Evaluation of the effectiveness of agricultural countermeasures after the accident at the Chernobyl NPP

Fesenko S.V., Sanzharova N.I., Lisyansky K.B.

Russian Institute of Agricultural Radiology and
Agroecology of RAAS, Obninsk

A brief description is presented of the decision support system FORCON that provides advice on agricultural countermeasure strategy on contaminated territory. A comparative analysis is made of different strategies of countermeasure implementation in the settlements that are situated on the contaminated territory. It has been shown that implementation of the most effective of the possible countermeasures could provide a 3-fold decrease in collective doses from the consumption of food produced in the affected areas.

The provision of rational farming under unfavorable ecological conditions [1, 2] is one of the problems of the rehabilitation of territories subjected to radioactive contamination. The problem is multifactoral and multioptional. It is therefore necessary that methods and software be developed and practically realized to provide informational and analytical support to those involved in the solution of this problem. This should include the development of computer systems for analyzing possible variants of agricultural production in contaminated areas and application of countermeasures in these situations.

Currently, the general strategy for the application of countermeasures in the contaminated regions of the Russian Federation is aimed at reducing the collective dose from the consumption of food-stuffs containing radionuclides [3]. Among the criteria for assessing the effectiveness of countermeasures one should consider, along with the traditional ones (decrease in the contamination levels of products), the averted dose resulting from the application of countermeasures (or dose saving). This is calculated as differences in collective doses to the population from the consumption of contaminated food-stuffs before and after the application of protective measures. One should also consider the cost of countermeasures and the averted dose normalized to costs.

To provide informational and analytical support for the solution of the above problems, a computer system FORCON was used at the Russian Institute of Agricultural Radiology and Agroecology (RIARAE). It has been developed as part of the International Project on the Consequences of the Chernobyl Accident jointly with the UK National Radiological Protection Board [4].

This system includes the following computational scheme and information required for the organization of agricultural production in contaminated areas:

- Analysis of the radiological situation and identification of possible directions of the application of countermeasures for the rehabilitation of contaminated agricultural lands.
- Modelling of protective measures with taking into account the existing conditions. Defining of scenarios of their application. Calculations of countermeasure costs and changes in the contamination level of farm products after countermeasure application.
- Analysis of the effectiveness of different scenarios and choice of the optimal variants of the organisation of agricultural production with the account of real conditions (e.g., availability of necessary resources and finances).

To provide further selection of possible options of countermeasures, additional information is available including an assessment of the potentialities of a farm in terms of the production of food-stuffs that satisfy the radiological standards, an assessment of countermeasure effectiveness on each individual field, as well as the effect from the allocation to other crops to each fielde. In total, this information offers the identification of those actions that would be most adequate in terms of farming organization. The following criteria are used in the system for evaluating the radiological situation and justifying the application of countermeasures:

- derived intervention levels (DILs) that limit the use of farm products in term of radionuclide content;
- the collective dose from the consumption of products before and after protective measures application, as well as dose saving as a result of the implementation of countermeasures;
- economic and combined indicators (amount and cost of resources for countermeasure application, dose saving normalized to the cost of measures).

Based on the analysis of the radiological situation on farms, variants of the organisation of agricultural production and countermeasure application are specified. For each variant the parameters corresponding to the above criteria are calculated making it possible to choose the most justified ways for obtaining safe products. Dialog mode computations allow one to make flexible decisions with taking into consideration specific features of the situation, which makes the FORCON system quite an effective tool for the support of decision making on the organisation of farming in contaminated areas. Figure 1 shows the FORCON conceptual scheme.

