Management Optimization of Rehabilitation Processes for Polluted Territories

Nikolay P. Tikhomirov
Plekhanov Russian University of Economics
per. Stremyannyj 36,
117997 Moscow, Russia.
kafedra_mme@mail.ru

Dmitry V. Aron
Nuclear Safety Institute
ul. Bolshaya Tulskaya 52,
115191 Moscow, Russia.
aron@ibrae.ac.ru

Abstract

Issues related to the management of the territory remediation after its radiation contamination using four criteria that shall define the decontamination procedures efficiency are discussed in the paper. Positive applicability of two of the discussed criteria for solving the problem of decontamination justification based upon assessment of the residual annual dose of radiation exposure for the population is demonstrated.

1 Introduction

Decontamination of territories contaminated without resettlement or with temporary resettlement of the population is considered by experts as the basic strategy of radiation safety in case of incidents with rather low expected doses of radiation exposure (up to 200 mSv/year). At the same time, implementation of such measures of intervention leads to considerable financial expenses. Thereupon, the regulatory documents that set the norms of mitigation of radiation contamination consequences [ICRP, 2007] recommend optimizing the decontamination works and corresponding financial funds. It is proposed to keep a well-founded balance between the economic benefits caused by decrease of the radiation exposure dose as a result of territory decontamination and the expenses related to these works. The regulatory socially accepted restrictions on the level of radiation risks for the population shall also be considered.

The following options [Crik, 2009] are proposed in the scientific papers as criteria of expenses optimization for implementing protective measures in case of radiation impact on the population:

– 1^{st}: maximum of benefits B defined as a difference between the cost of harm prevented by decontamination and expenses related to its implementation;

– 2^{nd}: minimum of decontamination costs Z represented by a sum of damage caused by a residual radiation dose and involving expenses;

– 3^{rd}: minimum of Λ, the involving expenses per cost unit of the prevented damage;

– 4^{th}: maximum of V, cost of the prevented damage per cost unit.

Further, we will consider the details of solving the problem of decontamination optimization using these criteria.

In: Yu. G. Evtushenko, M. Yu. Khachay, O. V. Khamisov, Yu. A. Kochetov, V.U. Malkova, M.A. Posypkin (eds.): Proceedings of the OPTIMA-2017 Conference, Petrovac, Montenegro, 02-Oct-2017, published at http://ceur-ws.org

2 Approaches to Radiological Damage Assessment With or Without Decontamination

Assessment of radiation contamination damage for territories has its own peculiarities concerned with the need to take into account several natural physical processes.

The territory pollution after an accidental emission of radioactive aerosols into the atmosphere arises from the radioactive deposition onto the soil surface. They are freely whipped up by winds and spread for kilometers beyond their place of origin. The deposition process can proceed with varying intensity on different surfaces from which the contaminant can later be raised again or washed away by an atmospheric precipitation. Most types of surfaces and materials absorb radioactive aerosols in varying degrees without the possibility of their complete removal.

Radionuclides penetrate the soil with water of the first precipitation, and, in general, they are distributed below the surface with a small shift of maximum concentration in depth. Gradually, all easily removable activity moves to the ground, including through various drainage communications. Finally, it is the surface soil layers and the organic debris accumulation areas that become the main sources of external exposure for people of inhabited territories.

Furthermore, people can receive a dose due to internal irradiation with consumption of food contaminated with the radionuclides and with radioactive aerosols inhalation. It is difficult to predict such doses but in practice if it was possible to exclude local food from the diet of the residents and the fallout was completed long ago it is reasonable to estimate the doses for the population only by external irradiation in the long term. In turn, the levels of external irradiation change due to natural physical processes or under human impacts on the territory.

The aim of decontamination is to decrease the initial (after an incident) individual dose of radiation exposure D_0 to residual level D_R (we consider here an annual dose measured in mSv/year). The difference $\Delta D = D_0 - D_R$ is considered as the radiation dose prevented due to decontamination. On the basis of these indicators, it is possible to estimate the financial equivalent of harm related to the prevented and residual radiation doses as well as expenses of decontamination recalculated per one individual. The corresponding functions for calculation of the financial equivalent will depend on levels of these doses.

The values of D_0 and D_R can be estimated with direct measurements just before and after the territory decontamination procedure since for long-lived radionuclides these values can be considered proportional to the value of gamma radiation dose rate.

