD) of 1 µm. This particle size is recommended by the ICRP for consideration of environmental exposures in the absence of specific information about the physical characteristics of the aerosols (ICRP, 1994). Dose coefficients per unit inhaled or ingested intakes from ICRP Publication 56, 66, 71 (ICRP 1989, 1994, 1995) have been used in calculations.

Health risk

To estimate radiological consequences from accidental iodine releases the following exposure pathways that might be important during early and intermediate stage of accident have been considered:

1) External exposure from radionuclides in air;
2) External exposure from radionuclides deposited on the ground surface;
3) Internal exposure due to inhalation of radionuclides during passage of the cloud;
4) Internal exposure due to ingestion of iodine in food.

For a given radionuclide and exposure mode the risk of death from cancer as a result of intake of the radionuclide or external exposure (mortality risk), and risk of experiencing a radiogenic cancer (morbidity risk) has been estimated. Values of mortality (morbidity) risk coefficients for different exposure pathways from (Eckerman et al., 1998) have been used in calculation.

Health risk from low-level environmental exposure to radionuclides for population living on the different distance from source x (m) is calculated according to (Eckerman et al., 1998) as

1) External exposure from radionuclides distributed in air:

$$R_k^{subm}(x) = r_{k,m}^{subm} \cdot A_{v,k}(x), \qquad (4)$$

where

r_m^{subm} – risk coefficient for external exposure to radiation from k-th radionuclide distributed in air, $m^3 \cdot Bq^{-1} \cdot s^{-1}$;

m – type of risk coefficient: mortality risk or morbidity risk.

2) External exposure from radionuclides deposited on the ground surface:

$$R_k^{plane}(x) = r_{k,m}^{plane} \cdot \int_0^T \delta_k(x) \cdot e^{-\lambda_k \cdot t} dt, \qquad (5)$$

where

$r_{k,m}^{plane}$ – risk coefficient for external exposure to radiation from k-th radionuclide on the ground surface, $m^2 \cdot Bq^{-1} \cdot s^{-1}$;

λ_k – . radioactive decay rate, s^{-1}.

3) Internal exposure due to inhalation of radionuclides:

$$R_k^{inh}(x) = r_{k,m}^{inh} \cdot V \cdot A_{v,k}(x), \qquad (6)$$

where

$r_{k,m}^{inh}$ – risk coefficient for inhalation of k-th radionuclide in air, Bq^{-1};

V = $2{,}06 \cdot 10^{-4}$ ì^3 ñ$^{-1}$ – age and sex lifetime averaged inhalation rate.

Health risk estimation for inhalation has been carried out for two form of inhaled radionuclides in term of the rate of absorption from lungs to blood (ICRP, 1994): type F and type M represent a fast and medium rate.

4) Internal exposure due to ingestion of iodine in food:

$$R_k^{ing}(x) = r_{k,m}^{ing} \cdot \int_0^T I_k(x,t)\, dt, \qquad (7)$$

where

$r_{k,m}^{ing}$ – risk coefficient for ingestion of k-th iodine isotope with food, Bq^{-1}.

RESULTS

Environmental contamination

For different distances from the source the following parameters have been calculated:

- Time-integrated activity of k-th radionuclide in air $A_{vk}(x)$, $Bq \cdot m^{-3} \cdot s$;
- Ground deposition density of k-th radionuclide $\sigma_k(x)$, $Bq \cdot m^{-2}$

Fig.1 shows time-integrated activity of iodine isotopes in air for the condition of dry deposition.

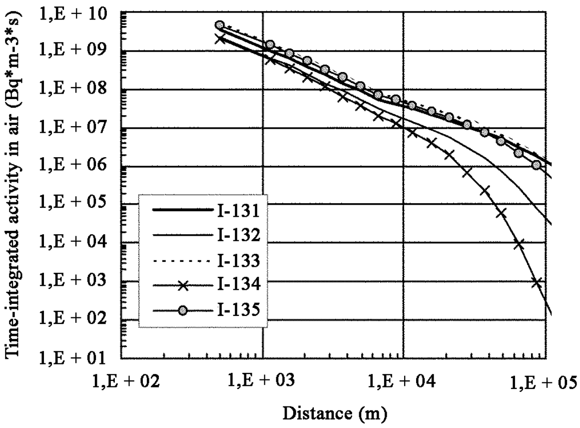

FIGURE 1. Time-integrated activity of iodine isotopes in air for the condition of dry deposition

Thyroid exposure

Inhalation and ingestion thyroid dose estimates for children at the age 5 years and adults are shown in Fig.2 and Fig.3.