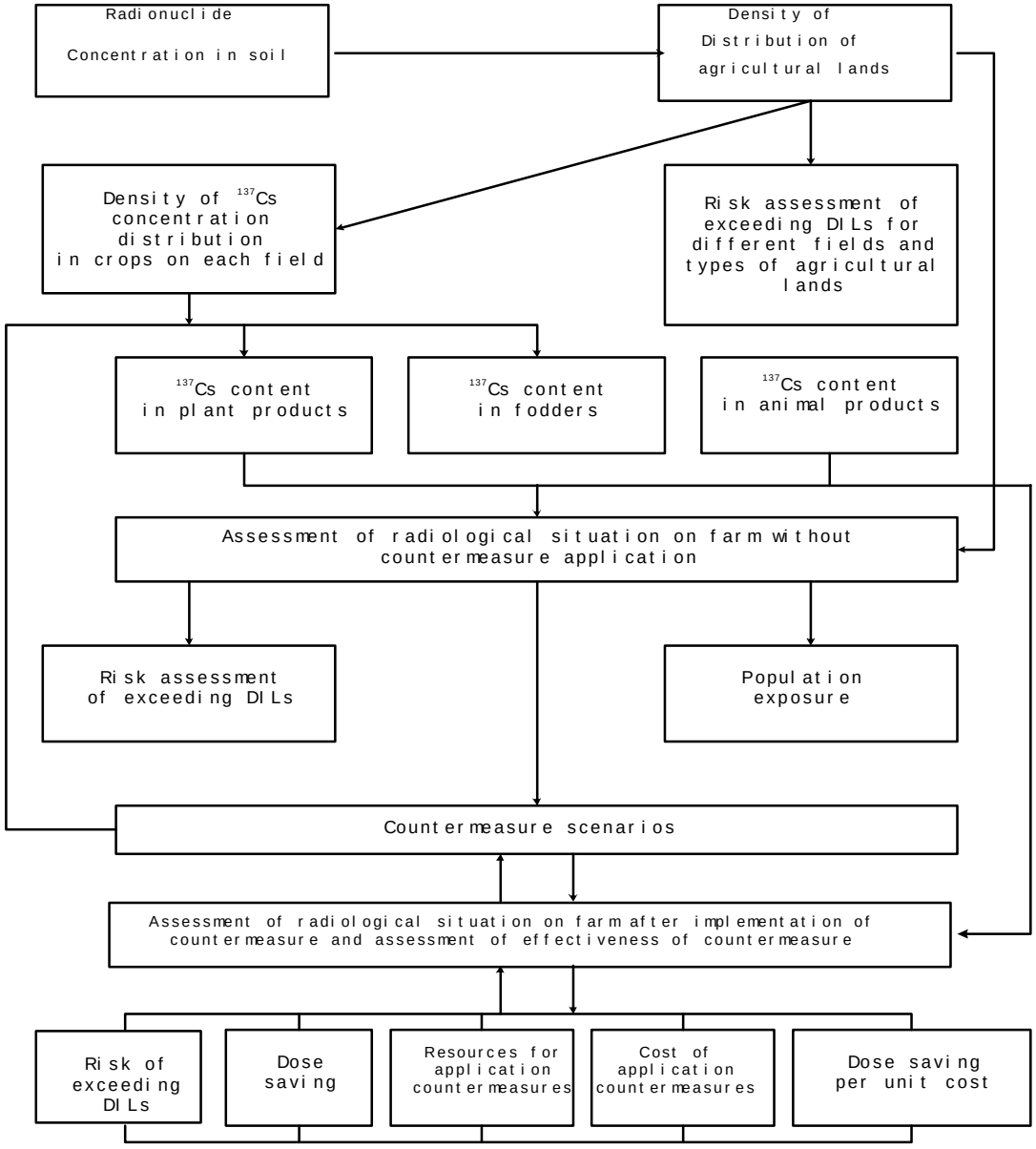

Fig. 1. FORCON conceptual scheme.

The FORCON system makes an assessment of the effect of 12 types of countermeasures. Each type includes different variants of their application. During every year after the accident different countermeasure combinations can be considered. A total of 300 various combinations of protective measures can be assessed within the FORCON system allowing a comprehensive analysis of a wide range of possible decisions to be made to ensure safe farming in different time periods following the radioactive contamination. Each countermeasure combination presents an individual scenario.

For a comparative analysis of different strategies of countermeasure application in agriculture, data of the field survey of the collective farm "Avangard", Zhizdra district, Kaluga region, as well as the information on this farm available in the RIARAE data base were employed. Previously (in 1991-1993), this farm was a base for practicing the technologies of farming in the contaminated districts of the Kaluga region. It is therefore a suitable site to study various strategies of countermeasure application. A preliminary analysis of the data available has shown that this farm is a typical one for the contaminated regions of Russia in both the levels of contamination and the soil properties, as well as other conditions of farming. Therefore, the results presented in this paper are general in nature and applicable to a wide range of situations.

The agricultural lands of the collective farm "Avangard" cover an area of 3456 ha: 2234 ha of arable land, 517 ha of hayland and 705 ha of pastures. The overall

area where field crops are rotated is 1172 ha, where fodder crops are rotated - 915 ha. The soils of the agricultural lands are mainly soddy-podzolic sandy and light sandy loam, in some localities peat-swamp soils can be found.

