DTU Library

EU-CIS joint study project 2. Conceptual framework of intervention level setting

Jensen, Per Hedemann; Demin, V.F.; Konstantinov, Y.O.; Yatsalo, B.I.

Publication date:
1994

Document Version
Publisher's PDF, also known as Version of record

Risø-R-716(EN)

EU-CIS Joint Study Project 2

Conceptual Framework of Intervention Level Setting

Per Hedemann Jensen, Vladimir F. Demin,
Yuri O. Konstantinov, Boris I. Yatsalo

Risø National Laboratory, Roskilde, Denmark
January 1994

Risø-R-716(EN)

EU-CIS Joint Study Project 2

Conceptual Framework of Intervention Level Setting

Per Hedemann Jensen, Vladimir F. Demin,
Yuri O. Konstantinov, Boris I. Yatsalo

Risø National Laboratory, Roskilde, Denmark
January 1994

Abstract Long-term protective measures taken in the CIS following the Chernobyl accident included relocating people from the most contaminated areas as well as continuing the restrictions on using foodstuffs contaminated with ^{137}Cs. The levels at which these countermeasures were introduced or still are being introduced for dose-saving purposes have been used to estimate avertable doses based on population distributions on both dose rate and surface contamination density of ^{137}Cs in space and time. The averted and avertable doses have been quantified by parameters of these distributions and intervention levels for relocation and foodstuff restrictions. The countermeasure efficiencies in agricultural production and various protection strategies in the agrosphere in Russia have been investigated. In addition, methods for estimating avertable radiation risks as well as residual risks from continuing exposures in terms of age-dependent radiation risk factors have been suggested. The sensitivity of changing intervention levels expressed in terms of changes in costs and avertable collective doses have been explored. The application of the present methodology in the decision-making process following a nuclear accident is discussed. Suggestions are made for including the methodology in simple models to be used for aiding decision-making on introducing protective measures.

This work has been performed as a part of the CEC/CIS Joint Study Project 2, "Development and Application of Techniques to Assist in the Establishment of Intervention Levels for the Introduction of Countermeasures in the Event of an Accident".

ISBN 87-550-1938-2
ISSN 0106-2840

Print: Pitney Bowes Management Services Danmark A/S, 2008

Contents

Foreword

The Chernobyl Centre for International Research (CHECIR) has been established by the former Soviet Union "for the purpose of research projects to be concluded on a bilateral or multilateral basis in the area of nuclear safety". The CEC-CIS bilateral research projects within the CHECIR programme for 1993 cover several **Experimental Co-operative Projects** (ECPs), and two **Joint Study Projects** (JSPs) have been set up. The two JSPs are:

(1) Development of computerized systems for predicting the radiological impact of accidents to aid off-site emergency management including models for dose assessment from predictions and measurements of deposited, inhaled and ingested radionuclides, and

(2) Development and application of techniques to assist in establishing intervention levels for introducing countermeasures in the event of an accident.

The Joint Study Project 2 (JSP 2) has in 1993 been subdivided in the following five tasks:

(1) Historical perspective of the decision-making process related to the countermeasures,

(2) Psychological and social factors related to the implementation of countermeasures,

(3) Conceptual basis for developing criteria for setting intervention levels,

(4) Development of a decision-aiding support system for countermeasures policy assessment, and

(5) Dose distributions.

In the second working year Task 3 has concentrated on the following subjects:

- current regulation on countermeasures in Russia
- averted and avertable doses by long-term protective actions in CIS
- efficiencies of agricultural countermeasures in Russia
- risk perspectives of intervention levels

This report covers the work of the Task 3 during the second year carried out by the Russian partners from the Russian Research Centre "Kurchatov Institute" in Moscow, the Institute of Agricultural Radiology and Agroecology in Obninsk, the Research Institute of Radiation Hygiene in St. Petersburg, and the CEC partner from Risø National Laboratory in Denmark.

1 Introduction

The protective measures taken in the CIS after the Chernobyl accident included long-term countermeasures such as relocating the population and continuing restrictions on the use of foodstuffs. The levels at which these measures were introduced were based on different rationales, and the levels have been changed by the competent authorities during the years following the accident.

The radiation doses to the population that were averted by long-term protective measures and the doses that can be averted in the future can be determined from differential population distributions on individual dose rate and differential foodstuff mass distributions on activity concentration of ^{137}Cs in the foodstuffs. The averted and avertable doses can be quantified by parameters of the dose and activity distributions and the intervention level. Such quantified relations would be of great importance to the decision makers responsible for setting intervention levels for implementing protective measures.

The radiation risks to the population groups affected by the countermeasures in terms of avertable risks by introducing the measures and the residual risks with and without countermeasures can be quantified in terms of age-dependent radiation risk factors and the above-mentioned parameters of the dose and activity distributions. Avertable and residual risk distributions would form an important baseline for a realistic and comprehensive information to the public on the levels of risk consequent upon their remaining in the contaminated areas of concern. These risks could be compared with risks in everyday life and with those from other environmental contaminants like radon.

2 Long-term countermeasures in CIS

After the Chernobyl accident a number of protective measures were instituted by the authorities to limit the radiation exposure of the population. These included early countermeasures like sheltering, administering stable iodine and evacuating those parts of the population who might be exposed to the plume. Long-term countermeasures, such as relocation and foodstuff restrictions, were taken to mitigate the effects of lower, but still significant levels of radiation from surface and soil contamination.

2.1 Relocation

Various concepts and criteria have been adopted and proposed for relocation following the accident. These include temporary dose limits, surface contamination criteria and the lifetime dose limit; each is summarised below.

Temporary Permissible Levels
Based on measured radionuclide composition in the environment obtained in the first days of the Chernobyl accident and corresponding long-term predictions of external radiation doses and intake of radionuclides of caesium into the body, it was considered appropriate to establish a temporary permissible dose level (TPL) of 100 mSv to the whole body in the first year. Of these 50 mSv was allocated to internal radiation and 50 mSv to external radiation. For the following years of 1987, 1988 and 1989 the dose limits were 30, 25 and 25 mSv, respectively.

Surface Contamination Criteria
Since the accident, surface contamination criteria have been used to delineate af-

fected areas for such matters as the payment of compensation. Strict Control Zones are those areas with a surface contamination density of ^{137}Cs above 15 Ci/km^2 (555 kBq/m^2) and Controlled Zones with a surface contamination density between 5 and 15 Ci/km^2 (185–555 kBq/m^2).

In April 1990, the Supreme Soviet of the USSR implemented the All-Union State and Republican Programme for the Elimination of the Consequences of the Chernobyl Accident, 1990–1992 in which criteria for relocation were specified in terms of surface contamination density. A surface contamination level for ^{137}Cs of 40 Ci/km^2 (1480 kBq/m^2) was adopted as the criterion for compulsory relocation. For pregnant women and children, the level was 15 Ci/km^2 (555 kBq/m^2). In Belarus, however, this lower level of 15 Ci/km^2 (555 kBq/m^2) was adopted as the criterion for compulsory relocation.

Lifetime Dose Concept and Current Official Concept

In 1988 NCRP developed the concept of safe living of the population based on a so-called lifetime dose limit (LDL). This was adopted to limit the lifetime risk of late health effects. The USSR Ministry of Public Health approved the LDL-concept with its numerical value set at 350 mSv. In the territories where the predicted lifetime dose would not exceed 350 mSv, the withdrawal of all limitations was suggested from 1990. In areas where it was envisaged that the LDL would be exceeded, protective measures should be implemented, including relocating the population.

The LDL concept was rejected by the USSR Supreme Soviet in April 1990, and a Committee of the USSR Academy of Sciences was assigned to develop an alternative concept. According to this new concept the main criterion for further implementation of protective measures is the annual effective dose from Chernobyl fallout, starting from 1991. When this dose is less than 1 mSv, no intervention is needed. If the dose would exceed 1 mSv, a complex of protective measures should be carried out in order to reduce the radiation level to an annual dose less than 5 mSv. This concept was brought into effect by a decree of the USSR Cabinet of Ministers on April 8, 1991. The same concept with minor variations was implemented in Ukraine and Byelorussia, and it is still in action in the CIS–members states, the Russian Federation, Ukraine and Belarus.

The Russian Federation Law "On social protection of the population suffered from radiation exposure due to the Chernobyl accident" (Law91) was adopted in May 1991 and confirmed with minor changes in June 1992. In accordance with this Law, protective and social measures should be implemented in territories with ^{137}Cs-contamination above 37 kBq/m^2 or with an annual effective dose in 1991 above 1 mSv. Those territories where the ^{137}Cs-contamination lies in the range of 185–555 kBq/m^2 are zones where the population has the right to be relocated. Territories where the contamination level exceeds 555 kBq/m^2 are zones for relocation, including compulsory relocation from settlements where the contamination level is above 1480 kBq/m^2 or the annual effective dose is above 5 mSv.

2.2 Foodstuff restrictions

In accordance with the annual temporary permissible dose level for internal radiation of 50 mSv (TPL–86), temporary permissible levels of activity concentration in foodstuffs were brought into effect on May 30, 1986. TPL–86 for foodstuffs was established for radiocesium, but they were used for the total β-activity in foodstuffs.

In 1988 social measures were implemented in territories where the radiocesium content in milk exceeded 370 Bq/ℓ, corresponding in Russia to a surface contamination density of 3–15 Ci/km^2 (111–555 kBq/m^2) depending on soil and agricultural conditions. In some regions, in Byelorussia in particular, the implementation of protective measures in 1988–1989 was enlarged, irrespective of the actual radiation doses to the local population, and included territories with an initial surface contamination density above 5 Ci/km^2 (185 kBq/m^2) and even areas with an initial contamination level above 1 Ci/km^2 (37 kBq/m^2).

Due to the predominant contribution of external radiation in the territories where restrictions of contaminated locally produced foodstuffs were efficient, TPL levels for radiocesium in foodstuffs were established considering that the internal radiation dose would constitute the smallest part of the total regulated annual dose: 8 mSv when the whole "food basket" is contaminated at the level of TPL–88 and 1.5 – 1.8 mSv with the actual proportion of contamination levels of TPL–91 in the main components of the diet.

In January 1991 the National Commission on Radiation Protection of the USSR (NCRP) proposed republican and regional control levels (CLs) for radionuclides in food products provided that they should not exceed the All–Union TPLs ranging from 3.7 Bq/kg for drinking water to 740 Bq/kg for meat.

2.3 Current regulation in Russia

Since mid-1991 the practical activity on the elimination of the Chernobyl accident consequences has been regulated by the Chernobyl Laws and the respective Concepts adopted in Belarus, Russia and Ukraine. The situation with a developing regulation, mainly in Russia, is reviewed below (Belyaev et al. 1991, Law91).

However, it became clear already in 1992 that the regulatory documents connected with both the elimination of the consequences of the Chernobyl accident and other applications needed to be further improved and developed. It was caused by a number of reasons. The most important of these are summarised below.

(1) The current Concept (Belyaev et al. 1991) and Law (Law91) have limited application: they apply only for the situation after 1990 in the regions affected by the Chernobyl accident.

(2) In the Law there are serious contradictions and non-justified principles which prevent optimal implementation of long-term protection and restoration measures. Moreover, implementation of the Law created additional social problems.

(3) As it was noted above, at the end of 1992 the levels of radiation exposure and socio-psychological conditions have changed considerably. Rehabilitation of these areas is therefore possible, at least in the Russian territories that were affected by the accident. This rather fast alteration of the situation in the Chernobyl region, which was not fully recognized previously, should be taken into account in decision making on an optimal intervention strategy.

(4) In Russia there are several contaminated regions in addition to those affected by the Chernobyl accident (Ural region, territories near nuclear weapons test sites, etc.). Since 1991 the issues of radiation protection, social rehabilitation and economic compensation in these territories have been under consideration by scientists and local and state authorities, and the experience from these areas are used to reconsider the past recommendations on intervention strategy and intervention levels.

Taking into account these demands on improved regulation documents, it was planned by some responsible organizations (NCRP; the Chernobyl State Committee and others) to develop in 1992–1994 new improved recommendations and guides for protection and restoration measures should a nuclear accident occur in the future, based on knowledge gained from those occurred in the past.

It is recognized now that in these documents one should:

- consider the interaction of all post-accident phases: early, long-term and a final restoration (rehabilitation), and

- develop in more detail not only radiation but also social protection aspects.

Social protection should have its own system of decision making regarding dose levels expressed in residual doses. Radiation protection criteria for intervention are usually expressed in avertable doses.

Three documents on these issues have being developed in 1993:

- a general concept of radiation, health, social protection and rehabilitation of the population after a nuclear accident (in preparation by a Russian NCRP working group),
- recommendations on intervention levels and strategies of protection and restoration measures after a nuclear accident, and
- a concept of remediation and restoration of radioactive contaminated sites.

The last two documents are developed in accordance with the Russian Chernobyl State Committee research program. Developing and adopting these documents could not be done in a short time. At present, these regulation documents continue to be in development.

In this situation and due to urgent needs for new regulation documents, three special documents were developed and adopted in 1993 with limited application:

(1) Recommendations on the practical realization of the current Concept of social protection of the population in the regions affected by the Chernobyl accident in the conditions of the rehabilitation and restoration phase that have begun (Belyaev et al. 1993).

(2) A Concept of radiation protection of the population and economic activity on territories affected by radioactive contamination (Concept-93; Ivanov et al. 1993).

(3) A Concept of rehabilitation of the population and normalization of the ecological, sanitary and socio-economical situation in settlements of the Altay region located in the zone affected by nuclear weapon tests on the Semipalatinsk proving ground ("Altay" concept) (Demin, Gordeev et al. 1993).

The first document above was briefly discussed. A short description of the last two documents is given below.

2.3.1 The concept – 93

The objective of implementing protective and rehabilitative measures in contaminated territories in the Russian Federation is to provide a high health standard for the population in these areas.

The main way to achieve this objective is by introducing the following protective measures in the radioactive contaminated territories:

- reducing the exposure of the population from all exposure pathways on the basis of optimisation,
- restricting harmful effects in the population due to non-radiation factors of a physical and chemical nature,
- improving the resistance to disease and general carcinogenic protection of the population,
- improving medical care in the population provided through monitoring of common health status, specialized medical monitoring to reveal illness in high risk groups, and efficient treatment of illness and rehabilitation,
- improving public education in the field of radiation hygiene, psychological protection of the population, and measures to prevent radiophobia,

- popularizing a healthy lifestyle in the population, and
- improving social, economic and legal public safety of the population.

