Assessment of individual risk criteria for the disposal of radioactive waste

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Abstract. This article discusses the possibilities of determining the risk to individuals as a result of radiation exposure, which is one of the most common and important characteristics of environmental hazard. Environmental damage with the likelihood of an event contributing to the determination of environmental risk. In this case, the risk itself shows the effect of radiation on the human body. When determining the risk, it is necessary to take into account the power of an individual dose for a certain period of time. The criteria curves considered in the article take into account stochastic and non-stochastic effects. These criteria show compliance of waste disposal methods with requirements related to specific risk levels.

1. Introduction
The general principle of nature conservation in the field of human labor is to minimize losses in inanimate and living nature. The rate of restoration (or self-healing) is functionally related to the level of anthropogenic changes in the environment as a result of the creation or functioning of an industrial facility. When analyzing the effectiveness of environmental protection measures, it is advisable to take into account the analysis of environmental risk. Environmental risk is one of the most common and important characteristics of environmental hazard. It connects natural and man-made catastrophic events with consequences for public health and aims to minimize damage to natural ecosystems [1].

2. Results and discussion
Quantitative approaches to environmental risk analysis are based on assessing the consequences of a negative event through the magnitude of potential damage. Dependence is proposed to be expressed by a formula where risk characterizes the possibility of causing this damage and is calculated as the product of damage and the probability of the occurrence of the event.

\[ R = D \cdot P \]

where \( R \) - ecological risk, \( D \) - damage, \( P \) - probability of the event.

The probability \( P(A) \) of the occurrence of event \( A \) is defined as:

\[ P(A) = \frac{N(A)}{N} \]

Based on the number of “chances” \( N(A) \) for the occurrence of an event, where \( N(A) \) is the number of all those outcomes \( o \) for which event \( A \) occurs (that is, the number of all).
When considering the long-term disposal of radioactive waste, decisions must be made regarding the level of protection that must be provided to future individuals. Since significant doses can be obtained as a result of incidents that violate the normal state of the repository and currently have an estimated probability of less than one. The goal of protecting individuals from all incidents involving the disposal of radioactive waste and involving exposure is best achieved with individual risk limitations. When sequentially determining risk values, both the probability of exposure and the amount of exposure can be included. For this, it is necessary to establish a risk limit and an upper limit of risk by analogy with dose limits and upper dose limits for conventional releases. Such a risk limit should correspond to that risk which is due to dose limits at which the individual's overall risk remains below the level considered unacceptable [2].

A number of well-known characteristics that can be used to judge the state of population’s health, such as life expectancy, total and child mortality rates, and some others, are insufficiently sensitive to changes in factors reflecting the living conditions of the population. The term “risk” is used to indicate the likelihood of serious health damage resulting from exposure. That is, risk is defined as the likelihood that a potential exposed individual or its descendants will have a serious health problem. The risk $R$ for an individual or a critical group as a result of an incident creating a dose in the range from $D$ to $D + dD$ is expressed by the equation:

$$R = P(D)p(ef/D),$$

where $P(D)$ is the probability of an event or other changes in the environment creating a dose from $D$ to $D + dD$ for an individual representing a critical group, and $p(ef/D)$ is the probability of a serious health problem for a given individual or his descendants from the received dose $D$.

For doses leading to stochastic effects for which an effective equivalent dose can be used, this expression is simplified as follows:

$$R = P(H_E)rH_E$$

where $r$ is the probability of a serious health problem per unit of effective equivalent dose.

Limiting doses over a lifetime to an average of 1 mSv per year means limiting the average annual risk to less than about $10^{-5}$. Similarly, the annual risk from probabilistic events for the critical group is also limited so that it is also less than about $10^{-5}$. The use of a system of restrictions on annual individual risk requires an assessment of the likelihood of exposure at different levels of the annual dose or above such levels [3]. When making such an assessment, it is important that a distinction is made between the probability of exposure and the probability of damage in the storage facilities for radioactive waste that may cause exposure. The information used to describe the probability of destruction of the storage includes data on the probability of its occurrence over a certain period of time, as a function of time (figure 1).

![Figure 1](image.png)

**Figure 1.** Possible fluctuations in the probability level of a destructive event as a function of time elapsed after the disposal of radioactive waste.
For some events, the probability of occurrence over a certain period of time will be constant or only slowly change over time. For other types of events, both natural and caused by human intervention, the probability of their occurrence over a given period of time will change with time after the closure of the store and may also depend on the occurrence of other events, so more complex modeling becomes inevitable [4]. In addition, it is necessary to assess the contribution of radiation under the assumption that the event has already happened, expressed by the individual dose rate, as a function of the time the event started and the time after it (figure 2).