The contamination levels on agricultural lands vary between 40 and 240 kBq/m^2. A specific feature of farming in the collective farm "Avangard" is that lands used for hay production and pasturing are located on peat soils which show a high migration ability of radionuclides within the soil-plant system. Only a limited application of protective measures were applied to this farm. Since 1989, there have been increased rates of K fertilisers and liming.

A scenario based on the existing land use structure without application of countermeasures was taken as a reference (base) variant used for a comparative assessment of the effectiveness of possible options of farming and evaluation of the efficiency of the countermeasures proposed. The ^{137}Cs levels in major products obtained from the farm are presented in Table 1. The collective dose from the consumption of these products amounts to 356 mSv.

Agrochemical countermeasures. To assess the effectiveness of agrochemical countermeasures for cereals, calculations have been made for two key in this region crops - winter rye and barley. In this case the effectiveness was studied of 7 possible variants of mineral and organic fertilising, as well as liming at different rates (Table 2). It should be noted that the effectiveness of agrochemical measures in terms of decreasing the contamination of products is quite close for winter and spring (barley) crops. These countermeasures are, however, significantly different in the viewpoint of the averted dose per unit cost.

Table 1
^{137}Cs content in farm products for conventional technologies, Bq/kg (1996)

Product	Specific ^{137}Cs content in farm products, Bq/kg (l)	
	Average	SD
	Plant products	
Winter rye (grain)	5.2 (671)	6
Barley (grain)	12.5 (189)	22
Potatoes	9.5 (1260)	7
Coarse fodder	72.3 (6590)	29
Succulent fodder	14.5 (7150)	48
Green fodder	35.3 (8958)	75
	Animal products	
Pasture period		
Milk	13.5 (802)	28
Meat	32.6 (20)	41
Indoor period		
Milk	4.1 (1093)	5
Meat	10.2 (27)	8

Note: In brackets is the amount of products in tonnes.

Table 2
Comparative assessment of the effectiveness of agricultural measures

Treatments	Average ^{137}Cs content in products, Bq/kg	Averted dose, person - mSv	Costs, thousand roubles (in prices of 1966)	Averted dose normalized to costs, person -mSv/mln roubles
	Barley (grain)			
Conventional technologies	12.5	0.0	0.0	0.0
$N_{80}P_{120}K_{160}$	7.0	6.3	18.5	0.34
Lime 1.5 Hg + $N_{60}P_{60}K_{60}$	5.9	11.2	16.3	0.69
Lime 1.5 Hg + $N_{60}P_{60}K_{60}$ + + manure 60 t/ha	5.6	10.7	134.6	0.08
Lime 1.5 Hg + $N_{80}P_{90}K_{160}$ + + manure 60 t/ha	5.0	4.3	148.4	0.03
	Winter rye (grain)			
Conventional technologies	5.2	0.0	0.0	0.0
$N_{80}P_{120}K_{160}$	3.1	8.5	50.0	0.17
Lime 1.5 Hg + $N_{60}P_{60}K_{60}$	2.3	15.4	69.2	0.22
Lime 1.5 Hg + $N_{60}P_{60}K_{60}$ + + manure 60 t/ha	2.4	13.6	81.5	0.17
Lime 1.5 Hg + $N_{80}P_{90}K_{160}$ + + manure 60 t/ha	2.2	5.5	401.4	0.01

The most effective countermeasure is liming at 1.5 Hg combined with increased rates of mineral ($N_{80}P_{90}K_{120}$) and organic (60 t/ha) fertilisers. This results in the resulting in the maximum reduction in ^{137}Cs uptake. At the same time it should be noted that manure application under winter crops is rather expensive (about 400 million roubles in 1996 prices). It is therefore necessary that a comprehensive approach to the assessment of the effectiveness of countermeasures be employed. Besides, the absolute dose saving resulting from these countermeasures is generally very low. This is connected with the yield increase as a result of countermeasure application and, as a consequence, with increased flux of radionuclides with farm products. Almost as effective is liming combined with usual or slightly increased rates of mineral fertilisers. Analysis using an additional criterion the averted dose per unit cost which amounted to 0.22 mSv/mln roubles for 1996 shows that this countermeasure is the most effective one in terms of both radiological criteria (decrease in ^{137}Cs content in products and decrease in internal irradiation) and costs.

