Journal of Environmental Radioactivity 119 (2013) 39–47

Contents lists available at ScienceDirect

Journal of Environmental Radioactivity

journal homepage: www.elsevier.com/locate/jenvrad

Justification of remediation strategies in the long term after the Chernobyl accident

S. Fesenko[a,*], P. Jacob[b], A. Ulanovsky[b], A. Chupov[a], I. Bogdevich[c], N. Sanzharova[d], V. Kashparov[e], A. Panov[d], Yu. Zhuchenka[f]

[a] *International Atomic Energy Agency, Vienna, Austria*
[b] *Helmholtz Zentrum München, Institute of Radiation Protection, Neuherberg, Germany*
[c] *Research Institute for Soil Science and Agrochemistry, Minsk, Belarus*
[d] *Russian Institute of Agricultural Radiology and Radioecology, Obninsk, Russia*
[e] *Ukrainian Institute of Agricultural Radiology, Chabany, Kiev Region, Ukraine*
[f] *Gomel State University, Gomel, Belarus*

A R T I C L E I N F O

Article history:
Received 24 August 2010
Accepted 31 August 2010
Available online 2 October 2010

Keywords:
Chernobyl accident
Caesium
Ionizing radiation
Radiation protection
Rehabilitation
Remediation

A B S T R A C T

Following the accident at the nuclear power plant in Chernobyl a number of different remedial actions were developed and implemented in Belarus, Russia, and Ukraine. Recommendations on the application of countermeasures and remedial actions were published by the IAEA as "Guidelines for agricultural countermeasures following an accidental release of radionuclides" in 1994. Since then, new information on the behaviour of radionuclides in the environment and effectiveness of countermeasures in the long term has been obtained and reviewed by many projects, including the Chernobyl Forum. Additionally, new approaches to derive remediation strategies were developed and successfully implemented in the most affected countries. This paper describes a justification of the remediation strategies suggested for rehabilitation of the areas most affected by the Chernobyl accident based on this experience.

© 2010 Elsevier Ltd. All rights reserved.

1. Introduction

The accident at the Chernobyl NPP was the most serious radiation accident in the history of nuclear energy generation. High contamination levels of agricultural lands, forests and settlements by long-lived radionuclides dictate a need to ensure radiation safety of the population in the long term after the accident. The consumption of farm and forest products with high ^{137}Cs activity concentrations was and currently remains one of the major exposure pathways for the population of the affected regions (Fesenko et al., 2001, 2007; Jacob et al., 2001). Two decades after the accident, internal exposure of the population due to consumption of contaminated foodstuffs in the affected settlements comprises up to 50% of the total dose (IAEA, 2006; Balonov, 2007; Panov et al., 2007). The contribution of the internal dose is even higher in areas dominated by sand, peat and wet peat soils for which extremely high values of transfer factor from soil to food products were recorded even in the long term after the accident (Alexakhin, 1993; Balonov, 1993; Alexakhin et al., 1996; Jacob et al., 2001; IAEA, 2006).

Another general point is that the rural population dominates in the Chernobyl affected territory and doses for the rural residents are markedly higher than those for the urban population (Fesenko et al., 2001; IAEA, 2006).

In order to protect people against radiation exposure a wide range of large-scale remedial actions has been implemented in the affected areas. The efficiency of application of countermeasures and the amount of required resources depend on various factors, including deposition characteristics, soil and climatic conditions and agricultural production management (Bogdevitch et al., 2002). Furthermore, food product origin, distribution, and dietary habits also affect countermeasure efficiency. Because of these multiple factors affecting the suitability of each countermeasure, generalised recommendations often result in inadequate decisions (Fesenko et al., 2007). These considerations have led to a need in practical environmental decision support systems (EDSS) suitable for providing advice on agricultural countermeasure strategies at different levels of the decision-making process, taking into account temporal and spatial variations of the above factors (Fesenko et al., 2001, 2006; IAEA, 2006).

* Corresponding author.
E-mail address: s.fesenko@iaea.org (S. Fesenko).

0265-931X/$ – see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jenvrad.2010.08.012

Recommendations on the application of agricultural countermeasures were published by the International Atomic Energy Agency (IAEA) as “Guidelines for agricultural countermeasures following an accidental release of radionuclides” in 1994 (IAEA, 1994). Since then, new information on the behaviour of radionuclides in the environment and on the effectiveness of remedial actions in the long term after the Chernobyl accident has been obtained and reviewed by several international projects (Howard et al., 2004, 2007), including the Chernobyl Forum (IAEA, 2006; Fesenko et al., 2007). In addition, a new site-specific approach to derive countermeasure strategies was recently developed and successfully implemented in most affected countries to reduce Chernobyl-related radiation doses below the action level of 1 mSv a^{-1} currently established in all three countries (Jacob et al., 2001).

Overall, experience gained after the Chernobyl accident showed that rehabilitation strategies need to consider a wide range of issues to ensure the long-term sustainability of large and variously contaminated areas (Oughton et al., 2004; Cox et al., 2005). The holistic philosophy of such an approach, considering both environmental and social problems, is in line with the recent UN initiative known as “Strategy for Recovery” (UNDP–UNICEF, 2002).

Therefore, the IAEA initiated in 2003 a regional technical cooperation project called “Long-Term Countermeasure Strategies and Monitoring of Human Exposure in Rural Areas Affected by the Chernobyl Accident”, and in 2008 the project entitled “Radiological support for the rehabilitation of the areas affected by the Chernobyl nuclear power plant accident” continued this activity. In the framework of these projects, an internationally agreed methodology as well as a software tool called “ReSCA – *Re*mediation *S*trategies after the *C*hernobyl *A*ccident” for optimising rehabilitation strategies for the affected areas were developed and validated (Jacob et al., 2009; Ulanovsky et al., submitted for publication).

The software is based on two decades of experience in implementing countermeasures against radioactive contaminations in the aftermath of the Chernobyl accident (IAEA, 2001, 2006). The International Commission on Radiological Protection (ICRP, 2007) introduced the concept of a Representative Person for radiation protection purposes. The Representative Person is defined as a person, “who will … be a hypothetical construct, receives a dose that is representative of the more highly exposed individuals in the population”. The present work utilises a fully compatible definition, and the dose to the Representative Person is the main radiological criterion in optimising the process of remediation.

The objectives of this paper are: (i) to present the main findings of the above IAEA Chernobyl-related projects (ii) to discuss possible remediation strategies in areas affected by the Chernobyl accident, their costs and impacts on the dose distribution; (iii) to provide general recommendations on remediation strategies more than two decades after the Chernobyl accident.

More details on implementation of remediation strategies in the areas affected by the Chernobyl accident especially in terms of costs and averted doses and on their efficiency and the possibility of involving stakeholders in the remediation process and decision-making can be found elsewhere (Jacob et al., 2009).

