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Toshimitsu HOMMA and Takeshi MATSUNAGA

日本原子力研究所
Japan Atomic Energy Research Institute

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OSCAAR Calculations for the Iput Dose Reconstruction Scenario of BIOMASS Theme 2

Toshimitsu HOMMA and Takeshi MATSUNAGA

Department of Reactor Safety Research
Nuclear Safety Research Center
Tokai Research Establishment
Japan Atomic Energy Research Institute
Tokai-mura, Naka-gun, Ibaraki-ken

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This report presents the results obtained from the application of the accident consequence assessment code, called OSCAAR, developed in Japan Atomic Energy Research Institute to the Iput dose reconstruction scenario of BIOMASS Theme 2 organized by International Atomic Energy Agency. The Iput Scenario deals with ^{137}Cs contamination of the catchment basin and agricultural area in the Bryansk Region of Russia, which was heavily contaminated after the Chernobyl accident. This exercise was used to test the chronic exposure pathway models in OSCAAR with actual measurements and to identify the most important sources of uncertainty with respect to each part of the assessment. The OSCAAR chronic exposure pathway models almost successfully reconstructed the whole 10-year time course of ^{137}Cs activity concentrations in most requested types of agricultural products and natural foodstuffs. Modeling of ^{137}Cs downward migration in soils is, however, still incomplete and more detail modeling of the changes of cesium bioavailability with time is needed for long term predictions of the contamination of food.

Keywords: Nuclear Accident, Accident Consequence Assessment, Model Validation, Dose Reconstruction, Food Chain Transport Model, Uncertainty and Sensitivity Analysis

BIOMASS テーマ２のイプート河川域線量再構築シナリオに対する OSCAAR コードの計算

日本原子力研究所東海研究所安全性試験研究センター原子炉安全工学部
本間　俊充・松永　武

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本報告書は、日本原子力研究所で開発した事故影響評価コード OSCAAR を国際原子力機関が主催する BIOMASS 計画テーマ２のイプート線量再構築シナリオに適用した結果を記載したものである。このシナリオはチェルノブイル事故で高汚染したロシアのブリアンスク地域の河川流域と農作地帯における ^{137}Cs の汚染を扱ったものである。このシナリオ解析は、OSCAAR の長期被曝経路モデルの実測データによる検証及び各評価モデルに関連した不確実さの主たる要因の同定に用いられた。OSCAAR の長期被曝経路モデルは、回答を求められた多くの農作物あるいは自然食品中の 10 年間にわたる ^{137}Cs 濃度の再評価に大方成功した。しかしながら、^{137}Cs の土壌下方への移行のモデル化は依然として十分ではなく、長期の食物汚染の予測には、植物が利用可能な形態の土壌中セシウムの時間変化を予測するより詳細なモデルが必要である。

東海研究所：〒319-1195　茨城県那珂郡東海村白方白根 2-4

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1. INTRODUCTION

The Japan Atomic Energy Research Institute (JAERI) has developed a computer code system, OSCAAR (Off-Site Consequence Analysis code for Atmospheric Releases in reactor accidents), for assessing the off-site radiological consequences of nuclear reactor accidents. OSCAAR is primarily designed for use in probabilistic safety assessments (PSAs) of light water reactors in Japan. OSCAAR calculations, however, can be used for a wide variety of applications including siting, emergency planning, and development of design criteria and in the comparative risk studies of different energy systems.

The quality assurance of environmental assessment models and codes has recently become a more important and formal procedure. Particularly, in cases where the results of radiological assessments are used in decision making, the quality assurance procedures are essential. Model intercomparison is one of the useful procedures for quality assurance of computer code. An international exercise organized by the Commission of the European Communities (CEC) and the Nuclear Energy Agency (NEA) of the OECD has provided a good opportunity to compare the predictions of the various codes, and to identify those features of the models which lead to differences in predicted results (NEA/CEC, 1994). The results of this intercomparison indicated that OSCAAR performed well, giving predictions in good agreement with the other codes such as MACCS (USA) and COSYMA (EC). Our efforts are now mainly made upon the validation of the individual models and the verification of the whole OSCAAR code system.

For the validation of OSCAAR, the chronic exposure pathway module, CHRONIC, has been applied to the Chernobyl scenario (Scenario A4) of BIOMOVS (BIOspheric Model Validation Study) Phase I. The scenario started with daily concentrations of ^{131}I in air and requested the prediction of concentrations of ^{131}I in vegetation and milk for several locations in the northern hemisphere (Peterson et al., 1996). The performance of other OSCAAR modules such as the atmospheric dispersion and deposition module as well as CHRONIC has been also examined for the ^{131}I atmosphere-pasture-milk pathway of the Hanford test scenario presented in the BIOMASS (BIOsphere Modelling and ASSessment Methods) project organized by the International Atomic Energy Agency (IAEA) as one of the Dose Reconstruction scenarios (Homma, et al., 2000). In this report the performance of OSCAAR for another important radionuclide, ^{137}Cs has been tested by using the Iput Scenario which was the second test exercise of the Dose Reconstruction Working Group of BIOMASS Theme 2.

This report contains a brief description of the Iput Scenario in Section 2 and a detailed description of OSCAAR models in Section 3. The results and discussions of the OSCAAR application to the test scenario are given in Section 4. Section 5 provides major sources of mispredictions and summary of lessons learned from the scenario is given in Section 6.

2. BIOMASS THEME 2

BIOMASS is an IAEA's Co-ordinated Research Project (CRP) aimed at the improvement of methods for assessing the impact of radionuclides in the environment. The scope of the BIOMASS program is the scientific, experimental, and technical aspects related to the analysis and assessment of the behavior of radionuclides in the environment and their associated impacts. Special emphasis is being placed on the improvement of the accuracy of model predictions, on the improvement of modelling techniques, and on the promotion of experimental activities and field data gathering to complement assessments.

The program is designed to address important radiological issues associated with accidental and routine releases and with solid waste management. Three important areas involving environmental assessment modelling are being covered: (1) biospheric analysis in the context of radioactive waste disposal, (2) remediation of areas contaminated as a result of nuclear accidents, unrestricted releases or poor management practices and (3) reconstruction of radiation doses received due to accidental or poorly controlled releases, usually in the early years of the nuclear industry.

Theme 2 of BIOMASS, Environmental Releases, focuses on issues of dose reconstruction and remediation assessment. Dose reconstruction and evaluation of remediation alternatives both involve assessment of radionuclide releases to the environment. Such assessments make use of a great variety of information gained from site characterization studies, source term evaluation, and so on. Ultimately, however, this information has to be combined in some sort of assessment model involving assumptions about how the system has behaved (or will behave). Mathematical modelling of this type is required because it is simply not possible today to measure directly what has happened in the past or what will happen in the future.

The overall objective of BIOMASS Theme 2 is to provide an international forum to increase the credibility of and confidence in methods and models for the assessment of radiation exposure in the context of dose reconstruction and remediation activities. Consideration is being given to assessment of concentrations of radionuclides in relevant environmental media and the associated radiation doses and risks to humans.

2.1. Description of the Iput Scenario

The test area is located in the Novozybkov district of the Bryansk Region of Russia (coordinates 52^0 30'-40' N, 31^0 50'-32^0 E), in the western part of Russia. From the south, the test area is close to Ukraine, and from the west, it is very close to the border of Belarus.

Surveys in the areas of Russia across which the radioactive clouds passed after the Chernobyl accident revealed very high contamination of the local area in the Novozybkov district of the Bryansk Region. This local area turned out to be the most highly contaminated area in Russia with respect to ^{137}Cs of Chernobyl origin.

Earlier versions of the Iput scenario included the entire contaminated catchment area, but later on the authors decided to simplify the scenario and consider only the most highly contaminated part of the Iput River watershed. The selected test area belongs to the Bryansk Region of Russia, specifically to the Novozybkov district of this region.

Data on the contamination of environmental components and on doses to humans in the test area were gathered during the course of systematic investigation carried out by Russian specialists over many years. The Institute of Agricultural Radiology performed measurements and prepared data sets (both input and test data) on contamination of lands and food products. SPA "Typhoon" took measurements of hydrometeorological parameters and contamination of water bodies. The Institute of Radiation Hygiene carried out detailed investigations of radiation doses to the local population, using actual measurements of the ^{137}Cs content in the local residents. A detailed description of the scenario distributed to the participants will be given in the Technical Document of IAEA. However, the tables in the scenario description used in the OSCAAR calculations are given in Appendix II.

2.2 Assessment Task

Participants were provided with input data containing the following main items:

- measurements of environmental ^{137}Cs in the test area (air concentrations, ground contamination, total deposition, and soil samples/vertical profiles);
- descriptions of the protective measures taken;
- environmental information (meteorological characteristics, topographical description, climatic conditions of inland waters and forests);
- agricultural information (practices by seasons, types of cultivated soils, production and use of feeds);
- information on agricultural production (foodstuffs);
- information on the collection of natural products (mushrooms, wild berries, and fish);
- information on food distribution; and
- information about the population (age, dwelling and industrial structures, as well as food consumption).

Predictions for the following time-dependent quantities of ^{137}Cs were requested with 95% confidence interval about the arithmetic mean:

- annual (1986-1996) average concentrations in leafy vegetables and potatoes;
- annual (1986-1996) average concentrations in cereals (wheat, rye);

- annual (1986-1996) average concentrations in animal feeds (hay);
- monthly (1986) and quarterly (1987-1996) average concentrations in milk;
- monthly (1986) and quarterly (1987-1996) average concentrations in beef;
- monthly (1986) and quarterly (1987-1990) average concentrations in pork;
- annual (1986-1996) average concentrations in mushrooms;
- annual (1986-1996) average concentrations in wild berries;
- annual (1986-1996) average concentrations in freshwater fish;
- average daily intake by humans (men and women);
- average concentrations in the whole body of humans (men and women);
- distributions of whole body concentrations for adult men;
- external dose (cloud and ground exposure);
- inhalation dose (cloud and resuspension);
- ingestion dose, with a summary of the three principal foods; and
- total dose from all pathways.

The test data for most endpoints are actual observations for those endpoints, including ^{137}Cs concentrations in feed, foodstuffs and whole body content. For those endpoints that could not be directly measured (i.e., doses), the authors of the scenario provided independent estimates based on observations.

3. DETAIL MODEL DESCRIPTION OF OSCAAR

OSCAAR consists of a series of interlinked modules and data files that are used to calculate the atmospheric dispersion and deposition of selected radionuclides for all sampled weather conditions, and the subsequent dose distributions and health effects in the exposed population. Using the Iput scenario, we have mainly tested the performance of the CHRONIC module, which calculated:

- long-term groundshine dose
- internal doses via inhalation of radionuclides resuspended from the ground
- and internal doses via ingestion of contaminated foodstuffs.

The migration of deposited material into soil as well as the radioactive decay is taken into account for the calculation of the long-term groundshine doses. The concentrations of resuspended materials are estimated by the time-dependent resuspension factor. The food chain model in CHRONIC is an extension of the methodology used in WASH-1400 (USNRC, 1975) and is available for important Japanese crops. It can reflect their seasonal dependence in probabilistic assessments.

Although OSCAAR does not include the model for aquatic pathways, the empirical model was developed for the Iput scenario to estimate the contribution of fish pathway to the total intake of ^{137}Cs. The detailed model descriptions and assumptions used to calculate the concentration of ^{137}Cs in the river fish are given in Appendix I.

3.1 External Dose

3.1.1 Cloudshine

The external dose from the passing cloud is estimated in OSCAAR using the air concentrations calculated from the atmospheric dispersion and deposition. In this calculation, however, because of lack of information about the source term and the meteorological conditions at the accident, the atmospheric dispersion and deposition model was not used. Instead the time-integrated concentration of ^{137}Cs in air was used according to the following equation:

$$D_c = TIC \cdot DF_c \cdot \sum f_i \cdot (OF_i^{out} + OF_i^{in} \cdot SF) \qquad (1\text{-}1)$$

where

D_c = external dose from the passing cloud (Sv)
TIC = time-integrated concentration of ^{137}Cs in air (Bq s m^{-3})
DF_c = dose conversion factor for cloudshine (Sv s^{-1} per Bq m^{-3})
f_i = fraction of *i*-th occupation group
OF_i^{out} = outdoor occupancy factor for *i*-th occupation group
OF_i^{in} = indoor occupancy factor for *i*-th occupation group
SF = shielding factor for wooden or brick house.

The time-integrated concentration in air was calculated from the ^{137}Cs concentrations in ground-level air of the test area given in Table I.I of the Scenario. The dose conversion factor for cloudshine was calculated by the DOSDAC system based upon the method of Kocher (1980). The fraction of rural inhabitants and the values of occupancy factor for three occupation groups were used from Table I.XLIV and I.XLV of the Scenario, respectively. The shielding factors for structures were calculated from the attenuation factor for 0.66 MeV gamma radiation in the Scenario description. Data used in the cloudshine dose calculations are given in Table 1.

3.1.2 Long-term Exposure due to Groundshine

The dose rate due to long-term groundshine is expressed by:

$$D_g(t) = SD_k \cdot R(t) \cdot E(t) \cdot DF_g \cdot L \cdot \sum_i f_i \cdot (OF_i^{out} + OF_i^{in} \cdot SF) \qquad (1\text{-}2)$$

where

$D_g(t)$ = dose rate on day t after the deposition of a radionuclide onto the ground (Sv s^{-1})
SD_k = total deposition of the radionuclide at place k (Bq m^{-2})
$R(t)$ = factor to account for radioactive decay occurring between the deposition and t
$E(t)$ = factor to account for the environmental decay of groundshine
DF_g = dose-rate conversion factor for groundshine (Sv s^{-1} per Bq m^{-2})
L = geometric factor
f_i = fraction of i-th occupation group
OF_i^{out} = outdoor occupancy factor for i-th occupation group
OF_i^{in} = indoor occupancy factor for i-th occupation group
SF = shielding factor for wooden or brick house.

The following exponential functions represent the two factors of $R(t)$ and $E(t)$ as a function of time :

$$R(t) = \exp(-\ln 2 \cdot \frac{t}{T_r}) \tag{1-3}$$

$$E(t) = d_f \cdot \exp(-\ln 2 \cdot \frac{t}{T_{sf}}) + d_s \cdot \exp(-\ln 2 \cdot \frac{t}{T_{ss}}), \quad d_f + d_s = 1 \tag{1-4}$$

where

T_r = half-life for radioactive decay (y)
d_f = fraction of fast decay term for the environmental decay of groundshine
d_s = fraction of slow decay term for the environmental decay of groundshine
T_{sf} = half-life for fast decay term for groundshine (y)
T_{ss} = half-life for slow decay term for groundshine (y).

The initial deposition of ^{137}Cs at the region was assumed to have the distribution given in Table I.XL of the Scenario. The dose conversion factor for groundshine was calculated by the DOSDAC system based on the method of Kocher (1980) in which the exposed individual was assumed to be standing on a smooth, infinite plane surface with uniform source concentration. The value of the geometric factor was determined from the comparison between the model predictions and the observations within the 30-km zone of the Chernobyl plant (Takahashi and Homma, 1999). The parameter values and uncertainty ranges in the environmental decay terms, Eq. (1-4) of deposited ^{137}Cs on the ground were determined from data in the expert judgement study (Goossens et. al., 1997). The shielding factors for structures are the same as that used in the cloudshine calculation. Data used in the groundshine dose calculations are given in Table 2.

3.2 Inhalation Dose

3.2.1 Inhalation of Passing Cloud

Like the external dose from the passing cloud, the internal dose from inhalation of the passing cloud is estimated in OSCAAR using the air concentrations calculated from the atmospheric dispersion and deposition model. In this calculation, however, the time-integrated concentration of ^{137}Cs in air was used according to the following equation:

$$D_i(t) = TIC \cdot DF_i \cdot BR \cdot \sum_i f_i \cdot (OF_i^{out} + OF_i^{in} \cdot FF) \tag{2-1}$$

where

D_i = internal dose from inhalation of the passing cloud (Sv)

DF_i = dose conversion factor for inhalation (Sv Bq^{-1})

BR = breathing rate of an average individual (m^3 d^{-1})

f_i = fraction of i-th occupation group

OF_i^{out} = outdoor occupancy factor for i-th occupation group

OF_i^{in} = indoor occupancy factor for i-th occupation group

FF = filtering factor for wooden and brick houses.

The time-integrated ^{137}Cs concentrations in ground-level air of the test area is the same as that used in the external dose. The dose conversion factor for inhalation was calculated by the DOSDAC system based upon the method of ICRP 30. The filtering factor for structures were determined from data on ^{137}Cs particulate, representative of about 1 μ m in the expert judgement study (Goossens et. al., 1997). Data used in the inhalation dose calculations are given in Table 3.

3.2.2 Inhalation of Resuspended Materials

The amount of a radionuclide consumed through inhalation of resuspended materials is calculated with:

$$I_r(t) = SD_k \cdot R(t) \cdot K(t) \cdot BR \tag{2-2}$$

where

$I_r(t)$ = amount of a radionuclide consumed by an individual through inhalation of resuspended materials on day t after the deposition of the radionuclide onto the ground (Bq y^{-1})

$K(t)$ = time-dependent resuspension factor (m^{-1}).