Such a dose rate is both a function of both the time of occurrence of the initial event $t$ and the time elapsed since its inception $(T-t)$. Therefore, it can be expressed as $g(t, T-t)$, where $T$ is the time when this dose rate is estimated. If we use a simplified expression for the risk of stochastic effects and assume that the dose rate changes slowly over the course of an individual’s life, $L$, then the conditional probability of death due to radiation will be $rLg(t, T-t)$.

If the probability of the initial event for a small period of time $dt$ is $f(t)dt$, then the absolute probability of death for this reason is for an individual living at time point $T$,

$$P(t)=rL \int \! f(t)g(t, T-t)dt$$

The approximate annual probability of death for this individual from this type of incident $P1(T)$ will be equal to $P(T)/L$. Therefore, an assessment of compliance with the limit will mean that it never exceeds the annual risk limit ($10^{-5}$) or the upper risk limit for any value of $T$.

The probability of a specific annual dose level at any time $T$ will depend on the likelihood that the event in question occurred during a certain period before time $T$. All these probabilities, in relation to a specific event, describe the overall probability of exceeding this level of the annual dose. For a particular event, the probability of exceeding very low annual doses is fairly constant and is associated with the probability that the event happened before time $T$; the probability of exceeding the maximum dose at time $T$ obtained as a result of this event at any time until time $T$ is zero [5].

For events that give rise to very long-term environmental pollution (hundreds or thousands of years), the results reflect the likelihood that the initial event happened not only before the individual lives, but also long before the radionuclides migrated from the geosphere to the biosphere. Therefore, the probability of exposure is associated with the cumulative probability for the corresponding time interval of the destructive event that occurred before time $T$.

The main condition for achieving compliance with the risk limit or some upper limit of risk is that it is less than the corresponding limit. The method for applying the conditions of probabilistic events associated with an individual is to represent these limits in the form of a criterion curve similar to the curves used in probabilistic approaches to the problem of nuclear safety [6]. Figure 3 shows a curve of
the criterion representing the maximum probability that can be tolerated for the estimated annual dose, and based on the limitation of annual risk at a level of $10^{-5}$ for the critical group.

![Figure 3. Curve of the criterion based on the limitation of annual risk at the level of 10-5 from all events.](image)

The characteristics of the criterion curve considered are: a probability limit of unity for annual doses up to 1 mSv; region of inverse proportionality; an area not proportional to the dose range in which non-stochastic effects can also occur; and a steady probability for doses that are fatal.

In the range of lethal doses, the probability is constant, regardless of the dose, since the consequence for the individual is the same, regardless of the dose received. For a dose range in which only stochastic effects can occur, the relationship between probability and dose is inversely proportional, and the values are the products of the probability of exposure at a given dose, the annual dose and the probability of an undesirable effect on health per unit dose. And finally, in the dose range where non-stochastic effects may occur, i.e. where individual doses exceed several sieverts, the shape of the criterion curve is non-linear in order to take into account the increasing probability of death. This segment of the curve should approximate the sigmoid relationship and may depend to some extent on the time during which the dose is received [7].

The upper limit of risk can be entered directly into the curve of the criterion. The proportional distribution between different sources, necessary in order to show the upper bound, requires that a certain part of the limit be selected for the considered source. Such a part can be introduced, as shown in figure 4. The size of such a change in the criterion curve will depend on this part selected for the upper boundary. The shape of the curve will change, since the occurrence of non-stochastic effects is in a rather narrow dose range.

![Figure 4. Curve of the criterion illustrating the type of change necessary to achieve compliance with the upper limit of risk.](image)

The proposed curve of the criterion can be used to show whether the selected method of waste disposal meets the requirements of certain risk levels [8]. First, identify an event or series of events with the potential ability to destroy a waste repository and cause exposure to individuals. Secondly, it is necessary to evaluate the probability of the occurrence of each event, the corresponding activity of radionuclides in emissions and subsequent doses of radiation to the critical group.
3. Conclusion

As a result, a point is formed representing the probability of the occurrence of the initial event and all other environmental conditions and the corresponding maximum dose. If this point lies in an unacceptable area of the graph, then this method should be discarded. However, if all points lie in an acceptable area, the proposal for any method of waste disposal under consideration may be unacceptable due to the possible addition of risk from events of various kinds. Therefore, at this stage, the suitability of the curve criterion is limited by its suitability as the main tool for decisions in order to verify whether any method is unacceptable. The next step involves checking whether this method meets the basic requirement that the total risk from all the expected events resulting from their combination should correspond to the upper limit of risk.

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