2. Materials and methods

2.1. Remediation tool ReSCA

The remediation tool ReSCA has been developed with the aim to support decision-making on optimisation of remedial actions in the rural settlements contaminated after the Chernobyl accident (Ulanovsky et al., submitted for publication). The tool is easy-to-use and its user-friendly interface supports flexible decision-making. The application of the tool requires settlement-specific input information such as contamination levels of areas used in farming, the data on the consumption habits and ^{137}Cs activity concentrations in agricultural and forest products.

Table 1
Effectiveness, costs, and degrees of acceptability of the remedial actions offered for by the ReSCA tool. Costs for RI/SI/FA are per cow, others are given per inhabitant

Remediation action	Reduction factor	Degree of acceptability	Cost, €		
			Belarus	Russia	Ukraine
RI[a]	1.7 … 8	1	350	390	450
SI	2	1	300	340	400
FA	2 … 3	0.75	30	60	40
FP	3	0.6	6	7	20
MF	3	1	0.8	2.5	1
IM	1.5	0.5	3	3	3
RS	1.5	0.1	325	325	325

[a] The tool allows the simulation of various RI options: the first application, repeated application and RI consisting drainage with the different effectiveness and cost.

The remediation tool simulates the application of seven remedial actions (see Table 1): surface (SI) and radical (RI) improvement of meadows and pastures; ferrocyn application to cows (FA); feeding pigs with uncontaminated fodder before slaughter (FP); application of mineral fertilisers to potato fields (MF); information campaign on consumption of mushrooms and other forest products (IM); and removal of contaminated soil from populated areas, including disposal of contaminated soil (i.e. decontamination of the settlement, RS).

A detailed description of the agricultural countermeasures including necessary resources, limitations of the application, costs and times of effectiveness has been given by Fesenko et al. (2007). The implementation of the remedial action ‘Removal of contaminated soil from populated areas’ has also been described in Ulanovsky et al. (submitted for publication). Removal of soil around the houses of ten inhabitants in the area with the highest contamination is considered as one remedial action, followed eventually by a decontamination of the next highest contaminated houses of further ten inhabitants, and so on.

The tool allows a consideration of the RS application to a part of the settlement or its population. Side effects of the remedial actions are subjectively quantified by a ‘degree of acceptability’.

It has been assumed that decontamination is effectively permanent after its application, radical and surface improvement are assumed to be effective for four years, while other actions are effective for one year. When the information on food contamination is not readily available, contamination of the foodstuffs can be obtained by using data on soil contamination density by ^{137}Cs and generic transfer factors (T_{ag}) to crops evaluated for the long term after the accident (Ulanovsky et al., submitted for publication).

Social acceptabilities (degree of acceptability) of the above remediation actions were assessed based on a questionnaire study carried out in 2003 (Fesenko et al., 2007). However, for practical application in the framework of the tool algorithm these levels of applicability were transformed into a numeric scale from 0 to 1.

As mentioned earlier, experience gained after the Chernobyl accident shows that rehabilitation strategies need to consider a wide range of various aspects to ensure the long-term sustainability of affected regions (Oughton et al., 2004). The selection of remedial actions has to be based not only on radiological criteria but also on technical feasibility and acceptability of a countermeasure, ethical and environmental considerations, and requirements for effective public communication (Howard et al., 2004; Fesenko et al., 2007). If both radiological factors and socio-economic aspects are taken into account, better acceptability of countermeasures by the public can be achieved (Fesenko et al., 2007). Therefore, the ReSCA tool considers three aspects of remedial options: radiological, economic and social. In building remediation strategies, ReSCA chooses sequentially remedial actions with the largest value of the expression given below:

$$\beta \cdot \frac{\min(CD_r)}{CD_r} + (1-\beta) \cdot DA_r,$$

where CD_r is the cost of 1 man-Sv being averted as a result of application of the remedial action r; DA_r is the degree of acceptability of the corresponding action. Parameter β is intended allowing the user to give preferences either to economic or to social aspects of the remediation planning. Thus, for the value of $\beta = 1$ the remedial actions are ranked according to the costs per averted dose, while for the minimum $\beta = 0.01$ the ranking is mainly based on acceptability of remediation actions. The remediation strategy is sequentially built as a list of separate remediation actions until a) the total cost exceeds available funds allocated for remediation purposes or b) there are no more settlements with annual dose exceeding the control dose limit or c) there are no more possible remedial actions to undertake or d) the remaining possible actions are too costly (typically, more than 100 thousand Euro per man-Sv). Thus, for the given input and model parameters, several strategies can be generated varying the amount of available funds and/or user priorities.

Table 2
General characteristics of the test settlements.

Country	Belarus	Russia	Ukraine
Region	Gomel	Bryansk	Rovno
Settlement	Svetilovichi	Veprin	Yelne
Population	1100	290	770
Numbers of pastures	3	3	2
Number of cows	$70 + 24 + 16$[a]	$10 + 5 + 10$	$190 + 49$
Dominating soil types on pastures	Sandy (96%)	Peat (75%)	Wet peat (100%)
^{137}Cs activity per unit area, Bq m^{-2}	800	600	60
Doses according to dose catalogues (mSv a^{-1})			
External	1.0	1.6	0.2
Internal	0.9	3.0	5.5
Total	1.9	4.6	5.7

[a] Information is given for separate pastures.

2.2. Test settlements

The objectives of the implementation of remediation actions in the test settlements were twofold: to validate the algorithm and the data on remediation effectiveness used for the identification of optimal management actions and for testing the possibility to reach visible results taking into account a relatively high uncertainty in the measurements of both ^{137}Cs ambient activity concentrations and doses to the population.

In the first stage 12 settlements (4 per country) were selected from the entire set of the affected rural settlements and three of them (see Table 2) were selected in the second round of evaluations based on the following criteria: (i) altogether they cover the diversity of the environmental conditions in the most contaminated areas, (ii) doses to population are significantly above 1 mSv, (iii) the settlements are typical in size, farming practice and population, and (iv) they are not affected by recent application of countermeasures.

The inhabitants of Svetilovichi (Belarus) utilize three fields dominated by sandy soils (96%) for cow grazing and haymaking. The reaction of the soils varies from acid to neutral. These soils are characterised by a low fixation of ^{137}Cs and by high caesium transfer factors from soil to plants. However, intensive farming practices in general, and the application of remedial actions within past years (liming, application of mineral fertilisers and radical improvement) have resulted in a low ^{137}Cs transfer factors to plants. Nevertheless, the soils had some potential for further decrease of radionuclide accumulation in the local food, although it can be done to a lesser extent compared to other test settlements.