It should also be noted that some countermeasures can have a dual effect. Thus, the application of higher rates of mineral fertilisers on low-fertile soils resulting in a significant decrease in the contamination of cereal crops can cause an increase in the collective dose from the consumption of these products by the population. It can be explained by the fact that higher rates of fertilisers are responsible for higher crop yields and in this connection for higher amounts of radionuclides uptaken in the human diet. On the other hand, the application of lime on acid soils, along with the reduction in ^{137}Cs availability for plants, causes a decrease in the content of nutrients in soil and, as a consequence, a decrease in yield. This shows the need for a weighted approach to the decision making on the application of agrochemical measures.

Changes in the land use structure. The computational results show that changes in the land use structure is an effective countermeasure option for the given farm. Thus only one measure - not to use peaty soils for growing fodder crops and pasturing and to use these for growing cereal crops which show minimum accumulation of radionuclides - provides an annual decrease in the collective dose from the consumption of plant and animal products of 25 to 48%, with ^{137}Cs content in milk in the pasture period being reduced by more than 50%. It should be stressed that this countermeasure will result in higher ^{137}Cs contents in cereal crops, therefore agrochemical measures will need to be applied. Calculations of costs of such countermeasures are complicated and beyond the framework of this paper. One, however, can expect large effects from these countermeasures, and the effectiveness of such a practice will remain for a long period of time.

The application of countermeasures in fodder and animal production. Nine scenarios have been discussed in the evaluation of the effectiveness of countermeasures for reducing radionuclide transfer to animal products:

1-surface improvement of pastures;
2-radical improvement of pastures and haylands;
3-surface improvement of pastures and haylands;
4-surface improvement of haylands and pastures with the application of higher rates of mineral fertilisers $N_{60}P_{90}K_{120}$;
5-radical improvement of haylands and pastures;
6-radical improvement of haylands and pastures with the application of higher rates of mineral fertilisers $N_{60}P_{90}K_{120}$;
7-radical improvement of haylands and pastures with the application of higher rates of mineral fertilisers $N_{60}P_{90}K_{120}$, liming of fields under ensilage crops with the application of higher rates of mineral fertilisers $N_{60}P_{90}K_{120}$;

8-the application of ferrocyn-containing compounds in pasture period, reseeding of haylands and liming of fields under ensilage crops with mineral fertilising at higher rates;

9-radical improvement of meadows and pastures with liming (1.5 Hg), as well as the application of higher rates of mineral fertilisers. Liming of fields under ensilage crops and application of higher rates of mineral fertilisers.

The analysis performed allows a conclusion that the most effective in terms of the reduction in the collective dose per unit cost is a complex involving the application of ferrocyn in pasture period, reseeding of haylands and liming of fields under ensilage crops with mineral fertilising at higher rates. The dose saving for this option reaches 117 man-mcSv. However, the need for constant administration of ferrocyn over a long period of time and certain difficulties of its purchasing cause one to make use of conventional measures connected with meadow and pasture improving. The data from Table 3 show that the effectiveness of traditional procedures (treatments 2-7) is rather high. The dose saving normalized to costs varies within the range of 0.4-0.7 mSv/mln roubles. In this case the effect from these countermeasures will persist for several years. The most effective in dose reducing are treatments 6 and 7 (radical improvement of haylands and pastures with the application of higher rates of mineral fertilisers $N_{60}P_{90}K_{120}$, as well as radical improvement of haylands and pastures with higher rates of mineral fertilisers $N_{60}P_{90}K_{120}$ plus additional liming of fields under ensilage crops and mineral fertilising at higher rates).

Table 3
Levels of ^{137}Cs content in plant products (Bq/kg (l)) and averted doses for different scenarios of countermeasures on haylands, pastures and fields under fodder crops

Indicator	Countermeasure options									
	Base	1	2	3	4	5	6	7	8	9
^{137}Cs content in animal products in pasture period										
Milk	13.5	10.4	6.6	7.2	5.9	4.2	3.9	3.9	2.6	0.8
Meat	32.6	26.1	15.2	18.1	14.7	10.5	9.7	9.7	0.5	1.9
^{137}Cs content in animal products in indoor period										
Milk	4.1	4.1	3.1	3.1	2.8	2.5	2.4	1.5	3.1	1.5
Meat	10.2	10.2	7.8	7.8	7.1	6.2	6.1	3.7	7.1	3.7
Averted dose, mSv	0.0	26	83	71	89	110	113	126	117	157
Cost of resources, mln roubles	0.0	58	113	11	203	201	204	292	131	335
Averted dose per unit cost, mSv/ mln roubles	-	0.7	0.6	0.4	0.5	0.6	0.4	0.9	0.5	0.47