The following expressions based upon the linear no-threshold concept for assessment of losses of life years from a dose received by an individual [ICRP, 2007] are often considered in the scientific literature as the functions estimating the prevented and residual harms of radiation:

$$Q^{+}(\Delta D) = \vartheta \cdot \psi \cdot \Delta D, \tag{1}$$

$$Q^{-}(D_R) = \vartheta \cdot \psi \cdot D_R, \tag{2}$$

where $Q^{+}(\Delta D)$ is economical equivalent of prevented radiological harm and at the same time the economical "benefit" of decontamination; $Q^{-}(D_R)$ is cost equivalent of residual radiation harm left after the decontamination; ϑ – price of radiation dose unit, which is recommended by ICRP [ICRP, 2007] to be set not lower as GNP per capita for 1 Sv assuming that the collective dose of 1 Sv/year is equivalent to loss of 1 year of individual life; ψ – averaged, expressed in years, coefficient considering the dynamics of dose accumulation during residing in contaminated territory for L years. The simple approximation for ψ was suggested in work [Aron, 2015] as exponential function of L and parameter of dose rate decease due to radioactive decay and nuclide migration in the natural environment.

$$\psi(\mu, L) = \frac{1 - exp(-\mu L)}{\mu}, \tag{3}$$

where μ is the dose rate decrease for one year due to radioactive decay and nuclide migration in the natural environment.

Expression (3) allows us to obtain satisfactory estimates of the indicator with limited initial data on the radionuclide composition in most cases. More accurate approximations for $\psi(L)$ will be used in more complicated form of (3) if there is additional detailed information on the composition of radioactive. Here should be taken into account the decline in radiative forcing through natural radioactive decay of all significant radionuclides and through natural migration in soil which depends both on chemical form of the deposition and the soil type or its surface conditions. In case of nuclear power plant accident here can be used formula of natural radioactive decay for cesium radionuclides and formula for caesium chemicals migration in soil presented in [WHO, 2013, p.43].

These determine the patterns of radionuclide behavior without any human interference. However, large-scale decontamination during which the integrity of the soil is violated, the top layer is removed or clean soil is added over the contaminated soil, affects the process of further radionuclide migration. Depending on the type of work performed, the migration processes can be accelerated or actually suspended. It is worth noting that one can neglect the penetration of radionuclides if deactivation is carried out to near background levels. These aspects of the problem should be taken into account in calculating numerical values of $Q^{+}(\Delta D)$ and $Q^{-}(D_R)$. Such complicated approach was used by the authors in calculation the radiological harm after the Fukushima nuclear accident, some of which are present in section 4.

3 Statement of the Problem of Decontamination Optimization

To demonstrate the work of the criteria let us consider the formulas (1) and (2).

Paper [Crik, 2009] substantiates that the decontamination expenses can be expressed by the following equation:

$$Q^{-}(D, D_R) = C_e \cdot \ln \frac{D}{D_R} = C_e \cdot \ln f, \tag{4}$$

where C_e − is cost per capita (per one resident) of the decontamination with repetition factor $f = e$.

The decontamination factor f is generally defined by direct measurements of contamination levels or radiation background just before and after decontamination procedures on each site of the territory.

Taking into account (1)-(2) and (4), the criteria can be written as follows:

$$B = \vartheta \cdot \psi \cdot (D_0 - D_R) - C_e \cdot \ln \frac{D_0}{D_R}, \tag{5}$$

$$Z = \vartheta \cdot \psi \cdot D_R + C_e \cdot \ln \frac{D_0}{D_R}, \tag{6}$$

$$\Lambda = \frac{C_e \cdot \ln \frac{D_0}{D_R}}{\vartheta \cdot \psi \cdot (D_0 - D_R)}, \tag{7}$$

$$V = \frac{\vartheta \cdot \psi \cdot (D_0 - D_R)}{C_e \cdot \ln \frac{D_0}{D_R}}. \tag{8}$$

In the considered criteria the target indicator is the residual radiation dose. If there are no limitations to its value, the optimal value can be defined by the equation:

$$\frac{\partial F(D_R)}{\partial D_R} = 0, \tag{9}$$

where $F(D_R)$ is the corresponding criterion.

While solving different variants of the optimization problem for residual (after decontamination) doses, lets take into account that the criteria (5) and (6), as well as (7) and (8), are pairwise equivalent.

Equivalence of criteria (7) and (8) is immediate from the equation:

$$\Lambda \cdot V = 1. \tag{10}$$

Equivalence of criteria (5) and (6) is the consequence of equivalency of solutions of the maximum problem of criterion and the minimum problem of criterion Z:

$$\frac{\partial B}{\partial D_R} = \frac{\partial Z}{\partial D_R} = \vartheta \cdot \psi - \frac{C_e}{D_R} = 0. \tag{11}$$

The conclusion follows from equation (11):

$$D_R^1 = \frac{C_e}{\vartheta \cdot \psi}, \tag{12}$$

which indicates that the optimal level of residual radiation exposure dose does not depend on either initial dose and repetition factor and is in a direct dependence on the per capita cost of decontamination and in an inverse dependence on the cost of one year of human life ϑ.