Soils in Veprin (Russia) are represented by peat and soddy-podzolic soils (75%). Twenty five percent of the soils are presented by peaty and flooded soils. These soils are characterised by high transfer rates of ^{137}Cs from soil to locally produced food products (especially milk) and, consequently, higher internal doses compared to external doses. For grazing cows and haymaking (main animal feeds in winter period) the inhabitants use mainly two meadows located on peaty/boggy soils in the floodplain of the Iput' River and one meadow created on former arable land.

Soils in Yelne (Ukraine) are represented by peat of a transitional type and low moor marshes, peat-bog and soddy-podzolic sandy light humified soils, characterised by extremely high ^{137}Cs transfer factors in a soil–plant system that predetermines extremely high ^{137}Cs transfer to agricultural products. Natural forage lands on peat-bog soils are characterised by low fertility and low quality of herbage consisting of sedge-cereals, miscellaneous grasses and a prevalence of rush (*Juncus* L.). High ^{137}Cs transfer factors are also determined by the species composition of fodder plants. Privately owned cows graze two large pastures where the application of remediation can reduce milk contamination considerably. The external dose to the Yelne population is very low because the ^{137}Cs density contamination of the Yelne territory was around 10 times lower compared to Veprin or Svetilovichi.

Radical improvement and ferrocyn (hexacyanoferrate compounds) in the form of bifege (addition to the diet of animals as a powder) were applied in all three settlements and the effects of their applications were documented at the different levels of application. The first stage of this activity comprised a survey of farming practices, agricultural lands, local consumption habits and monitoring of foodstuff contamination. Radical improvement of fodder lands was started in 2004, in order to prepare these fields for grazing and hay production in 2005–2006, while application of ferrocyn was started in autumn 2004 and lasted till spring 2005, depending on the preparedness of the settlement to implement the remedial actions.

For Russia and Ukraine, catalogue doses were taken directly from the official dose catalogues for the year 2004 (Russian Government, 2006; Likhtarev and Kovgan, 2005) while for Belarus (see Section 2.3) internal and external doses for this purpose were approximated based on the data on ^{137}Cs activity concentrations in food products.

The intensive monitoring programmes, including measurements of radioactivity in food and foodstuffs, WBC measurements, documenting feeding rations of animals and study of the dietary habits of the local population as well as documenting applications of the remedial actions, were performed in each test settlement and continued from 2003 to 2008.

The external doses to the population were based both on gamma-rate measurements at typical locations in Svetilovichi and Elne and TLD measurements in Veprin.

The WBC data used for assessment of the effectiveness of remedial actions in terms of dose reduction were obtained for the times when maximum remediation effect could be expected.

Thus, average effective doses to the inhabitants were estimated from the WBC and TLD measurements made in these settlement from 2001 to 2005, while factors 1.8 and 3 were taken to relate population-average external and internal doses to doses to the Representative Person, respectively (IAEA, 2006).

2.3. Data used for large-scale assessments

Settlements with less than 10 000 inhabitants, which had, according to official dose catalogues for 2004 (Russian Government, 2006; Likhtarev and Kovgan, 2005), annual doses exceeding 1 mSv, were taken for assessments. Unfortunately, these data were not available for Belarus, and the settlements for our assessments were selected on the basis of retrospective dose calculations to 2004 with aid of the ReSCA software (Jacob et al., 2009). Altogether, 541 settlements were considered as still "affected settlements", where application of remedial actions can be justified according to the national legislations of Belarus, Russia and Ukraine.

The data collected for these settlements included information on the number of inhabitants, the number of grassland areas for cows, the mean ^{137}Cs deposition density, the ^{137}Cs activity concentrations in beef, pork, potatoes and mushrooms, and the consumption rates of locally collected mushrooms relative to the average consumption of mushrooms in the country (Jacob et al., 2009).

3. Results and discussions

3.1. Effectiveness of remedial actions in the test settlements

A holistic approach was taken for the evaluating the remediation effects, and effectiveness of the individual remedial actions was monitored starting from the changes in the soil properties due to remediation and up to the reduction of effective doses to the population. Some examples of the results achieved within this monitoring program are given in Fig. 1 which shows that effect of remediation is observed at different levels of assessment: animal feeds → milk → internal dose. It has been also found that the reduction factors observed after remediation for animal fodder are higher than those for milk and the latter are higher than those calculated for the internal doses to the population. These differences can be explained by the fact that a certain fraction of the population did not use ferrocyn to dose cows regularly, and a fraction of locally produced agricultural products in the diet of the inhabitants was less than 100%.

3.2. Validation of the remediation tool based on the data from the test settlements

Mean reduction factors of ferrocyn application to cows (reduction factors) across all test settlements were 3.4 ± 2.0 for milk and 2.7 ± 1.8 for beef and these values are in agreement with the parameters used in the ReSCA. Observed values of reduction factors for radical improvement (2.0 ± 2.0 non-peat and 6.0 ± 3.0 for wet peat) are also in good agreement with the values accepted in the RESCA software tool for those parameters.

However, the complete ReSCA validation also requires a comparison of external or internal doses, calculated by the ReSCA, with the results of the measurements or corresponding estimates made in the test settlements (Table 3).

Internal and external doses, taken as doses before remediation, were measured in the test settlements in 2003–2004, while doses after remediation were based on measurements starting from 2005.

As mentioned earlier, no remedial actions against external exposure were implemented in the test settlements. Measurements