The results presented clearly demonstrate the existing means to reduce the irradiation doses from the consumption of foodstuffs produced in the contaminated areas. These cover a broad spectrum of possible decisions and show that depending on the situation and economic resources countermeasures can provide a 1.3 to 15-fold decrease in the contamination level of animal products and, as a consequence, decrease in the collective dose of 7 to 45%.

Combination of different countermeasures. The maximum decrease is achieved by combining the most effective variants of using fodder lands mentioned above and application of agrotechnical and agrochemical measures on arable lands. The reported results make it possible to identify several rational ways of the organisation of agricultural production and countermeasure implementation and these can be assumed optimum as dependent on a particular situation (the presence of some or other resources, facilities, etc.). The following scenario can be considered to illustrate the organisation of agricultural production including all types of countermeasures described above:

- not to use peaty soils to grow fodder cereals and animal pasturing;
- liming of fields under cereal and fodder crops including mineral fertilising at increased rates ($N_{70}P_{90}K_{140}$);
- radical improvement of pastures, reseeding of perennial grasses, liming and application of increased rates of mineral fertilisers.

The results of calculations for this variant show the maximum decrease in ^{137}Cs uptake to farm products on the farm "Avangard" due to the implementation of the whole complex of the above countermeasures; the reduction in dose burdens to the population from the consumption of food-stuffs can reach 65%. The maximum decrease can be achieved in animal products (to 5-fold), and between 2 and 3 times for plant products. The cost of this complex of countermeasures is 499 million roubles in prices of the early 1996.

Four scenarios have been considered for a comparative analysis of countermeasure strategies. In the first scenario no countermeasures were applied and the decrease in the contamination level of products and, as a consequence, dose burdens to the population was determinated by changes in ^{137}Cs bioavailability in soil. The second scenario considered alteration in the land use structure without any other countermeasures. The third one consisted in the combination of different measures resulting in a maximum effect. And the fourth scenario considered a real situation found on the farm "Avangard" after the Chernobyl accident. Dose estimations for this fourth scenario were based on the data of radiation monitoring of farm products conducted by the

services of the RF Ministry of Agricultural Products. So the above scenarios cover a wide range of situations and allow one to evaluate the consequences of this accident in agriculture within the limits of human possibilities. The averted dose and changes in ^{137}Cs content in critical products were taken as criteria for the comparison.

The results of calculations presented in Figure 2 clearly demonstrate that rational alteration of the land use structure reduces the collective dose by 30-40%, and the application of countermeasures results in a 3-fold decrease in the collective dose from the consumption of food-stuffs containing radionuclides. A real reduction in this parameter in 1989-1992 amounted to 40-50% and was mainly connected with the exclusion of animal pasturing on contaminated pastures on peaty soils.