The resuspension factor is defined as the ratio of the air concentration of a resuspended radionuclide to the total deposition onto the ground. The following gives the time-dependent resuspension factor, $K(t)$:

$$K(t) = k_0 \cdot \exp(-\ln 2 \frac{t}{T_{Rf}}) + k_e \cdot \exp(-\ln 2 \frac{t}{T_{Rs}}) \tag{2-3}$$

where

k_0 = initial value of fast decay term of the time-dependent resuspension factor (m^{-1})

k_e = initial value of slow decay term of the time-dependent resuspension factor (m^{-1})

T_{Rf} = half-life for fast decay term (y^{-1})

T_{Rs} = half-life for slow decay term (y^{-1}).

The parameter values (Sprung et. al., 1990) in the resuspension factor, Eq. (2-3) of deposited ^{137}Cs on the ground are given in Table 4.

The total intake of a radionuclide through inhalation, CF_r^j (Bq), during time interval j can be calculated by integrating Equation (2-2). The internal dose, D_r^j (Sv), in each time interval can be estimated by:

$$D_r^j = \sum_{n=1}^{j} DF_{inh}^n \cdot CF_r^{j+1-n} \cdot \sum_i f_i \cdot (OF_i^{out} + OF_i^{in} \cdot FF) \tag{2.4}$$

where

DF^n_{inh} = dose conversion factor for inhalation for time interval n after intake of a radionuclide (Sv Bq^{-1}).

3.3 Ingestion of Contaminated Foodstuffs

The food-chain model included in the CHRONIC module takes account of the transfer of radionuclides to cow's milk (including milk products), beef and edible crops. The edible crops are classified into four categories: leafy vegetables, cereals, root crops and fruits (including non-leafy vegetables). It is assumed that dairy and beef cows consume only pasture grass, and pasture grass and edible crops are contaminated both by direct deposition from the atmosphere and by root uptake from the soil. The model deals with the growing periods of the pasture grass and the crops, so that their seasonal dependence on the ingestion dose can be evaluated. To take account of the seasonality, a year is divided into three seasons: dormant season, growing season and grazing season for pasture grass, and dormant season, growing season and harvest season for crops. It is assumed that cows and individuals cannot consume pasture grass and crops under growing, respectively. The productivity of pasture grass and crops is also assumed to be constant during the grazing season and the harvest season, respectively.

3.3.1 Direct Deposition

a) Milk and Milk Product Pathway

It is assumed that pasture grass is grown during a grazing season and dairy cattle consume the pasture grass continuously. The amount of a radionuclide consumed by an individual via milk at a given time can be expressed by:

$$I_{dm}(t) = IC_0 \cdot R(t) \cdot L(t) \cdot A(t) \cdot S_m \cdot V_m \tag{3-1}$$

where

$I_{dm}(t)$ = amount of a radionuclide consumed by an individual via milk on day $t+d_m$ after the deposition of the radionuclide onto the ground (Bq d^{-1})

t = days from the radionuclide deposition (d)

d_m = days from milk production to consumption (d)

IC_0 = first days' intake of the radionuclide by an average cow (Bq d^{-1})

$L(t)$ = factor to account for loss of the radionuclide from pasture grass due to weathering

$A(t)$ = fraction of the radionuclide consumed by a cow that is secreted into a milk sample (d L^{-1})

S_m = factor to account for decay of the radionuclide during the time from milk production to consumption

V_m = volume of milk consumed daily by an average individual of the population (L d^{-1}).

The parameter of IC_0 is estimated as follows for a reference deposition of 1 Bq m^{-2},

$$IC_0 = \frac{RF_g}{Y_g} \cdot J_l \tag{3-2}$$

where

RF_g = initial retention factor for pasture grass

Y_g = productivity density of pasture grass (kg m^{-2})

J_l = consumption rate of pasture grass by an average cow (kg d^{-1}).

The mass interception factor, $\frac{RF_g}{Y_g}$ was assumed to be 2.0 (m^2 kg^{-1}) and the productivity density Y_g and consumption rate J_l of pasture grass by an average cow were used from Table I.XXXII and Table I.XXXV of the Scenario, respectively. The parameters of $L(t)$ and S_m can be expressed by the following exponential functions:

$$L(t) = l_1 \cdot e^{-\lambda_w \cdot t} + l_2, \qquad \lambda_w = \frac{\ln 2}{T_w} \tag{3-3}$$

$$S_m = e^{-\lambda_r \cdot d_m} \tag{3-4}$$

where

T_w = half life for weathering (d)

l_1 = initial value of a decay term of the time-dependent retention factor

l_2 =constant term of the time-dependent retention factor ($l_1 + l_2 = 1$).

Only exponential decay term was considered ($l_1=1$) in Equation (3-3). The following empirical equations are determined to express the parameter of $A(t)$:

$$A(t) = \{TR_1 + TR_2 \cdot t\} \cdot \{1 - e^{-TR_3 \cdot t}\} \tag{3-5}$$

where

TR_1 = empirical coefficient of the fraction of the radionuclide consumed by a cow that is secreted in to a milk sample (d l^{-1})

TR_2 = empirical coefficients (l^{-1})

TR_3 = empirical coefficients (d^{-1}).

The parameter values of these coefficients were given in Table 5 as default values in CHRONIC (Comar and Lengemann, 1966).

As the accident has occurred in the growing season, the total intake of ^{137}Cs via milk, CF_{dm} was calculated by:

$$CF_{dm} = FF(t_p) \cdot \int_0^{T_g} I_{dm}(t)dt \tag{3-6}$$

where

$FF(t_p)$ = factor to account for loss of a radionuclide from pasture grass due to weathering

t_p = days from the accident to the beginning of the grazing season (d)

T_g = period of the grazing season (d).

The factor of $FF(t_p)$ is represented by:

$$FF(t_p) = l_1 \cdot e^{-\lambda_{eff} \cdot t_p} + l_2 \cdot e^{-\lambda_r \cdot t_p} \tag{3-7}$$

b) Beef Pathway

It is assumed that pasture grass is grown during a grazing season and beef cattle consume the pasture grass continuously. The amount of a radionuclide consumed by an individual via beef at a given time can be expressed by:

$$I_{db}(t) = B_d(t) \cdot S_b \cdot V_b \tag{3-8}$$

where

$I_{db}(t)$ = amount of a radionuclide consumed by an individual via beef on day $t+d_b$ after the deposition of the radionuclide onto the ground (Bq d^{-1})

d_b = days from beef production to consumption (d)

$B_d(t)$ = concentration of the radionuclide in beef (Bq kg^{-1})

S_b = factor to account for decay of the radionuclide during the time from beef production to consumption

V_b = amount of beef consumed daily by an average individual of the population (kg d^{-1}).

The radionuclide concentration in beef, $B_d(t)$, is estimated by the following differential equation:

$$\frac{dB_d(t)}{dt} = G_{d0} \cdot R(t) \cdot L(t) \cdot \tau_{gb} - \{ \lambda_r + \tau_{meta} + \tau_{meat} \} \cdot B_d(t) \tag{3-9}$$

where

G_{d0} = concentration of a radionuclide in pasture grass at the time of accident (Bq m^{-2})

τ_{gb} = transfer rate of the radionuclide from pasture grass to beef (m^2 kg^{-1} d^{-1})

τ_{meta} = removal rate of the radionuclide from beef due to metabolism (d^{-1})

τ_{meat} = average rate at which cows are slaughtered (d^{-1}).

In determining τ_{gb}, equilibrium conditions were assumed in the grass and meat compartments in Equation (3-9):

$$\tau_{gb} = \tau_{meta} \frac{B_{eq}}{G_{eq}} = \frac{\ln 2}{T_B} \cdot (F_b \frac{J_l}{Y_g})$$

where

T_B = biological half-life of cesium (d)

F_b = equilibrium transfer coefficient from feed to meat for cesium (d kg^{-1}).

The biological half-life (Brown et. al., 1997) and the transfer coefficient (IAEA, 1994) used are given in Table 5. The parameter of G_{d0} for a reference deposition of 1 Bq m^{-2} can be estimated to be RF_g where RF_g is an initial retention factor for pasture grass.

It is noted that a radionuclide consumed by cow remains in beef after the grazing season since the metabolism in cow's body is slow. After the grazing season, the amount of the radionuclide consumed by an individual via beef, $I_{d'b}(t)$, can be represented by:

$$I_{d'b}(t) = B_{d0} \cdot V_b \cdot e^{-\lambda_r \cdot d_b} \cdot e^{-\lambda_b \cdot t} \tag{3-10}$$

where

B_{d0} = concentration of a radionuclide in beef at the end of the grazing season (Bq kg^{-1}).

Total intake of a radionuclide via beef, CF_{db}, can be estimated by the similar methodology to that for milk pathway. As the accident has occurred in the growing season, CF_{db} was calculated by:

$$CF_{db} = FF(t_p) \cdot \left\{ \int_0^{T_g} I_{db}(t)\, dt + \int_0^{\infty} I_{d'b}(t)\, dt \right\} \tag{3-11}$$

c) Crop Pathway

Crops are assumed to be grown and harvested continuously during the harvest season. The amount of a radionuclide consumed by an individual via an edible crop at a given time can be expressed by:

$$I_{dc}(t) = \frac{C_d(t)}{Y_c} \cdot S_c \cdot V_c \tag{3-12}$$

where

$I_{dc}(t)$ = amount of a radionuclide consumed by an individual via an edible crop on day $t+d_c$ after the deposition of the radionuclide onto the ground (Bq d^{-1})

d_c = days from crop production to consumption (d)

$C_d(t)$ = concentration of the radionuclide in the crop (Bq m^{-2})

Y_c = productivity density of the crop (kg m^{-2})

S_c = factor to account for decay of the radionuclide during the time from crop production to consumption

V_c = amount of the crop consumed daily by an average individual of the population (kg d^{-1}).

The radionuclide concentration in the crop, $C_d(t)$, can be expressed by:

$$C_d(t) = C_{d0} \cdot R(t) \cdot L(t) \tag{3-13}$$

where

C_{d0} = concentration of a radionuclide in the crop at the time of accident (Bq m^{-2}).

The parameter of C_{d0} for a reference deposition of 1 Bq m^{-2} is estimated to be RF_c where RF_c is an initial retention factor for the crop. Equation (3-15) can be rewritten as follows:

$$I_{dc}(t) = \frac{RF_c}{Y_c} \cdot V_c \cdot e^{-\lambda_r \cdot d_c} \cdot \left\{ l_1 \cdot e^{-\lambda_{eff} \cdot t} + l_2 \cdot e^{-\lambda_r \cdot t} \right\} \tag{3-14}$$

The total amount of a radionuclide consumed by an individual via a crop, CF_{dc}, can be estimated by the same equation as that for milk pathway. However, the accident has occurred before the sowing of crops, so the direct contamination pathway for crops except winter grain was not considered in the calculation. The parameter values for winter grain used in Equation (3-14) were given in Table 5.

3.3.2 Root Uptake

After deposition of radioactive material on the soil surface and subsequent mixing in the soil, the only important pathway by which the material can enter food chains is absorption from the soil. Therefore, the soil is important as a reservoir of long-lived radionuclides. The dynamics of a radionuclide in the soil is simply expressed by the following Equation (3-17) in CHRONIC. The loss of availability of the radionuclide for uptake is represented by the soil sink with a transfer rate of τ_{pd}. Uptake of the radionuclide by grass or crops is governed by a transfer rate τ_{pg}, or τ_{pc}. In estimating the removal rate of ^{137}Cs from the soil of a root zone, the soil migration rate and the process of soil fixation were considered. The available ^{137}Cs in the soil root zone was described by:

$$\begin{aligned} P(t) &= P_0 \cdot \exp\{-(\tau_{pd} + \lambda_f)t\} \cdot \exp(-\lambda_r t) \\ &= P_0 \cdot \exp\left\{-(\frac{\ln 2}{T_{pd}} + \lambda_f)t\right\} \cdot \exp(-\lambda_r t) \end{aligned} \qquad (3\text{-}15)$$

The half-time T_{pd} of ^{137}Cs in the root zone (10cm) for sandy and sandy loam soils was used from Belli and Tikhomirov (1996) and the soil fixation rate was used from Brown et. al. (1997). The parameter values in Equation (3-15) are given in Table 5.

a) Milk and Milk Product Pathway

The amount of a radionuclide consumed by an individual via milk at a given time can be expressed by:

$$I_{um}(t) = M_u(t) \cdot S_m \cdot V_m \qquad (3\text{-}16)$$

The radionuclide concentration in milk, $M_u(t)$ (Bq/l), can be calculated by three differential equations as follows:

$$\frac{dP(t)}{dt} = -\{\lambda_r + \tau_{pg} + \tau_{pd}\}\, P(t) \qquad (3\text{-}17)$$

$$\frac{dG_u(t)}{dt} = \tau_{pg} \cdot P(t) - \left\{ \lambda_r + \frac{J_l}{A_g \cdot Y_g} \right\} G_u(t) \tag{3-18}$$

$$\frac{dM_u(t)}{dt} = \tau_{gm} \cdot G_u(t) - \{ \lambda_r + \tau_{milk} \} M_u(t) \tag{3-19}$$

where

$P(t)$ = concentrations of a radionuclide in soil (Bq m^{-2})

$G_u(t)$ = concentrations of a radionuclide in pasture grass (Bq m^{-2})

τ_{pg} = transfer rate of the radionuclide from soil to pasture grass (d^{-1})

τ_{pd} = removal rate of the radionuclide from the soil of a root zone (d^{-1})

A_g = area of a pasture grass land which is given to single cow (m^2)

τ_{gm} = transfer rate of the radionuclide from pasture grass to milk (m^2 l^{-1} d^{-1})

τ_{milk} = secretion rate of milk (d^{-1}).

In determining the transfer rate of the radionuclide from soil to plant τ_{pg}, a simple assumption was made that the equilibrium concentration ratio reached for a plant growth period:

$$\tau_{pg} = \frac{1}{T_G}\frac{G_{eq}}{B_{eq}} = \frac{1}{T_G} \cdot (B_V \frac{Y_g}{\rho L})$$

where

T_G = plant growth period (d)

B_V = soil-to-plant transfer factor for grass (Bq kg^{-1} dry weight plant to Bq kg^{-1} dry weight soil)

ρ = bulk density of soil (kg m^{-3})

L = depth of soil root zone (m).

The soil-to-plant transfer factor for grass was taken from IAEA(1994) and the plant growth period was used from Table I.XXXI of the Scenario. Data on the transfer rate of cesium from soil to grass are given in Table 5.

To derive the transfer rate of cesium from pasture grass to milk τ_{gm}, the same assumption as the transfer rate from grass to meat was made that equilibrium conditions were assumed in the grass and milk compartments in Equation (3-19):

$$\tau_{gm} = \tau_{milk} \frac{M_{eq}}{G_{eq}} = \frac{V_m}{U} \cdot (F_m \frac{J_l}{Y_g})$$

where

V_m = production rate of milk per cow (L d^{-1})

U = capacity of the udder (L)

F_m = equilibrium transfer coefficient from feed to milk for cesium (d L^{-1}).

τ_{milk} was determined assuming V_m of 7.1 L d^{-1} taken from Table I.XXXIX of the Scenario and U of 10 L, and the transfer coefficient from feed to milk was taken from IAEA(1994). Data on the transfer rate of cesium from pasture grass to milk are given in Table 5.

b) Beef Pathway

The amount of a radionuclide consumed at a given time by an individual can be expressed by:

$$I_{ub}(t) = B_u(t) \cdot S_b \cdot V_b \tag{3-20}$$

where

$I_{ub}(t)$ = amount of a radionuclide consumed by an individual via beef on day $t+d_b$ after the deposition of the radionuclide onto the ground (Bq d^{-1})

$B_u(t)$ = concentration of the radionuclide in beef (Bq kg^{-1}).

The following calculates the radionuclide concentration in beef, $B_u(t)$:

$$\frac{dB_u(t)}{dt} = \tau_{gb} \cdot G_u(t) - \{\lambda_r + \tau_{meta} + \tau_{meat}\} \cdot B_u(t) \tag{3-21}$$

where

$G_u(t)$ = concentration of a radionuclide in pasture grass (Bq kg^{-1})

τ_{gb} = transfer rate of a radionuclide from pasture grass to beef (m^2 kg^{-1} d^{-1}).

The parameter values in Equation (3-21) are given in Table 5.

The amount of a radionuclide consumed by an individual via beef after the grazing season, $I_{u'b}(t)$, can be represented by:

$$I_{u'b}(t) = B_{u0} \cdot V_b \cdot e^{-\lambda_r \cdot d_b} \cdot e^{-\lambda_Y \cdot t} \tag{3-22}$$

where

B_{u0} = the concentration of a radionuclide in beef at the end of the grazing season (Bq kg^{-1}).

c) Crop Pathway

The amount of a radionuclide consumed at a given time by an individual can be expressed by:

$$I_{uc}(t) = \frac{C_u(t)}{Y_c} \cdot S_c \cdot V_c \tag{3-23}$$

where

$I_{uc}(t)$ = amount of a radionuclide consumed by an individual via an edible crop on day $t+d_c$ after the deposition of the radionuclide onto the ground (Bq d^{-1})

$C_u(t)$ = concentration of the radionuclide in the crop (Bq m^{-2}).