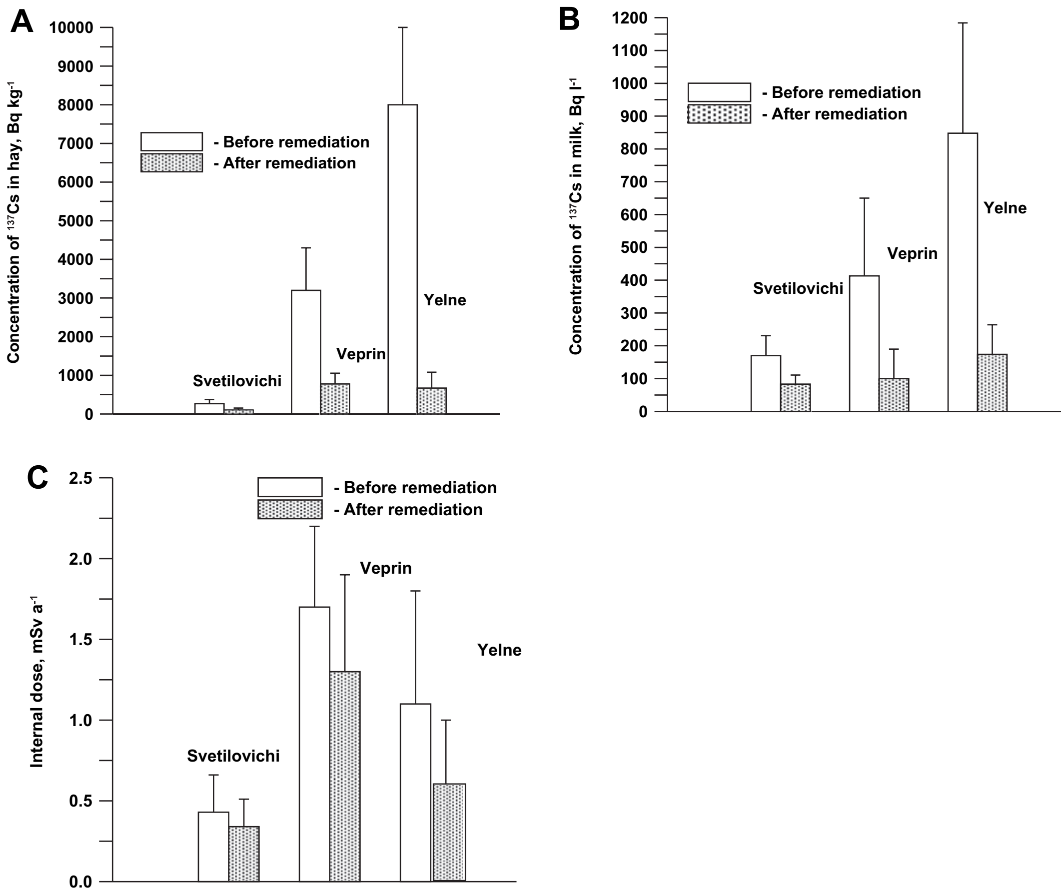

Fig. 1. Concentration of ^{137}Cs in hay (A), milk (B) and internal doses to the population in the test settlements before (white bars) and after (gray bars) remediation.

carried out in 2003–2004 suggested doses to the population of 1.0 ± 0.3 mSv a^{-1}, 0.9 ± 0.3 mSv a^{-1} and 0.1 ± 0.04 mSv a^{-1} for Svetilovichi, Veprin and Yelne, respectively. Accordingly, doses to the members of the critical groups of the population in these settlements were estimated as 1.8 ± 0.54 mSv a^{-1}, 1.6 ± 0.54 mSv a^{-1} and 0.2 ± 0.07 mSv a^{-1}. For the same conditions the ReSCA gave for these settlements external doses of 1.7 mSv a^{-1}, 1.2 mSv a^{-1} and 0.2 mSv a^{-1}. For Svetilovichi and Yelne these values are in good agreement with external dose values for these settlements given earlier, while for Veprin the mean value based on the TLD measurements is 1.3 fold higher than that given by the ReSCA.

Table 3
Internal doses to the population of the test settlements (mSv a^{-1}): ReSCA calculations compared to monitoring data.

Settlement	Monitoring data		ReSCA calculations
	Average dose	Representative Person	Representative Person
Dose before remediation			
Svetilovichy	0.5 ± 0.3	1.5 ± 0.9	0.7
Veprin	1.0 ± 0.6	3.0 ± 1.8	1.7
Yelne	1.6 ± 1.0	4.8 ± 3.0	2.9
Dose after remediation			
Svetilovichy	0.3 ± 0.2	0.9 ± 0.6	0.5
Veprin	0.4 ± 0.2	1.2 ± 0.6	0.7
Yelne	0.6 ± 0.4	1.8 ± 1.2	1.1
Ratio of dose before remediation to the corresponding dose after remediation			
Svetilovichy	1.7 ± 1.5	1.7 ± 1.5	1.6
Veprin	2.5 ± 2.0	2.5 ± 2.0	2.4
Yelne	2.6 ± 2.4	2.6 ± 2.4	2.6

Monitoring data on internal doses to the population or Representative Person for the test settlements and corresponding doses calculated by the ReSCA are given in Table 3.

It can be seen from Table 3 and data on the external doses presented earlier that both the external and the internal doses calculated by the ReSCA tool for the case “before remediation” are in a range between average doses measured in the test settlements and doses to a Representative Person calculated using the monitoring data. Indeed, it would be unrealistic to expect that the dose calculated by ReSCA value would exactly coincide with the monitoring data at the level of individual settlements.

It should also be mentioned that the external doses calculated by the ReSCA software tool for the remediation strategy actually implemented for 2005 and 2006 are in perfect agreement with the doses measured in test settlements, while the internal doses calculated by the ReSCA tend to be lower compared to the doses to a Representative Person calculated using the monitoring data. On the other hand such differences are statistically insignificant and the measured effectiveness of remediation in terms of internal dose reduction (ratio of the internal doses before remediation to those after remediation) almost coincides with the expected effectiveness calculated by the ReSCA (Table 3).

These facts lead to the conclusion that the effectiveness of remedial actions expressed as reduction factors calculated by the ReSCA software tool is in good agreement with the reduction factors derived from the monitoring data.

Besides the test settlements, the internal dose calculations were also validated using extensive sets on whole body measurements in settlements within contaminated territories of Belarus, Russia, and Ukraine (Jacob et al., 2009). The validation of the approach used for

