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ORIGINAL ARTICLE

Stipulating the radioecological impact of consequences of accidents at nuclear power facilities

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A conservative risk-oriented method of predicting the impact of radiation consequences of accidents in a wide range of changes in accidental radiation doses has been proposed. The method is based on the complex application of stochastic and deterministic methods of modelling radiation consequences of accidents. It is necessary to improve statistical post-accident data bases on negative effects without taking into account the impact of negative processes directly related to the accident. Analysis of Chernobyl and Fukushima-Daiichi NPP accident outcomes determines the expediency of prediction techniques improvement for the impact of radiation consequences of accidents within a wide range of radiation dose rates.

Keywords: Radiation accident, Consequences risk.

Introduction

One of the lessons taught by the most significant accidents in the history of nuclear power engineering at the Chernobyl NPP in 1986 and the Fukushima-Daiichi NPP in 2011 shows the need to improve the methods for predicting the impact of radiation consequences of accidents on employees, the population and the environment.

The risk of a person being under conditions of radioecologically damaged environment is determined by a set of factors of different nature that have different contributions to the total risk level, which changes significantly at different accident and post-accident stages in the process of liquidation of radioecological consequences. At the same time, the radioecological factor has the most significant direct and indirect influence on the state of public health through the environmental objects, intensifies and initiates or aggravates the new factors of non-radiation nature, which existed at the pre-accident stage.

The application of stochastic methods of predicting radiation consequences in most cases is limited due to the uncertainty of statistical data regarding the direct impact of radiation accidents on the occurrence of negative phenomena/effects. Predictive assessments of stochastic scenarios of radiation consequences should include additional analysis of harmful effects directly related to radiation accidents (changes of environmental conditions, pathological and infectious diseases, lifestyle and other factors).

Predictive assessments of deterministic approaches for predicting radiation consequences are based on modeling the effects of ionizing radiation at the cellular level of bio and ecosystems. To date, however, specialists lack an unambiguous approach to modeling the adverse effects of radiation consequences in the dose-effect format.

Thus, the development of complex risk-oriented methods based on stochastic and deterministic methods, considering the limitations of their applicability, is relevant.

Literature Analysis and Problem Statement

A large number of studies is focused on the analysis of causes and consequences of the largest radiation accidents at the Chernobyl NPP and Fukushima-Daiichi NPP (Nosovskii, 2006; Doklad, 1992; IPHECA, 1995; Buldakov, 2002; Ivanov, 1994; WHO, 2001; WHO, 2013; UNSCEAR, 2014; ICRP, 2012; González, 2013; UNSCEAR, 2014; WMO, 2013; OECD/NEA, 2013; Skalozubov, 2010). However, the matters of predicting the impact of radiation accidents on the employees, the population and the environment independence to a wide range of received radiation doses have been studied insufficiently. The limits of maximum radiation dose rates for the progression of irreversible processes of radiation sickness (1 Gy) and oncological diseases (0.3 Gy) have been determined. A significant increase in thyroid cancer in children who had received high radiation doses has also been determined during the accident has been anticipated.

The application of stochastic and deterministic methods for predicting the impact of radiation consequences of accidents is limited due to the following major factors (Skalozubov et al., 2013; Skalozubov et al., 2015):

1. The statistics of negative effects/diseases of stochastic approaches may be substantially influenced by effects not directly related to radiation consequences of accidents.

2. There are no well-grounded universal deterministic models of the impact of ionizing radiation on bio- and ecosystems over a broad spectrum of radiation dose variations.
3. The highly conservative non-threshold deterministic model is based on extrapolating the dose-effect relationship into the range of radiation doses less than 1.0 Gy.
4. The "Threshold" deterministic model is based on the fact that cell death occurs only when radiation hits the most sensitive cell elements in the low radiation doses range. Thus, based on experiments with microbeams of ionizing particles of 0.1 μm diameter, the "lethal" dose for the cell nucleus is 10-100 times less than that for other parts of the cell.

Highlights of the risk-based method for forecasting the radiation consequences of accidents

Stochastic risk probability of occurrence of negative events/effects in post-accident period *t* according to the registered statistics of the responders/population exposed to the cumulative dose *D* at the time of the accident:

$$R_s(t,D) = N_0^{-1}(D)\left[N_n(d,t=0) + \int_0^t N'_n(D,\tau)\mathrm{d}\tau \right], \quad \text{..................(1)}$$

where $N_n(D, t=0)$- is the number of registered negative effects with the dose received D at the time of the accident; $N_0(D)$ is the total number of persons who received the total dose D during the accident; $N'_n(D, \tau)=dN_n(D)/d\tau$ is the rate of change of the registered negative effects with the initial dose D in the post-accident period.

Negative events/effects define possible oncological or other serious diseases/disorders due to radiation exposure. According to the statistics of registered adverse effects of groups with initial by the time of a radiation accident total dose D, possible stochastic risk Rs are presented in Fig. 1.