The territories contaminated by radionuclides are subdivided into *zones*. This zoning is based on the annual effective individual dose, E_a, to the population due to the contamination. Three zones of annual doses are introduced:

(1) **Zone of radiation control (1–5 mSv/y)**. Monitoring of environmental contamination, contamination of agricultural products, and individual doses from external and internal exposure is carried out. Protective measures are put into effect to reduce individual doses based on optimisation.

(2) **Zone of voluntary relocation (5–50 mSv/y)**. Monitoring and protective measures are carried out similar to the zone of radiation control. The radiation risk due to the exposure from the contamination is explained to the residents and they are assisted in resettling outside the zone based on their own decision.

(3) **Zone of compulsory relocation (> 50 mSv/y)**. Residents are not allowed in this zone. Economic activities and use of natural resources are controlled by special acts. Individual doses are monitored and protective measures taken for workers engaged in these activities.

In territories where E_a does not exceed 1 mSv/y lifestyle and economic activities are free from any restrictions. This dose level defines in practice a border between normal and abnormal conditions.

The above-mentioned annual doses for the classification of the zones are *average effective doses for critical groups of a settlement* from the deposited radionuclides **without** any protective measures implemented.

The decisions on relocation are based on the same doses but **with** protective measures implemented.

A number of protective measures to reduce the radiation doses to the population in the zones are implemented. These measures include:

- resettling on a compulsory basis or limiting the residence time and activities for the population in the contaminated territories,
- resettling on a voluntary basis,
- decontaminating territories, buildings and other objects,
- implementing a system of protective measures in agricultural production to reduce the content of radioactive contamination in locally grown vegetables and animal food products,
- rationing and controlling agricultural and natural food products and implementing further contamination reduction processes as well as providing clean foodstuffs to the population, and
- implementing special rules on lifestyle for residents in the contaminated areas.

When implementing protective measures due consideration should be given not only to the planned positive effects but also to the negative effects such as economic damage, negative psychological effects, side health effects, and additional exposure to people who are implementing the protective measures.

Each protective measure should be optimised taking into account the actual situation.

Radiation safety for individuals involved in economic activities in zones of radiation control and in zones of relocation is provided by measures of individual and collective protection from external and internal exposure. The annual effective doses to people living and working in these zones should be limited to 5 mSv/y. For radiation workers living and working in these zones the annual effective dose should be limited to 50 mSv/y.

2.3.2 The "Altay" concept

Goals, tasks of the concept and the experience of its elaboration have wider significance than a simple substantiation of practical activity in the Altay region. This is the first case of elaboration of a social protection concept (Demin, Gordeev et al. 1993) for a population affected by an uncontrolled source (the concept can also be used in connection with nuclear weapon tests, but only conditionally).

It was recognized after open publication of data on the atmospheric nuclear weapon tests in the years 1949 – 1962 and 1965 and recent scientific research, that a considerable part of the Altay region was seriously affected by these tests. Aspects of the present situation to be noted are:

- the population was exposed during the period of the nuclear weapon tests; the current doses to the population are insignificant,
- due to specific features of the nuclear detonations, the doses received by the population should be described mainly as acute (short-term) radiation doses,
- for such short-term exposures the radiological risk coefficients are higher for a given total dose than for long-term exposure, and
- the present local population has had some health problems.

In the Concept, two levels of *acute effective dose*, AE, were established to enable decisions to be made on social protection:

$$AE_1 = 0.05 \text{ Sv} \quad \text{and} \quad AE_2 = 0.25 \text{ Sv}$$

In terms of *long-term effective dose*, these values are equivalent to at least 0.1 Sv and 0.5 Sv, respectively, i.e. at least a factor of 2 higher than the acute effective dose.

The lower level, AE_1, is practically a non-action level: social protection measures are introduced only if the total individual doses, E, from the nuclear weapon tests are higher than AE_1. The population under social protection activity is subdivided into two categories, depending on the total individual dose level, E:

Category 1
People with doses $E > AE_2$ and their children and grandchildren.

Category 2
People with doses E in the interval $AE_1 < E \leq AE_2$ and their children and grandchildren.

Collective and individual social protection measures are envisaged for the first category. Only collective social protective measures are envisaged for the second category.

Analysing the Concept-93 and the Altay concept causes the following comments: Concept-93 is an attempt of its authors to develop the current Chernobyl Concept (Concept-91) and to extend its application to other radioactive contaminated regions. The two low levels of 1 and 5 mSv/y in Concept-93 are identical to the levels in Concept-91. Concept-93 has an additional level of 50 mSv/y for compulsory relocation. There are, however, reasons to consider this level with its qualitative and quantitative definitions as unreasonable.

Consider the existing contaminated sites (Chernobyl, Ural regions etc.) and a settlement for which relocation have not been done in proper time in the past. Obviously, with the present rather low dose rates there is no serious radiation-protection reasons for obligatory relocation, though there might be reasons from a social point of view. It should be noted here that only in three villages on Russian territory (two in the Chernobyl region and one in the Ural region near Techa river) were the doses in 1992 near or a little higher than 5 mSv. In other settlements the annual doses are lower or even much lower.

Considering a future possible post-accident situation it is obvious that relocation should not be addressed in the rehabilitation phase of a post-accident situation. If there would be radiation-protection reasons for relocating the population it should have been done at an earlier stage of the post-accident phase when the results from environmental measurements have been evaluated. In any case, the value 50 mSv/y as a level for introducing relocation is rather high for radioactive contamination conditions with a slowly decreasing dose rate which would be expected in the rehabilitation phase as only long-lived radionuclides would still be present.

There is another essential difference between Concept-91 and Concept-93. In Concept-91 the average annual effective dose for a *settlement* is used for comparison with the Intervention Level whereas in Concept-93 the average annual effective dose for a *critical group* of people is used. A distinction between the average dose and the actual distribution of individual doses seems to be reasonable if the variation in individual doses is too great. However, additional explanation and definitions should be included in the Concept. For example, a critical group could have a specific age distribution and the age dependence of the radiological risk might therefore be taken into account (see Chapter 5 of the present report).

3 Avertable doses by long-term protective measures

In the years following the Chernobyl accident a huge amount of environmental measurements have been performed together with calculations of individual radiation doses based on these measurements and assumptions on the intake of food that contains activity below the Intervention Levels for foodstuffs. Some of these data have been used to illustrate methodologies for assessing both avertable doses by protective measures at different levels of intervention and the efficiency of specific agricultural countermeasures.

3.1 Relocation

The avertable doses from relocation are the external γ–doses from activity deposited on ground and structural surfaces as well inhalation doses from resuspended material. The basic data needed to calculate avertable doses would be the external effective dose rate, $\dot{E}(t)$, and surface contamination density, $Q(t)$, for deposited radionuclides, both as a function of time, t, and also distributed on the population. The calculation of avertable doses from relocation will include time-averaged location factors, $\overline{L}$, for shielding and occupancy in the area under consideration.

The number of people that would exceed the intervention level for relocation can be calculated from the differential population distribution on the effective dose rate, $n(\dot{E},t)$, or the differential population distribution on surface contamination density, $n(Q,t)$, both at time t. These distributions represent the size of the population for which the outdoor effective dose rate is between $\dot{E}$ and $\dot{E} + \mathrm{d}\dot{E}$ or for which the surface contamination density is between Q and $Q + \mathrm{d}Q$.

The population size for which the outdoor effective dose rate exceeds the intervention level, IL, would then be:

$$N(IL,t) = \int_{IL}^{\infty} n(\dot{E},t)\ \mathrm{d}\dot{E} \qquad (1)$$

The avertable external **collective** effective dose per unit time from exposure in areas with an **individual** outdoor effective dose rate above the IL can be calculated to be:

$$\dot{S}(IL,t) = \overline{L} \int_{IL}^{\infty} \dot{E}(t) \cdot n(\dot{E},t)\ \mathrm{d}\dot{E} \qquad (2)$$

A similar calculation can be made for the avertable collective effective inhalation dose from resuspended material based on the distribution function, $n(Q,t)$.

The distribution functions, $n(\dot{E},t)$, and $n(Q,t)$, make it possible also to calculate the sensitivity of changing the Intervention Level, IL, either downwards or upwards around a given value. Table 1 shows the CIS population distribution on intervals of surface contamination density and dose rate for 1990 (IAC91).

Table 1. *Distribution of CIS population on intervals of surface contamination density of ^{137}Cs and intervals of effective dose rate from ^{137}Cs in open areas for the year 1990 (IAC91).*

Distribution of CIS population, N, on dose rate, $\dot{E}$, and surface contamination density, Q		
Dose rate, $\dot{E}$ (μSv/d)	Surface contamination density, Q (Ci/km^2)	Population, N (thousands)
6.2 – 12.4	5 – 10	412
12.4 – 18.6	10 – 15	87
18.6 – 24.8	15 – 20	118
24.8 – 31.0	20 – 25	28
31.0 – 37.2	25 – 30	25
37.2 – 43.4	30 – 35	16
43.4 – 49.6	35 – 40	5
49.6 – 74.4	40 – 60	10
74.4 – 99.2	60 – 80	3
> 99.2	> 80	1

Based on the data in Table 1 the differential population distributions on the surface contamination density of ^{137}Cs and on the effective dose rate in open areas from ^{137}Cs have been determined. The population distribution on surface contamination density has been found to be:

$$n(Q,t) = \frac{\mathrm{d}N(Q,t)}{\mathrm{d}Q} = a \cdot \left(Q \cdot \mathrm{e}^{\lambda t}\right)^{-b} \qquad (3)$$

The value of the parameters a and b are $1.20 \cdot 10^7$ persons/(Ci·km^{-2})^2 and 2.5, respectively, when the contamination level is expressed in Ci·km^{-2}.

The differential population distribution on the outdoor effective dose rate in open areas from ^{137}Cs can be determined from the relation between surface contamination density and outdoor effective dose rate from ^{137}Cs over large open areas ($k = 1.24{\cdot}10^{-3}$ mSv·d^{-1}/Ci·km^{-2}). It is found to be:

$$n(\dot{E},t) = \frac{\mathrm{d}N(\dot{E},t)}{\mathrm{d}\dot{E}} = a \cdot k^{b-1} \cdot \left(\dot{E} \cdot \mathrm{e}^{\lambda t}\right)^{-b} \qquad (4)$$

The distributions are shown in the Figs 1 and 2 for both years 1990 and 1994, assuming an effective removal half-life of ^{137}Cs of 7 years.

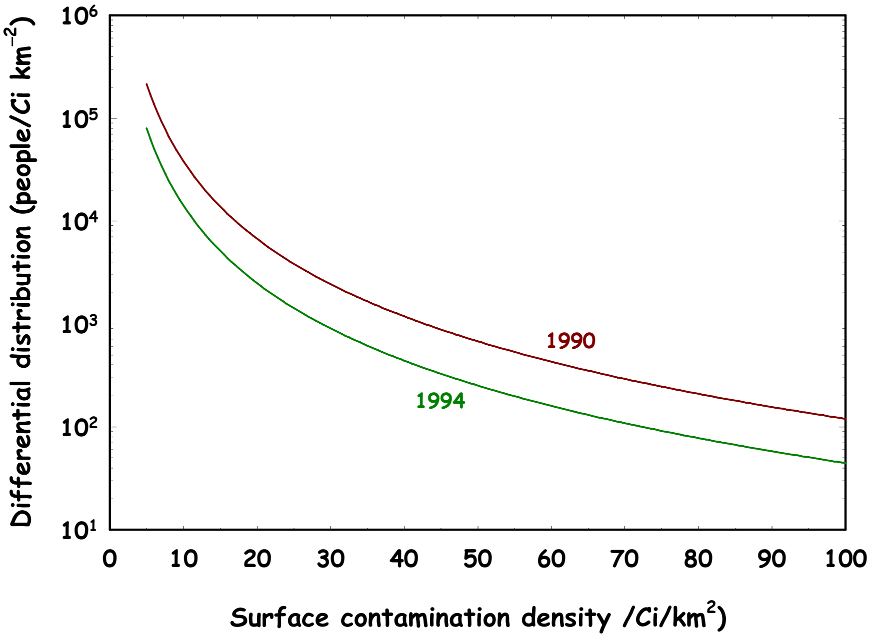

Figure 1. Differential distribution of CIS population on the surface contamination density of ^{137}Cs for the years 1990 and 1994.

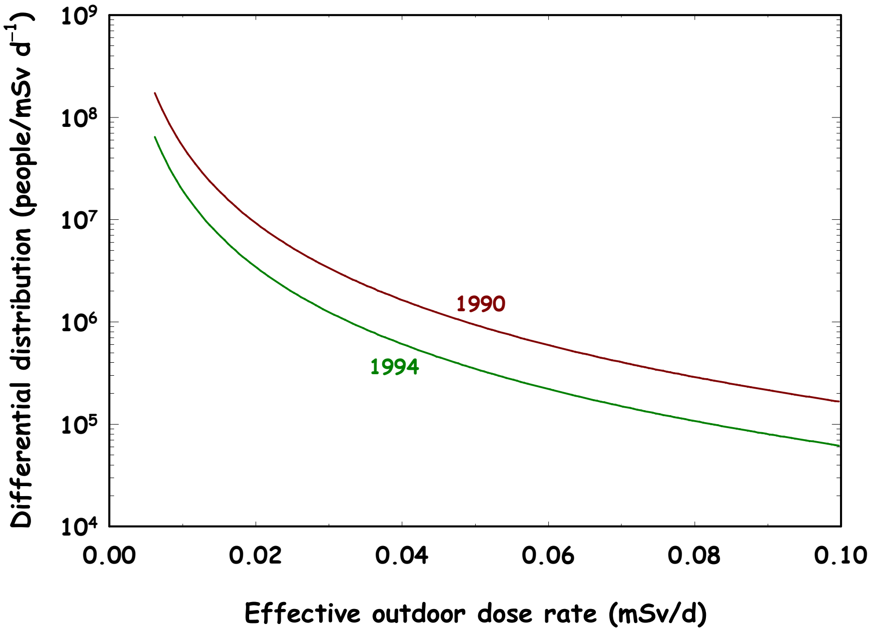

Figure 2. Differential distribution of CIS population on the outdoor effective dose rate in open areas from ^{137}Cs for the years 1990 and 1994.