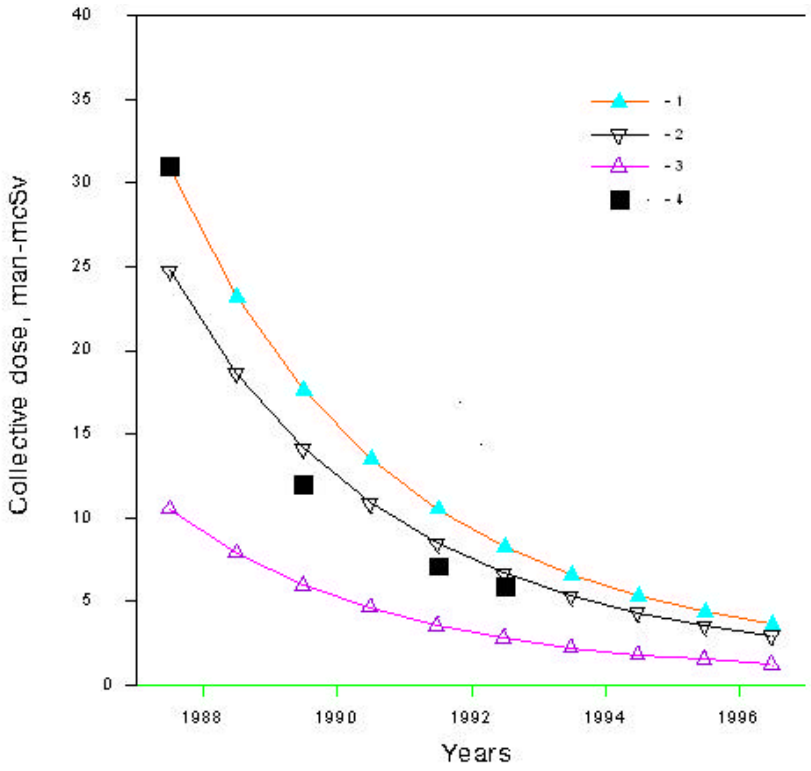

Fig. 2. Dynamics of changes in the collective dose as a result of the consumption of foodstuffs produced on the farm "Avangard".

It is seen from Figure 2 that doses calculated on the basis of the radiation monitoring data (real situation) for the first postaccidental period (1987) are virtually the same as doses without countermeasure application. It means that countermeasures on this farm came into use with some delay (in 1989-1990) and had a rather small effect.

The results derived correlate well with the scales and times of implementation of countermeasures on the contaminated territory of Russia. Thus in 1987-1988, large-scale countermeasures were only applied in the most contaminated districts of the Bryansk region, in the Kaluga region these were started in 1989-1990 and on smaller scales.

The data in Figure 2 generally correlate with the evaluations that reflect changes in ^{137}Cs content in the most critical dose-forming products. For illustration Figure 3 shows variations in the annual means of ^{137}Cs content in milk. It is clear that potential ^{137}Cs levels in milk could be reduced from 7-8 times in the first year after the accident to 3-4 times in the 90s.

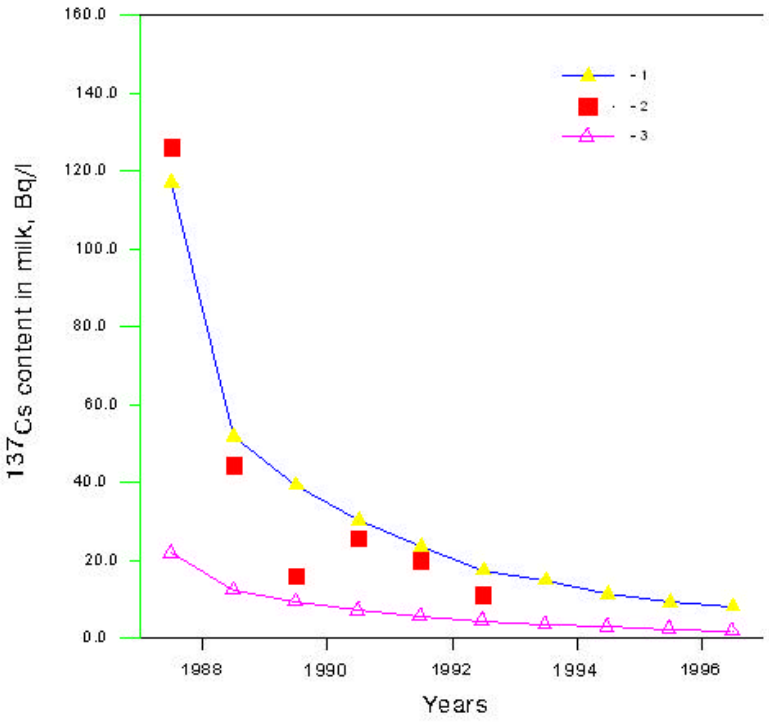

Fig. 3. Dynamics of changes in ^{137}Cs content in milk for different countermeasure options.

The reported calculations make it possible to evaluate the potential variants connected with the tardy application of countermeasures. Thus in the absence of countermeasures, the collective dose over the first 10 years after the accident could have amounted to 12.4 man-mSv and only to 4.2 man-mSv if these have been actively started since 1987. Besides, the estimations based on the real data show that the application of countermeasures on the farm considered was not effective enough and dose saving for 10 years after the accident amounted to about 2 man-mSv or 25% of potential.

On the whole, the examples presented clearly demonstrate the potentialities for reducing negative effects of radioactive contamination of agricultural land. Simultaneously, these results emphasize the need for flexible means for analyzing the long-term countermeasure strategy.

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