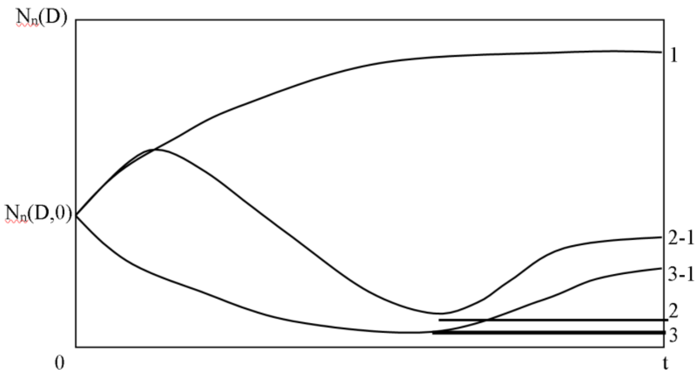

Fig. 1. Scenarios of stochastic risk according to the statistics of reported negative effects of groups with initial dose D: 1-marginal negative scenario; 2-variable scenario; 2-1-scenario not related to the radiation consequences of the accident; 3-scenario of stable reduction of negative effects with initial dose D; 3-1-scenario not related to the radiation consequences of the accident.

Marginal negative scenario 1 is characterized by a steady increase in N_n (D) and N'_n (t)>0. Variable scenario 2 is characterized by an initial rate of $N'_n(t)>0$ followed by a steady decrease $N_n(N'_n<0)$. Scenario 2-1 is characterized by a repeated increase of Nn and is not the result of initial radiation exposure. Favorable scenario 3 is characterized by a stable decrease of reported negative effects throughout the whole time span and a relatively minimal stochastic risk Rs. Scenario 3-1, similar to scenarios 2-1, is not a consequence of the initial radiation exposure. When N'_n (t)=0 the predicted stochastic risk is R_s (t)=R_s (t=0). The area of the predicted deterministic risk of negative effects Rd in dependence on the total radiation doses received in an accident is presented in Fig. 2. The limits of the predicted area are the "non-threshold" model (maxR_d) and the "threshold" model (minR_d). The marginal conservative dose of occurrence of negative effects max D=0,3 Gy (Nosovskii, 2006).

Within the framework of the proposed risk-based method, the predicted risk of negative R_F effects due to radiation accidents is determined in dependence on the predicted estimates with stochastic R_s and deterministic R_d methods:

If $R_s \geq \max R_d$, then

$$R_F(t) = R_s(t) \quad \text{. ....(2)}$$

If $\min R_d < R_s < \max R_d$, then

$$R_F(t) = \max R_d \quad \text{. ....(3)}$$

If $R_s \leq \min R_d$, then

$$R_F(t) = \min R_d \quad \text{. ....(4)}$$

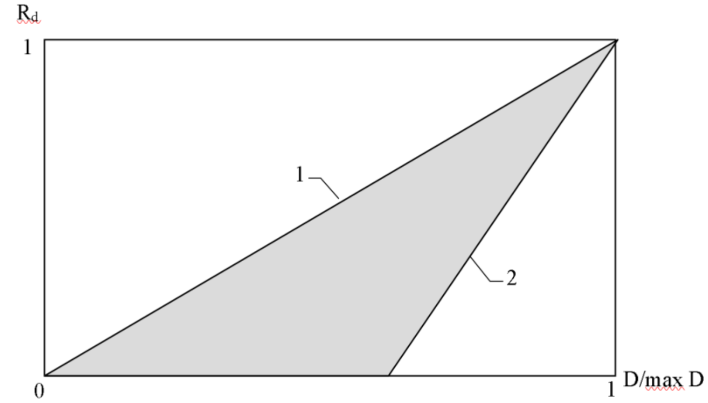

Fig. 2. Area of predicted deterministic risk of negative effects: 1-" non-threshold" model; 2-" threshold" model. The ordinate axis is the number of negative effects R_F, the abscissa axis is the D/Dmax ratio.

Suppose stochastic scenarios of occurrence of negative effects not related to radiation accidents take place (Fig. 1). In that case, the risk of negative effects directly related to a radiation accident is estimated according to formulas (2)-(4) depending on the ratio of Rs and Rd by the start of the "non-accidental" scenario of development of negative effects.

Conclusion

Analysis of Chernobyl and Fukushima-Daiichi NPP accident outcomes determines the expediency of improving methods to predict the impact of radiation consequences of accidents within a wide range of radiation dose rates. A conservative risk-oriented method of predicting the impact of radiation consequences of accidents in a wide range of changes in accidental radiation doses has been proposed. The method is based on the complex application of stochastic and deterministic methods of modeling radiation consequences of accidents. It is necessary to improve statistical post-accident databases on adverse effects without considering negative processes directly related to the accident.

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