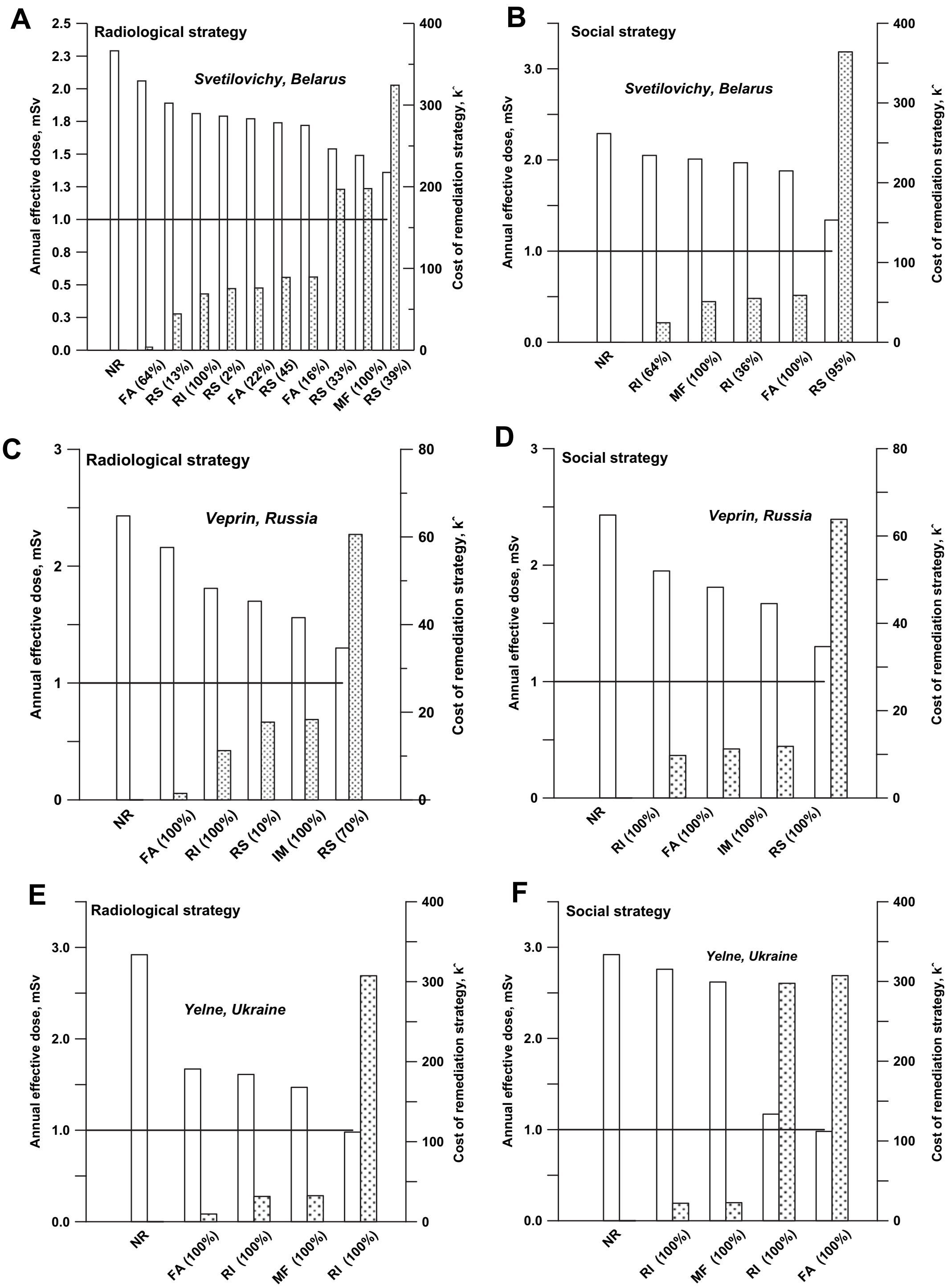

Fig. 2. Effectiveness of the remedial actions in terms of dose reduction and the related costs. Effective dose values are shown by empty bars (left axis) and remediation costs by shaded bars (right axis).

the external dose assessments at the regional scale is also given elsewhere (Golikov et al., 1999). The results of the validation given in the paper demonstrate the robustness of the approach, showing agreement between experimental and calculated values for diverse site-specific environmental conditions and farming practices.

No new experiments with soil removal from the populated areas were performed in the test settlements, bearing in mind that sufficient information on this subject was obtained previously (Golikov et al., 1999, 2002; IAEA, 2006).

3.3. Justification of remediation strategies at different levels of decision-making

When planning remediation in the areas affected by the Chernobyl accident it is important to consider local (individual settlements) and regional (affected regions) factors. Decisions at the local level are mainly related to optimisation of the remedial actions which result in a decrease of the population doses below the action level. At the regional level, the considerations are mainly focused

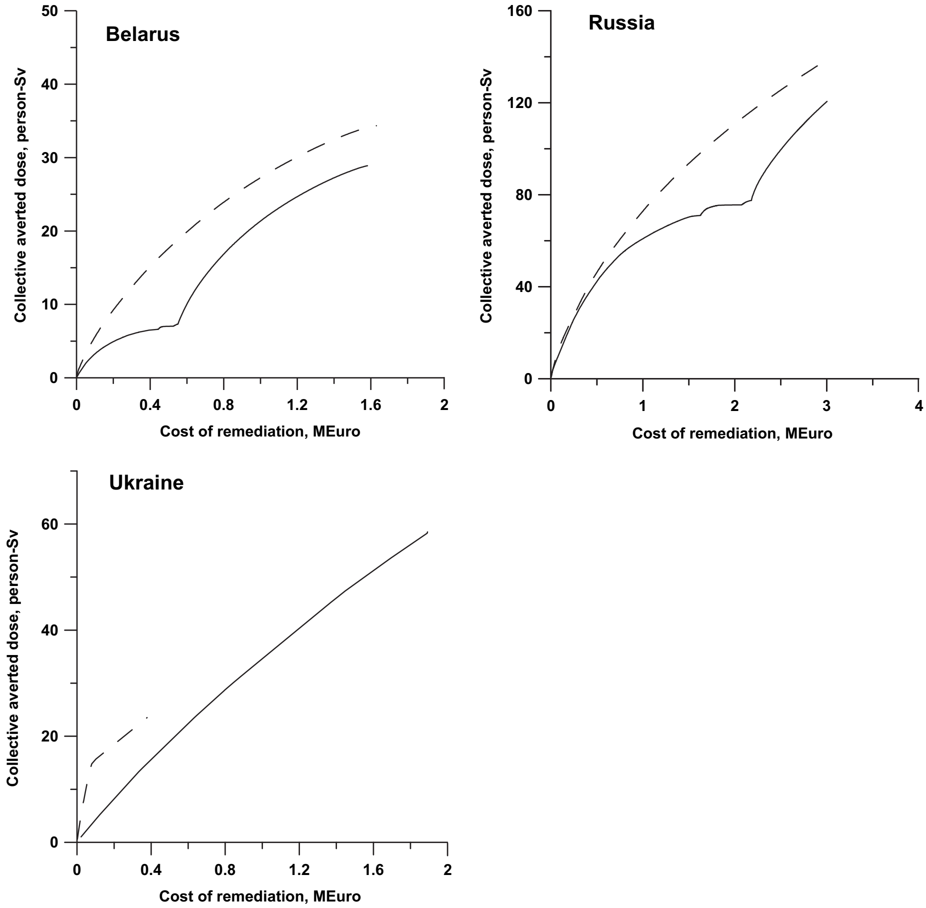

Fig. 3. Total averted collective dose (person-Sv) as function of funds invested in remediation in three countries. (Solid line corresponds to the social strategy and dashed line to the radiological strategy.)

on a justification of the investments in remediation from the national budgets provided on national-specific priorities and perspectives. Regional cost estimates and a contribution to mitigation of the health effects are also subjects for consideration at the regional level.

3.3.1. Remediation planning at the level of individual settlements

Examples of the application of the ReSCA tool to remediation planning in the test settlements are shown in Fig. 2. Two strategies based on alternative priorities were developed and they formed a basis for further analysis. The first strategy was based on ranking of remedial actions according to their costs per averted dose (radiological approach), while the second one was based on the ranking according to public acceptance of remediation actions (social approach).