The following calculates the radionuclide concentration in a crop, $C_u(t)$:

$$\frac{dC_u(t)}{dt} = \tau_{pc} \cdot P(t) - \left\{ \lambda_r + \frac{V_c}{A_c \cdot Y_c} \right\} \cdot C_u(t) \tag{3-24}$$

where

$P(t)$ = concentration of a radionuclide in soil (Bq m^{-2})

τ_{pc} = transfer rate of the radionuclide from soil to a crop (d^{-1})

A_c = cultivated area of crops which is given an individual (m^2).

The transfer rate of the radionuclide from soil to crop τ_{pg} was determined by the following same equation as for the transfer rate from soil to pasture grass:

$$\tau_{pc} = \frac{1}{T_G}\frac{C_{eq}}{B_{eq}} = \frac{1}{T_G} \cdot (B_V \frac{Y_c}{\rho L})$$

The soil-to-plant transfer factors for crops were taken from IAEA(1994) and the plant growth periods for crops were used from Table I.XXXI of the Scenario. Data on the transfer rates of cesium from soil to crops are given in Table 5.

3.4 Countermeasures Assumptions

According to the Scenario description and Tables I.LIV - I.LX of the Scenario, the following agricultural countermeasures were taken into account to estimate the concentrations in foodstuffs.

- In June 1986 to spring 1987, slaughtering of cattle was forbidden in the regions with contamination level exceeding 555 kBq m^{-2}.
- In 1987, about 40% of agricultural land with contamination density higher than 1480 kBq m^{-2} was take out of agricultural production.
- In 1988, all agricultural lands with contamination density higher than 1480 kBq m^{-2} were completely taken out of agricultural production.
- In 1986 to 1989, a reduction of 1.7 in root uptake transfer to crops due to application of agrochemical measures was taken into account for areas with contamination density higher than 555 kBq m^{-2}.
- A reduction of 3 in root uptake transfer to meadows and pastures due to radical amelioration was taken into account for areas with contamination density higher than 555 kBq m^{-2}. Cumulative percentages of the application areas of this measure from 1989 to 1990 were taken from data in Table I.LX of the Scenario.

For restriction in consumption of local food products and forest gifts, temporary permissible levels for ^{137}Cs concentrations in foodstuffs in Table I.LIII of the Scenario were take into account to estimate the intake of the test persons over the controlled area with contamination density higher than 555 kBq m^{-2}. Consumption rates of various food products were used from the values in Table I.XLVIII - I.LII of the Scenario.

3.5 Uncertainties and Variability

OSCAAR is coupled with the uncertainty and sensitivity analysis techniques to quantify uncertainty associated with accident consequence assessments and to identify uncertain processes and important parameters contributed to consequences. Among a number of techniques available for propagating parameter uncertainties through complex models, a Monte Carlo method has been implemented to perform uncertainty and sensitivity analyses of OSCAAR. The software package PREP/SPOP is used to allow for an automatic performance of all necessary steps in uncertainty and sensitivity analysis. The different sampling schemes, such as pure random, Latin hypercube and quasi-random sampling, are allowed to be used in PREP(Homma and Saltelli, 1992). SPOP performs the uncertainty and sensitivity analyses on the output of the model. SPOP includes several parametric and non-parametric techniques, based on regression-correlation measures, as well as some "two-sample" tests (Saltelli and Homma, 1992).

In this calculation, the uncertainties in the model results, both due to the uncertainty in model parameter values and due to the variability of contamination in the test area, are determined by Latin hypercube sampling from prescribed distributions of the model parameters and initial contamination. The 95% confidence intervals about the arithmetic mean for all quantities are estimated using Chebyshev theorem.

4. COMPARISON OF MODEL PREDICTIONS WITH TEST DATA

Uncertainty in model output was calculated using 500 parameter sets generated by Latin hypercube sampling for prescribed distributions of all uncertain parameters. For the calculation of both external and internal cloud exposure, the initial input values of time-integrated concentrations in air were derived from uniform distribution in the range of $2.09 \times 10^5 \pm 1.36 \times 10^5$ (mBq d m^{-3}) given in Table I.I of the Scenario. The ground contamination levels were also derived from piecewise uniform distribution with weight factors calculated by contamination areas given in Table I.XL of the Scenario. These levels were used as input for the calculation of ground exposure, resuspension dose, and concentrations in food products. The ground contamination levels for the forest were derived from uniform distribution in the range of $9.80 \times 10^2 \pm 4.60 \times 10^2$ (kBq m^{-2}). The range was determined from data given in Table I.XX of the Scenario. The distributions of both agricultural lands and forest by ^{137}Cs contamination are given in Figure 1.

4.1 Concentrations in Food Products

4.1.1 Leafy Vegetables

The 95% confidence intervals about the mean predictions cover the only observations between 1988 and 1990. Their mean predictions between 1987 and 1990 underestimate by a factor of within 2, while larger overestimation can be observed after 1991 (Figure 2).

A large underprediction for 1986 is probably due to the neglect of direct deposition onto vegetation because the dates of sowing for cabbage and vegetable given in the Scenario occurred after the accident. The overpredictions after 1991 are due to the neglect of effectiveness of the agrotechnical countermeasures for several years after their application.

4.1.2 Potatoes

The confidence intervals about the mean predictions cover the observations between 1987 and 1990 (Figure 3). The same comments are valid, as is the case of leafy vegetables. During the first five years the dynamics of predictions show a good agreement with that of observations and the predictions fall within a factor of 1.7.

4.1.3 Cereals

The confidence intervals about the mean predictions cover the only observations for 1990, 1995 and 1996 (Figure 4). Between 1987 and 1989 OSCAAR underestimated concentrations in cereals by factors between 2.0 and 5.6, while it overestimated the cereal data by factors between 1.2 and 3.8 after 1991.

The underestimation between 1987 and 1989 might be due to higher bioavailability of the deposited ^{137}Cs in the soil during the first few years.

4.1.4 Milk

OSCAAR calculated the average concentrations of ^{137}Cs in milk produced by a cow grazing on the contaminated pasture during the grazing season. So the predictions are compared with observations for August or third quarter (Figure 5). The confidence intervals about the mean predictions cover the observations between 1991 and 1993. The predictions between 1987 and 1990 are lower than the observation by factors of 2.5 to 12. The prediction for 1986 is higher than the observation by a factor of 8.3.

OSCAAR does not provide the intermediate output for concentrations in pasture grass. So it is difficult to find the major sources of mispredictions. The overestimation produced for 1986, however, is probably due to overestimation of the pasture contamination from the direct deposition. On the other hand, the underestimation during 1987 to 1990 might be due either to underestimation of the transfer factor from grass to milk or to underestimation of the pasture contamination from the root uptake pathway.

4.1.5 Beef

OSCAAR also assumes that the beef cow is grazing on the contaminated pasture during the grazing season. As with milk, the predictions are compared with observations for August or third quarter (Figure 6). The same dynamics for beef predictions are observed as for the milk predictions. The underpredictions are observed between 1987 and 1990, while the overpredictions after 1991 fall within a factor 3 of the observations.

The reason for the underpredictions in the early phase is not clear either due to a low feed to meet transfer factor used or due to the unclear description of feeding practice. The overpredictions after 1991 are probably due to the neglect of continuing effectiveness of the agrotechnical countermeasures such as deep plowing and radical amelioration of pastures after their application.

4.1.6 Pork

OSCAAR does not take into account the pork pathway, but in order to estimate the contribution of this pathway to the total intake of ^{137}Cs, the same model as for beef pathway was applied. So we observed the same behaviour for pork predictions as for the beef predictions (Figure 7). The differences are due to both the amount of feed and the feed to meet transfer factors used.

4.1.7 Mushrooms and Berries

OSCAAR also does not have models for predicting concentrations in natural products. So a simple approach using aggregated transfer coefficients (m^2 kg^{-1}) was used to estimate the ^{137}Cs concentrations in mushrooms and berries. The ecological half-life of ^{137}Cs in natural ecosystems was assumed to be very long enough in comparison with the physical half-life.

All predictions for mushrooms are higher than the observations by a factor of 3 to 10. The confidence intervals about the mean predictions do not cover any observations (Figure 8). This is probably due to the high aggregated transfer coefficient used or the neglect of forest countermeasures.

On the other hand, the predictions for berries are relatively in good agreement to the observations. The confidence intervals about the mean predictions cover the only observations for 1987 and 1988. The predictions for the other years, however, fall within a factor 1.9 (Figure 9).

4.1.8 Fish

The predictions are in good agreement to the observations and all except for 1996 fall within the confidence intervals about the observations (Figure 10). The detail model description of estimating concentrations of ^{137}Cs in river fish is given in Appendix I.

4.2 Human Intake

The predictions for both women (Figure 11a) and men (Figure 11c) over the controlled area are mostly underestimated by a factor of 1.2 to 3.7. The prediction for 1986 is lower than a factor of about 9. The dynamics of the predictions, however, are in good agreement to that of the observations.

For the non-controlled area, the predictions for both women (Figure 11b) and men (Figure 11d) are in good agreement to the observations and fall within a factor of 2 except for 1987.

4.3 Dose

The predicted doses both from cloud external exposure and from inhalation of cloud are slightly higher than the test data (Figure 12). This is due to the differences in shielding factor or filtering factor used and in dose conversion factors. The predicted doses from ground deposits are slightly lower than the test data by a factor of within 1.3 till 1995, while the lifetime predicted dose is slightly higher than the test data (Figure 13). This is also due to the differences in shielding factor and in dose conversion factors, and partly due to weathering half-life of deposits on the ground. The predicted doses from inhalation of resuspended ^{137}Cs are quite lower than the test data by an order of magnitude (Figure 14). This is due to the difference in resuspension factors used in the estimation.

5. MAJOR SOURCES OF MISPREDICTIONS

The underpredictions of concentrations in crops during in 1987-1989 are probably due to lower root uptake factors used in our analysis. Unfortunately the effect of the fixation of cesium on longer term predictions can not be clearly observed because the observations included the effect of agricultural countermeasures at the same time. As described in the previous section, the underpredictions of concentrations in vegetables and potatoes for 1986 are probably due to the neglect of direct deposition onto vegetation, although the dates of sowing given in the Scenario occurred after the accident. The overpredictions after 1990 are due to the neglect of effectiveness of the agrotechnical countermeasures for subsequent several years after their application.

The dynamics of concentrations for milk and meet are similar to that for crops. This is because the dynamics for milk and meet in OSCAAR are mostly governed by the dynamics for grass. Comparing between Figure 5 to 7, larger underpredictions of concentrations in milk are clear. This is probably because a lower feed to milk transfer factor is used due to a lower secretion rate of milk assumed.

6. SUMMARY OF LESSONS LEARNED FROM THE SCENARIO

We have experienced from a number of severe accident consequence assessments that ^{137}Cs external ground exposure and ingestion pathways were the two main important contributors to chronic effects to the population. The Iput dose reconstruction scenario, therefore, provided the good opportunities to test our chronic exposure sub-models in OSCAAR. The OSCAAR chronic exposure pathway models almost successfully reconstructed the whole 10-year time course of ^{137}Cs activity concentrations in most requested types of agricultural products and natural foodstuffs. Modeling of ^{137}Cs downward migration in soils is, however, still incomplete and more detail modeling of the changes of cesium bioavailability with time is needed for long term predictions of the contamination of food.

The OSCAAR food-chain model is primarily designed to estimate the total intake of radionuclides for the population at each district. However, predictions of the contamination in foods are also important to be used as criteria for the food restriction countermeasures in accident consequence assessments. Hence, it is necessary to allow for more animal products and animal feeds for flexible applications of OSCAAR. Although modeling of agricultural countermeasures is a difficult task, at least a simple reduction factor approach should be introduced in OSCAAR to take into account the effects of countermeasures on dose reduction to the population.

This scenario also provides a good example of regional variations in the environment. Accident consequence assessment codes include default values for many of parameters in the calculations. These default values and also data libraries such as dose conversion factors are applicable to a particular region, and may not be appropriate for other applications and introduce uncertainties into the predictions. The computer code like OSCAAR should be capable of handling regional differences in one application.

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Table 1. Parameter values used in cloud exposure calculations

Variable	Mean	Min	Max	Distribution	Units
$SF(wood)$	0.52	0.26	0.78	Uniform	-
$SF(brick)$	0.20	0.10	0.30	Uniform	-
DF_c	2.88×10^{-14}	-	-	Constant	Sv s^{-1} /Bq m^{-3}

Table 2. Parameter values used in ground exposure calculations

Variable	Mean	Min	Max	Distribution	Units
d_s	0.52	0.40	0.71	Uniform	-
T_{Sf}	1.1	0.41	1.4	Uniform	y
T_{Ss}	28	24.3	29.4	Uniform	y
L	0.45	0.2	0.7	Uniform	-
$SF(wood)$	0.52	0.26	0.78	Uniform	-
$SF(brick)$	0.20	0.10	0.30	Uniform	-
DF_g	5.86×10^{-16}	-	-	Constant	Sv s^{-1} /Bq m^{-2}

Table 3. Parameter values used in cloud inhalation calculations

Variable	Mean	Min	Max	Distribution	Units
$FF(wood)$	0.64	0.43	0.84	Uniform	-
$FF(brick)$	0.64	0.43	0.84	Uniform	-
BR	23.	-	-	Constant	m^3 d^{-1}
DF_i	8.63×10^{-9}	-	-	Constant	Sv Bq^{-1}

Table 4. Parameter values used in resuspension calculations

Variable	Mean	Min	Max	Distribution	Units
k_0		3.6×10^{-9}	4.9×10^{-8}	Uniform	m^{-1}
k_e	1.0×10^{-9}	-	-	Constant	m^{-1}
T_{Rf}	1.35	0.50	2.2	Uniform	y
T_{Rs}	100.	-	-	Constant	y

Table 5. Parameter values used in ingestion calculations

Variable	Mean	Min(μ *)	Max(σ *)	Distribution	Units
T_w	14	1.20	0.24	Lognormal	days
RF_c*(cereal)*	0.05	-	-	Constant	-
RF_g/Y_g	2.03	0.26	0.29	Lognormal	m^2 kg^{-1}
Y_c*(vegetable)*	2.3	-	-	Constant	kg f.w. m^{-2}
Y_c*(potato)*	2.0	-	-	Constant	kg f.w. m^{-2}
Y_c*(cereal)*	0.19	-	-	Constant	kg f.w. m^{-2}
Y_g*(grass)*	0.136	-	-	Constant	kg d.w. m^{-2}
TR_1	1.38×10^{-2}	-	-	Constant	d L^{-1}
TR_2	7.3×10^{-5}	-	-	Constant	L^{-1}
TR_3	3.0×10^{-1}	-	-	Constant	d^{-1}
T_{pd}*(plough)*	146	110	186	Uniform	year
T_{pd}*(pasture)*	73	55	93	Uniform	year
λ_f	2.2×10^{-4}	-	-	Constant	d^{-1}
B_v*(vegetable)*		4.6×10^{-2}	4.6×10^{0}	Loguniform	Bq kg^{-1} d.w. /Bq kg^{-1} soil
B_v*(potato)*		1.7×10^{-2}	1.7×10^{0}	Loguniform	Bq kg^{-1} d.w. /Bq kg^{-1} soil
B_v*(cereal)*		2.6×10^{-3}	2.6×10^{-1}	Loguniform	Bq kg^{-1} d.w. /Bq kg^{-1} soil
B_v*(grass)*		2.4×10^{-2}	2.4×10^{0}	Loguniform	Bq kg^{-1} d.w. /Bq kg^{-1} soil
T_G*(vegetable)*	60	50	70	Uniform	days
T_G*(potato)*	140	130	150	Uniform	days
T_G*(cereal)*	95	75	120	Uniform	days
T_G*(grass)*	60	50	70	Uniform	days
ρ	1.4	-	-	Constant	g cm^{-3}
L*(grass)*	10	-	-	Constant	cm
L*(crops)*	20	-	-	Constant	cm
F_m		1.0×10^{-3}	2.7×10^{-2}	Loguniform	d L^{-1}
τ_{milk}	0.7	-	-	Constant	d^{-1}
F_b*(beef)*		4.0×10^{-2}	6.0×10^{-1}	Loguniform	d kg^{-1}
F_b*(pork)*		3.0×10^{-2}	1.1	Loguniform	d kg^{-1}
T_B*(beef)*	25	13	37	Uniform	days
T_B*(pork)*	21	11	31	Uniform	days
τ_{meat}	3.8×10^{-3}	-	-	Constant	d^{-1}
TF_v*(mushroom)*		3×10^{-3}	7	Loguniform	m^2 kg^{-1}
TF_v*(berry)*		2×10^{-3}	2×10^{-1}	Loguniform	m^2 kg^{-1}

* μ and σ are the mean and standard deviation, respectively, of the normally distributed parameters. If the parameter, x is log-normally distributed, μ and σ refer to those of the log-transformed parameters ($\log_{10}(x)$).