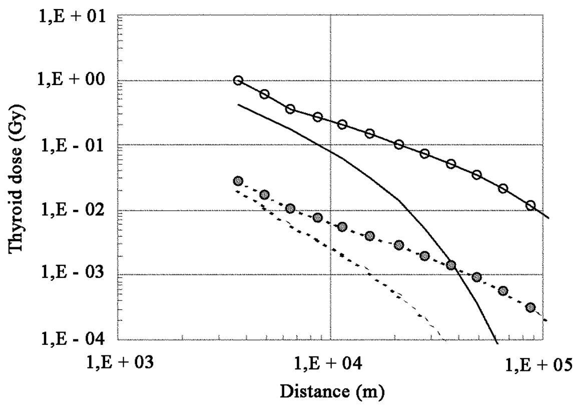

FIGURE 2. Thyroid doses from radioiodine for children at the age 5 years: o - ingestion (dry deposition), —- ingestion (wet deposition), • - inhalation (dry deposition), -- - inhalation (wet deposition)

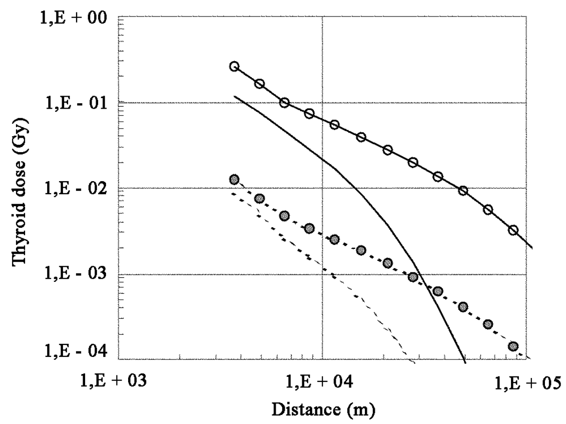

FIGURE 3. Thyroid doses from radioiodine for adults: o –ingestion (dry deposition), —- ingestion (wet deposition), • - inhalation (dry deposition), -- -inhalation (wet deposition)

Health risk

Fig.4 and Fig.5 show examples of estimates of mortality risk for the conditions of dry and wet deposition to population living on the distance 11,5 km from the NPP. Numbers indicate the following pathways: 1 – ingestion of iodine isotopes with food; 2 – inhalation of radionuclide type F; 3 – inhalation of radionuclide type M; 4 – external exposure from radionuclides deposited on the ground surface; 5 – external exposure from radionuclides distributed in air.

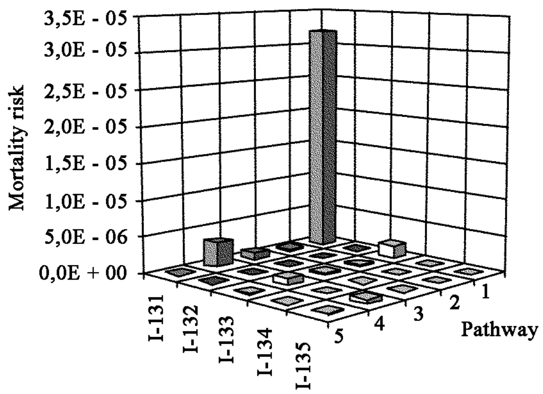

FIGURE 4. Mortality risk for the condition of dry deposition (distance = 11,5 km)

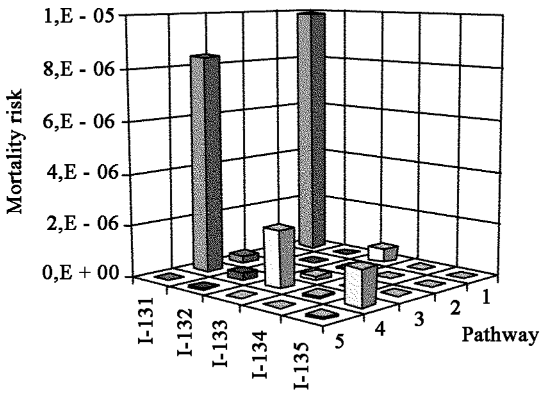

FIGURE 5. Mortality risk for the condition of wet deposition (distance = 11,5 km)

DISCUSSION

Radiological significance of radiation accident is determined by correlation between level of potential exposure to population and established accidental dose limits. Countermeasures and thyroid dose criteria for protection of the population in the case of radiation accidents according to the (ICRP, 1984; GAN, 1993) are given in Table 2.