Solutions of the problem of unconditional optimization of decontamination (without any additional restrictions imposed on the problem statements) with 3^{rd} and 4^{th} criteria seem to be trivial enough, following from their definitions. It is obvious that, for example, the minimum value of 3^{rd} criterion equals to zero, and the maximum value of 4^{th} criterion – equals to infinity, are reached at zero expenses for the decontamination, i.e. when the decontamination is not implemented.

This result can be received by substituting criterion V (8) in the equation (9). After obvious reductions, one shall receive:

$$\frac{D_0 - D_R}{D_R} = \ln \frac{D_0}{D_R}. \tag{13}$$

Considering that $\frac{D_0}{D_R} = f$, equation (13) can be reduced to the following form:

$$f - \ln f = 1, \tag{14}$$

from which the condition $D_0 = D_R$ follows.

This result indicates that there is an inadequacy of the relative 3^{rd} and 4^{th} criteria to the problem statement of the unconditional optimization of decontamination without limitations. However, one shall also pay a special attention to using the absolute 1^{st} and 2^{nd} criteria for the solution of this problem. This is related to the fact that the solution (12) of this problem depends on subjective and not very accurately defined variables ϑ and C_e, that characterize the cost of one year of human life and per capita expenses of the decontamination.

For example, for the Russian Federation, the ϑ indicator, in accordance with ICRP recommendations [ICRP, 2007] can be defined as US$ 14-15 thousand. Thus, the optimum value of the residual radiation dose D_R^1 after decontamination of territory previously contaminated with isotope ^{137}Cs with the annual decrease of radiation rate in the natural environment μ=0.06 [Tikhomirov, 2016] and duration L of residing there for 25 years, will make approximately 22 mSv/year at any value of the initial dose $D_0 > D_R$. With increase of the initial radiation dose, this optimum should be provided by increase of decontamination factor f. For example, at the initial dose of radiation D_0 equal to 44 mSv/year, the optimum value D_R^1 of the residual dose will be reached at the double decontamination, at D_0=66 mSv/year – at a triple decontamination, etc.

At the same time, with increase of the cost of individual life year, the level of the optimum residual radiation dose will decrease. For the developed countries, this indicator makes US$ 30-40 thousand, and the corresponding solution is already in the limits of 7-10 mSv/year. In this way, distinctions in assessments of the cost of one life year allow manipulation of the problem solutions.

Considerable divergence in assessments of the optimum level of a residual radiation dose can be explained by various approaches to the definition of decontamination cost (C_e).

Technically, the same dose reduction result can be achieved both by small or large costs. This is due to the fact that during the procedure of decontamination, considerable staff time can be associated with manual work, labor safety, preventing the spread of radioactive dust, waste collection and disposal, the process water filtration, and other operations that have no direct influence on ΔD, but may impact on better recovery of the living environment and may catalyze the return of the population.

If take into account, as a part of this cost, the expenses for cleaning of sparsely populated territories (recreational zones, agricultural lands, etc.) and other works, which will not affect the radiation dose decrease for the population in the long-term period, this will unfairly increase per capita assessments of C_e that will also lead to increase of the optimum level of a residual radiation dose.

At the same time, variation of assessments of decontamination costs as well as the damage prevented does not practically change the considered approach to definition of economically justified residual radiation dose. Note that, in a real situation, its value can be corrected taking into account the restrictions to the level of socially accepted radiation effects on human.

4 Effects of Evacuation Order Cancelation

At the same time, in practice, these solutions should be considered as the upper limits, because, besides the life losses, the prevented damage should include the other types, for example, material losses (buildings, structures, non-manufactured products as a result of a production stop, etc.), compensatory payments to the population in the affected territories, etc.

This approach is applicable unconditionally in cases when the radiation contamination is not accompanied by evacuation of the population and serious collateral economic damage. Alternatively, in the 1^{st} and 2^{nd} criteria the damage from evacuation and the benefits of its cancelation and return of the population should be taken into account.

Take the real example of the large-scale remediation of the territory in 2012-2014 in the aftermath of the Fukushima-1 nuclear power plant accident. Tamura municipality (Fukushima prefecture) was inhabited around 400 people before the evacuation, and they were supposed to return to their place of usual residence by April 2014. The total cost of decontamination for this territory was estimated on the basis of official Japanese data on staff time at US$ 68,000 per inhabitant. This is largely due to the initial objective to reduce the radiation doses for the population to natural background levels. At the same time, caused by initially low levels of pollution for this territory just before decontamination, its f-factor was estimated approximately as 1.6. In this case, the ψ factor is also considered for a period of 25 years after the return of inhabitants and was estimated at 10.2 years (taking into account the composition of the radioisotopes in the pollution and the effect of deactivation procedure on their migration in soil, described in (3) and its complicated form). In this context, per capita cost C_e for decontamination with a f-factor of e is about US$ 145,600. If we estimate the year of life value for Japan basing on the average per capita GDP for the period 2011-2012 in the amount of US$ 34,400, then the 1^{st} criterion will show the optimal value of the residual radiation dose D_R^1=415 mSv/year.