The number of people for which the outdoor effective dose rate exceeds the operational intervention level, OIL, can be calculated from the distribution shown in Fig. 2, $n(\dot{E}, t)$, and Eq.(1) to be:

$$N(OIL, t) = \frac{a \cdot k^{b-1}}{b-1} \, \mathrm{e}^{-b\lambda t} \cdot OIL^{1-b} \tag{5}$$

The operational intervention level is a quantity derived from the Intervention Level of avertable dose and is expressed in terms of measurable quantities like dose rate. The derivation of the OILs will include both accident and site-specific parameters.

The collective dose to individuals exceeding the operational intervention level of outdoor effective dose rate from ^{137}Cs can be calculated from the same distribution and Eq.(2) to be:

$$\dot{S}(OIL, t) = \overline{L} \cdot \frac{a \cdot k^{b-1}}{b-2} \, \mathrm{e}^{-b\lambda t} \cdot OIL^{2-b} \tag{6}$$

The values of $N(OIL, t)$ and $\dot{S}(OIL, t)$ are shown as a function of OIL in Figs 3 and 4, respectively. The value of $\overline{L}$ has assumed to be 0.4 (IAC91) in the calculation of $\dot{S}(OIL, t)$.

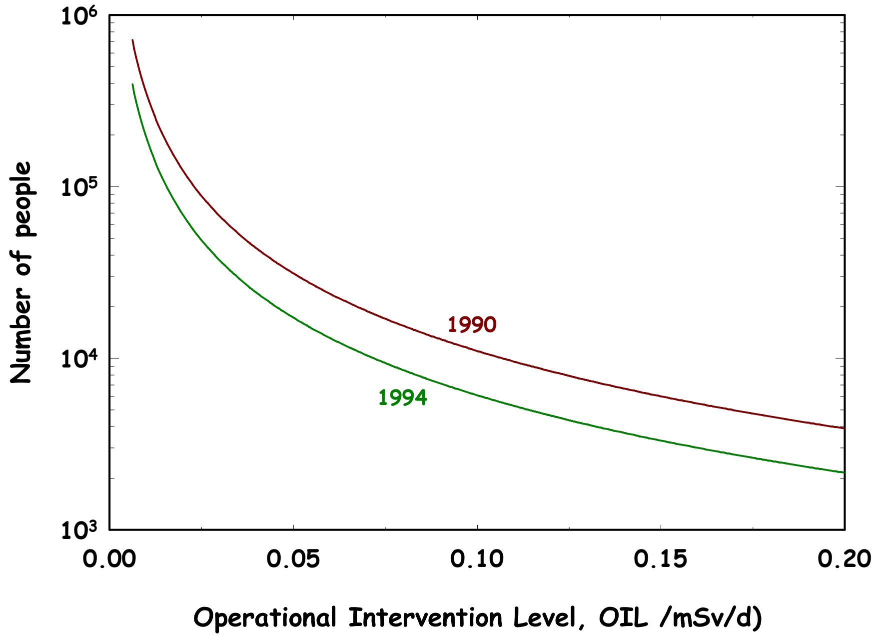

Figure 3. Number of people in CIS in the years 1990 and 1994 exceeding a given operational intervention level of individual outdoor effective dose rate from ^{137}*Cs.*

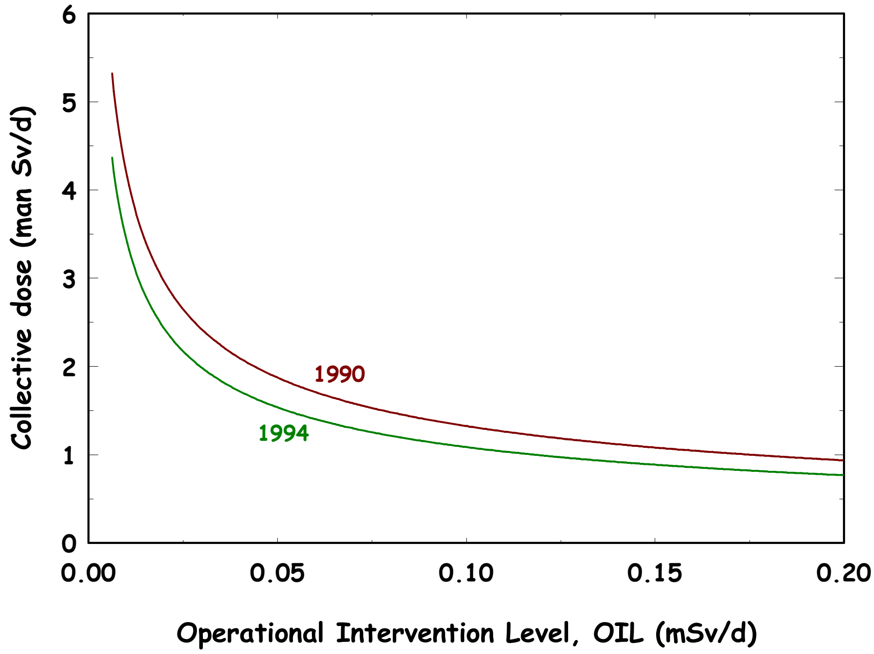

Figure 4. Collective effective dose per unit time to individuals in CIS in the years 1990 and 1994 who exceed a given Operational Intervention Level of individual outdoor effective dose rate from ^{137}Cs.

3.2 Foodstuff restrictions

The doses from contaminated foodstuffs will probably never, even for locally grown foodstuffs, enter the deterministic region. Therefore, the avertable doses by restricting foodstuffs can be expressed as an *avertable collective effective dose per unit mass* of a specific category of foodstuff. The basic data needed for such calculations would be the differential foodstuff mass distribution on ^{137}Cs-concentration, C, in that foodstuff, $m(C)$. The relevant foodstuff production to be considered in applying such restrictions could be limited to selected villages or larger areas.

The amount of foodstuff, M, at time t with a concentration larger than the intervention level, IL, would be:

$$M(IL,t) = \int_{IL}^{\infty} m(C,t)\ \mathrm{d}C \tag{7}$$

where $m(C,t)$ is the amount of foodstuff at time t with a concentration between C and $C + \mathrm{d}C$. As the concentration will decrease with time the amount of foodstuff with concentration above the IL will decrease correspondingly.

The avertable collective dose by restricting foodstuffs with a concentration $C > IL$ can be calculated as:

$$S(IL,t) = e(50) \int_{IL}^{\infty} C(t) \cdot m(C,t)\ \mathrm{d}C \tag{8}$$

The differential distribution function of activity in various foodstuffs, $m(C)$, can be derived from the population distribution on surface contamination density in Table 1.

If it is assumed *for illustrative purposes only* that the foodstuff production in the contaminated areas is equal to the foodstuff consumption and that the foodstuffs are produced within these areas, the differential distribution functions for different foodstuffs, $m_i(C)$, can be expressed by the transfer factors, σ_i, and the consumption rates, f_i, as:

$$m_i(C,t) = \frac{\mathrm{d}M(C,t)}{\mathrm{d}C} = a \cdot \sigma_i^{b-1} \cdot f_i \cdot \left(C \cdot \mathrm{e}^{\lambda t}\right)^{-b} \tag{9}$$

If it is further assumed that the transfer factor for caesium from grass to milk is 18.5 Bq·kg^{-1}/Ci·km^{-2} (5·10^{-10} Ci·kg^{-1}/Ci·m^{-2}; the Ci-unit is used here because the original distribution was expressed in this unit (IAC91)) and the corresponding annual consumption rate 365 kg·y^{-1}, the differential distribution of annual masses of milk on activity concentration of ^{137}Cs in milk will be as shown in Fig. 5.

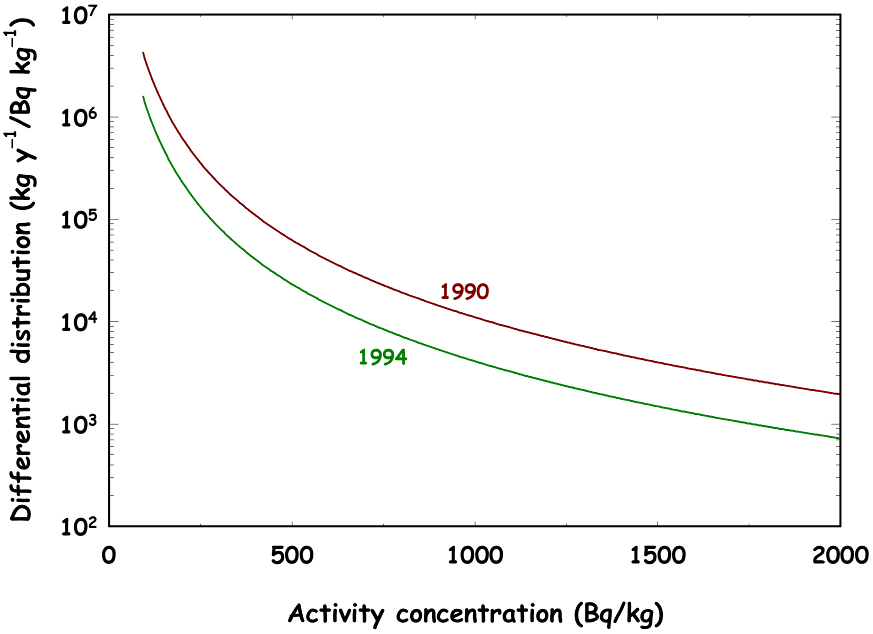

Figure 5. Differential distribution of the annual amount of milk in CIS on the activity concentration of ^{137}Cs in milk in the years 1990 and 1994 from contaminated areas with a surface contamination density of ^{137}Cs greater than 5 Ci·km^{-2}.

The amount of milk having a concentration of ^{137}Cs that exceeds the intervention level in terms of activity concentration can be calculated from the distribution $m(C,t)$ and Eq.(7) to be:

$$\dot{M}(IL,t) = \frac{a \cdot \sigma_{milk}^{b-1} \cdot f_{milk}}{b-1} \, \mathrm{e}^{-b\lambda t} \cdot IL^{1-b} \tag{10}$$

The collective dose originating from intakes of foodstuffs with a concentration that exceeds the Intervention Level can be calculated from the same distribution and Eq.(8) to be:

$$\dot{S}(IL,t) = e(50) \cdot \frac{a \cdot \sigma_{milk}^{b-1} \cdot f_{milk}}{b-2} \, \mathrm{e}^{-b\lambda t} \cdot IL^{2-b} \tag{11}$$

The values of $\dot{M}(IL,t)$ and $\dot{S}(IL,t)$ are shown in Figs 6 and 7, respectively.

It appears from Figs 6 and 7 that for an intervention level of 340 Bq/kg the amount of milk being restricted in 1990 would be about 37,000 tonnes and the averted collective dose about 500 person·Sv/y. If the intervention level were doubled to 740 Bq·kg^{-1} the amount of milk being restricted in 1990 would be about 13,000 tonnes and the averted collective dose about 350 person·Sv/y.

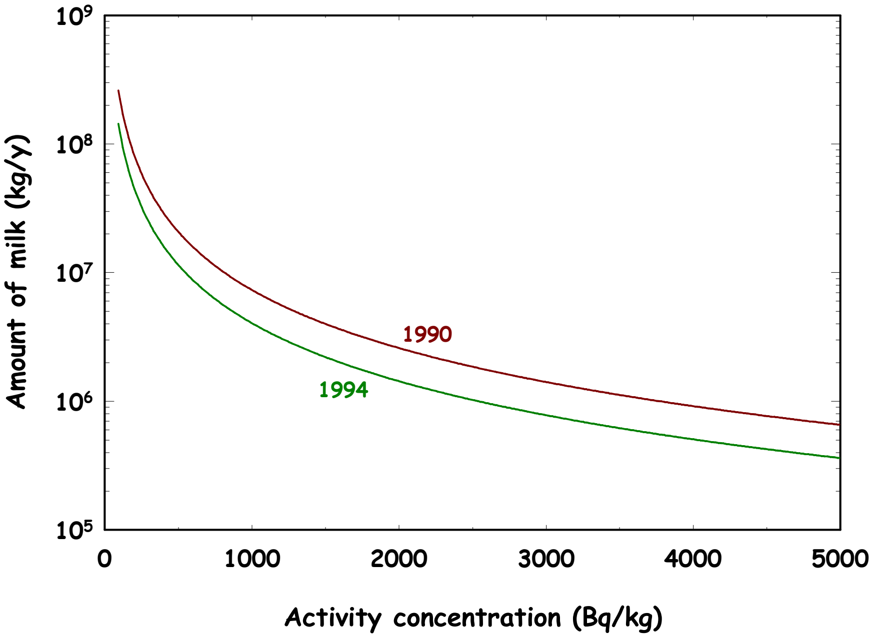

Figure 6. Amount of milk in CIS in the years 1990 and 1994 exceeding a given intervention level for ^{137}Cs-concentration.

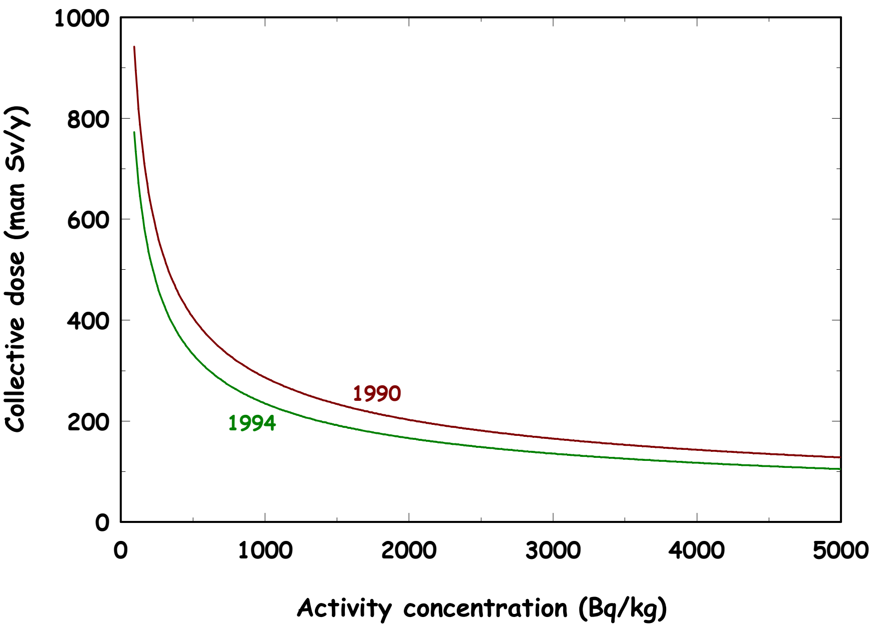

Figure 7. Collective dose in CIS in the years 1990 and 1994 from intakes of milk with a content of ^{137}Cs exceeding a given intervention level for ^{137}Cs-concentration.