The data given in Fig. 2 show that the radiological strategy (Fig. 2a, c and e) provides more flexible, complex and step-wise scenarios of remediation, including, for Belarusian and Russian settlements, decontamination of certain parts of the populated areas. Applications of ferrocyn to cows followed by radical improvements implemented to the most contaminated animals and areas are a specific focus of the suggested scenarios. The social approach (Fig. 2b, d and e) demonstrates more straightforward remediation scenarios, giving priorities to radical improvement, fertilisation of potato fields and application of ferrocyn to cows. Removal of soil from the populated areas appears always at the end of the remediation scenarios because of both high cost and low acceptability of the action by the population.

As mentioned earlier, the test settlements were selected among the settlements with relatively high effective doses to the population, where different environmental properties did not guarantee successful rehabilitation. Thus, the reduction of the effective dose below 1 mSv a^{-1} in the test settlements could not always be achieved, even if all possible options (including soil removal in populated areas) could be implemented. It should also be mentioned that in many cases a substantial decrease of the effective doses can be achieved only by application of very expensive actions and such remediation strategies appear to require further justification based on more detailed analysis of the remediation plans.

Overall, the results obtained confirm that the reduction of the internal doses in the settlements, where environmental conditions are favourable for application of remedial actions, is a more realistic task than decreasing the external exposure. Thus, application of radical improvement in Yelne, where this measure is highly effective because of the wet peat soil, which is specific for this settlement, allowed a decrease in annual effective dose from 2.9 to 0.98 mSv, i.e. below the action level of 1 mSv a^{-1}. It should be emphasised that this effect was exclusively achieved by agricultural remedial actions. Unfortunately, it was not the case for Svetilovichi where the total dose decreased from 2.3 to 1.3 mSv and in Veprin where reduction of the total dose from 2.4 to 1.3 could be achieved only after application of all possible remedial actions.

3.3.2. Remediation planning at the large-scale level

The present paper is based on information obtained from rural settlements, where annual effective doses exceeded 1 mSv in 2004.

Table 4
Costs, averted doses and costs per averted dose for two remediation strategies calculated under assumption if 1 M€ are available for remediation in each affected country.

Country	Cost of remediation, M€		Averted dose (man-Sv)		Costs of 1 man-Sv averted, k€	
	Radiological strategy	Social strategy	Radiological strategy	Social strategy	Radiological strategy	Social strategy
Belarus	1.0	1.0	27.3	21.4	37	47
Russia	1.0	1.0	73.0	61.1	14	17
Ukraine	0.38	1.4	23.5	45.3	16	30
Total	2.4	3.4	123.9	127.8	19	27

For each of these settlements, calculations of the effective doses to the Representative Person were performed. The dose to the Representative Person was defined by the sum of the averages of the upper deciles of the effective dose distributions from external and internal exposures. All settlements, which according to the ReSCA calculations had in 2004 annual doses exceeding 1 mSv, were defined as 'affected settlements' and were therefore eligible for consideration for remedial actions.

Among the 545 settlements, listed in the national dose catalogues, there were only 290 settlements, in which in 2004 the effective dose for the Representative Person exceeded 1 mSv. In total, these affected settlements had 78 172 inhabitants and most of them (57 960) lived in the Russian settlements. The number of settlements with annual doses exceeding 1 mSv is expected to decrease due to natural processes and radioactive decay until 2020 to 121 settlement with 35 044 inhabitants. Thus, without remedial actions the number of inhabitants in settlements with annual doses exceeding 1 mSv would decrease slowly. Collective dose assessed for 2004 for the affected settlements is about 65 man-Sv, three quarters of this occurring in Russia (Jacob et al., 2009). The distributions of the doses of external and internal exposures in the affected settlements differ in the three countries: in Belarus, external exposure dominates; in Russia, both pathways are equally important; in Ukraine, the dose is mostly due to internal exposure. In about half of the Belarusian and Russian affected settlements, the annual dose from consumption of mushrooms and forest products is comparable to the annual dose from milk. In Ukraine, however, milk is a major source of internal exposure in most of the affected settlements.

As in the case of the test settlements, in order to consider possible alternatives the assessments were made for two different remediation strategies for the year 2010: the social strategy which gives a higher importance to public acceptability of the suggested remedial actions, and the radiological strategy which is based on minimisation of costs per averted dose. Social remediation Strategy was derived for β equal to 0.1, i.e., the degree of acceptability of the remedial actions was considered to be important for developing the strategy. Radiological remediation strategy was derived for β equal to 1.0, i.e., only costs per averted dose are taken into account in the process of optimisation.

The results of the ReSCA calculations show that in Belarus, the social strategy shares the resources between radical improvement or ferrocyn application to cows and removal of contaminated soil from populated areas, while the radiological strategy focuses mainly on soil removal.

In Russia, the social strategy recommends radical improvement and ferrocyn application, while the radiological strategy suggests resources should be shared between radical improvement (or ferrocyn application) and soil removal.

In Ukraine, the radiological strategy reduces annual doses in all affected settlements below 1 mSv with costs of less than 0.4 M€. The strategy is based on ferrocyn application to cows with recommendations to implement radical improvement in a few cases. On the other hand, the radiological strategy considers mainly radical improvement with additional applications of ferrocyn only in the settlements where the effectiveness of radical improvement is not sufficient to reduce effective doses below 1 mSv a^{-1}.

The effect of the remediation is dependent on both site-specific factors, which are directly included in the analysis, and availability of funds for remediation purposes. Thus, the relationships, reflecting dependence of averted doses on the remediation costs, turn out to be different among affected countries (Fig. 3). In Belarus the trends, reflecting increase of the averted dose with the invested funds, become similar for two strategies considered if funds available for remediation purposes exceeds 1 M€ and in Ukraine if they are higher 0.1 M€ (Fig. 3). In Russia, the significant difference between two strategies persists up to several M€ of available funds, because of the larger number of the affected settlements (Fig. 3).

In contrast to Belarus and Ukraine, the cost-effectiveness of two strategies is similar in Russian affected settlements, if the available resources are below 0.5 M€, while the social strategy begins to be less cost-effective compared to the radiological strategy at higher expenditures (see Fig. 3).

The radiological strategy pays more attention first to applications of ferrocyn to cows, this action has to be applied continuously, and then, in Belarus and Russia, the strategy recommends removal of highly contaminated soil from the populated areas. This second action, although being quite effective in reduction of external doses to the population, raises substantial problems with disposal of the contaminated soil.