Obtained values of internal thyroid doses show, that the following countermeasures can be put into operation during considered accidental scenario:

- Stable iodine prophylaxis among children and pregnancy women within 10-km zone around NPP (thyroid dose more than 250 mGy);
- Evacuation of children and pregnancy women within 6-km zone around NPP (thyroid dose more than 500 mGy).

TABLE 2. Countermeasures and thyroid dose criteria for protection of the population in the case of radiation accident (ICRP, 1984; GAN, 1993)

Countermeasure	Dose criteria, mGy	
	Lower level	Upper level
Stable iodine prophylaxis		
Adults	50	500
Children, pregnancy women	50	250
Evacuation		
Adults	500	5000
Children, pregnancy women	200	500

Dose contribution by pathway and by iodine isotopes is shown in Fig.6. As can be seen from figure the majority of internal thyroid dose is formed due to ingestion of ^{131}I. If shortly after the accident consumption of local produced food is prohibited (only inhalation is considered), the thyroid doses not exceed 250 mGy outside the 3- km zone around NPP.

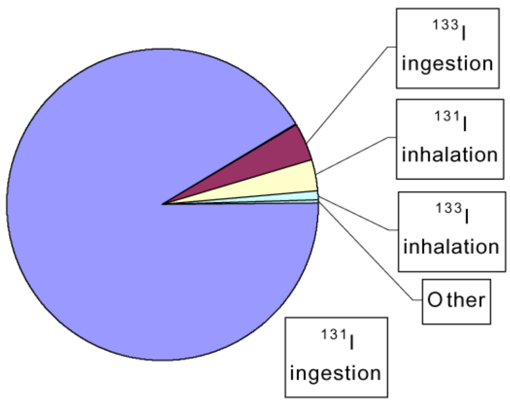

FIGURE 6. Dose contribution by pathway and by iodine Isotopes

The comparative analysis of exposure pathways during early and intermediate stage of accident has conducted. Fig.4 and Fig.5 show that the main radiological consequences from accidental iodine releases can be caused by internal exposure due to radionuclide ingestion. In case of wet deposition, external exposure from radionuclides deposited on the ground surface contributes significantly to the mortality risk.

Depending on the risk value and radiological danger the radionuclides in release can be classified into the three groups: 1st group – radionuclides with maximal value of risk; 2nd group – with high value of risk; and 3d – with moderate value of risk. Classification of iodine isotopes in accidental release for different exposure pathways is given in Table 3.

TABLE 3. Radiological danger of iodine isotopes in release for different exposure pathways

Pathway	Group of radiological danger		
	1	2	3
Ingestion	^{131}I	^{133}I	^{132,134,135}I
Inhalation, type F	^{131,133}I	^{135}I	^{132,134}I
Inhalation, type M	^{131,133}I	^{132,135}I	^{134}I
External exposure from deposited radionuclides	^{131}I	^{133,135}I	^{132,134}I
External exposure from radionuclides in air	^{135}I	^{132,133}I	^{131,134}I

As can be seen from Table 3, the maximal risk of exposure from accidental iodine release is associated with ^{131}I, high risk – with ^{133}I and ^{135}I, moderate risk – with ^{132}I and ^{134}I.

CONCLUSIONS

The radiological consequences of a beyond design-basis accident at an NPP for a VVER-1000 reactor are evaluated. Using the software code COSYMA and accounting for radioiodine activity release to the atmosphere at the early stage of the accident, the radionuclide concentration in air and ground deposition densities were estimated. Inhalation and ingestion thyroid doses to different population sub-groups have been calculated. Using modern knowledge about the risk of radiation-induced cancer, the radiological danger of radionuclides released is evaluated for different exposure pathways: (a) external exposure from radionuclides in air; (b) external exposure from radionuclides deposited on the ground surface; (c) internal exposures from inhalation of radionuclides in air; and (d) internal exposure from ingestion of radionuclides with contaminated foodstuffs. Thyroid doses and risk was estimated for populations living at different distances from the source.