3.3 Efficiencies of agricultural countermeasures in selected regions in Russia

Methodological aspects of the cost-benefit analysis (CBA) have been used as the basis for assessing countermeasure efficiency in agricultural production and various protection strategies potentially applied in the agrosphere of areas subjected to radioactive contamination. Non-uniformity of the contamination structure of the production being obtained in these areas is taken into account, as well as various strategies of using "pure" (contamination *below* the established Control Levels

(CL)) and “dirty” (*above* CL) production. Estimates are given of radiological characteristics of “pure” and “dirty” production before and after countermeasures are applied, as well as those of “optimal” levels for the intervention strategies under consideration. The various strategies themselves are then compared by the use of CBA.

3.3.1 Estimation of efficiency in plant breeding

The effectiveness of countermeasures in plant breeding for the main crops and soil types characteristic of the middle zone of Russia (including feed crops, grasses (hay) on pastures and natural lands) is discussed in this Section.

The main information is based on data of Tables 2 and 3 below, as well as those of transfer factors (Alexakhin 1991) and data on costs of countermeasures (Bakalova 1992).

<u>**Table 2.**</u> *Characteristics of countermeasures.*

Crop	Effectiveness (f)/(additional crop yield) $[\frac{\text{hkg}}{\text{ha}}]$				Cost $[\frac{\text{roubles}}{\text{ha}}]$
	a	**b**	**c**	**d**	
Liming					
I	(1.5-3)/2	(1.2-1.5)/2.2	(—)/1.5	—	60
II	(1.5-2.5)/5	(1.2-2.0)/17	(—)/3	—	60
III	(1.2-3.0)/8	(1.2-2.0)/13	(—)/53	—	40-90
IV	(2.0-3.0)/2	(1.3-2.0)/4	(—)/2	(2.0-3.5)/6	40-100
Application of organic fertilizers					
I	(1.5-2.0)/10	(1.5-2.0)/6	(1.1-1.5)/4	—	205
II	(2.0-3.0)/70	(1.5-2.0)/50	(1.2-1.6)/30	—	270
III	(1.5-3.0)/30	(1.2-2.5)/20	(1.3-1.8)/10	—	300-500
Application of mineral fertilizers					
I	(1.5-2.5)/7.5	(1.2-2.0)/6	(1.2-1.5)/4	—	90-110
II	(2.0-4.0)/30	(1.5-3.0)/25	(1.3-1.5)/20	—	90-120
III	(2.0-3.0)/25	(1.5-2.0)/20	(1.3-1.5)/25	—	80-110
IV	(2.5-3.5)/25	(1.2-2.5)/20	(1.5-2.0)/18	(2.5-4.0)/39	80-110
Combined countermeasures					
I	(1.5-3.5)/18.7	(1.3-3.0)/15.6	1.5/10	—	340-360
II	(3.0-4.0)/90	(2.5-3.5)/80	1.5/60	—	400-430
III	(2.5-5.0)/40	(2.0-4.0)/35	1.6/30	(2.0-5.0)/45	$(\frac{400-430}{140-280})^*$
Radical reclamation**					
IV	(5.0-10.0)/50	(3.0-9.0)/40	4.0/25	(8.0-10.0)/60	$(\frac{650-810}{350-500})^{***}$

Note

* without organic (denominator)

** waterless valley for **a** — **c**, low land for **d**

*** numerator — waterless valley, denominator — low land

a - soddy-podsolic, sandy and sandy loam

b - soddy-podzolic, light and intermed loam

c - chernozem leached

d - hydromorphouse (peat and peat/swamp)

I - winter grain,

II - potato,

III - sown grasses,

IV - grasses of natural lands.

Table 3. *Cost of applying countermeasures, 1989*

Product	Cost $[\frac{\text{roubles}}{\text{hkg}}]$
Winter grain	25
Potato	20
Sown grasses (hay)	1.5
Grasses of natural lands (hay)	3.4
Grasses of natural lands (grasses)	0.9
Milk (roubles/ℓ)	12

The countermeasure under consideration will be justified if the net benefit of the countermeasure, B_w, is positive:

$$B_w = Y - Y_c - P_c + B_a = \alpha\Delta S - P_c + B_a > 0 \tag{12}$$

where B_a in the given case is the value of an additional crop yield caused by application of this countermeasure. The cost of the countermeasure is P_c and $Y - Y_c$ is the cost equivalent of the avertable radiation detriment. If there is no additional yield, B_a will be equal to zero, and the condition is equivalent to:

$$\varepsilon = \frac{P_c}{\Delta S} < \alpha \tag{13}$$

where ε is the cost of averting a unit collective dose (person $\cdot$ Sv).

If it is supposed, that:

$$r = \frac{B_a}{P_c} \tag{14}$$

then, evidently, if $r > 1$, the countermeasure is efficient from a "purely economical" point of view (the cost of the additional yield exceeds the expenses for the countermeasure).

The considerations above can also be expressed as:

$$\varepsilon_r = \varepsilon \cdot (1 - r) \tag{15}$$

The quantity, ε_r, may be called a "modified effectiveness" which is the difference between the "cost-effectiveness" method and the full scale "cost-benefit" method.

In Table 4 an estimate is given of the effectiveness, ε, for the case when additional yields are absent and with consideration of these (50% of the values given in Table 2 were used as the additional yields which are, in fact, the maximum possible additions. The value of 50% is obtained as a result of an economic analysis of the change in crop yield due to the application of various agricultural countermeasures (Bakalova 1992)).

Table 4. *Effectiveness, ε, of agriculture countermeasures, 10^5 roubles/person·Sv, in prices of 1989-1990 (without/with consideration of additional yields).*

Soil type	Crop	Contamination [Ci/km^2]			
		1	5	15	40
Liming					
a	I	12/14	2.4/3	0.8/0.9	0.3/0.34
	II	1.5/1.5	0.3/0.3	0.1/0.1	0.04/0.04
	III	11/13	2/3	0.7/0.9	0.3/0.32
	IV	5/6	1/1.1	0.4/0.4	0.13/0.14
b	I	138/182	27/36	9/12	3.5/4.5
	II	4/4.4	0.8/0.9	0.26/0.3	0.1/0.11
	III	29/50	6/10	2/3	0.7/1.2
	IV	11/14	2.2/3	0.7/1	0.3/0.4
d	IV	22/24	4/5	1.4/2	0.5/0.6
Application of organic fertilizers					
a	I	51/110	10/22	3.4/7.3	1.3/2.7
	II	5.5/6.8	1.1/1.4	0.4/0.5	0.14/0.17
	III	75	15	5	2
b	I	314/480	63/96	21/32	4.9/12
	II	15/22	3/4	1/1.5	0.4/0.5
	III	180	35	12	4.4
c	I	930/2000	187/400	62/130	23/50
	II	63/90	12/18	4/6	1.6/2
	III	860	170	57	21.4
Application of mineral fertilizers					
a	I	20/28	4/5.6	1.3/1.9	0.5/0.7
	II	1.6/1.8	0.3/0.4	0.11/0.12	0.04/0.04
	III	18/27	4/5.4	1.2/1.8	0.5/0.7
	IV	10/17	2/4	0.64/1.2	0.24/0.4
b	I	158/280	32/56	11/19	4/7
	II	4/4.4	0.8/0.9	0.27/0.3	0.1/0.11
	III	51/110	10/22	3.4/7	1.3/3
	IV	19/154	4/31	1.3/10	0.5/4
c	I	410/880	82/186	27/59	10/22
	II	21/26	4/5	1.4/1.7	0.5/0.7
	III	180/1610	36/320	12/107	4.5/40
	IV	28/74	5.6/15	2/5	0.7/2
d	IV	40/70	8/14	3/5	1/2

Table 4 continued.

Soil type	Crop	Contamination, [Ci/km^2]			
		1	5	15	40
Combined countermeasures					
a	I	56/93	11.2/18.6	3.7/6	1.4/2.3
	II	6.8/8	1.4/1.6	0.4/0.5	0.17/0.2
	III	75/106	15/21	5/7	2/2.7
b	I	447/1490	89/298	30/100	11/37
	II	15/18	3/4	1/1.2	0.4/0.5
	III	163/250	33/50	11/17	4/6
c	I	1071/5355	214/1071	72/357	27/134
	II	80/154	16/31	5/10	2/4
	III	740/4400	150/890	50/300	19/110
d	III	32/46	7/9	2/3	0.8/1.2
Radical reclamation					
a	IV	60/81	12/16	4/5	1.5/2
b	IV	80/90	16/19	5.3/6	2/2.2
c	IV	133/174	27/35	9/12	3.3/4
d	IV	116/156	23/31	7.7/10	3/4

Values of the modified effectiveness ε_r is defined for the countermeasures, crops and soil types under consideration and shown in Table 5.

Table 5. *Modified effectiveness, ε_r, of agricultural countermeasures,* 10^5 *roubles/person·Sv, in prices of 1989-1990.*

Soil type	Crop	Contamination, [Ci/km^2]			
		1	5	15	40
Liming					
a	I	8.3	1.8	0.5	0.2
	II	0.3	0.06	0.02	0.001
	III	8.3	1.9	0.6	0.2
	IV	5.5	1.0	0.4	0.13
b	I	98	19	6.5	2.4
	II	<0	<0	<0	<0
	III	21	4.2	1.3	0.5
	IV	12	2.5	0.8	0.3
d	IV	18	3.8	1.5	0.5
Application of organic fertilizers					
a	I	44	8.8	2.9	1.1
	II	<0	<0	<0	<0
	III	122	25	8.2	3.1
b	I	302	60	20	76
	II	<0	<0	<0	<0
	III	295	57	19	7
c	I	1520	304	99	38
	II	<0	<0	<0	<0
	III	1598	320	107	40

Table 5 continued.

Soil type	Crop	Contamination, [Ci/km^2]			
		1	5	15	40
Application of mineral fertilizers					
a	I	<0	<0	<0	<0
	II	<0	<0	<0	<0
	III	12	2.4	0.8	0.3
	IV	8	2	0.6	0.2
b	I	48	9.5	3.2	1.2
	II	<0	<0	<0	<0
	III	60	12	3.8	1.6
	IV	92	19	6	2.4
c	I	396	79	26	10
	II	<0	<0	<0	<0
	III	708	141	47	18
	IV	47	10	3.2	1.3
d	IV	16	3.2	1.1	0.5
Combined countermeasures					
a	I	29	5.8	1.9	0.7
	II	<0	<0	<0	<0
	III	87	17	5.7	2.2
b	I	641	128	43	16
	II	<0	<0	<0	<0
	III	210	42	14	5
c	I	3374	675	225	84
	II	<0	<0	<0	<0
	III	3828	774	261	96
d	IV	35	6.8	2.3	0.9
Radical reclamation					
a	IV	71	14	4.4	1.8
b	IV	81	17	5.4	2.0
c	IV	164	33	11	3.8
d	IV	114	23	7.3	2.9

The avertable (collective) doses were calculated as:

$$\Delta S = k_1 \cdot e(50) \cdot M \cdot K_m \cdot K_t \cdot q \cdot (1 - \frac{m}{f}) \qquad (16)$$

where

- f is the effectiveness of the countermeasure;
- q is the surface contamination density, Ci/km^2;
- K_t is the transfer factor of the radionuclide ^{137}Cs from the given soil to crop studied, (Ci·kg^{-1}/Ci·km^2);
- $m = M_c/M$ is the ratio of the (average) crop yield after applying the countermeasure to the (average) crop yield without the countermeasure;
- $e(50)$ is the committed effective dose per unit activity ingested;
- k_1 is a coefficient of decrease of ^{137}Cs level in the product as a result of technological processing and culinary treatment (for grain k_1 is 0.55, for potato 0.5, and for milk 1); and

- $K_m = 1$ for grain crops and potato; for grasses $K_m = 0.01$, the average value of the transfer coefficient of ^{137}Cs from a daily ration to milk.

The method for estimating the avertable collective dose, ΔS, from the equation above actually provides estimates of the maximum possible avertable doses for any real value of m, since a considerable fraction of the potato and grain crops is dispatched for processing followed by a marked decrease in their content of radionuclides (Crick 1991).

The estimates of the effectiveness given in Tables 4 and 5 are based on the value of avertable dose defined by the results of only one year. However, the effect of decreased radionuclide uptake in plants takes place also in subsequent years (first of all, this is the case for countermeasures such as radical reclamation, as well as combined countermeasures, application of organic matter and liming). For a concrete calculation of the avertable doses which takes into consideration the effects of countermeasures for arable lands, information on crop rotation is necessary. As for the situation with radical reclamation of natural lands, it may be stated that avertable dose will be several times higher than that found from the equation above.

Thus, even based on available data on rapid decrease of the amount of ^{137}Cs available for plants (with an effective half-life of its transfer to plants of about 3 years (Vlasov 1992A)) and taking into account some decrease in radiological effectiveness of the countermeasure, it may be stated that the avertable dose in this case would be about a factor of 2 higher during the first 3–5 years. Since additional expenses for radical reclamation in these years are unnecessary, then it may be asserted that the effectiveness, ε, of this countermeasure would be a factor of 2 lower.