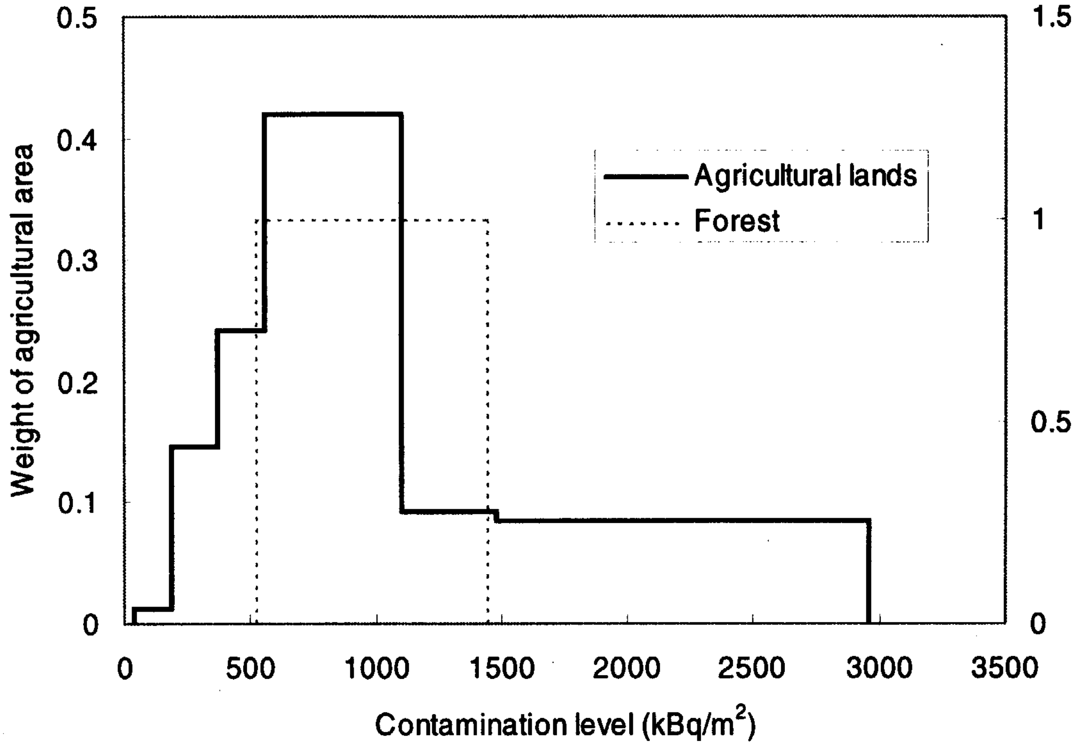

Figure 1. Distribution of Lands by ^{137}Cs Contamination

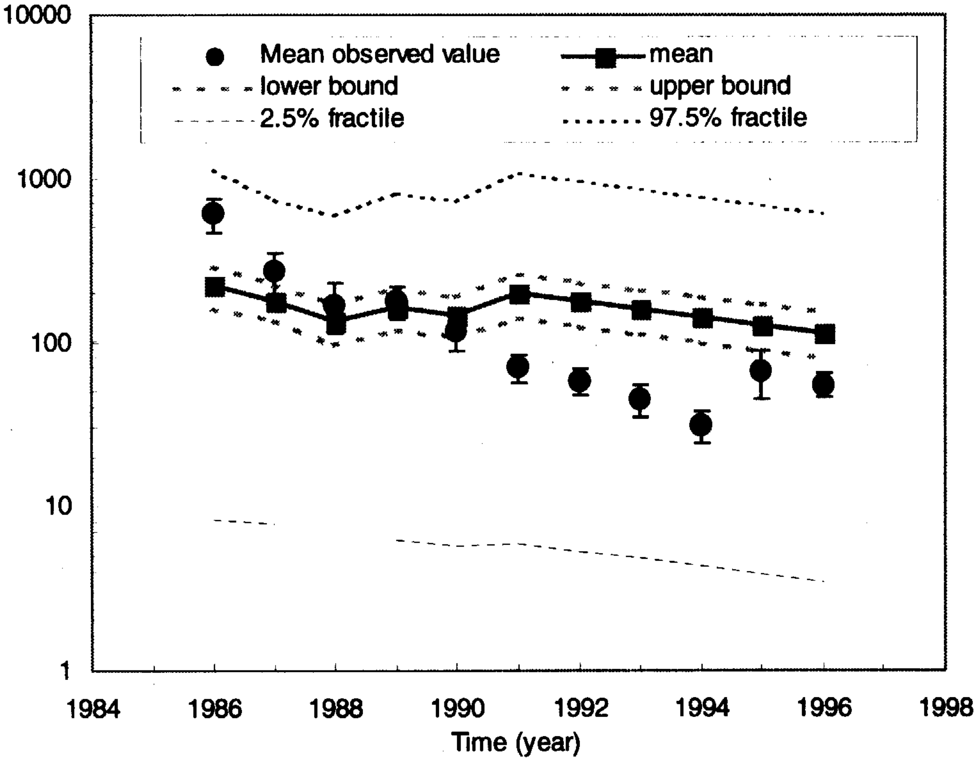

Figure 2. Observed and predicted concentrations of ^{137}Cs in Leafy Vegetables, Bq kg^{-1} f.w.

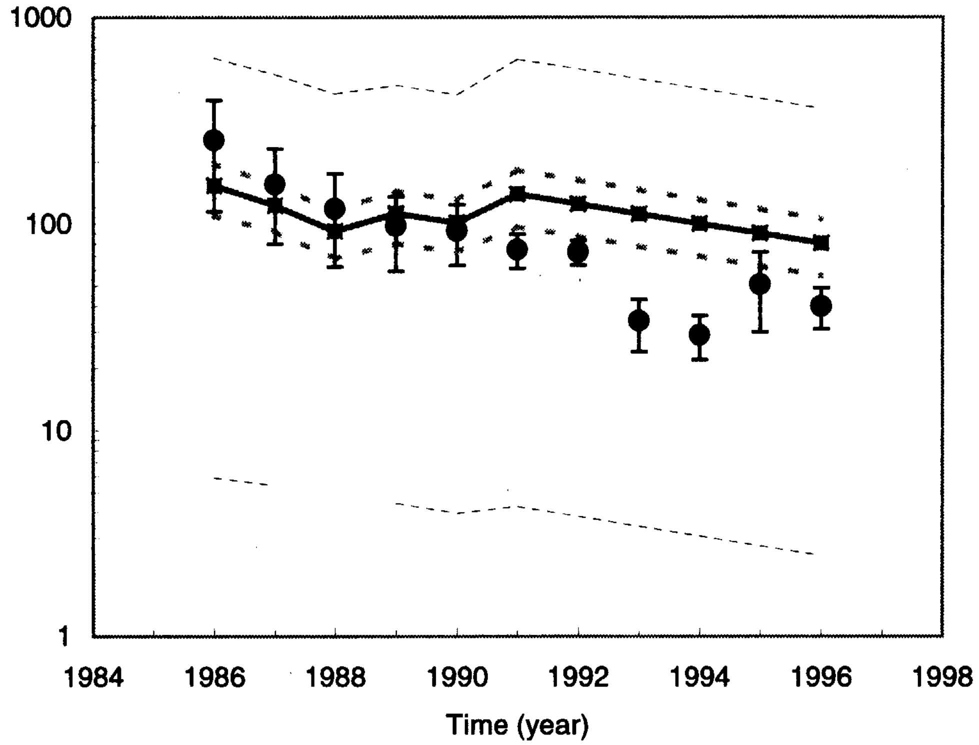

Figure 3. Observed and predicted concentrations of ^{137}Cs in Potatoes, Bq kg^{-1} f.w.

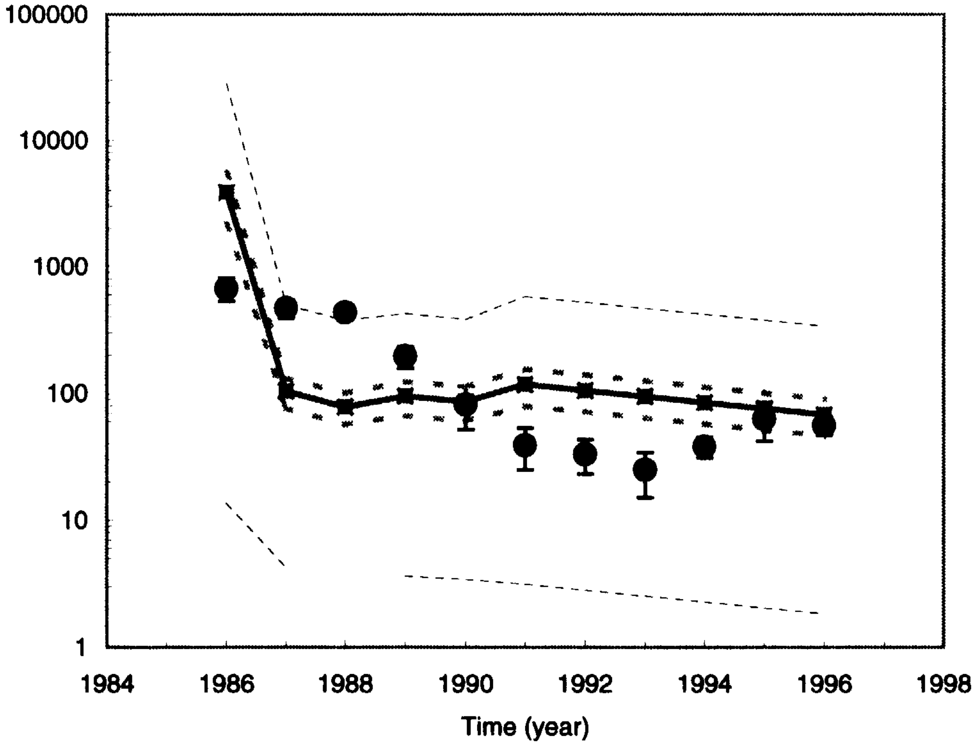

Figure 4. Observed and predicted concentrations of ^{137}Cs in Cereals, Bq kg^{-1} d.w.

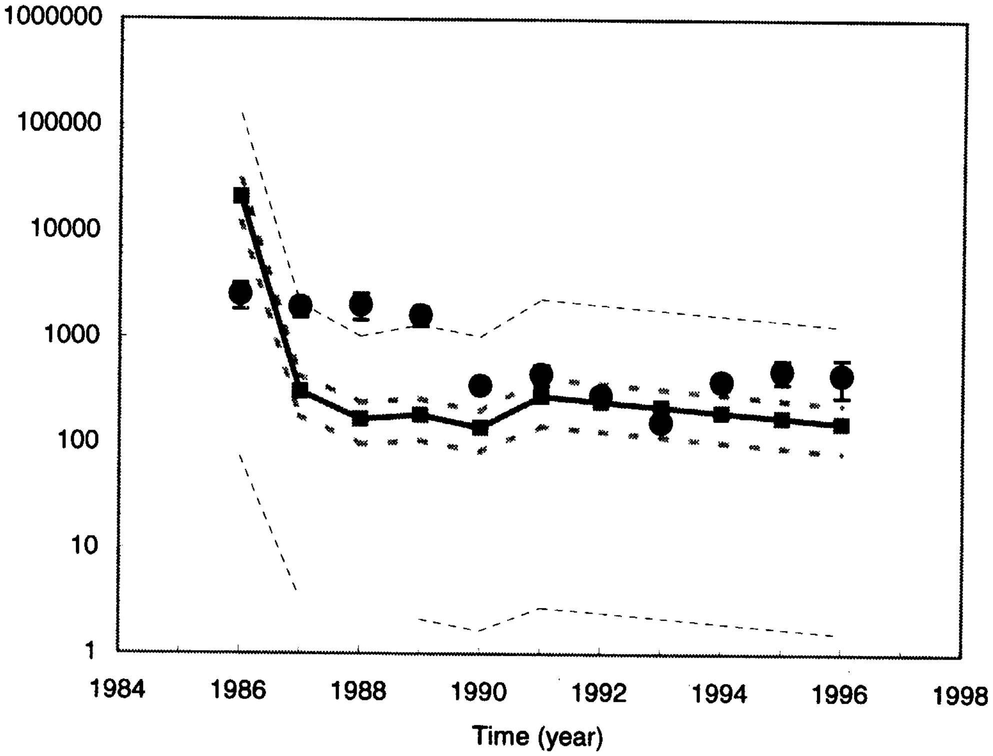

Figure 5. Observed and predicted concentrations of ^{137}Cs in Milk, Bq L^{-1}

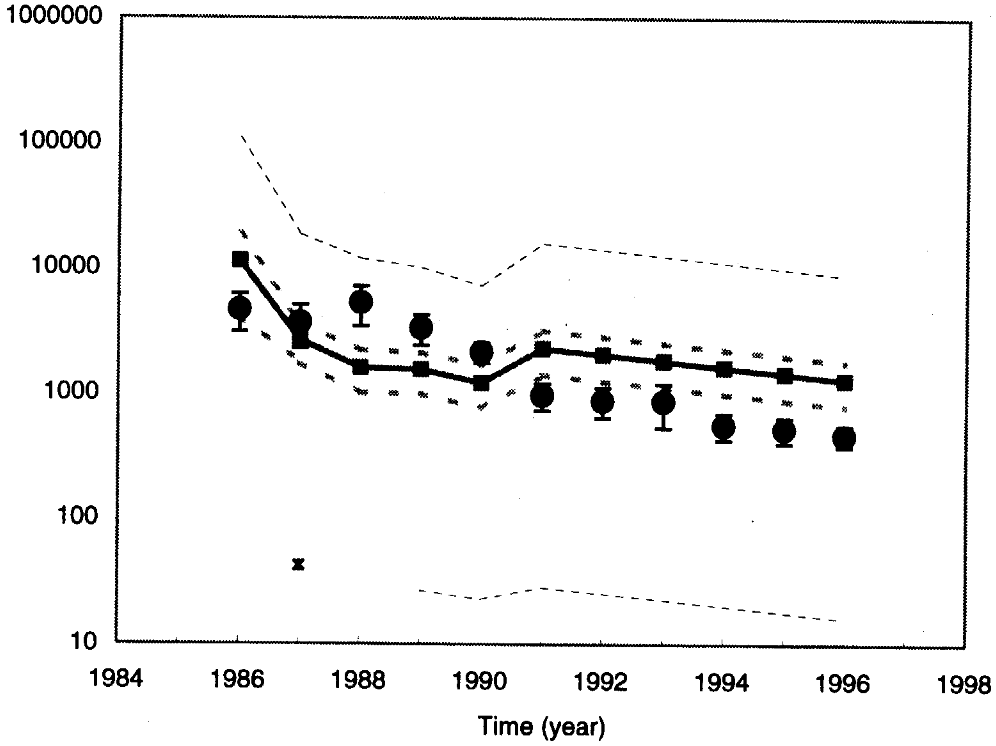

Figure 6. Observed and predicted concentrations of ^{137}Cs in Beef, Bq kg^{-1} f.w.

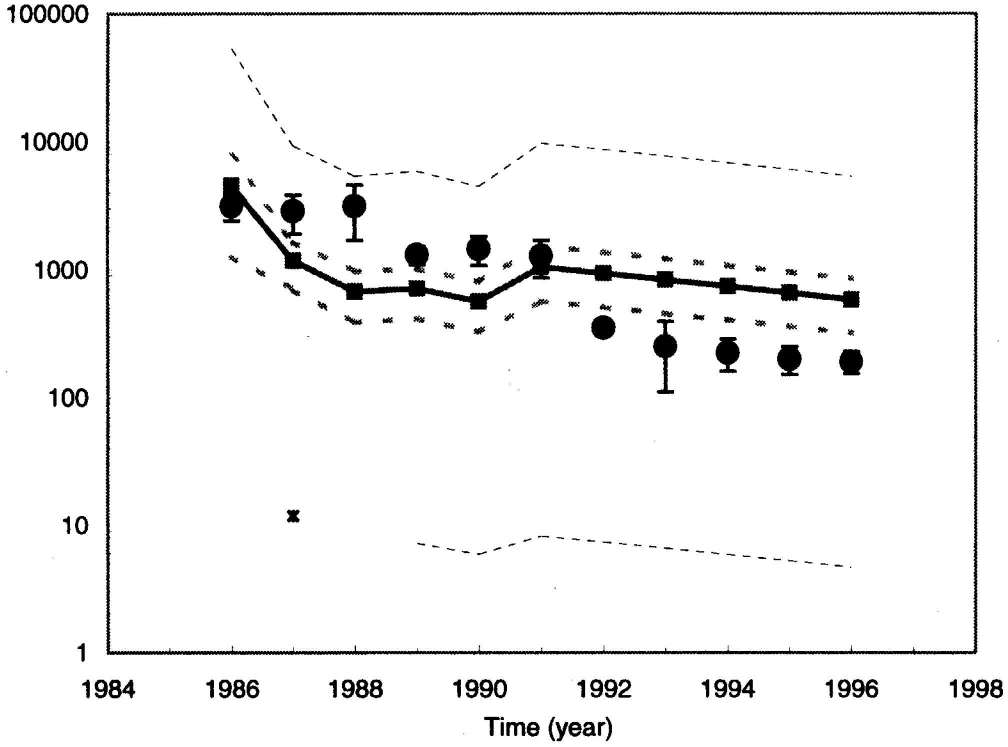

Figure 7. Observed and predicted concentrations of ^{137}Cs in Pork, Bq kg^{-1} f.w.