Obtained values of internal thyroid doses show, that the following countermeasures can be put into operation during considered accidental scenario:

- Stable iodine prophylaxis among children and pregnancy women within 10-km zone around NPP (thyroid dose more than 250 mGy);
- Evacuation of children and pregnancy women within 6-km zone around NPP (thyroid dose more than 500 mGy).

The majority of internal thyroid dose is formed due to ingestion of ^{131}I. If shortly after the accident consumption of local produced food is prohibited (only inhalation is considered), the thyroid doses not exceed 250 mGy outside the 3-km zone around NPP.

The comparative analysis of exposure pathways during early and intermediate stage of accident has conducted. Depending on the risk value and radiological danger the radionuclides in release have been classified into the three groups. The maximal risk of exposure from accidental iodine release is associated with ^{131}I, high risk – with ^{133}I and ^{135}I, moderate risk – with ^{132}I and ^{134}I.

Preliminary results show that the methodology and models can be applied to the evaluation of radiological danger of an accident at an NPP. Experience from the Chernobyl accident has shown that the damage from a radiation accident can be vast. Expenditures on advanced simulations of the different accident scenarios are worth the cost because they allow radiation protection of populations for these low probability cases, but nevertheless possible accidents at an NPP.

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REFERENCES

[1] Drozdovitch, V.V., G.M.Goulko, et al. "Thyroid dose reconstruction for the population of Belarus after the Chernobyl accident", *Radiat Environ Biophys*, **36**:17–23 (1997).

[2] Drozdovitch, V.V. *Modeling of thyroid doses formation from ^{131}I for estimation of the radiological consequences of the Chernobyl accident*. Preprint IPEP–37. Minsk (1998). (In Russian)

[3] Eckerman, K.F., R.W.Legget, et al. *Health risks from low-level environmental exposure to radionuclides. Radionuclide-spesific lifetime radiogenic cancers risk coefficients for the U.S. population, based on age-dependent intake, dosimetry and risk models: Federal Guidance Report No. 13, Part I*, U.S. EPA, Washington DC (1998).

[4] Gosatomnadzor of Russia (GAN). *Placing of Nuclear Power Plant: Main criteria and requirements on the safety ensuring*, Moscow (1993).

[5] Grishmanovsky, V.I., Kozlov V.F., et al. "Estimation of the radiation consequences of hypothetical accidents on NPP with VVER reactor", *Atomnaya Energiya*, **67**(4):262–266 (1989).

[6] Gusev, N.G., E.E.Kovalev, et al. *Protection from the ionizing radiation*. Vol.2. Moscow, Energo-atomizdat (1990) (In Russian).

[7] Jones, J.A., P.A.Mansfield, et al. *PC COSYMA: An accident consequence assessment packadge foe use on a PC: EUR Report 16239*, Brussels (1995).

[8] International Commission on Radiological Protection (ICRP) *Protection of the public in the event of major radiation accidents: principles for planning: ICRP Publication 40*, Oxford, Pergamon Press (1984).

[9] International Commission on Radiological Protection (ICRP) *Age-dependent doses to members of the public from intakes of radionuclides. Part I. Ingestion dose coefficients: ICRP Publication 56*, Oxford, Pergamon Press (1989).

[10] International Commission on Radiological Protection (ICRP) *1990 Recommendations of the International Commission on Radiological Protection: ICRP Publication 60*, Oxford, Pergamon Press (1991).

[11] International Commission on Radiological Protection (ICRP) *Human Respiratory Tract Model for Radiological Protection: ICRP Publication 66*, Oxford, Pergamon Press (1994).

[12] International Commission on Radiological Protection (ICRP) *Age-Dependent Doses to Members of the Public from Intake of Radionuclides. Part 4. Inhalation dose coefficients: ICRP Publication 71*, Oxford, Pergamon Press (1995).

[13] Romanov, G.N. *Liquidation of the radiation accident consequences*. Moscow, IzdAT (1993) (In Russian).

[14] Savushkin, I., V.Drozdovitch, et al. *Radiological consequences of iodine releases following the beyond design-basis accident on VVER reactor*. Preprint IPEP47, Minsk (1999) (In Russian).