When the countermeasures are studied from the point of view of justification, the respective value of α should be specified as realistically as possible. The range of values ($\alpha_{\min}$, $\alpha_{\max}$) characteristic for the choice of α may be used in the following way: If ε (or ε_r) $< \alpha_{\min}$, the countermeasure may be considered justified; if $\varepsilon > \alpha_{\max}$, the countermeasure is not justified according to a cost-benefit analysis; if $\varepsilon \in (\alpha_{\min}, \alpha_{\max})$, it is necessary either to make a more detailed estimate, or take into account additional socio-economic factors.

3.3.2 Estimation of efficiency in animal breeding

The effectiveness of countermeasures of this class will be estimated with the example of *ferrocyne* and *befege*. The basic data for estimating the effectiveness are presented in Table 6.

Table 6. *Basic economic date for using cesium binders in animal breeding in 1992-prices.*

Basic data	Ferrocyne	Befege
Expenses, roubles/kg	350	50
Dosage recommended, g/head · day	3	40
Efficiency (f)	5	5
Cost of the dose for a pasturage period, rouble/head	130-160	240-300

Note: 1992-prices/1990-prices = 10–30

The estimate of the avertable collective dose, ΔS, has been made by the formula:

$$\Delta S = k_1 \cdot e(50) \cdot y \cdot M \cdot K_m \cdot K_t \cdot q \cdot (1 - \frac{1}{f}) \tag{17}$$

where

- y is the milk yield during pasture period; $y = 1100$–2000 l/year;
- M is the mass of grass consumed per day: $M = 50$–30 kg/(head·day);
- K_t is the ^{137}Cs transfer factor from soil to grass (Crick 1991).

In Table 7 values of the effectiveness, ε, are given for different pastures and contamination levels. These measures are characterized by a much higher effectiveness compared to countermeasures in plant breeding (see also Tables 4 and 5).

Table 7. *Expenses for doses averted using cesium binders in animal breeding,* 10^5 *roubles/person·Sv in 1992–prices.*

Soil type	Contamination [Ci/km^2]			
	1	5	15	40
Ferrocyne				
a	1.2–1.4	0.24–0.28	0.08–0.09	0.03–0.035
b	3.5–4.2	0.7–0.8	0.2–0.3	0.09–0.1
Befege				
a	2.2–2.6	0.4–0.5	0.15–0.17	0.05–0.07
b	6–8	1–2	0.4–0.55	0.15–0.2

a — soddy podzolic, sandy and sandy loam

b — chernozem leached

Consider the problems connected with limitations for "dirty" milk, with the application of ferrocyne taken as an example. Based on an optimisation, the application of the countermeasure will be more profitable than replacing "dirty" milk by "pure" milk, and more profitable than consuming milk without applying the countermeasure, if, respectively:

$$P_c + k_1 \cdot \alpha \cdot e(50) \cdot \frac{C}{f} < b \tag{18}$$

$$P_c + k_1 \cdot \alpha \cdot e(50) \cdot \frac{C}{f} < k_1 \cdot \alpha \cdot e(50) \cdot C \tag{19}$$

For $k_1 = 1$, $b = 12$ roubles/ℓ (see Table 3), and $f = 5$:

$$P_c = \frac{130 - 160}{1100 - 2000} \approx 0.1 \text{ roubles}/\ell$$

Besides, the "optimum" value of CLs for milk can be calculated from:

$$\Theta^* = \frac{b}{k_1 \cdot \alpha \cdot e(50)} = 2.5 \cdot 10^{-2} \cdot \frac{1}{\alpha}$$

to lie within the range $(12.5 - 2.5) \cdot 10^{-8}$ Ci/ℓ. The presently used CL for milk of $1 \cdot 10^{-8}$ Ci/l lies below the lower level, and the question would be appropriate as to whether it is justified or not (the values of α within the range are taken as the basis (Luykx 1991; Hedemann Jensen et al. 1993)):

$$\alpha = 2 \cdot 10^5 - 1 \cdot 10^6 \, \frac{\text{roubles}}{\text{person·Sv}}$$

Based on the equations above, the concentration, C, will fall in the range:

$$y_{\min} \cdot \Theta^* = C_{\min} < C < C_{\max} = y_{\max} \cdot \Theta^* \qquad y = \frac{C}{\Theta^*} \tag{20}$$

Considering concrete values of the parameters, the range of C is:

$$C_{\max} = (12.4 - 62) \cdot 10^{-8}\ \mathrm{Ci}/\ell; \quad C_{\min} = (0.025 - 0.125) \cdot 10^{-8}\ \mathrm{Ci}/\ell$$

Thus, based on "borderline" values of ranges of varying Θ^*, the countermeasure under consideration will always be effective within the range:

$$C \in (0.13 - 12) \cdot 10^{-8}\ \mathrm{Ci}/\ell$$

For an average value of Θ^*, the countermeasure is effective within the range:

$$(0.1 - 30) \cdot 10^{-8}\ \mathrm{Ci}/\ell$$

Applying such a countermeasure will always be effective provided that the countermeasure costs do not exceed:

$$P_{c,\max} = (1 - \frac{1}{f}) \cdot b \cong 10\ \mathrm{roubles}/\ell.$$

Based on an optimisation, the values of C_{max} can be a factor of 2 larger, i.e. applying ferrocyne will be effective in the range $0.1 - 60$ of existing CLs (based on the average value of Θ^*), or if the estimates are the most cautious, within the range:

$$(0.13 - 24) \cdot \mathrm{CL}$$

In this latter case such a countermeasure will be effective provided that the costs do not exceed 19 roubles/ℓ. The estimates for applying befege are, in fact, analogous.

Thus, in the case of $P_c < P_{c,\max}$ and if $C < C_{\min}$, milk can be consumed without carrying out the countermeasure under consideration; if $C_{\min} < C < C_{\max}$, the countermeasure is applied; if $C > C_{max}$, a limitation on the consumption of milk should be introduced. If $P_c > P_{c,max}$, the countermeasure is not profitable, and if $C > \Theta^*$, limitations (or prohibition) on milk consumption are necessary.

3.3.3 An estimation of the efficiency of the countermeasure system in the Novozybkov district of the Bryansk region

Based on the data of radioactive contamination of agricultural lands, structure of crop rotation and production of milk in Novozybkov district, Bryansk region (for 1989), the effectiveness of the countermeasure system (chosen in accordance with the scenarios) in plant- and animal breeding has been investigated. The calculations were based on (Vlasov et al. 1992A; Vlasov et al. 1992B; Vlasov et al. 1993); the calculations of plant breeding products and milk contamination were carried out by V.A. Matyash and I.A. Pichugina.

The system of countermeasures was chosen as follows: Based on the model estimates, the fraction of "pure" production of the crop considered in the given zone of contamination and the given soil type was assessed; if this fraction was less than 90%, the countermeasure was carried out. The data for the areas where countermeasures were carried out, as well as total expenses are presented in Table 8. The lands with winter wheat and potato were fertilized; on arable lands with grasses, either fertilization or combined countermeasures were carried out; on (non-cultured) natural hay lands and pastures, radical reclamation was realized; according to the chosen algorithm, countermeasures on lands with winter rye were not applied.

Table 8. *Characteristics of the countermeasure system under investigation (Novozybkovsky district, Bryansk region, year 1989).*

Crop	Area of lands where counter-measures were taken [10^3 ha]	Total expenses for counter-measures [10^3 roubles]	Cost of increasing "pure" production without/with consideration of additional yields [10^3 roubles]	Cost of increasing total production (countermeasures, addit. yields considered) [10^3 roubles]
Winter wheat	0.13	27	17.7/27	16.4
Potato	2.47	668	2006/3243	1920
Annual grasses on ploughland (hay)	2.6	1017	248/317	94
Perennial grasses on ploughland (hay)	5.2	1890	323/475	189
Hay of natural haylands	1.16	755	4/6	37
Grasses of natural pastures	15.8	10270	—	—
Total (pastures not considered)	11.56	4357	2600/4068	1573
Total (pastures considered)	27.36	14627	—	—

The results of the estimates are given in Tables 8–12. In Tables 10 and 11 more detailed data on the effectiveness of different countermeasures for changing the structure of contamination of cows milk which is the major contributor to dose (about 90 % contribution to the internal radiation dose) are also presented. The extent of the contamination of milk during pasture period was determined using the program complex developed (Vlasov et al. 1992A; Vlasov et al. 1992B; Vlasov et al. 1993).

A comparison of avertable doses from contaminated milk produced during the pasture period and defined, on the one hand, by the data on ^{137}Cs content in hay, and on the other hand, by the data on production of milk and model estimates of the structure of its contamination, shows that avertable doses in the latter case (3.4 person·Sv) are about three times less than that in the former (12.2 person·Sv). This is quite explainable when one takes into account the share of dairy cows in total livestock capita.

The contribution of potatoes to the total collective dose from internal irradiation (around 20%) is also exaggerated. These notions may be considered by appropriate corrections which take into account the character of the use of plant products (including feed production) and animal products for different needs (food, forage, technology, etc.).

The main contribution to the avertable dose due to the system of countermeasures applied is from the radical reclamation of pastures. When one considers the note made in the previous section on the relationship between the values of avertable doses in the first year and in the subsequent 3–8 years, as well as the argument that a 50% decrease of the dose is a more reliable estimate of avertable dose (see Table 9), about 200 person·Sv is quite realistic for the avertable dose in the given case.

Table 9. *Effectiveness of the countermeasure system under investigation (Novozybkovsky district, Bryansk region), year 1989.*

Crop	Expenses for countermeasures [10^3 roubles]	Avertable doses with/without additions [person·Sv]	Effectiveness of countermeasures without/with additions/ reduced effectiveness, [10^5 roubles/person·Sv]
Winter wheat	27	0.22/0.17	1.2/1.6/0.6
Potato	668	45/41	0.15/0.16/-0.14
Hay of annual grasses (ploughland)	1017	4.1/3.6	2.5/2.8/2.5
Hay of perennial grasses (ploughland)	1890	5.5/4.7	3.4/4/3.6
Hay from natural haylands	755	2.6/2.3	2.8/3.2/3
Grasses of natural pastures	10270	146*	0.7
Total (pastures not considered)	4357	57.6/52	0.76/0.84/0.54
Total (pastures considered)	14627	204	0.72
Total (50% milk for processing, 50% grain and potato for forage and other needs)	14627	105	1.4
Total* (pastures considered)	14627	195	0.75
Total* (50% milk for processing, 50% grain and potato for forage and other needs)	14627	100	1.5

*Calculated by the model of animal product contamination.

After analysing the data in Table 9, a conclusion may be drawn on the avertable doses and effectiveness of the countermeasures without considering (probable) additions of crop yield due to the countermeasures. However, in some cases (see the data in Table 5 on wheat and potato), a consideration of additions using "cost-benefit" methods may provide a more complete picture of the effectiveness of the countermeasure (or system of countermeasures) used.

The data on the cost of increment of "net" production presented in Table 8 are of particular value when investigating strategies based on various approaches to the use of "pure" and "dirty" production. Tables 10 and 11 present the data on the effectiveness of the countermeasure system under consideration and ferrocyne application in the pasture period.

Table 10. *Effectiveness of the system of countermeasures under investigation for milk production (Novozybkovsky district, Bryansk region, year 1989).*

Complex of measures	% of "pure" production		Cost of addition of "pure" production [10^3 roubles]
	total	pasture/stable period	
No countermeasure	35	13/76	-
Complex of countermeasures in plant breeding	66	55/87	2631
Use of ferrocyne in pasture period	62	54/76	2218

Table 11. *Effectiveness of countermeasures according to the data on decrease of milk contamination. The calculations are based on the models of animal production in 1989-1990 prices.*

Measure	Avertable dose [person·Sv]		Effectiveness [10^5 roubles/person·Sv]
	total	pasture/stable period	
Complex of countermeasures in plant breeding	149.4	146/3.4	0.9
Use of ferrocyne in pasture period	145	145/0	0.005

A comparison of avertable doses (from the data on decreased radioactivity in milk, Tables 10, 11 and 12) provides evidence of a high efficiency of ferrocyne. At the same time, the effectiveness of application of ferrocyne during pasture period, 500 roubles/person·Sv, exceeds the effectiveness of the countermeasure system considered in plant breeding actually by two orders of magnitude:

$$\varepsilon \approx (0.7 - 0.9) \cdot 10^5 \frac{\text{roubles}}{\text{person} \cdot \text{Sv}}$$

In Table 12 the structure of milk contamination in the pasture period in the zone of contamination level of 15–40 Ci/km^2 is presented as an example of different variants of countermeasure applications.

Table 12. *Structure of milk contamination in the pasture period in the contamination zone of 15–40 Ci/km^2; Novozybkovsky district, Bryansk region; Control Level (CL) = 10^{-8} Ci/ℓ (according to the data of model calculations, year 1989).*

Measure	% of pure production	Aver. contamination of production [10^{-8} Ci/ℓ]	Total activity of ^{137}Cs in production [mCi]		
			total	in "pure"	in "dirty"
No countermeasure	9	6.6	330	0.15	230
System of countermeasures in plant breeding	43	1.3	67	7	60
Use of ferrocyne in pasture period	43.5	1.4	68	8	60
System of countermeasures in plant breeding and use of ferrocyne in pasture period	98	0.3	15	14	1

In case of a combined use of radical reclamation and ferrocyne, the amount of ^{137}Cs activity in net production is decreased by a factor of 50 – 100. If all "dirty" milk were to be used for processing butter (a decrease in ^{137}Cs content about 40 times), the amount of activity in food without any countermeasure would be:

$$q \approx 0.15 + \frac{230}{40} = 6 \text{ mCi}$$

when radical reclamation or ferrocyne is used, and 9–10 mCi and 14 mCi for a combined application of these countermeasures. Thus, it follows from Table 12 and the above estimates that, notwithstanding the general decrease of activity content in production obtained, the collective dose due to consumption of "pure" and processed "dirty" production may be increased.

4 Sensitivity of changing intervention levels

Intervention levels (ILs) relate to specific protective actions taken to mitigate the consequences of an accidental release of radionuclides or of other de facto radiation sources. Intervention levels are specified in terms of the dose that is **anticipated to be averted** (avertable dose) by the associated protective action and ILs are specified separately for different protective actions. The avertable dose is to be compared to the Intervention Level, and if the avertable dose exceeds the intervention Level the protective action should be introduced.