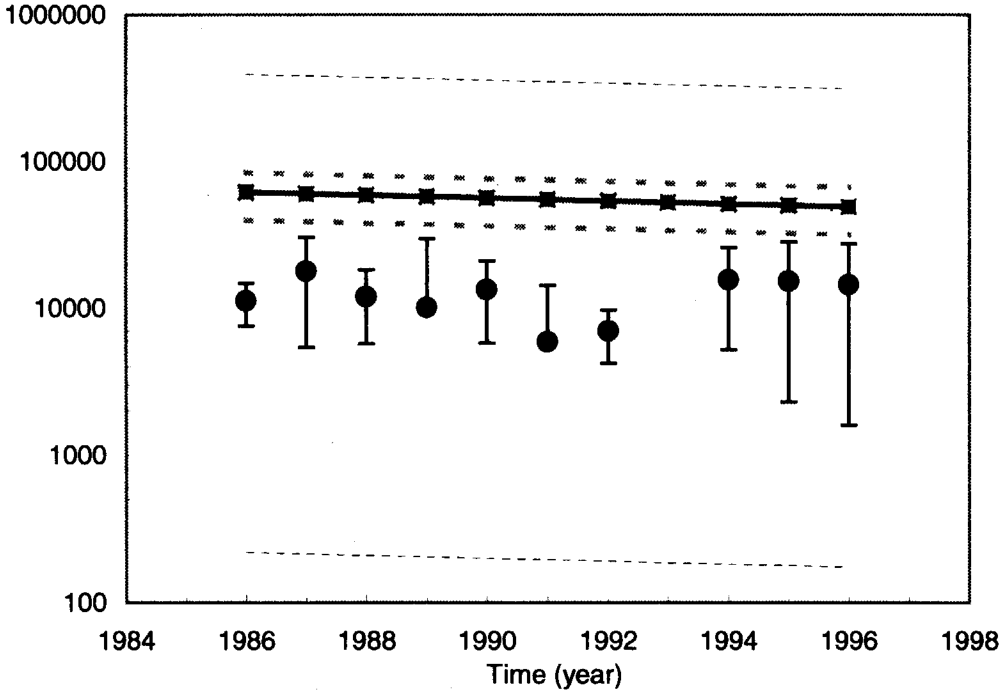

Figure 8. Observed and predicted concentrations of ^{137}Cs in Mushrooms, Bq kg^{-1} f.w.

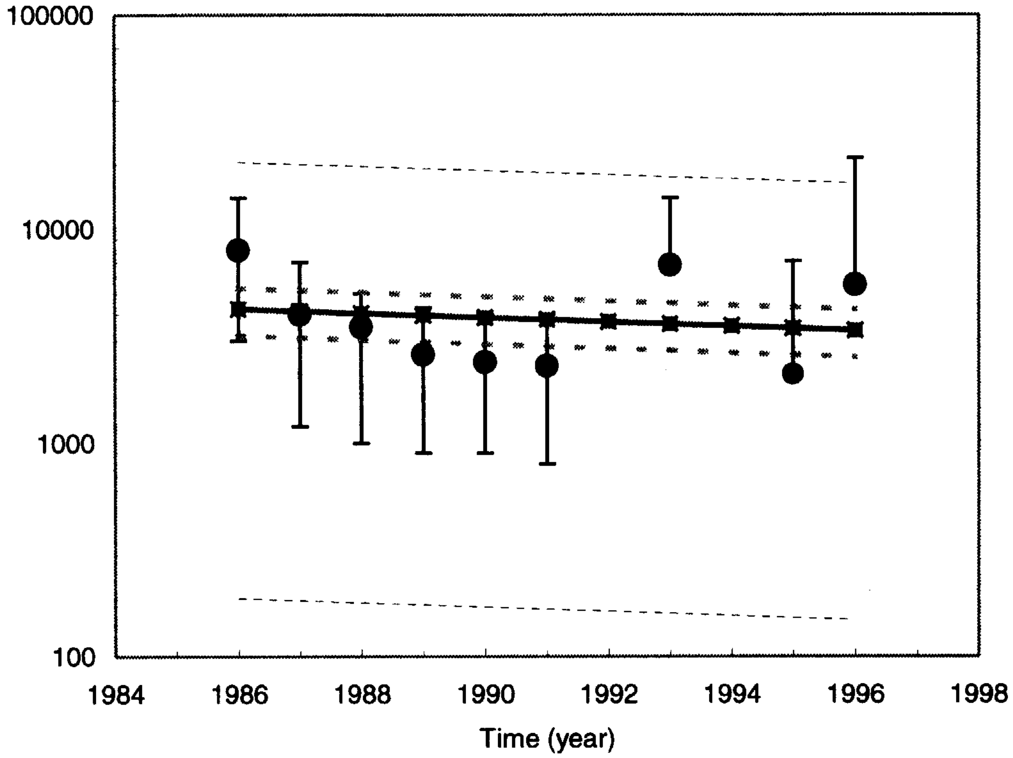

Figure 9. Observed and predicted concentrations of ^{137}Cs in Berries, Bq kg^{-1} f.w.

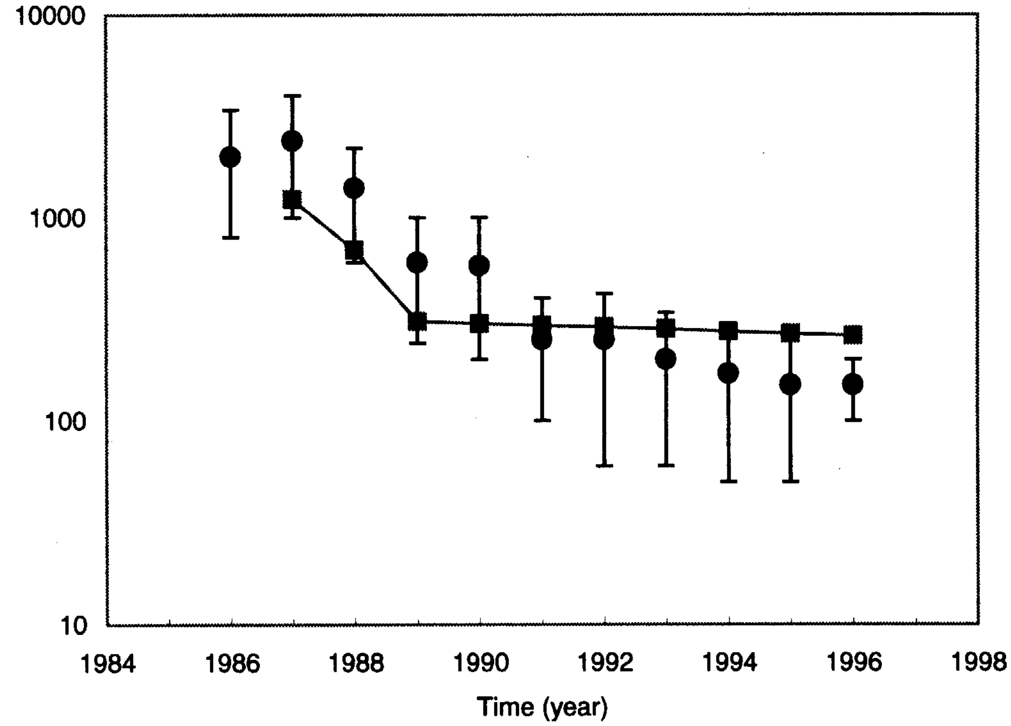

Figure 10. Observed and predicted concentrations of ^{137}Cs in River Fish, Bq kg^{-1} f.w.

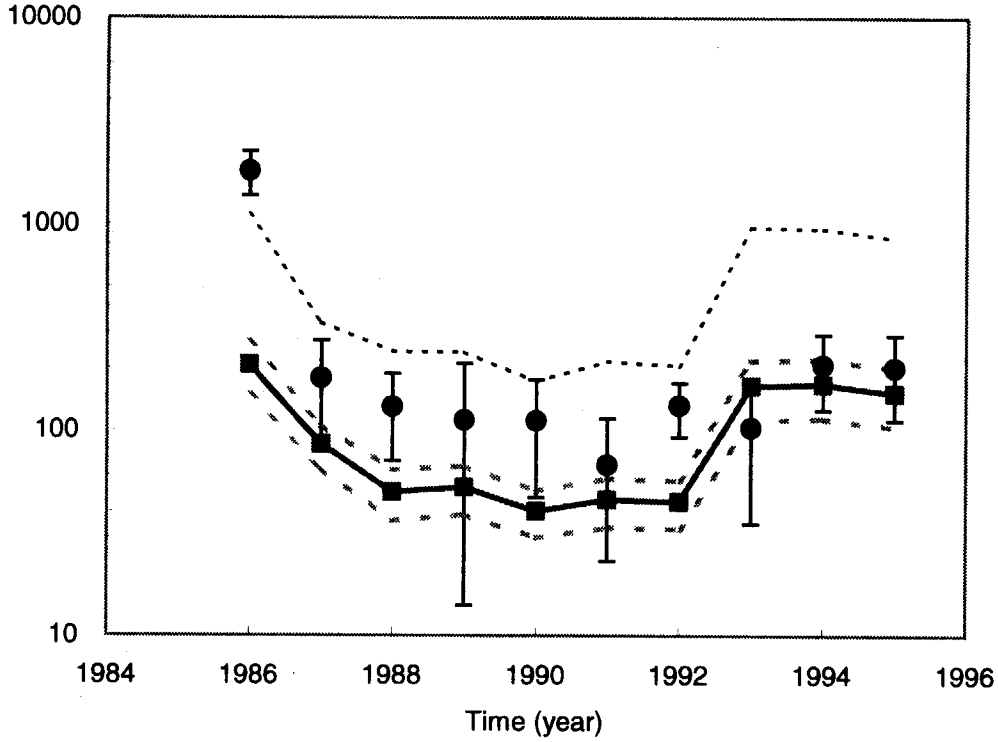

Figure 11a. Observed and predicted amounts of ^{137}Cs in Human Intake, Bq d^{-1} (Controlled area, Women)

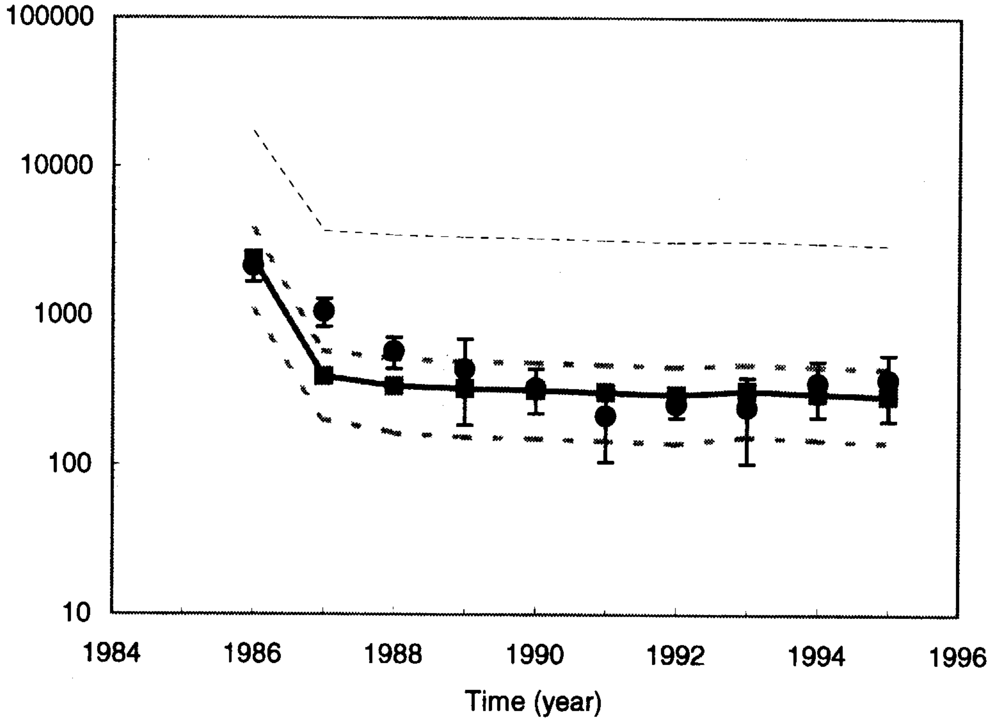

Figure 11b. Observed and predicted amounts of ^{137}Cs in Human Intake, Bq d^{-1} (Non controlled aea, Women)

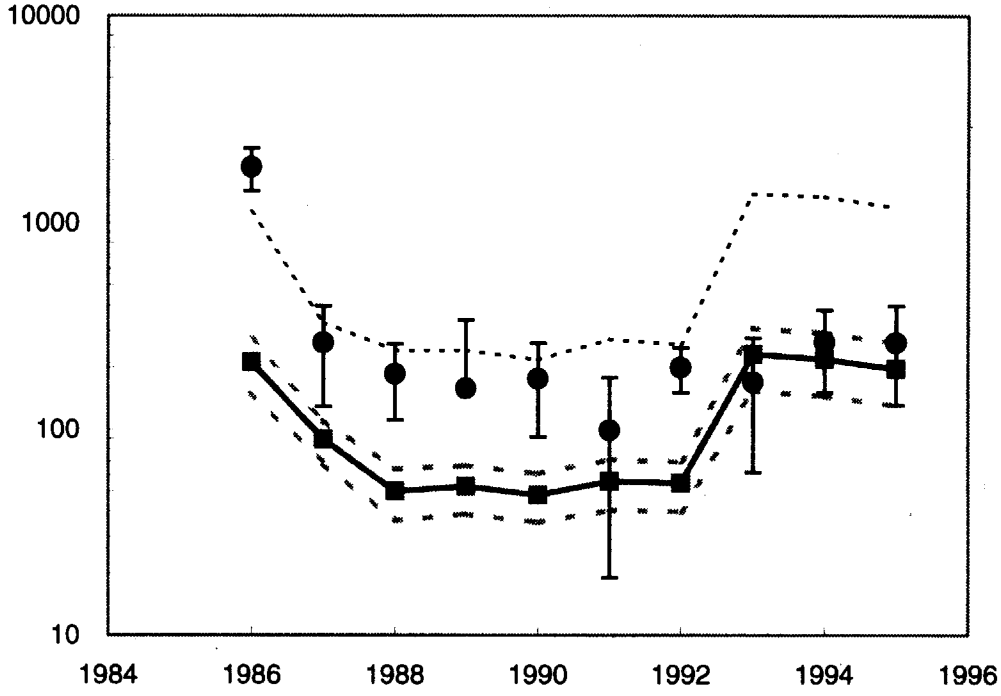

Figure 11c. Observed and predicted amounts of ^{137}Cs in Human Intake, Bq d^{-1} (Controlled area, Men)

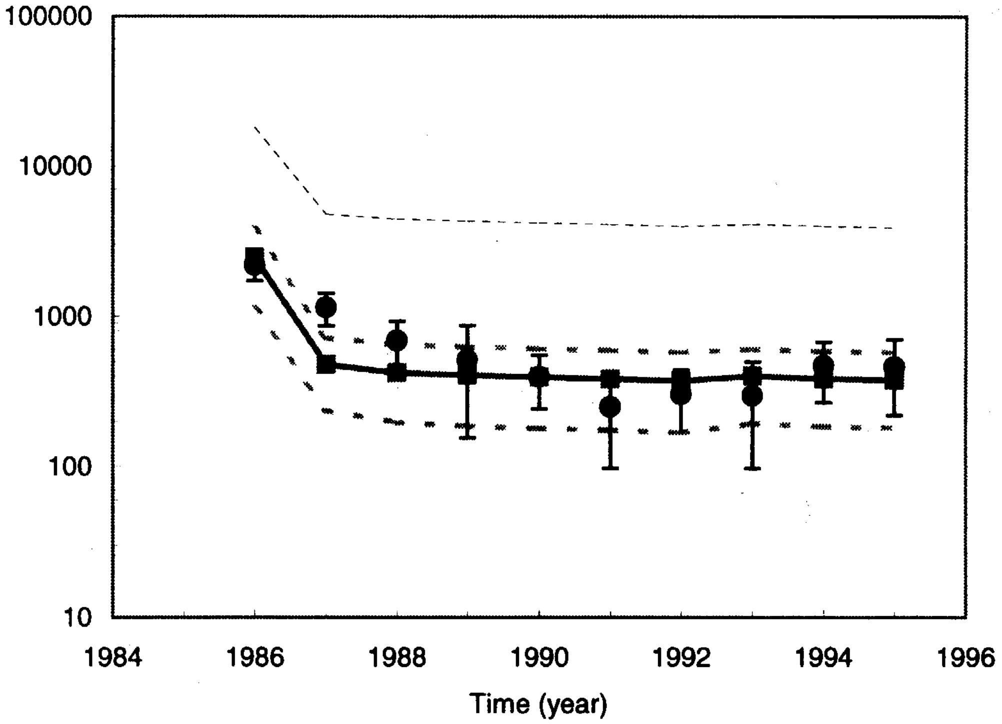

Figure 11d. Observed and predicted amounts of ^{137}Cs in Human Intake, Bq d^{-1} (Non controlled area, Men)