Such intervention measures to ensure radiation safety in a number of municipalities of Fukushima prefecture look excessively expensive. In some of them, decontamination and other restoration works were carried out at initial doses of radiation at a level of 1-5 mSv/year. Under such a small effect of reducing the radiation background, the cost of work and decontamination staff time can seem unreasonably high. However, not always such a conclusion is justified in practice. To assess the effectiveness of decontamination, it is worth considering not only the damage from radiation exposure, but also the additional costs of the company associated with evacuation, as well as the benefits of its possible cancelation.

For example, during the evacuation period, all residents of the contaminated territories received monthly assistance of US$ 980 that had to be canceled after returning. To stimulate the return, the one-time settling allowance of US$ $7,200$ per family was proposed. Finally, the value of all paid compensations could exceed the total decontamination cost for this territory in the long term. The successful decontamination should activate the return of the population and canceling of all payments. In the long term, It should lead to the efficient land release and the resumption of economic activity that can assessed as a positive economic effect and the benefit of decontamination.

Generally, the socially accepted restrictions on the level of radiation risks for the population require the decontamination to decrease of D_R level to a certain level D_R^d, established by a special commission for the region-specific conditions. So, for the territory of Japan this value has been established approximately at 1 mSv/year. The additional economic benefits $q^+(L)$ from the cancelation of evacuation and related payments can be gained in the foreseeable period of time L only after D_R reducing to D_R^d level.

Obviously, if $q^+(L)$ is taken into account in 1^{st} and 2^{nd} criteria (expressions (1) and (2)), then the optimal value of D_R^1 will still be determined by the expression (12), (provided that $q^+(L)$ is not directly dependent on ϑ) provided that $D_R^d \geq \frac{C_e}{\vartheta \cdot \psi}$. If $D_R^d < \frac{C_e}{\vartheta \cdot \psi}$, then D_R^d automatically becomes optimal, since only when it is achieved it is possible to obtain the benefit $q^+(L)$.

Thus, when taking into account the effect of additional economic benefits owing to the evacuation order canceling, the optimal value of residual dose will be determined by the following expression (15):

$$D_R^1 = min(\frac{C_e}{\vartheta \cdot \psi}, D_R^d). \tag{15}$$

In most cases D_R^d is less then $\frac{C_e}{\vartheta \cdot \psi}$ and there is no need to use 1^{st} and 2^{nd} criteria. However, if there is no additional benefit $q^+(L)$ or $D_R^d \geq \frac{C_e}{\vartheta \cdot \psi}$, the practical application of these criteria can be justified.

Acknowledgements

This work was supported by Plekhanov Russian University of Economics, Project “Methodological approaches and methods of evaluation and management of personnel potential of constituent entities of the Russian Federation”.

References

[Aron et al., 2015] Aron D.V., Tikhomirov N.P., Tsuglevich V.N. (2015). Analysis of Decontamination Effectiveness in Fukushima by the Example of Tamura Municipality). *Nature Management Economics. (no.3.)*, (pp.113-121). Moscow: VINITI.

[Crik, 2009] Crik M.J. (2009). *Derived Intervention Levels for Invoring Countermeasures in the Management of Contaminated Agricultural Environment*, (23 p.). Division of Nuclear Safety, IAEA. Vienna.

[Tikhomirov & Aron, 2016] Tikhomirov N.P., Aron D.V. (2016). Methods of a Substantiation Rational Strategy for Ensuring Radiation Safety (in Emergency Situations With Radiation Leaks). *Nature Management Economics. (no.4)*, (pp.75-84). Moscow: VINITI.

[ICRP, 2007] Valentin J.(Ed.)(2007) *The 2007 Recommendations of the International Commission on Radiological Protection. ICRP Publication 103. Ann. ICRP 37 (2-4).* United Kingdom: Elsevier, ISBN 978-0-7020-3048-2.

[WHO, 2013, p.43] World Health Organization(2013) *Health Risk Assessment Erom the Nuclear Accident After the 2011 Great East Japan Earthquake and Tsunami, Based on a Preliminary Dose Estimation.* 172 p., Geneva: WHO Press, ISBN: 978-92-4-150513-0.