The decision maker might want to reduce the level at which the protective action is to be introduced on the grounds that action will then be taken at lower doses, which would then be in the best interests of those affected. This view is, however, misguided and ignores the negative features of the protective action itself which may be considerable.

The effect of changing the ILs in either a downwards or upwards direction, i.e. making the situation for the affected population "more or less safe", has been analysed based on the CIS data and also on standard atmospheric dispersion conditions.

4.1 Chernobyl accident conditions in CIS

In the following it is assumed that the costs of relocation and foodstuff restrictions are proportional to the number of people to be relocated, N, and the amount of foodstuff to be banned, M. From Section 3.1 and 3.2 it appears that N and M are each proportional to a power function of the Intervention Level, IL:

$$N(IL) \propto IL^{1-b}$$
$$M(IL) \propto IL^{1-b}$$

A reasonable assumption would be that the cost, P, of the countermeasures is proportional to N and M.

The avertable collective dose by relocation and foodstuff restrictions are also proportional to a power function of IL, but with an exponent being 1 less than for the costs (for $b > 2$):

$$S \propto IL^{2-b}$$

If IL is changed by a factor f the avertable collective dose would be changed by a factor of:

$$\Delta S = \frac{(f \cdot IL)^{2-b}}{IL^{2-b}} = f^{2-b} \tag{21}$$

The corresponding change in costs can be calculated in a similar way as:

$$\Delta P = \frac{(f \cdot IL)^{1-b}}{IL^{1-b}} = f^{1-b} \tag{22}$$

For the conditions in CIS in 1990 with a value of b of 2.5, a decrease of the intervention level by a factor of 10 ($f = 0.1$) will increase the avertable collective dose by a factor of $0.1^{-0.5} \cong 3$. The costs would correspondingly be increased by a factor of $0.1^{-1.5} \cong 30$.

Similarly, if IL were increased by a factor of 5 ($f = 5$) the avertable collective dose would be decreased by a factor of $5^{-0.5} \cong 0.5$ and the costs decreased by a factor of $5^{-1.5} \cong 0.1$.

An important conclusion can be drawn from the above relations, namely that the change in avertable collective dose would be f times the change in costs, independently of the value of b as long as $b > 2$. Thus, in general for $b > 2$:

$$\frac{\Delta S}{\Delta P} = f \tag{23}$$

The absolute change of either avertable collective dose or costs would, however, depend on the value of b with increasing changes for increasing values of b.

4.2 Standard atmospheric dispersion conditions

The simplest picture of the atmospheric transport mechanism is that of a horizontal plume made up of the released airborne material and lined up with the direction of the wind. The vertical and horizontal dimensions of the plume will increase with increasing distance from the source because of turbulent mixing. In the plume the concentration of the effluent will be determined by the release rate, the distance from the release point, the wind speed, the turbulence, and the removal of material from the plume by dry and wet deposition.

The Gaussian plume model can be used for making simple calculations of air and ground concentrations of activity released to the environment in a nuclear accident. However, the model is applicable only when a certain number of conditions have been fulfilled. In this context, the model will be used to analyse the changes in doses and costs as a result of changes of Intervention Levels, e.g. surface contamination density.

The size of the ground area, $A(\chi)$, within which the time-integrated air concentration exceeds the value χ at a wind speed, u, after a ground level release of activity, q, can be expressed as:

$$A(\chi) \cong \alpha \cdot \left(\frac{\chi\, u}{q} \right)^{\beta} \tag{24}$$

The value of the dispersion/deposition parameter β will be in the range –1.2 to –1.7.

The relation between the surface contamination density, Q, and the time-integrated air concentration can be expressed by the deposition velocity, v_d (dry or wet deposition), as:

$$Q = v_d \cdot \chi \tag{25}$$

Consequently, the relation between area size, $A(Q)$, with surface contamination density greater than Q will be:

$$A(Q) \cong \alpha \cdot \left(\frac{v_d^{-1} u\, Q}{q} \right)^{\beta} = \gamma \cdot Q^{\beta} \tag{26}$$

If it is assumed that the concentration of activity in milk produced in the area of size A, in which the surface contamination density, Q, is greater than a given intervention level, IL, the collective dose from consumption of that milk would be proportional to the total activity in the area, i.e.:

$$S \quad \propto \quad \int_{IL}^{\infty} A(Q)\ \mathrm{d}Q = \frac{\gamma}{\beta + 1} \cdot IL^{\beta+1} \tag{27}$$

The cost, P, of banning milk from the area, A, would be proportional to the amount of milk produced in this area and thus to A, at the value of $Q = IL$, i.e.:

$$P \quad \propto \quad \gamma \cdot IL^{\beta} \tag{28}$$

If IL were changed by a factor f the avertable collective dose would be changed by:

$$\Delta S = \frac{(f \cdot IL)^{\beta+1}}{IL^{\beta+1}} = f^{\beta+1} \tag{29}$$

The corresponding change in cost would be:

$$\Delta P = \frac{(f \cdot IL)^{\beta}}{IL^{\beta}} = f^{\beta} \tag{30}$$

Again, the change in avertable collective dose would be f times the change in costs:

$$\frac{\Delta S}{\Delta P} = f \tag{31}$$

The most probable stability category would normally be Pasquill D (about 60% of all time) with a value of β of about –1.3.

4.3 Comparison between CIS conditions and standard dispersion conditions

If an intervention level were changed it would have an effect on both the avertable collective dose and the corresponding costs. A change of the IL downwards would result in an increased avertable collective dose and increased costs. A change upwards would have the opposite effect.

For the situation in CIS after the Chernobyl accident the sensitivity of changing ILs has been analysed from the distribution of the population on the surface contamination density of ^{137}Cs. While the change in the cost of changing the IL by a factor of f ($f > 1$ corresponds to a relax of the situation, whereas $f < 1$ corresponds to a more restrictive situation) would be proportional to f^{1-b}, where b is the distribution parameter found to be 2.5, the corresponding change in collective dose would be proportional to f^{2-b}. This means that the change in avertable collective dose would be f times the change in costs. For example, if the situation were made more restrictive by $f = 0.1$, the increase in costs would be 10 times the increase in avertable collective dose and vice versa.

For standard atmospheric dispersion situations, a similar relation has been found. Changing the IL by a factor of f would result in a change in costs by a factor of f^{β} while the avertable dose would be changed by a factor of $f^{\beta+1}$. The parameter β describes the dispersion conditions and for many weather situations β would be about –1.3.

For both the CIS conditions and the standard dispersion conditions the same functional dependence has been found and the ratio $\Delta S/\Delta P$ will in both situations be equal to f. The absolute changes in ΔS and ΔP differ only slightly for the two situations. For the cost change the factor is $f^{-1.5}$ and $f^{-1.3}$, respectively, and for the change in avertable collective dose the factor is $f^{-0.5}$ and $f^{-0.3}$, respectively.

It is therefore concluded that the sensitivity of changing the ILs for protective measures can be adequately described by standard dispersion situations with a value of the parameter β close to –1.5 to be used in most situations.

5 Risk perspective of intervention levels

During the past decade, new information about the carcinogenic effects of radiation has come from epidemiological studies of Japanese atomic bomb survivors; patients irradiated therapeutically for ankylosing spondylitis and other conditions; workers exposed to radiation in various occupations; and populations residing in areas of high natural background radiation. New data have also come from long-term studies of the carcinogenic effects of irradiation in laboratory animals and from experiments on neoplastic transformation in cultured cells. The new data have been summarised in reports from UNSCEAR (UNSCEAR88) and NAS/BEIR (NAS90).

5.1 Concept of risk

In many areas of hazard assessment, specific meanings of the word *risk* are avoided and preference is given to words which more directly indicate the relevant quantity, e.g. *probability, consequence*, and *mathematical expectation* of the consequence. This leaves the word *risk* free to be used in the everyday meaning and makes it possible to include in the risk concept a number of factors which, in addition to those more readily quantifiable, influence decisions on risk acceptance.

With this wider meaning of the word, *risk* is a concept rather than a quantity. The ICRP (ICRP90) has decided to abandon its practice of always strictly using *risk* with the specific meaning of probability and attempts to use instead the more direct term *probability*. This should reduce the ambiguity when describing the probabilities and consequences of an event and makes it easier to communicate with regulatory agencies and others who deal with non-radiation risks as well. For example, the concept of *death probability rate* is used by the ICRP rather than *mortality rate*. The reason is that the rates will be integrated and the integral to be used by the ICRP is the *attributable lifetime probability* of death, related to the *average individual*, rather than the observed or expected number of deaths per 100,000.

The ICRP is mainly concerned with two quantifiable risk quantities:

- P_i which is the *probability* of each harmful effect (i), e.g. lethal or curable cancer or severe hereditary effects;
- W_i which is the *consequence* if the effect occurs. The consequence can be described in a variety of ways, indicating the severity of the effect and its distribution in time.

The *mathematical expectation* of consequence, identical to the average consequence, is:

$$\overline{W} = \sum_i P_i \cdot W_i \tag{32}$$

This quantity is sometimes used in the effort to express the magnitude of the "risk".

5.2 Age dependent radiation risk

A radiation dose will involve a risk commitment, i.e. a commitment of an increased cancer death probability rate in the future, after a minimum latent period which may be from a few years in the case of leukaemia to tens of years for other malignant conditions. Any change in the age-specific death probability rate would therefore occur later in life, when the risk of death from other causes is also higher. The risk committed by a radiation dose at a given age can therefore not be added to the background risk at the same age.

The *attributable lifetime probability of death* from radiation exposure has been used by the ICRP, and radiation risks have been expressed in *per cent per sievert*. However, our total probability of death, which is 100%, cannot be increased. The introduction of a new risk source will not change our lifetime probability of death but only the distribution of the probable causes of death. Any increment that a new risk source causes, is an increment to our *death probability rate* at any given age, provided that the person is alive at that age, i.e. a conditional probability rate.

A defined exposure scenario may add a *conditional* source-related increment of probability rate, $\mathrm{d}p/\mathrm{d}u$, to the background rate. The rate is conditional, because it will be expressed only if the individual is alive at the ages (u) for which it is defined. From this increment, an *unconditional* probability rate, $\mathrm{d}r/\mathrm{d}u$, can be calculated when a reference time (age) has been defined, e.g. the age at the onset of the exposure period. The attributable lifetime probability of death from the source under consideration must therefore be calculated from the unconditional incremental death probability rate, $\mathrm{d}r/\mathrm{d}u$, taking account of the probability of reaching each age (u) by considering the likelihood of dying from other causes as well as from radiation.

The unconditional incremental probability rate is obtained as the product of the conditional incremental probability rate $\mathrm{d}p/\mathrm{d}u$ and the *survival* probability, $S(T,u)$, modified by the incremental radiation risk:

$$\frac{\mathrm{d}r}{\mathrm{d}u} = S(T,u) \cdot \frac{\mathrm{d}p}{\mathrm{d}u} \tag{33}$$

The modified survival probability, $S(T,u)$, is related to the age, T, from which the probability is calculated.

The attributable lifetime probability of death can be calculated as the integral of the unconditional incremental death probability rate as:

$$r(T) = \int_T^{\infty} \left(\frac{\mathrm{d}r}{\mathrm{d}u}\right) \mathrm{d}u = \int_T^{\infty} S(T,u) \cdot \left(\frac{\mathrm{d}p}{\mathrm{d}u}\right) \mathrm{d}u \quad (34)$$

Fig. 8 shows the variation of the attributable lifetime probability of death with age at the time of exposure (NAS90). The substantially higher risk for the youngest age group is notable. However, it must be recognised that most of this higher risk will be expressed first at high ages.

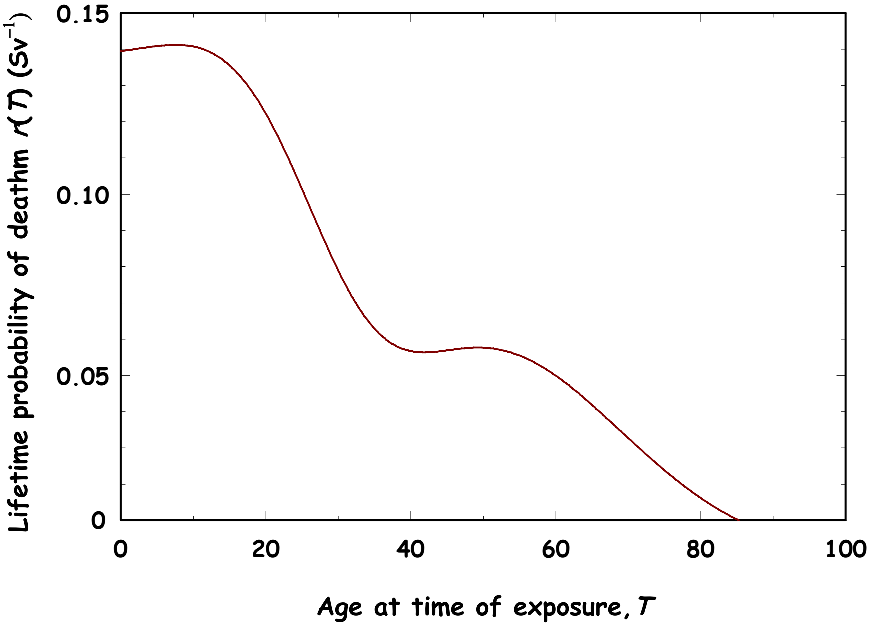

Figure 8. he attributable lifetime probability of death from a single small dose at various ages at the time of exposure (NAS90).

The lifetime risk factors in Fig. 8 are the calculated average for both sexes. In these factors the BEIR Committee have reduced the contribution from leukaemia by a dose rate effectiveness factor (DREF) of 2 (using a linear-quadratic response) whereas for solid tumors a linear response was used, i.e. no DREF-reduction. For high dose, high dose rate the leukaemia contribution should therefore be doubled.

5.3 Radiation risk for different exposure situations

The attributable lifetime probability of death, $R(T)$, due to a chronic radiation exposure starting at a given age, T, can be calculated from the dose rate as a function of age (time), $\dot{E}(t)$, and the probability rate of death per unit dose, $\dot{p}(t,\tau)$.