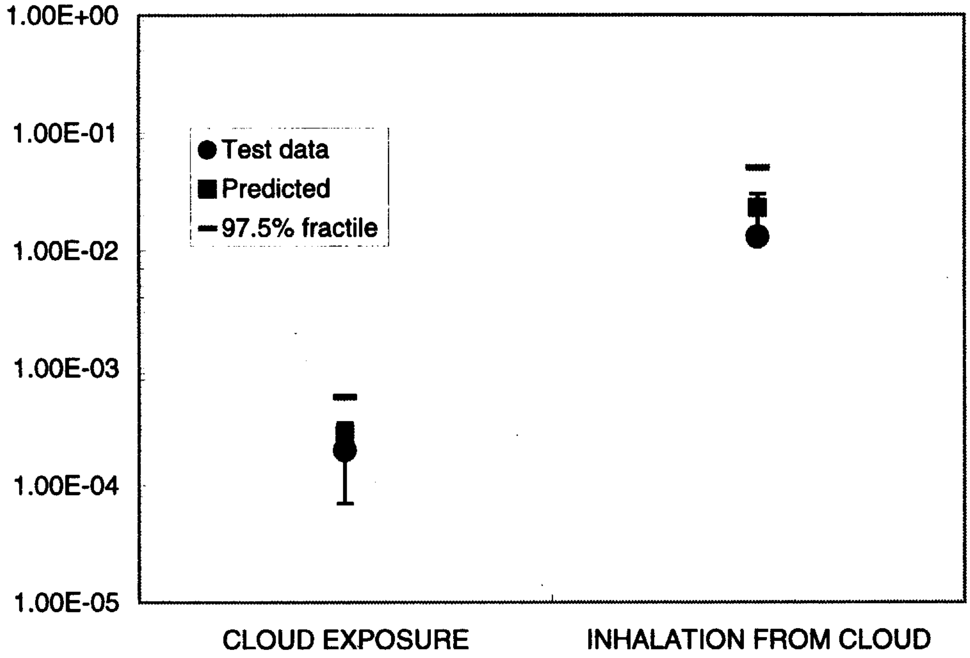

Figure 12. Observed and predicted dose from ^{137}Cs cloud exposure and inhalation, mSv

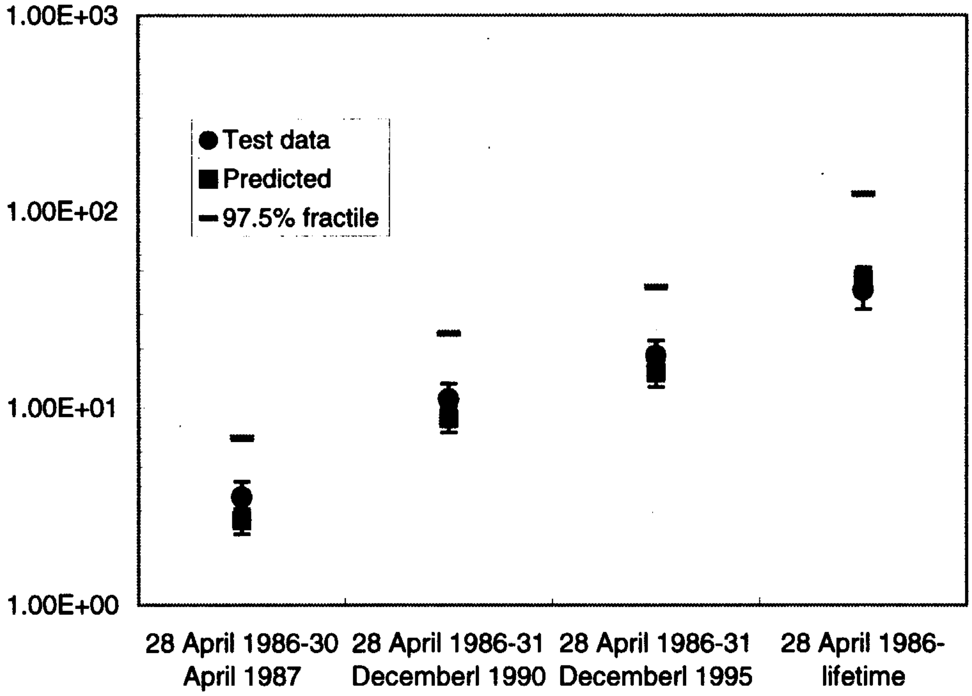

Figure 13. Observed and predicted dose from ^{137}Cs ground deposits, mSv

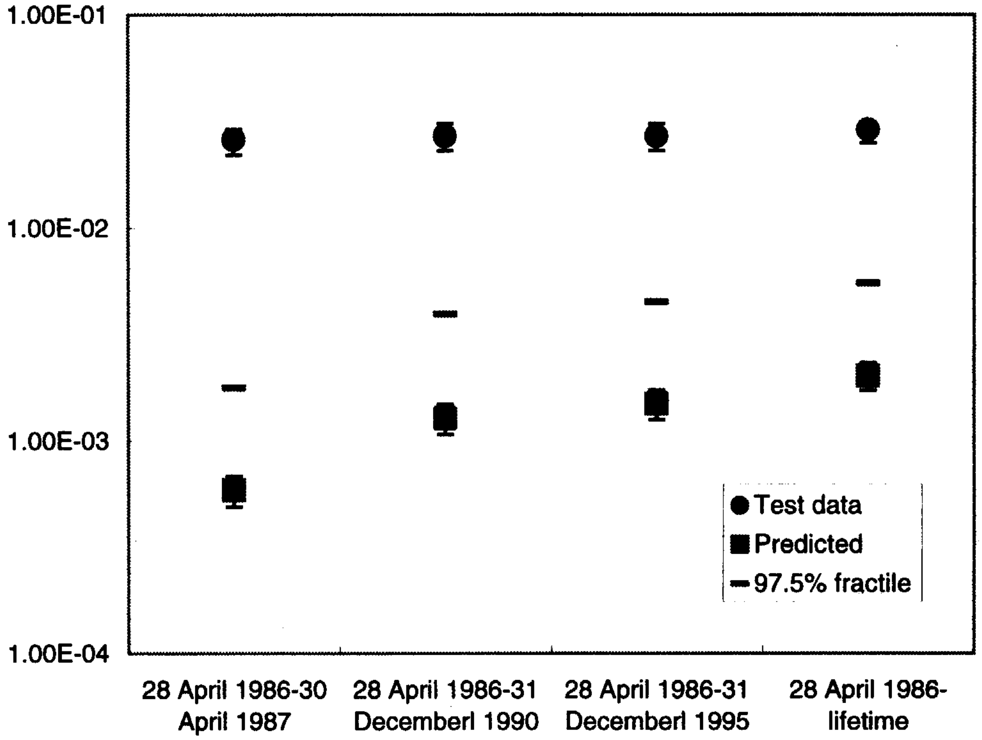

Figure 14. Observed and predicted dose from resuspended ^{137}Cs, mSv

Appendix I

Estimation of radioactive concentration of ^{137}Cs in fish

1. General description

The concentration of ^{137}Cs in fish was estimated based on the "concentration factor approach" [1]. We assumed the equilibrium between the radioactive concentrations in the fish and the ambient water concerning intake and elimination of ^{137}Cs by the fish. The whole range of interest of the Iput river was considered to consist of seven sections of the stream. Each section corresponds to a local watershed and a hydrometric post defined in Table I.XI of the Scenario. The concentration of ^{137}Cs in the fish was estimated by following equation (Eq.1).

$$A_{s,y} = CF \times C_{s,y} \qquad (1)$$

where,

$A_{s,y}$: concentration of ^{137}Cs in the fish at the river section s in year y, (Bq kg^{-1}).

$C_{s,y}$: concentration of ^{137}Cs in river water at the river section s in year y, (Bq l^{-1}).

CF : concentration factor (l kg^{-1})

The subscript s denotes the section number of the river corresponding to a local watershed. The subscript y denotes the year for estimation, 1987 - 1996.

The concentration of ^{137}Cs in the fish ($A_{s,y}$) was averaged over the sections with a weight related to the stream length of each section as shown in Fig. I.1. Finally, a selected concentration factor was employed to this averaged ^{137}Cs concentration in river water to obtain the concentration in the fish. The above methodology was applied for the years 1987 - 1996. Concerning the latter half of 1986, a special consideration that is described later was made. The final result is shown in Table I.1 of this appendix.

2. Detailed description

2.1 Concentration of ^{137}Cs in river water

The concentration of ^{137}Cs in river water was distinguished by a section of the river, the month and the year of interest. It was assumed that the concentration of ^{137}Cs in river water follows a log linear relationship of the water flow rate:

$$C_{s,m,y} = a_s \, Q_m^{\,bs} \qquad (2)$$

where,

$C_{s,m,y}$: the concentration of ^{137}Cs in river water of the section s in the month m of the year y, Bq s^{-1}

Q_m : monthly averaged flow rate, m^3 s^{-1}

a_s, b_s : parameter defined for each section.

This assumption has been generally applied for the load of fluvial discharge of dissolved and suspended substances [2), 3), 4)]. The determination of the parameters is described below.

(i) Parameter b_s

Following equations are deduced from Eq.2:

$$C_{s,m1,y} / C_{s,m2,y} = (Q_{m1} / Q_{m2})^{bs} \tag{3}$$

$$b_s = \log_{10}[(C_{s,m1,y} / C_{s,m2,y})/(Q_{m1} / Q_{m2})] \tag{4}$$

where,

m_1, m_2 : months having distinct differences in Q and C, for example, flooding month (m_1) and dry month (m_2).

By applying the observed concentrations during a flooding period (Table I.VI of the Scenario) and a low-water period (Table I.VII) in 1991 to this equation, the parameter b_s was calculated for each section of No.1-7. The water flow rate was from Table I.XVII. Because the data size to determine b_s was limited, its average value was used for all sections. This means that the hydrological response of the relocation process to the precipitation event, which causes relocation and controls the river water flow rate (Q), is assumed to be uniform for all the local watersheds. The average of b_s over the sections No.1-7 was determined as 0.23, that is denoted as b, hereafter.

(ii) Parameter a_s

The annual discharge of ^{137}Cs from a section s is expressed by Eq.5.

$$D_{s,y} = \Sigma_m Q_m \times C_{s,m,y} \times t_m \times 1.0 \times 10^{-12} \tag{5}$$

where,

D : the annual discharge of ^{137}Cs from a section s in the year y (TBq a^{-1})

Q_m : monthly averaged water flow rate of the month m (m^3 s^{-1})

t_m : seconds in the month m (s)

1.0×10^{-12} : a conversion factor from Bq to TBq

On the other hand, the variable D must be equal to the sum of the amount of relocated ^{137}Cs from the local watershed to the river water through the sections from the first one to the section No.s (Eq.6, the summation was from the first one to the section No.s). The amount of ^{137}Cs relocated from the local watershed was connected to the stored amount of ^{137}Cs in the local watershed by Eq. 7.

$$D_{s,y} = \Sigma_s L_{s,y} \tag{6}$$

$$L_{s,y} = w_{s,y} \times A_{s,y} \tag{7}$$

where,

$L_{s,y}$: the amount of relocated ^{137}Cs from the local watershed ground of the section s in the year y , Bq a^{-1}

$A_{s,y}$: the stored amount of ^{137}Cs in the local watershed ground of the section s in the year y, Bq

$w_{s,y}$: the annual wash-off rate ^{137}Cs from the local watershed ground of the section s in the year y, Bq a^{-1}

A set of values of $A_{s,y}$ are given in Table I.XI of the Scenario. The values of $A_{s,y}$ at each year were calculated from those values taking into account radioactive disintegration. (The Table I.XI was considered to be of 1991 in our analysis, in spite of no mark in the Table.) Loss due to relocation to the river was neglected compared to the disintegration.

The value of $w_{s,y}$ was given only for 1987 (1.9×10^{-3}) and 1988 (1.1×10^{-3}) for the last section (No.7). On the other hand, it seemed reasonable that the temporal change of the value $w_{s,y}$ analogizes with that of the concentration of ^{137}Cs in river water judging from the closeness between the stored radioactivity and that concentration (Fig. I.2). Table I.XII of the Scenario gives temporal decrease of the annual average concentration of ^{137}Cs at the last section (No.7) from 1987 to 1991. Then, it was postulated that decreased after the same fashion of that concentration.

The result of this estimation is shown in Table I.2 of this appendix. Although that concentration could be extrapolated exponentially as shown in Fig. I.3, we thought this extrapolation might not be correct because of a limited number of experimental data (five points, Table I.2). Therefore, following conservative values were chosen as $w_{s,y}$ for every section s :

1987	1.9×10^{-3}
1988	1.1×10^{-3}
1989 and later	0.5×10^{-3}

The value of 0.5×10^{-3} is a mean of 0.66×10^{-3} (1989) and 0.39×10^{-3} (1990) (see Table I.2). The values obtained by exponential extrapolation were also tested for the sake of comparison. This test resulted in lower concentration of ^{137}Cs in river fish than observed data by one order of magnitude in late years (after 1991).

Once the value of $w_{s,y}$ was determined, $D_{s,y}$ was calculated by Eq. 6 and Eq.7. Finally, one had an equation that determine a_s as follows:

$$\Sigma_m Q_m \times a_s Q_m^{bs} \times t_m \times 1.0 \times 10^{-12} = \Sigma_s w_{s,y} \times A_{s,y} \qquad (8)$$

After determination of a_s and b, the concentration $C_{s,m,y}$ was calculated. Then it was averaged annually to give $C_{s,y}$ in Eq.1. Fig. I.4 shows the estimated concentration of ^{137}Cs in river water ($C_{s,y}$) according to the present model.

2.2 Concentration factor

General values of the concentration factor of ^{137}Cs in freshwater fish have been reviewed in several literatures. Blaylock [5)] presents a database of the factors as listed in Table I.2 of this appendix. According to Peterson[1)], the concentration factors can be given as function of a concentration of dissolved potassium in water as follows:

For piscivorous fish,

$$CF\ (l\ kg^{-1}\ \text{fresh mass}) = 1.5 \times 10^4 \times [K]^{-1}$$

and for nonpiscivorous fish,

$$CF\ (l\ kg^{-1}\ \text{fresh mass}) = 5 \times 10^3 \times [K]^{-1}$$

with [K] is the concentration of potassium ion in mg l^{-1}. The concentration of potassium ion in the Iput river is given as 1-2 (mg l^{-1}) in the scenario. Using the mean value 1.5 (mg l^{-1}) produces 1×10^4 and 3.3×10^3 (l kg^{-1}) for piscivorous and nonpiscivorous fish, respectively. More recently, a review by IAEA [6)] gives a mean of 2×10^3 (l kg^{-1} edible portion) with a range of 3×10^1 - 3×10^3 (l kg^{-1}). It also gives a function of dissolved potassium and calcium concentrations.

A survey of radioactive contamination on the fish in rivers and impoundments (the river Pripyat, the Cooling Pond, the lake Glubokoye, and the river Uzh) around the Chernobyl Nuclear. Power Plant was conducted by the Ukrainian authority (Y. Tkachenko, *private communication*). Using their monitoring data, concentration factors were derived in a range of 6×10^2 - 3.6×10^3 (l kg^{-1} fresh mass, muscle portion) with a mean of 2×10^3 (l kg^{-1}) approximately. From a viewpoint of a broad geography, the environmental condition in the

Iput River area must be closer to that in Chernobyl rivers and lakes than to the environmental conditions which appear in the review literature such as in American rivers and lakes, for example (Blaylock[5)]). Therefore, we decided to use the value of 2 x 10^3 ($l\ kg^{-1}$) which was obtained as a mean in the Chernobyl study. Although the concentration factor must be different by species of fish, one uniform value of the concentration factor was used in the present estimation.

2.3 Derivation of weighed average concentration of ^{137}Cs in fish

As already explained, concentrations of ^{137}Cs in fish were calculated for each section (no.1-7) in each year (1987-1996) firstly. Secondly, these concentrations were averaged by the weight corresponding to the distance of the river sections belonging to the monitoring points. The weight G_s is given by the below.

$G_s = F_s / \Sigma_{s'} F_{s'}$

G_s : weight to be multiplied to the ^{137}Cs concentration (fish) at the section s

F_s : distance covered by the section s

$F_s = [(P_{s+1}-P_s) + (P_s-P_{s-1})] /2$

where,

P_s : distance from Iput river source (km) given in Table I.VI. of the Scenario,

provided that

$D_1 = 2 \times [(P_2-P_1) / 2]$

$D_7 = 2 \times [(P_7-P_6) / 2]$.

2.4 Estimation of the value in 1986

Because no observed value was provided in the Scenario, the value was estimated by the following consideration. The concentration of ^{137}Cs in river water in 1986 after the accident was higher than that in 1987 by about one order of magnitude (ten times higher) in the river Pripyat at Chernobyl. On the other hand, the propagation of the increase of ^{137}Cs in river water to the fish in the river may need some time due to the accumulation of the radionuclide in the fish body and the linkage between the predatory and non-predatory species. Then, we estimated that the ^{137}Cs concentration in fish in 1986 could be higher than that in 1987 by a factor of two, not by ten times which is the case for the river water.