Overall, the social strategy is considerably less cost-effective and requires larger resources for the remediation due to wider application of radical improvement (Table 4). However, compared to international values for the cost-effectiveness of actions for reducing occupational exposures, both remediation strategies are still quite cost-effective, varying from 14 k€ person-Sv^{-1} (Ukraine, the radiological strategy) to 47 k€ person-Sv^{-1} (Belarus, the social strategy). It should be also mentioned that in terms of the averted collective dose the effectiveness of these strategies is similar and quite high, averting 120–130 person-Sv depending on the remedial actions implemented.

The relationships between the number of the affected settlements where annual doses are above 1 mSv a^{-1} and the related population, as a function of funds available for remediation, are given in Fig. 4. It can be seen from these data that in both remediation scenarios (Fig. 4), the numbers of settlements with annual doses exceeding 1 mSv after remediation are quite similar in Belarus and Russia. The radiological strategy is considerably more effective in terms of reduction of the number of affected settlements compared to the social strategy only in Ukraine. With the aid of the radiological strategy the annual dose in all settlements can be reduced below 1 mSv with a relatively small investments to the remediation.

It can be also seen from Fig. 4 that, independently of the remediation strategies, implementation of all possible remedial actions in Belarus and Russian will not allow one to eliminate the settlements with annual effective dose above 1 mSv a^{-1}.

Although the collective doses which can be averted by remediation, are quite high for both strategies, the number of inhabitants in Belarusian and Russian settlements with annual doses

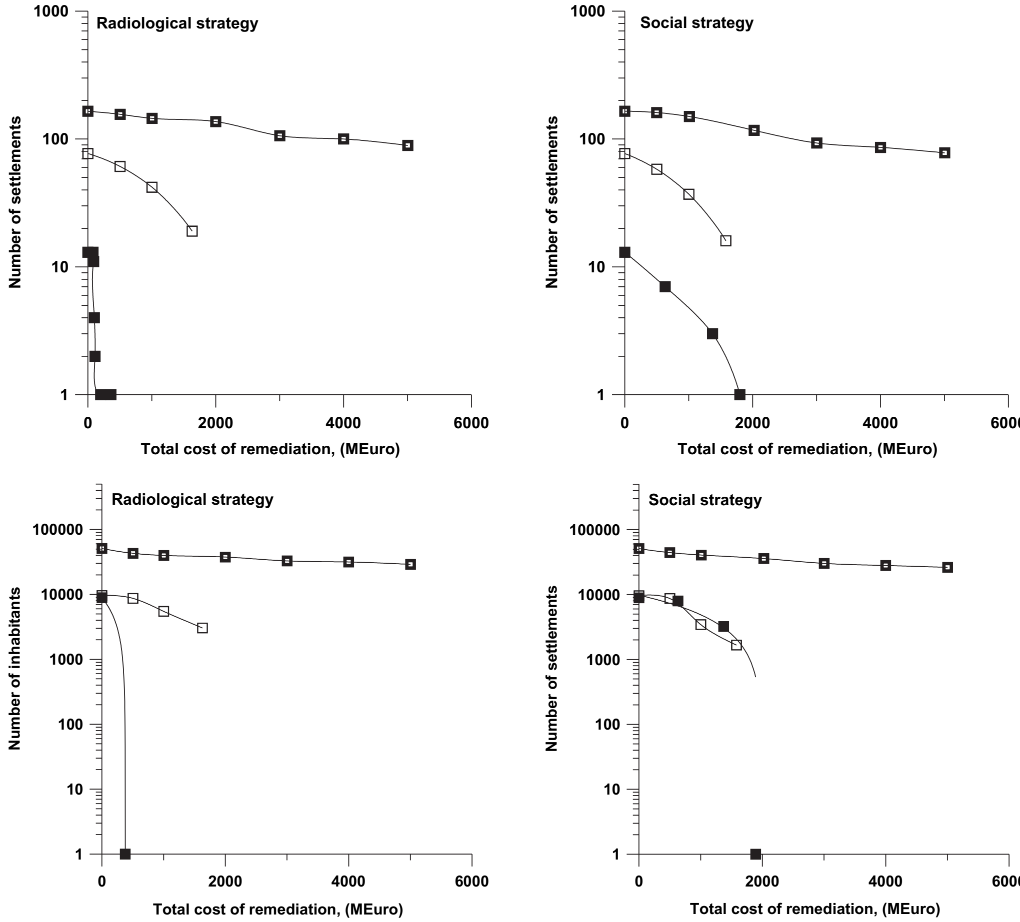

Fig. 4. Variations in the number of settlements and the population in the settlements (lower row) where annual effective dose exceeds 1 mSv (upper row) with funds allocated for remediation purposes.

exceeding 1 mSv remains large (Fig. 4). In Belarus in 2010, after application of all possible countermeasures, which cost approximately 1.6 M€, a significant number of people (several thousands, depending on the strategy) remain living in settlements with annual dose exceeding 1 mSv. In Russia, for the same case (if all possible remedial actions were to be implemented) even the investment of 5 M€ will not allow the reduction of the effective dose below 1 mSv a^{-1} in settlements with more than 26 000 inhabitants.

Thus, in such settlements no further remediation is possible even though the annual doses still exceed the allowable dose constraint. Therefore, it is necessary to continue development and application of new remedial actions, especially those aimed at reducing radiocaesium uptake by forest products, like mushrooms and berries.

4. Conclusions

The current analysis of possible strategies for remediation of rural areas affected by the Chernobyl accident, for cases where annual effective dose for Representative Person exceeds 1 mSv, shows that even two decades after the Chernobyl accident application of remedial actions is still cost-effective. Thus, further remediation of affected areas allows considerable reduction in the exposure of the population in the long term after the accident.

In Belarus, regardless of the fact that disposal of the contaminated soil can raise some problems, special attention should be paid to the high cost-effectiveness (in term of total dose reduction) of removal of contaminated soil from populated areas. In conditions where wide application of agricultural remedial actions has already provided substantial reductions in internal dose, this option is a method which can provide further mitigation of the consequences of the Chernobyl accident.

In Russia, agricultural remedial actions should be kept as a central element of remediation strategies. Consumption of contaminated milk is still an important pathway for radiation exposures in the aftermath of the Chernobyl accident. Depending on the strategy, smaller or larger amounts of resources should be invested in removal of contaminated soil from populated areas.

In Ukraine, only agricultural remedial actions such as radical improvement of fodder lands or application of ferrocyn to cows are advisable. External doses to the rural population are quite low because inhabitants of the settlements contaminated with ^{137}Cs higher than 555 kBq m^{-2} were resettled. Therefore, a reduction of total annual doses below 1 mSv can be achieved with involvement of very limited resources.

References

Alexakhin, R.M., 1993. Countermeasures in agricultural production as an effective means of mitigating the radiological consequences of the Chernobyl accident. Sci. Total Environ. 137, 9–20.