A chronic exposure with dose rate $\dot{E}(t)$ starting at age T will cause an attributable probability of death of:

$$\int_T^{\tau} \dot{E}(t) \cdot \dot{p}(t,\tau)\ \mathrm{d}t \quad (35)$$

where $\dot{p}(t,\tau)$ is the conditional probability rate of death per unit dose.

The attributable lifetime risk, $R(T)$, from a chronic exposure starting at age T can be calculated as:

$$R(T) = \int_T^{\infty} \dot{E}(t) \left(\int_t^{\infty} S(T,\tau) \cdot \dot{p}(t,\tau)\mathrm{d}\tau\right) \mathrm{d}t \quad (36)$$

The risk calculation in (36) assumes that the survival probability function, $S(T,\tau)$, is independent of the added radiation risk. This is, of course, an approximation.

If the risk from the considered radiation exposure is significant compared to the "background" risk, the survival function should be modified, i.e. it should be decreased due to the added radiation risk.

The exposure of a population after a nuclear accident would always be decreasing in time due to radioactive decay and other removal processes for the radioactive materials deposited in the environment at the time of the accident.

The survival probability function, $S(T,\tau)$, can be calculated from the conditional probability rate of death from all causes which can be found from demographical data. The conditional probability rate per unit radiation dose can be calculated from the basic radiation risk factors and risk projection models given by UNSCEAR (UNSCEAR88) and the BEIR Committee (NAS90).

5.4 Risk and intervention levels

The control of exposures following an accident in which radionuclides are released into the environment can be achieved only by some form of intervention. Once a course of intervention has been chosen, the protective measures taken should be optimised so the benefit to the population affected by the measures is maximised. This optimisation process will produce intervention levels (ILs) for the different protective measures expressed in terms of avertable doses. If the doses foreseen to be received over a given time period without the protective measure were to exceed the IL the protective measure should be implemented and maintained as long as the avertable doses exceed the IL.

5.4.1 Avertable individual risks

The avertable doses from a protective measure can be expressed in terms of avertable individual risks or avertable expected consequences for the population affected by the protective action. If a protective measure were introduced for a time period, ΔT, for which the foreseen individual doses would exceed the IL, the avertable individual lifetime probabilities of cancer death for people at age T affected by the protective measure would be:

$$R(T) = \int_{T}^{T+\Delta T} \dot{E}(t) \left(\int_{t}^{\infty} S(T,\tau) \cdot \dot{p}(t,\tau) \mathrm{d}\tau \right) \mathrm{d}t \tag{37}$$

where T is the age of the individuals in the population group and $\dot{E}(T+\Delta T) = IL$.

5.4.2 Residual individual risks

The underlying principles of intervention is that protective measures affecting the exposure pathways considered should be introduced if the foreseen individual doses over a given future time period were to exceed the optimised intervention level for that specific protective measure. Furthermore, the protective measure should continue to be in action as long as the avertable individual doses continue to be larger than the IL. When the foreseen avertable doses fall below the IL the protective measure should be lifted.

Such a scheme of intervention would have the consequence that in areas where the foreseen avertable individual doses would be less than the IL, no protective measures would be introduced. The people living in these areas would be exposed to a residual lifetime risk which would be equal to at most that for individuals in a population for whom the protective actions are lifted after a time period ΔT. The residual lifetime risk for an individual can be calculated as:

$$R(T) = \int_{T+\Delta T}^{\infty} \dot{E}(t) \left(\int_{t}^{\infty} S(T,\tau) \cdot \dot{p}(t,\tau) \mathrm{d}\tau \right) \mathrm{d}t \tag{38}$$

where T is the age of the individuals in the population at the start of the intervention and the dose per unit time when the intervention is lifted, $\dot{E}(T+\Delta T) = IL$.

5.4.3 Dose indices

From the Altay situation and other situations it can be seen that some modification of the current effective dose is needed for risk estimates in a post-accident situation. In general, doses from an accident can include a short-term (acute) and a long-term (chronic) component. The last one can be accumulated over many years. To describe such a situation it is proposed to use a so-called *normalised effective dose*, E_{norm}, as a dose index:

$$E_{norm}(T) = c(T) \cdot E_{sh} + \int_T^{\infty} v_T(t) \dot{E}_{chr}(t) \; \mathrm{d}t \tag{39}$$

which could take into account all necessary exposure modes and age distributions. $c(T)$ and $v_T(t)$ are weighting factors, t is a current age, T is the age at the acute exposure, E_{sh}, and the start of the chronic exposure, and $\dot{E}_{chr}(t)$ is the dose rate for the chronic exposure. The weighting factor, $v(t)$, can be calculated as:

$$v_T(t) = \frac{1}{r_E} \int_t^{\infty} S(T, \tau) \dot{p}(t, \tau) \; \mathrm{d}\tau \tag{40}$$

where $S(T, \tau)$ is a survival function from age T to age τ and $\dot{p}(t, \tau)$ is the age-specific radiological risk coefficient per unit dose or probability rate of death per unit dose at the age τ form a single exposure at age t ($t \leq \tau$).

The weighting factor, $c(T)$, is defined as:

$$c(T) = \zeta \cdot w(T) \tag{41}$$

where ζ is the ratio of radiological risk from an acute exposure to that from a chronic exposure of the same magnitude accommodating the higher risk of doses given with high dose rate.

The weighting factor, w, is defined as:

$$w(T) = \frac{r(T)}{r_E} \tag{42}$$

where $r(T)$ is the radiological risk coefficient for a single dose given at age T and r_E is the average value of $r(T)$ which defines the current effective dose.

Based on the definitions above, the *normalised effective dose* can be calculated as:

$$E_{norm}(T) = \frac{1}{r_E} \cdot \left(\zeta \cdot r(T) \cdot E_{sh} + \int_T^{\infty} \dot{E}_{chr}(t) \left(\int_t^{\infty} S(T, \tau) \cdot \dot{p}(t, \tau) \; \mathrm{d}\tau \right) \; \mathrm{d}t \right) \tag{43}$$

The suggested modification of the current effective dose concept can also be used in situations where dose levels for decision making purposes have been established for a critical group which might have a particular age distribution or a particular background age-specific death rate distribution.

These issues are now being studied in the framework of Tasks 3 and 4 of JSP 2.

5.5 Risk comparisons

A large variety of risks in a society can be quantified in terms of the loss of life expectancy (LLE) they cause in the society (Cohen, Lee 1979; Cohen 1991). The advantage of using LLE in quantifying risks is that it is easily understandable in terms of everyday experience. For example, a mortality risk of 10^{-3} is not as easily understandable to most people as a LLE of 20 days. In addition, LLE considers the important fact that a premature death of an elderly person is less regrettable than the death of a young person.

Risks considered here for comparison with the radiation risks at given intervention levels include cigarette smoking, carcinogens in foodstuffs and natural background radiation.

5.5.1 Cigarette smoking

Cigarette smoking is common in all countries and the risk of dying of lung cancer caused by smoking is fairly well known. In Denmark the number of cigarettes smoked every day is around 20 million. The attributable number of lung cancer deaths is around 3000 per year. If it is assumed that a lung cancer death in average causes a LLE of 20 years, the average LLE as a result of smoking one cigarette can then be calculated to be:

$$\mathrm{LLE}_{\mathrm{cigarette}} = \frac{3000 \cdot 20}{20 \cdot 10^6 \cdot 365} \cong 8 \cdot 10^{-6} \text{ year}\cdot\text{cigarette}^{-1}$$

The average LLE of dying of a radiation-induced cancer from low doses given at low dose rates is about 0.8 year·Sv^{-1} (UNSCEAR88). Consequently, the equivalent radiation risk of smoking one cigarette can be calculated as:

$$\begin{aligned} r_{\mathrm{eq}}(\text{cigarette}) &= \frac{\mathrm{LLE}_{\mathrm{cigarette}}}{\mathrm{LLE}_{\mathrm{radiation}}} \\ &= \frac{8 \cdot 10^{-6} \text{ year}\cdot\text{cigarette}^{-1}}{0.8 \text{ year}\cdot\text{Sv}^{-1}} \\ &= 10^{-5} \text{ Sv}\cdot\text{cigarette}^{-1} \end{aligned}$$

Based on this relative risk figure the following average consequences of smoking one pack of cigarettes a day in a lifetime can be calculated:

- a loss of life expectancy of 1,200 days,
- an equivalent risk of an effective annual dose of 70 mSv·year^{-1}, and
- an equivalent risk of an effective lifetime dose of 4 Sv.

The natural background radiation causes an annual effective dose of 2–3 mSv/year worldwide. This dose corresponds to an annual smoking of about 250 cigarettes, i.e. less than one cigarette per day.

5.5.2 Foodstuffs

Ingestion of various foodstuffs containing carcinogens or having a high content of calories might cause attributable deaths due to cancer or heart diseases. A continued consumption of calorie-rich desserts would increase one's body weight and increase the risk of heart diseases. For calorie-rich deserts the following value of LLE has been estimated (Cohen, Lee 1979; Cohen 1991):

$$\mathrm{LLE}_{\text{calorie-rich}} = 50 \text{ minutes/250 g calorie-rich dessert}$$

Based on the LLE of 0.8 year·Sv^{-1}, the following equivalent risks can be calculated:

$$\begin{aligned} r_{\mathrm{eq}}(\text{calorie-rich}) &= \frac{\mathrm{LLE}_{\text{calorie-rich}}}{\mathrm{LLE}_{\mathrm{radiation}}} \\ &= \frac{10^{-4} \text{ year}\cdot\text{dessert}^{-1}}{0.8 \text{ year}\cdot\text{Sv}^{-1}} \\ &\cong 10^{-4} \text{ Sv}\cdot\text{dessert}^{-1} \end{aligned}$$

The equivalent risk can also be expressed in terms of a given activity content of ^{137}Cs in these items giving the same risk as the consumption of the item itself. The risks would then be expressed as:

$$
\begin{aligned}
r_{\mathrm{eq}}(\text{calorie-rich}) &= \frac{\mathrm{LLE}_{\text{calorie-rich}}}{\mathrm{LLE}_{\text{activity}}} \\
&= \frac{10^{-4}\ \text{year}\cdot\text{dessert}^{-1}}{0.8 \cdot 1.3 \cdot 10^{-8}\ \text{year}\cdot\text{Bq}^{-1}} \\
&\cong 10^{4}\ \text{Bq}\cdot\text{dessert}^{-1}
\end{aligned}
$$

Based on these relative risk figures the following average consequences of consuming a calorie-rich desert each day during a lifetime can be calculated:

- a loss of life expectancy of 800 days,
- an equivalent risk of an effective annual dose of 40 mSv·year^{-1},
- an equivalent risk of an effective lifetime dose of 2.6 Sv, and
- an equivalent risk of a daily ingestion of 10,000 Bq of ^{137}Cs.

5.5.3 Natural background radiation

The radiation that occurs naturally in man's environment is referred to as natural background radiation. All life forms, including man, have been exposed throughout their existence to natural sources of ionising radiation. The natural background of ionising radiation received by man comprises cosmic rays and radiation from naturally occurring radionuclides that are present in the environment and are incorporated in the body from the intake of radionuclides in foods. There are some 40 naturally occurring radioelements and about twice this number of naturally occurring radionuclides.

Globally, the average annual dose due to natural sources is about 2.8 mSv (CEC93). Within this statistical average are typical individual doses that range from less than one to several millisieverts a year and in extreme cases, to a sievert or more. The variability of the human exposures to natural radiation has been mapped in a Radiation Atlas (CEC93) for seventeen different countries in Europe. Radon exposure in homes is responsible for the wide variation between the natural doses in these countries.

The *average* annual doses from the background radiation in these countries varies between 2 mSv/year and 8 mSv/year corresponding to a lifetime dose in 70 years between 140 mSv and 560 mSv. This variation may be used to put the intervention levels for relocation expressed in Ci·km^{-2} in perspective.

If it is assumed that a surface contamination density of 40 Ci·km^{-2} of ^{137}Cs has an effective half-life of 10 years, the lifetime dose in 70 years from external γ-radiation will be about 100 mSv for a time-averaged location factor of 0.4. This dose is of the order of 25% of the variation in average lifetime doses in the seventeen countries in Western Europe. If it were further assumed that the internal lifetime dose from ingesting foodstuffs grown in areas with a surface contamination density of 40 Ci·km^{-2} of ^{137}Cs is equal to the external lifetime dose, the total lifetime dose would be 200 mSv, or about 50% of the variation in average lifetime dose in these countries.

Based on these assumptions the following average consequences and relation can be calculated, normalised to a surface contamination density of 1 Ci·km^{-2} of ^{137}Cs:

- a loss of life expectancy of 35 hours,
- a lifetime dose of 5 mSv, and
- 1% of the variation in average lifetime doses in Western Europe.

It is believed that the 1% relation to the lifetime dose variation would change only marginally if the natural background radiations from the remaining European countries were included in the Radiation Atlas.

6 Application in decision making

The long-term consequences of a nuclear accident can be mitigated by interventions such as relocation of people from contaminated areas, restrictions of foodstuffs and decontamination of contaminated areas. The decisions on the introduction of these countermeasures will be based on factors of a radiological, economical and socio-political nature. The interactions between these factors are often very complicated and the decision maker(s) will need some baseline information to aid the decision process. The baseline information will include:

- dose distributions on population,
- activity distribution in foodstuff productions,
- avertable doses at given intervention levels for different protective actions,
- avertable and residual radiation risks by the protective actions,
- the economic costs of different protective actions,
- the efficiencies of protective actions,
- sensitivity of changing the intervention levels, and
- risk perspectives at given intervention levels.

This information will give the decision maker an overview of the situation from a radiation protection point of view and form a baseline for the final decisions which might include factors of a more political nature.

In the following, the use of the present methodology in a simple model for aiding the decision-making process on protective measures after a release of radionuclides into the environment is discussed.

6.1 Differential distributions on environmental quantities

Quantities such as *dose rate, surface contamination density* and *activity concentration* in foodstuffs can easily be measured and applied as surrogates for intervention levels of *avertable dose*. However, such operational quantities should be used carefully and applied together with the local conditions and the circumstances of the accident which include types of radionuclides, environmental half-lives, transfer factors of deposited activity and location factors for housing conditions in the affected areas.