3. Reflection of the present model analysis

The present result of our methodology fell into the 95% confidence level associated with the field observation, showing a reasonability of the method. Our method does not require a special, detailed type of the experimental data. The following observation data were employed in the method:

a. Stored amount of ^{137}Cs in the watershed;
b. A multiple set of 1) the radioactive concentration in river water and 2) the river water flow rate under different hydrological conditions in terms of the river water flow rate.
c. Monthly averaged river water flow rate through a year;
d. Annual wash-off rate of ^{137}Cs;
e. Temporal change in the radioactive concentration in river water for years;
f. A mean concentration factor of ^{137}Cs for river fish.

Generally speaking, those data are fundamental ones as long as a radiological contamination of a river watershed is concerned. Therefore they will be available in an area to be studied. Then, the model must have a wide applicability. The method needs an assumption that the radioactive concentration in river water follows a log-linear relationship with the river water flow rate. The value of "the rating" in the relationship (parameter b_s or b) is determined by a response of the radioactive concentration to a difference of river water flow rate. A coefficient, which determines the magnitude of the radioactive concentration of river water, is deduced from a constraint of an amount of annual, fluvial discharge of the radionuclide. The key issue in the model is the log-linear relationship. This relationship can be applied for radionuclides of high adsorptivity to the soil in a river watershed and the suspended particles/bottom sediments in a river. They are radiocesium[3)] and transuranic elements. On the contrary, strontium isotopes (e.g. ^{90}Sr) has a distinct property regarding to the river water flow rate and other hydrological conditions because of its high solubility.

Concerning the concentration factor, there remains a freedom in selecting values. An extensive study on the accumulation of Chernobyl-derived ^{137}Cs for river fish was conducted by allied European countries[7)]. According to their report[7)], the concentration factor lies between 1000 and 10000 (l kg^{-1}) approximately. Observed values of the concentration factor were similar within a factor of 2 for each of fish species. It also changed by fish size among identical species. These findings of them suggest a validity of the concentration factor concept, and also the various elements to be considered in its use.

We consider following issues should be solved hereafter:

- Long-term evaluation of the concentration of the interested radionuclides in river water.
- Selection of a mean value of the concentration factor with considerations on 1) the variability with a category of the trophic level of fish, and 2) the kind and the size of fish for consumption in out dietary.

One more important issue must be the evaluation in the early stage after the occurrence of contamination. The distribution of the interested radionuclides over non-biological component, first of all, must be far from the equilibrium in the early stage. Further, the radionuclides in a lower trophic level do not necessarily reach a higher level of organisms. Some evaluation should be considered for such "unstable" phase of radioactivity distribution other than a transfer factor or a concentration factor approach. This is because that exposure at the early stage is decisive in many cases among the whole exposure including delayed one in coming years after the contamination. Thus, an approach to the first evaluation with a limited available data for the early stage exposure is keenly require, we believe.

Acknowledgment

The authors are grateful to Dr. Yuri Tkachenko of RADEK (Ukraine) for his help in providing aquatic contamination data in Chernobyl.

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Table I.1 Estimated concentration of ^{137}Cs in river fish in comparison to observed values

(kBq kg^{-1} f.w.)

Year	Estimated Concentration	Observed concentration		
		Mean	Lower bound	Upper bound
1986	2.5	2.0	0.8	3.4
1987	1.2	2.4	1.0	4.0
1988	0.70	1.4	0.6	2.2
1989	0.31	0.6	0.24	1.0
1990	0.30	0.58	0.2	1.0
1991	0.29	0.25	0.1	0.4
1993	0.29	0.25	0.06	0.42
1993	0.28	0.20	0.06	0.34
1994	0.28	0.17	0.05	0.30
1995	0.27	0.15	0.05	0.25
1996	0.26	0.15	0.10	0.20

Table I.2 Wash-off rate estimated by analogy to decrease in concentration of ^{137}Cs in river water

Year	Concentration of ^{137}Cs in river water (annual average at Section No.7)			Wash-off rate**
	observed (Bq L^{-1})	estimated* (Bq L^{-1})	decreasing ratio relative to 1987	(-)
1987	2.0	2.1	1	1.9 x10^{-3}
1988	1.4	1.2	0.59	1.1 x10^{-3}
1989	0.6	0.7	0.35	6.6 x10^{-4}
1990	0.55	0.4	0.21	3.9 x10^{-4}
1991	0.23	0.26	0.12	2.3 x10^{-4}
1992	-	0.15	0.072	1.4 x10^{-4}
1993	-	0.09	0.043	0.8 x10^{-4}
1994	-	0.05	0.025	0.5 x10^{-4}
1995	-	0.03	0.015	0.3 x10^{-4}
1996	-	0.02	0.009	0.2x10^{-4}

* estimated by postulating exponential decreasing.

** calculated using the decreasing ratio with an initial value of 1.9 x10^{-3} in 1987.

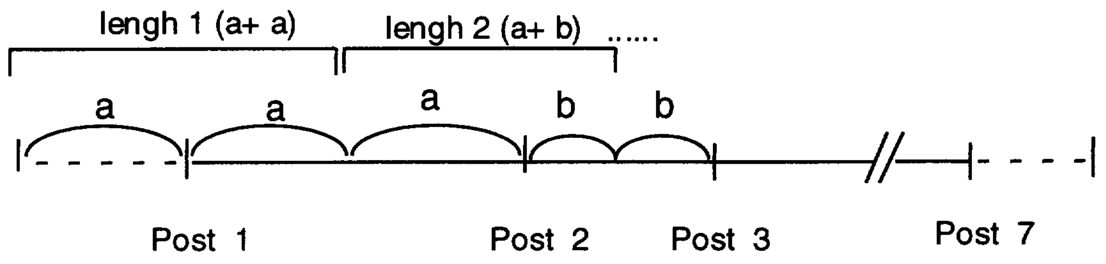

Fig. I.1 Illustration of weighing of the concentration of ^{137}Cs to produce its average through the sections.

The length of the stream of a section was determined as a sum of the half distance to neighboring posts. At the sections at both ends, an imaginary half length was added.

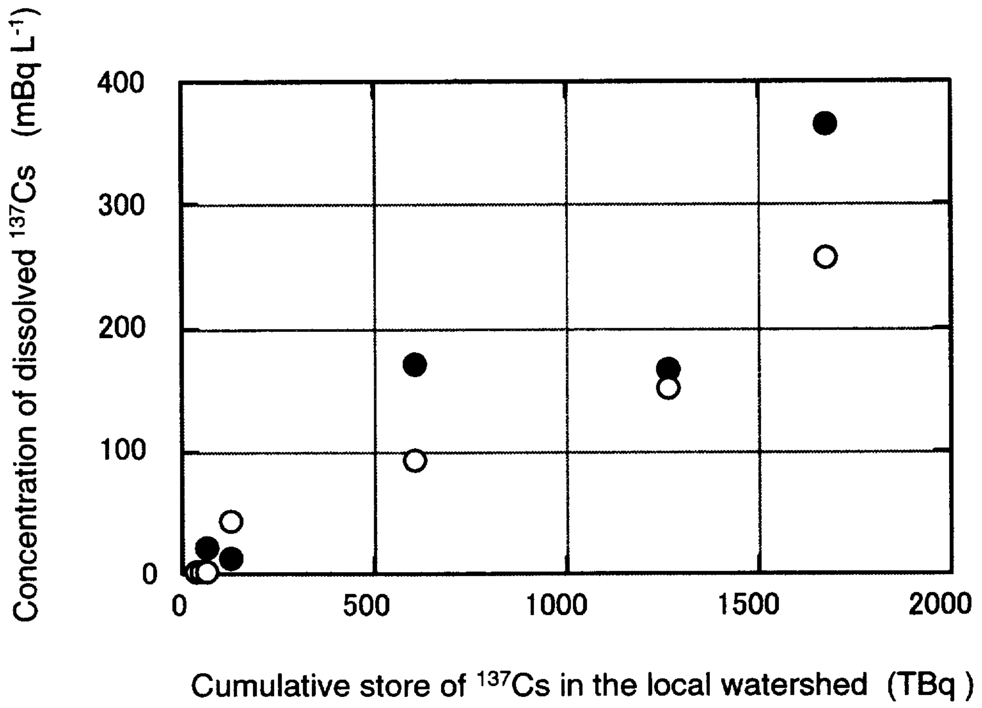

Fig. I.2 Relationship between the concentration of dissolved ^{137}Cs and the cumulative store of ^{137}Cs in the local watershed. Both data are observed values from the Scenario. Open circles : under low-water condition; closed circles under flooding condition.

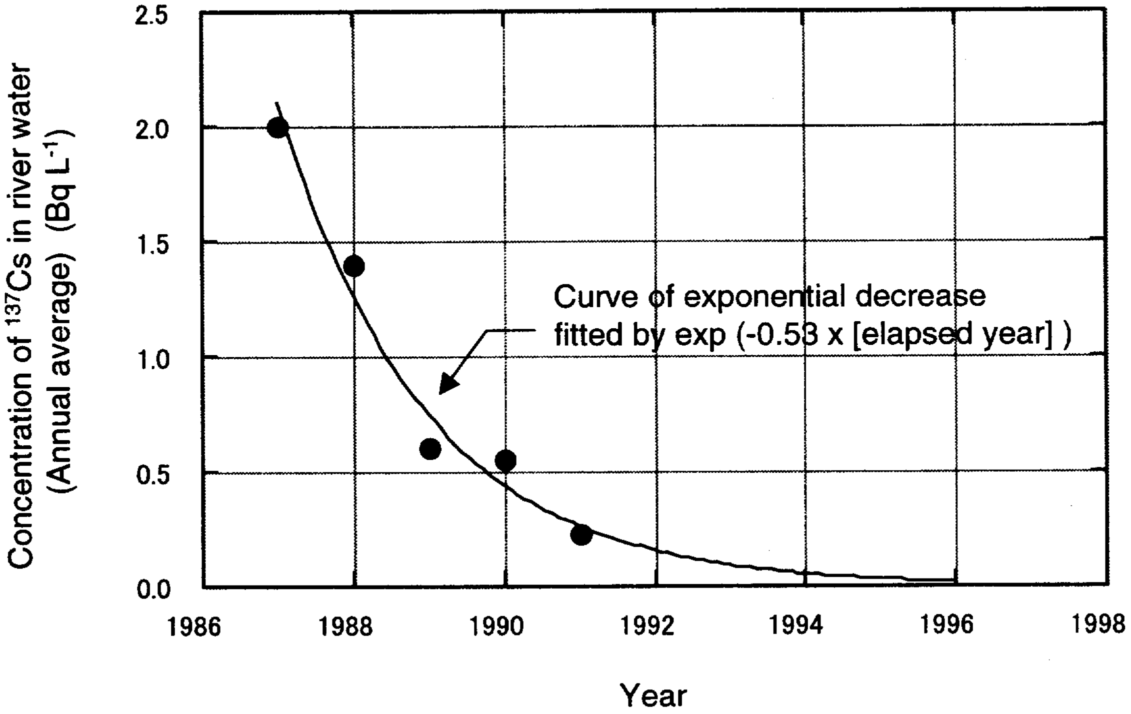

Fig. I.3 Fitting result of annual decrease in the concentration of 137Cs in river water.
Circles : observed cocentraion (annual average at the end of the Section No.7), taken from the Scenario.

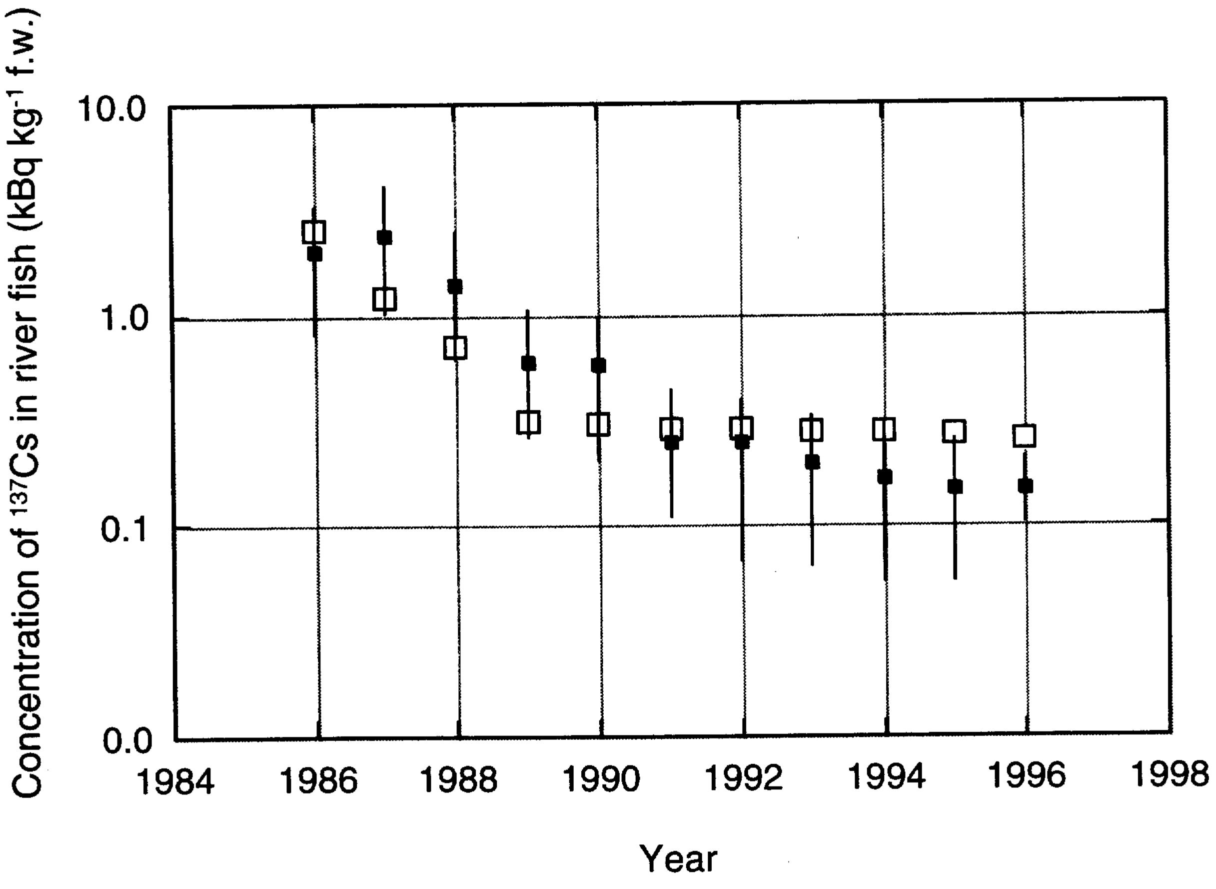

Fig.I.4 Concentration of ^{137}Cs in river fish in the test area of the Iput river.
Open square : estimation; closed square : observed mean value; range by a bar : 95 % confidence interval concerning observed concentrations.

Appendix II

Tables in the scenario description used in the OSCAAR calculations

Table I.I. Assessments of the ^{137}Cs concentrations in ground-level air of the test area, 1986 (Novozybkov district).

Time	Concentration, mBq m^{-3}
28.04-30.04.86	60000 ± 40000
1.05-10.05.86	2000 ± 1200
11.05-20.05.86	400 ± 200
21.05-31.05.86	200 ± 100
1.06-30.06.86	80 ± 40

Table I.VI. Section-averaged concentrations of ^{137}Cs in the river water during a flooding period (9 April - 15 April, 1991).

Hydrometric post	Distance from Iput river source, km	Concentration of ^{137}Cs, mBq L^{-1}	
		Solution	Suspension
1	170	3.0 ± 1.1	1.1 ± 0.2
2	230	3.3 ± 1.1	<0.1
3	254	21.1 ± 0.7	1.1 ± 0.1
4	264	14 ± 7	6.3 ± 1.8
5	304	170 ± 30	4.4 ± 0.4
6	330	166 ± 26	7.8 ± 0.7
7	363	366 ± 40	17 ± 10

Table I.VII. Section-averaged concentrations of ^{137}Cs in the river water during a low-water period (27 July - 9 August, 1991).

Hydrometric posts	Concentration of ^{137}Cs, mBq L^{-1}	
	Solution	Suspension
1	1.5	<0.1
2	2.6	1.1
3	3.0	<0.1
4	44	3
5	94	11
6	151	12
7	257	20

Note: The average uncertainty is 20% (95% confidence interval).

Table I.XI. Characteristics of the Iput watershed contaminated with ^{137}Cs.

Hydrometric post	Local watershed		Total watershed (cumulative)	
	Watershed area, km^2	Activity stored in watershed, TBq	Watershed area, km^2	Activity stored in watershed, TBq
1. (Krytojar)	4020	34	4020	34
2. (Belovodka)	1340	13	5360	47
3. (Kazarichi)	510	16	5860	64
4. (Tvorishino)	180	58	6040	122
5. (Usherpie)	2280	483	8320	604
6. (St. Bobovichi)	855	660	9170	1265
7. (Vishkov)	440	410	9610	1676

Table I.XII. Average annual activity of ^{137}Cs in water (Bq L^{-1}) of the Iput river (hydrometric post in Dobrush, Belorussia, near the inflow of the Iput river into the Sozh river).

Year	1987	1988	1989	1990	1991
Iput, near Dobrush	2.0	1.4	0.60	0.55	0.23

Table I.XVII. Month-to-month distribution of discharges of water and suspended matter to the Iput river.