Alexakhin, R.M., Fesenko, S.V., Sanzharova, N.I., 1996. Serious radiation accidents and the radiological impact on agriculture. Radiat. Prot. Dosimetry 64, 37–42.

Balonov, M., 2007. Retrospective analysis of impacts of the Chernobyl accident. Health Phys. 93, 383–409.

Balonov, M.I. (Ed.), 1993. Guide-Book on Radiation Situation and Radiation Doses Received in 1991 by Population of Areas of Russian Federation Subjected to Radioactive Contamination Caused by the Accident at the Chernobyl NPP. Ariadna – Arcadiya Publishers, Saint Petersburg (in Russian).

Bogdevitch, I., Sanzharova, N., Prister, B., Tarasiuk, S., 2002. Countermeasures on natural and agricultural areas after Chernobyl accident. In: Kolejka, J. (Ed.), Role of GIS in Lifting the Cloud off Chernobyl. Kluwer Academic Publishers, pp. 147–158.

Cox, G., Beresford, N.A., Alvarez, B., Oughton, D., Kis, Z., Eged, K., Thørring, H., Hunt, J., Wright, S.M., Barnett, C.L., Gil, J., Howard, B.J., Crout, N.M.J., 2005. Identifying optimal agricultural countermeasure strategies for a hypothetical contamination scenario using the STRATEGY model. J. Environ. Radioact. 83, 383–397.

Fesenko, S.V., Alexakhin, R.M., Balonov, M.I., Bogdevitch, I.M., Howard, B.J., Kashparov, V.A., Sanzharova, N.I., Panov, A.V., Voigt, G., Zhuchenka, Yu.M., 2007. An extended critical review of twenty years of countermeasures used in agriculture after the Chernobyl accident. Sci. Total Environ. 383, 1–24.

Fesenko, S.V., Jacob, P., Alexakhin, R., Sanzharova, N.I., Panov, A., Fesenko, G., Cecille, L., 2001. Important factors governing exposure of the population and countermeasure application in rural settlements of the Russian Federation in the long term after the Chernobyl accident. J. Environ. Radioact. 56, 77–98.

Fesenko, S.V., Alexakhin, R.M., Balonov, M.I., Bogdevich, I.M., Howard, B.J., Kashparov, V.A., Sanzharova, N.I., Panov, A.V., Voigt, G., Zhuchenka, Yu.M., 2006. Twenty years' application of agricultural countermeasures following the Chernobyl accident: lessons learned. J. Radiol. Protect 26, 351–359.

Golikov, V., Balonov, M., Erkin, V., Jacob, P., 1999. Model validation for external doses due to environmental contaminations by the Chernobyl accident. Health Phys. 77, 654–661.

Golikov, V., Balonov, M., Jacob, P., 2002. External exposure of the population living in Russian areas contaminated due to the Chernobyl accident. Radiat. Environ. Biophys. 41, 185–193.

Howard, B.J., Beresford, N.A., Voigt, G., 2007. Countermeasures for animal products: a review of effectiveness and potential usefulness after an accident. J. Environ. Radioact. 56, 115–137.

Howard, B.J., Liland, A., Beresford, N.A., Andersson, K.G., Cox, G., Gil, J.M., Hunt, J., Nisbet, A., Oughton, D., Voigt, G., 2004. A critical evaluation of the strategy project. Radiat. Prot. Dosimetry 109, 63–67.

IAEA, 1994. Guidelines for agricultural countermeasures following an accidental release of radionuclides. IAEA Technical Reports Series No. 363.

IAEA, 2001. International Atomic Energy Agency. Present and Future Environmental Impact of the Chernobyl Accident. TECDOC-1240. IAEA, Vienna, 128 pp.

IAEA, 2006. Environmental Consequences of the Chernobyl Accident and Their Remediation: Twenty Years of Experience. Report of the Chernobyl Forum Expert Group. International Atomic Energy Agency, Vienna.

ICRP, 2007. Assessing Dose of the Representative Person for the Purpose of Radiation Protection of the Public and the Optimisation of Radiological Protection: Broadening the Process. ICRP Publication 101. Elsevier.

Jacob, P., Fesenko, S., Firsakova, S.K., Likhtarev, I.A., Schotola, C., Alexakhin, R.M., Zhuchenko, Y.M., Kovgan, L., Sanzharova, N.I., Ageyets, V., 2001. Remediation strategies for rural territories contaminated by the Chernobyl accident. J. Environ. Radioact. 56, 51–76.

Jacob, P., Fesenko, S., Bogdevitch, I., Kashparov, V., Sanzharova, N., Grebencschikova, N., Isamov, N., Lazarev, N., Panov, A.V., Ulanovsky, A., Zhuchenka, Y.M., Zhurba, M., 2009. Rural areas affected by the Chernobyl accident: radiation exposure and remediation strategies. Sci. Total Environ. 408, 14–25.

Likhtarev, I.A., Kovgan, L.M., 2005. General Dosimetric Passportisation of Settlements in Ukraine Radioactive Contaminated after Chernobyl Accident, Summarised data for 2001–2004 p. (Collection 10). MES, Kiev, 57 pp. (in Russian).

Oughton, D., Forsberg, E.-M., Bay, I., Kaiser, M., Howard, B., 2004. An ethical dimension to sustainable restoration and long-term management of contaminated areas. J. Environ. Radioact. 74, 171–183.

Panov, A.V., Fesenko, S.V., Alexakhin, R.M., Pasternak, A.D., Prudnikov, P.V., Sanzharova, N.I., Goriainov, V.A., Novikov, A.A., Muzalevskaya, A.A., 2007. Radioecological situation in the agricultural sphere in the contaminated areas of Russia in the long term after the Chernobyl NPP accident. Radiatsionnaya biologiya. Radioekologiya 47, 423–434 (in Russian).

Russian Government, 2006. Average annual effective doses of irradiation in 2004 to the residents of settlements of the Russian Federation assigned to zones of radioactive contamination by the RF Governmental Act No. 1582 of 18 December 1997 "On approving the list of settlements located within the radioactive contamination zone after the accident at the Chernobyl NPP". Information Bulletin, Moscow, 176 p. (in Russian).

Ulanovsky, A., Jacob, P., Fesenko, S., Bogdevitch, I., Kashparov, V., Sanzharova, N. ReSCA – remediation strategies after the Chernobyl accident. Environ. Model. Softw., submitted for publication.

UNDP–UNICEF, 6 February 2002. The Human Consequences of the Chernobyl Nuclear Accident. A Strategy for Recovery. A report commissioned by UNDP and UNICEF with the support of UN-OCHA and WHO. UNDP, New York. http://chernobyl.undp.org/english/docs/strategy_for_recovery.pdf.