After an accidental release of radioactive material, measurements are necessary to confirm the presence of environmental contamination and obtain an indication of the seriousness of the release. The nature and type of measurements will vary with the circumstances of the release, but may include measurements of *external dose rates* and *the activity levels of radionuclides* in air and in a wide range of environmental materials (e.g. on the ground and structural surfaces, in foodstuffs and drinking water). Dose rates and measured activity levels of radionuclides in environmental materials can, with suitable models, be interpreted in terms of doses to individuals, both *avertable doses* by the introduction of protective measures and *projected doses*.

Differential population distributions on outdoor effective dose rate or surface contamination density represent the number of people exposed to these quantities in differential intervals. The distributions can be determined from environmental measurements with subsequent isoplots on maps with information on placement of villages, towns and food production facilities.

The differential population distribution on dose rate (or surface contamination density) is an important planning tool for long-term countermeasures like relocation. It can be used to calculate the number of people who – in the absence of relocation – would receive individual doses above a given intervention level. In addition, calculations can be made of the avertable collective dose in given individual dose intervals and of the cost component being proportional to the number of people to be relocated.

Similarly, a differential mass distribution for foodstuffs on activity concentrations of different radionuclides can be used to calculate the amount of foodstuffs with an activity concentration above a given intervention level and also the corresponding avertable collective ingestion dose.

Modules for calculating distributions on environmental quantities

- Module for graphical presentation of environmental measurements
- Module for preparing isoplots of the environmental measurements
- Module for calculating differential population distributions on each environmental quantity
- Module for calculating differential foodstuff mass distributions on concentration of radionuclides in the foodstuffs

6.2 Avertable doses and avertable risks

The calculation of avertable doses using the results of environmental measurements for comparison with intervention levels requires a modelling of the various processes involved in the transfer of an environmental contaminant to man. The models adopted may be of varying complexity depending upon the processes involved in the transfer of the environmental contamination to man. In general, the models should be realistic and particular to the circumstances under consideration. They should avoid incorporating pessimism as this may compromise the underlying objective of intervention.

For the purpose of determining avertable doses for comparison with intervention levels, the habits assumed for individuals need to be carefully delineated. As the intention is to compare the exposure of a typical individual with the intervention levels, average habits should normally be assumed. The more important habits and characteristics of individuals that need to be defined will depend upon the mode of exposure and may include *age, dietary intake, methods of food preparation* and *time spent indoors*.

In deriving such data it is important to ensure that they are reasonably representative of the group of individuals whose potentially avertable doses are to be compared with the intervention levels. In theory, data on habits should be site specific, but in practice it will generally be sufficient to use data based on regional or national statistics.

Modules for calculating avertable doses and risks

- Module for preparing site- and accident-specific data bases on nuclide dosimetry, transfer factors, location factors for shielding and occupancy and environmental half-lives
- Module for calculating the number of people exceeding a given individual dose level over a specified future time period without implementation of relocation
- Module for calculating avertable individual and collective doses at a given intervention level
- Module for calculating the amount of different foodstuffs having an activity concentration exceeding a given intervention level
- Module for calculating avertable collective doses by restricting foodstuffs at a given intervention level

The radionuclide dosimetry data base can be structured in the following way: For each nuclide the data base should include – summed over all relevant exposure pathways for the given countermeasure – the avertable dose per unit measurable quantity (e.g. dose rate) over the time period for which the countermeasure would be applied. Such calculations could be made from simple models, still reasonably accurate for the purpose of intervention (Hedemann Jensen 1992).

6.3 Costs, efficiencies and sensitivities

Data on costs of protective actions can be derived from differential population distributions on dose rate and differential foodstuff mass distributions on activity concentration in foodstuffs. From these distributions the amount of foodstuffs to be withdrawn or the number of people to be relocated can be found, and correspondingly the monetary costs as well.

The efficiency of different agricultural countermeasures vary considerably as does the efficiency of decontamination of different types of areas (e.g. urban or rural). The efficiencies, ε, of different protective measures can be expressed as cost per unit avertable collective dose from that countermeasure. The efficiencies can be judged by comparing them to the monetary value of the unit collective dose, α. If $\varepsilon < \alpha$, the protective measure would be justified from a purely *avertable dose/monetary cost* point of view.

Under most conditions, a national authority would place at least as much effort and resources into avoiding a radiation-induced health effect as it would into avoiding risks to health of a similar magnitude and nature. However, the allocation of resources to protecting health after a large radiation accident ought not differ significantly from that to protecting against other hazards. Otherwise, a significant fraction of a country's economy could be diverted into saving relatively few health effects, out of all proportion to how the money could have been better spent on general health care. In extreme cases, it could have disastrous effects on a country's economy, and even place severe economic burdens on future generations. Based on such considerations, a set of reference values for the monetary value of the unit collective dose, α, could be developed for CIS conditions.

The change of an intervention level, IL, in either direction would alter the avertable dose/monetary cost ratio. If the IL were lowered, the avertable doses would be increased as would the monetary costs of the countermeasure. Similarly, if the IL were raised, the avertable doses would decrease as would the monetary costs. The ratio of changes in cost to changes in avertable doses appears to be constant.

Modules for calculating costs, efficiencies and sensitivities

- Data base on cost parameters, including costs of foodstuffs and costs of protective measures
- Reference values of the monetary value of the unit collective dose, α, for CIS
- Module for calculating the cost per unit collective dose averted by the different countermeasures
- Module for calculating the changes of monetary costs and avertable doses by changing the intervention level

6.4 Risk perspectives

The radiation risk over a lifetime from a continuous exposure following a nuclear accident will depend on the age of the exposed population groups. In general, the risk will decrease with increasing age, being orders of magnitude less for elderly people than for children. The avertable and residual risks for a given intervention and exposure situation can be calculated from the basic risk factors and risk projection models given by UNSCEAR and the BEIR Committee.

The radiation risks can be put in perspective by comparing them with other societal risks, including cigarette smoking and exposure to natural background radiation.

Modules for calculating risk perspectives

- Module for calculating the radiation risk at different ages for a specified prolonged exposure situation
- Module for calculating the avertable and residual risks for given protective measures
- Module for calculating the equivalent societal risks of the avertable and residual risks

7 Conclusions

Making decisions on introducing measures for protecting a population affected by a radiological or nuclear accident is a complex process in that it requires that a balance be made between a number of conflicting objectives. Although the basic principles of intervention as recommended by the ICRP are clear in terms of *avertable doses* and *costs* of protective measures, several non-radiation factors will enter the decision-making process for intervention. The decision makers will therefore need a radiation protection baseline as a starting point for their decision-making process.

This project has elaborated on some of the radiation protection factors that are useful for a radiation-protection overview of an accidental situation where radioactive materials have been dispersed in the environment. These factors include avertable doses and avertable individual lifetime risks by long-term countermeasures as relocation, agricultural countermeasures and foodstuff restrictions as well as the monetary costs of the countermeasures. The avertable collective doses have been related to differential distributions of population and foodstuffs on dose rate, surface contamination density and activity concentration in foodstuffs. The avertable and residual individual radiation risks can be expressed by equivalent societal risks

The quantification of the avertable and residual doses and risks and the monetary costs of the countermeasures can be included as modules in decision-aiding models which – based on inputs from environmental measurement programmes – can make relatively simple estimates of avertable doses, avertable risks, countermeasure efficiencies and costs.

References

Alexakhin, R.M. et al., *Recommendations for organisation of agriculture under conditions of land contamination as a result of the Chernobyl NPP accident for 1991–1995.* RIARAE-Report, Moscow, 1991.

Bakalova, O.N., *Ecological and economical efficiency of countermeasures in agriculture of areas subjected to radioactive contamination.* RIARAE-Report, Obninsk, 1992.

Belyaev, S.T. et al., *A Concept of living conditions for people in the regions affected by the Chernobyl accident.* Document prepared by a USSR AS Working Group under the Chairmanship of S.T. Belyaev. Adopted by the USSR Government April 8, 1991. Resolution N 164.

Belyaev, S.T. et al., *Recommendations on practical realization of the current Concept of social protection of the population in the regions affected by the Chernobyl accident in the conditions of rehabilitation and restoration phase that have begun.* Document prepared by a Russian NCRP Working Group under the Chairmanship of S.T. Belyaev. Adopted by the Russian NCRP January 13, 1993.

CEC93, Commission of the European Communities. *Natural Sources of Ionising Radiation in Europe. Radiation Atlas.* EUR 14470, Luxembourg (1993).

Cohen, B.L.; Lee, I.S., *A catalog of risks.* Health Physics. 36:707–722; 1979.

Cohen, B.L., *Catalog of risks extended and updated.* Health Physics. 61:317–335; 1991.

Crick, M.J., *Derived Intervention Levels for invoking countermeasures in the management of contaminated agricultural environments.* Division of Nuclear Safety, International Atomic Energy Agency, Vienna, 1991.

Demin, V.F.; Gordeev, K.I. et al., *A Concept of rehabilitation of the population and normalization of ecological, sanitary and socio-economical situation in settlements of the Altay region, located in the zone affected by nuclear weapons tests on the Semipalatinsk proving ground.* Document prepared by a Chernobyl State Committee Working Group under the Chairmanship of K.I. Gordeev and a Russian NCRP Working Group under the Chairmanship of V.F. Demin. Adopted by the Russian NCRP May 7, 1993.

Hedemann Jensen, P., *Atmospheric Dispersion and Environmental Consequences. Exposure from Radioactive Plume Pathways.* Risø-M-2849(EN), November 1992.

Hedemann Jensen, P.; Konstantinov, Yu.O.; Demin, V.F., *Conceptual Framework of Intervention Level Setting.* CEC-CIS Joint Study Project 2/Task 3, Part 1, 1993.

IAC91, *The International Chernobyl Project.* Technical Report. Report by an International Advisory Committee, IAEA, Vienna (1991).

ICRP90, International Commission of Radiological Protection. *1990 Recommendations of the International Commission on Radiological Protection.* Publication 60, Pergamon Press, Oxford, New York, Frankfurt, Seoul, Sydney, Tokyo (1991).

Ivanov, E.V. et al., *A Concept of radiation protection of the population and economic activity in territories suffered from radioactive contamination.* Document prepared by a Russian NCRP Working Group under the Chairmanship of E.V. Ivanov. Adopted by the Russian NCRP, 1993.

Law91, Russian Federation Law, *On social protection of population suffered from radiation exposure due to the Chernobyl accident.* May 15, 1991.

Luykx, F., *Foodstuff Intervention Levels.* Commission of the European Communities, Luxembourg, 1992.

NAS90, U.S. National Academy of Sciences. *Health Effects of Exposure to Low Levels of Ionizing Radiation.* Report by the Committee on the Biological Effects of Ionizing Radiations (BEIR V). National Academy of Sciences/National Research Council, Washington D.C. (1990).

UNSCEAR88, United Nations Scientific Committee on the Effects of Atomic Radiation. *Sources, Effects and Risks of Ionising Radiation.* UNSCEAR 1988 Report to the UN General Assembly, with Annexes. United Nations, New York (1988).

Vlasov, O.K.; Yatsalo, B.I.; Mirzeabasov, O.A.; Matyash, V.A.; Brovkin, V.A., *Development of methods, models, expert and geoinformation systems for decisions of optimal countermeasures invoking in agriculture on lands subjected to contamination.* RIARAE-Report, 1992 (A), Obninsk.

Vlasov, O.K.; Yatsalo, B.I.; Mirzeabasov, O.A., *Using probabilistic methods for tasks of regional radioecological modelling.* Proceedings of the International Symposium "Problems of Ecoinformatics", Zwenigorod, Moscow, 1992 (B).

Vlasov, O.K.; Yatsalo, B.I.; Mirzeabasov, O.A.; Matyash, V.A.; Brovkin, V.A.; Lisyansky, B.G., *Development of information and expert system for decisions on introduction of countermeasures in agroindustrial complex in areas contaminated with radionuclides.* Proceedings of the 4th International Annual Scientific and Technical Conference of the Nuclear Society, N.Novgorod, 1993, Vol. 1, pp. 186-188.

Yatsalo, B.I.; Demin, V.F., *Assessment of countermeasure efficiency in agriculture and choice of intervention levels considering non-uniform contamination structure of production based on cost-benefit analysis. Methodological aspects and practical application.* November 26, 1993.

Bibliographic Data Sheet **Risø–R–716(EN)**

Title and author(s)

CEC–CIS Joint Study Project 2
Conceptual Framework of Intervention Level Setting

Per Hedemann Jensen, Vladimir F. Demin, Yuri O. Konstantinov, Boris I. Yatsalo

ISBN	ISSN
87-550-1938-2	0106-2840

Dept. or group

Section of Applied Health Physics, Department of Safety

Date

January 1994

Journal No.	Project/contract No.
	AHF 02932-00

Pages	Tables	Illustrations	References
46	12	8	22

Abstract (Max. 2000 char.)

Long-term protective measures taken in the CIS following the Chernobyl accident included relocating people from the most contaminated areas as well as continuing the restrictions on using foodstuffs contaminated with ^{137}Cs. The levels at which these countermeasures were introduced or still are being introduced for dose-saving purposes have been used to estimate avertable doses based on population distributions on both dose rate and surface contamination density of ^{137}Cs in space and time. The averted and avertable doses have been quantified by parameters of these distributions and intervention levels for relocation and foodstuff restrictions. The countermeasure efficiencies in agricultural production and various protection strategies in the agrosphere in Russia have been investigated. In addition, methods for estimating avertable radiation risks as well as residual risks from continuing exposures in terms of age-dependent radiation risk factors have been suggested. The sensitivity of changing intervention levels expressed in terms of changes in costs and avertable collective doses have been explored. The application of the present methodology in the decision-making process following a nuclear accident is discussed. Suggestions are made for including the methodology in simple models to be used for aiding decision-making on introducing protective measures.

Descriptors INIS/EDB

BELARUS; CESIUM 137; CHERNOBYL–4 REACTOR; DECISION MAKING; FOOD; POPULATION RELOCATION; RADIATION DOSE DISTRIBUTIONS; RADIATION DOSES; RADIATION HAZARDS; RADIATION PROTECTION; REMEDIAL ACTIONS; RISK ASSESSMENT; RUSSIAN FEDERATION; SURFACE CONTAMINATION; UKRAINE