Month	Average water discharge, m^3 s^{-1}	Suspended matter discharge, kg s^{-1}
January	20	0.13
February	15	0.097
March	38	0.45
April	230	2.3
May	73	0.41
June	20	0.17
July	14	0.12
August	14	0.099
September	19	0.079
October	22	0.086
November	26	0.13
December	23	0.13

Table I.XX. Characteristics of the forests in the territory of the Iput test area.

Forest Unit	Area, km^{-2}	Contamination, kBq m^{-2}		Type of forest	Number of inhabitants
		Average	St. Err.		
1	13.6	1100	220	Deciduous, 56%	1535
2	19.8	870	150	Deciduous, 66%	1950
3	17.2	1900	640	Coniferous, 52%	1508
4	3.5	1500	340	Coniferous, 60%	1420
5	15	910	100	Coniferous, 91%	1716
6	24.5	520	100	Coniferous, 90%	1074
7	3	780	170	Deciduous, 68%	863
8	8.5	620	120	Coniferous, 81%	296
9	6.7	460	40	Coniferous, 66%	682
10	8.8	360	80	Deciduous, 85%	1031
11	13	1500	330	Coniferous, 77%	134
12	28.9	1500	410	Coniferous, 81%	919
13	6.8	810	130	Coniferous, 92%	85
14	48.6	750	190	Coniferous, 67%	1183
15	11.4	910	100	Coniferous, 58%	985

Table I.XXXI. Time of sowing and harvesting of crops.

Crop type	Dates of sowing	Dates of harvesting
Winter rye	20.08 - 10.09	20.07 - 05.09
Winter wheat	20.08 - 10.09	20.07 - 05.09
Spring barley	15.04 - 05.05	20.08 - 30.08
Maize (for silage)	10.05 - 30.05	01.09 - 15.09
Potato	01.05 - 10.05	20.09 - 10.10
Root crops	20.04 - 10.05	20.09 - 30.09
Cabbage	15.05 - 30.05	20.08 - 30.08 (early) 20.09 - 30.09 (late)
Vegetables	20.05 - 30.05	20.07 - 10.08
Grasses	10.04 - 20.04	1 term 10.06 - 20.06 2 term 20.07 - 30.07 3 term 10.09 - 20.09

Table I.XXXII. Yields of grass stand and silage in the test area, 1986.

Type	Yield (kg m^{-2})
Hay: perennial grasses (dry weight)	0.308
Natural grasses (dry weight)	0.136
Silage (fresh weight)	4.05

Table XXXIII. Keeping of animals.

Pasture period	Start - 1 May -10 May End - 10 Oct.- 20 Oct. Average duration is 170-180 days
Stable period	Duration of stable period may range from 146 to 200 days

Table I.XXXIV. Annual ration for bull calves at a farm in the test area, kg a^{-1}.

Components of ration	Amount, kg a^{-1}
Green	2724
Hay	532
Silage*	3163
Root crops	146
Potato	125
Pasture	-
Concentrates **	815

* The main component of silage is green-cut maize, content of dry matter is 20%.

**Concentrates include grain of barley, ray, wheat, mineral and vitamin supplements, phosphorus acid ammonium salts.

Table I.XXXV. Daily ration for dairy cows in different seasons, kg per d (weight, 500 kg; productivity, 5-6 Ld^{-1}).

Component of ration	Amount, kg day^{-1}
Stable period	
Hay	4
Straw	2
Silage	15
Beet roots	3
Concentrates	2
Pasture period	
Grass stand	50
Concentrates	2

Table I.XXXVI. Ration of pigs, kg d^{-1} (weight 80 - 120 kg).

Components of ration	Amount, kg d^{-1}
Winter period	
Concentrates	2
Beet roots	6
Ground hay	0.2
Summer period	
Concentrates	2.8
Grass (legumes)	5.5

Concentrates include meals (barley, oats, wheat, pea); bran (wheat, meat, meat + bone or fish meal) and mineral supplements.

Table I.XXXVIII. Yields in 1986 for the agricultural area AGRO1, Novozybkov District.

Crop	Yield, kg m^{-2}
Cereals	0.19
Vegetables	2.3
Potatoes	2.0
Root vegetables	2.8

Table I.XXXIX. Average milk production per cow in 1986.

Agricultural area	District	Milk production, L a^{-1}
AGRO 1	Novozybkov	2,600

Table I.XL. Distribution of agricultural lands in the test area by ^{137}Cs contamination.

Contamination level kBq m^{-2}	Contaminated area, km^2		
	plough land	hay pasture	total
37-185	3	5	8
185-370	72	16	88
370-555	96	49	145
555-1,100	161	90	251
1,100-1,480	37	19	56
1,480-2,960	25	26	51

Table I.XLIV. Distribution of adult rural inhabitants of the test area according to dwelling type and occupation group (for external dose evaluation).

Dwelling type	Occupation group, %		
	Indoor	Outdoor	Pensioners
One-storey wooden house	18	33	19
One-storey brick house	8	14	8

Table I.XLV. Seasonal values of occupancy factors for rural environment, relative units.

Indoor workers, November-March				
Type of location	Mean	5th quintile	95th quintile	Std. dev.
Living area (indoors)	0.59	0.49	0.70	0.066
Living area (outdoors)	0.11	0.00	0.28	0.080
Work area (indoors)	0.24	0.13	0.30	0.056
Work area (outdoors)	0.05	0.00	0.10	0.039
Ploughed field	0.00	-	-	-
Virgin land	0.00	-	-	-
Rest area	0.01	0.000	0.03	0.009
Indoor workers, April-October				
Living area (indoors)	0.42	0.27	0.58	0.100
Living area (outdoors)	0.28	0.10	0.50	0.120
Work area (indoors)	0.23	0.07	0.31	0.077
Work area (outdoors)	0.02	0.000	0.17	0.061
Ploughed field	0.02	0.000	0.16	0.069
Virgin land	0.01	0.000	0.02	0.018
Rest area	0.02	0.000	0.10	0.035
Outdoor workers, November-March				
Living area (indoors)	0.55	0.33	0.73	0.106
Living area (outdoors)	0.11	0.000	0.33	0.093
Work area (indoors)	0.12	0.000	0.36	0.142
Work area (outdoors)	0.10	0.000	0.33	0.123
Ploughed field	0.10	0.000	0.38	0.147

Virgin land	0.02	0.000	0.21	0.071
Rest area	0.00	-	-	-
Outdoor workers, April-October				
Living area (indoors)	0.42	0.31	0.61	0.097
Living area (outdoors)	0.19	0.04	0.33	0.099
Work area (indoors)	0.05	0.000	0.31	0.100
Work area (outdoors)	0.07	0.000	0.33	0.115
Ploughed field	0.21	0.000	0.50	0.187
Virgin land	0.04	0.000	0.28	0.086
Rest area	0.02	0.000	0.08	0.062
Pensioners, November-March				
Living area (indoors)	0.84	0.67	0.96	0.096
Living area (outdoors)	0.15	0.04	0.33	0.093
Work area (indoors)	0.00	-	-	-
Work area (outdoors)	0.00	-	-	-
Ploughed field	0.00	-	-	-
Virgin land	0.00	-	-	-
Rest area	0.01	0.000	0.013	0.013
Pensioners, April-October				
Living area (indoors)	0.56	0.34	0.85	0.144
Living area (indoors)	0.40	0.16	0.60	0.129
Work area (indoors)	0.00	-	-	-
Work area (outdoors)	0.00	-	-	-
Ploughed field	0.00	-	-	-
Virgin land	0.00	-	-	-
Rest area	0.04	0.000	0.14	0.055

Table I.XLVIII. Consumption rate of natural food products by the population surveyed in the villages of the test area, g d^{-1}.

Area, Time period	Gender	Number of respondents	Wild mushrooms	Forest berries
"Controlled", Nov. 1994	Male	59	18	3.4
	Female	74	9	4.0
"Controlled", Oct. 1994	Male	67	15	3.7
	Female	34	11	6.2
"Observed" Oct. 1995	Male	58	33	12
	Female	103	25	12

Note: Average fish consumption in 1994-1996 is 18 g d^{-1}.

The average uncertainty for consumption of natural food products is 40-60%.

Table I.XLIX. Mean daily consumption of major <u>locally produced</u> food products by inhabitants of the "Controlled Area" before and after the Chernobyl accident, kg d^{-1} or L d^{-1}(Mean±SE).

Year (Gender)	Local food product				
	Milk	Meat	Potato	Vegetables	Bread
1985 (M)	0.76±0.07	0.177±0.01	0.64±0.03	0.30±0.01	0.39±0.02
1985 (F)	0.56±0.03	0.170±0.08	0.56±0.02	0.27±0.01	0.29±0.01
10 May 1986 (M+F)	0.56± 0.06	0.086±0.01	0.60±0.05	0.28±0.01	0.34±0.02
20 May 1986 (M+F)	0.33±0.04	0.078±0.01	0.60±0.05	0.28±0.01	0.34±0.02
June 1986 (M+F)	0.29±0.03	0.078±0.01	0.60±0.05	0.28±0.01	0.34±0.02
July1986 (M+F)	0.28±0.03	0.078±0.01	0.60±0.05	0.28±0.01	0.34±0.02
August1986 (M+F)	0.27±0.03	0.078±0.01	0.60±0.05	0.28±0.01	0.34±0.02
September 1986	0.14±0.02	0.040±0.01	0.60±0.05	0.28±0.01	0.34±0.02
1987 (M+F)	0.00	0.010±0.004	0.50±0.04	0.28±0.01	0.34±0.02
1988 (M+F)	0.00	0.010±0.004	0.50±0.04	0.28±0.01	0.34±0.02
1990 (M)	0.00	0.010±0.004	0.50±0.04	0.25±0.04	0.36±0.03
1990 (F)	0.00	0.016±0.003	0.39±0.02	0.21±0.01	0.28±0.01
1993 (M)	0.13±0.06	0.148±0.020	0.84±0.02	0.29±0.02	0.40±0.02
1993 (F)	0.11±0.04	0.095±0.013	0.63±0.03	0.28±0.02	0.31±0.01
1994 (M)	0.24±0.05	0.164±0.012	0.81±0.05	0.21±0.01	0.41±0.02
1994 (F)	0.29±0.04	0.109±0.086	0.70±0.39	0.18±0.01	0.34±0.02

Table I.L. Mean daily consumption of major <u>locally produced</u> food products by inhabitants of the "Observed Area" ("Non Controlled Area") before and after the Chernobyl accident, kg d^{-1} or L d^{-1} (Mean ±SE).

Year (Gender)	Local food product				
	Milk	Meat	Potato	Vegetable	Bread
1985 (M)	0.76±0.07	0.177±0.01	0.64±0.03	0.30±0.01	0.39±0.02
1985 (F)	0.56±0.03	0.170±0.08	0.56±0.02	0.27±0.01	0.29±0.01
10 May 1986 (M+F)	0.49±0.05	0.116±0.01	0.60±0.05	0.28±0.01	0.34±0.02
20 May 1986 (M+F)	0.32±0.03	0.116±0.01	0.60±0.05	0.28±0.01	0.34±0.02
June 1986 (M+F)	0.31±0.03	0.116±0.01	0.60±0.05	0.28±0.01	0.34±0.02
July1986 (M+F)	0.30±0.03	0.116±0.01	0.60±0.05	0.28±0.01	0.34±0.02
August1986 (M+F)	0.29±0.03	0.116±0.01	0.60±0.05	0.28±0.01	0.34±0.02
September 1986	0.29±0.03	0.116±0.01	0.60±0.05	0.28±0.01	0.34±0.02
1987 (M+F)	0.28±0.03	0.097±0.01	0.60±0.05	0.28±0.01	0.34±0.02
1988 (M+F)	0.20±0.05	0.044±0.006	0.45±0.03	0.21±0.02	0.29±0.02
1990 (M)	0.20±0.05	0.044±0.006	0.45±0.03	0.21±0.02	0.29±0.02
1990 (F)	0.15±0.02	0.058±0.006	0.46±0.02	0.23±0.01	0.28±0.01
1993 (M)	0.35±0.06	0.150±0.018	0.84±0.05	0.26±0.02	0.37±0.03
1993 (F)	0.39±0.04	0.116±0.008	0.66±0.03	0.29±0.02	0.30±0.02
1995 (M)	0.57±0.09	0.160±0.026	0.77±0.08	0.29±0.02	0.53±0.05
1995 (F)	0.52±0.05	0.107±0.007	0.59±0.03	0.20±0.01	0.48±0.02

Table I.LI. Percent of adult rural inhabitants of the test region consuming local fish before and after the Chernobyl accident.

Time	Sex	Number	No (%)	Yes (%)
Before accident (common)	Male	196	54	46
	Female	390	60	40
1986-87 (Controlled Area)	Male	83	86	14
	Female	165	92	8
1986-87 (Observed Area)	Male	102	56	44
	Female	198	55	45
1990 (common)	Male	110	86	14
	Female	300	89	11
1993 (common)	Male	71	61	39
	Female	141	75	25
1994 (Controlled Area)	Male	76	59	41
	Female	112	78	22
1995 (settlement Voronok)	Male	40	58	42
	Female	86	62	38

Table I.LII. Percent of adult rural inhabitants of the test region consuming mushrooms before and after the Chernobyl accident.

Territories	Sex	Number	No (%)	Yes (%)
Before accident (common)	Male	195	30	70
	Female	391	29	71
1986-87 (Controlled Area)	Male	83	52	48
	Female	165	57	43
1986-87 (Observed Area)	Male	102	54	46
	Female	198	50	50
Settlement Korchi, 1994	Male	22	27	73
	Female	21	57	43
Settlement Shelomii, 1994	Male	38	32	68
	Female	53	38	62
Settlement Gordeevka, 1994	Male	67	30	70
	Female	34	20	80
Settlement Voronok, 1995	Male	58	16	84
	Female	103	19	81

Table I.LIII. Temporary permissible levels for radionuclide concentrations in foodstuffs and drinking water in the Chernobyl-affected areas, Bq kg^{-1}.

Foodstuffs	30.05.86	10.06.88	22.01.91	1993
	total beta-activity	^{137}Cs+^{134}Cs	^{137}Cs	^{137}Cs
Drinking water	370	18.5	18.5	-
Milk	370* (since 1.08.86)	370	370	370
Cheese	7,400	370	370	370
Butter	7,400	1,110	370	
Condensed milk	18,500	1,110	1,110	
Meat and fish products	3,700	1,850	740	600
Eggs	1,850 per one egg	1,850	740	
Bread, cereals	370	370	370	370
Sugar	1,850	370	370	
Vegetables, fruit, juices	3,700	740	590	
Mushrooms	18,500	1,850	1,480	600
Wild berries	3,700	1,850	1,480	600
Baby food	-	-	-	185

Note: * before August, 1986: 3,700 Bq L^{-1}.

Table I.LIV. Effectiveness of agrotechnical countermeasures.

Agrotechnical countermeasures	Soil category	Grass as a crop type	Reduction in root uptake transfer
Rotary cultivation or disking	Soddy-podzolic sandy, sandy loam	Natural meadow	1.2-1.5
	Peaty		1.3-1.8
Ploughing	Soddy-podzolic sandy, sandy loam	Natural meadow	1.8-2.5
	Peaty		2.0-3.2
Ploughing with turnover of the upper layer	Soddy-podzolic sandy, sandy loam	Natural meadow	8.0-12.0
	Peaty		10.0-16.0
Radical improvement	Soddy-podzolic sandy, sandy loam	Natural meadow	2.7-5.3
		Perennial grasses	2.3-4.6
	Peaty	Natural meadow	2.9-6.2
		Perennial grasses	3.9-11.2
Superficial improvement	Soddy-podzolic sandy, sandy loam	Natural meadow	1.6-2.9
		Perennial grasses	1.3-1.8
	Peaty	Natural meadow	1.8-3.1
		Perennial grasses	1.5-2.7

Table I.LV. Effectiveness of agrochemical countermeasures.

Agrochemical countermeasures	Soil category	Crop type	Reduction in root uptake transfer
Liming	Soddy-podzolic sandy, sandy loam	Barley, winter rye, oats, maize silage, potato, beet roots, vegetable	1.8-2.3
Application of increased doses of P-K fertilizers	Soddy-podzolic sandy, sandy loam	Barley, winter rye, oats, maize silage, potato, beet roots, vegetable	1.2-2.2
Application of organic fertilizers	Soddy-podzolic sandy, sandy loam	Barley, winter rye, oats, maize silage, potato, beet roots, vegetable	1.3-1.6
Application of clay minerals	Soddy-podzolic sandy, sandy loam	Barley, winter rye, oats, maize silage, potato, beet roots, vegetable	Dubious effect, in light soils results mainly in 1.5-3.0 fold decrease of radionuclide accumulation by plants
Combined application of lime, organic and mineral fertilizers	Soddy-podzolic sandy, sandy loam	Barley, winter rye, oats, maize silage, potato, beet roots, vegetable	2.5-3.5

Table I.LVI. Effectiveness of countermeasures in animal breeding (Application of sorbents).

Type of treatment	Product	Dosage	Reduction factor
Ferrocine	Milk	3-6 g per day	3-5
	Meat(cows)	3-6 g per day	2-3
	Meat (sheep)	0.5-1 g per day	3-4
Boli ferrocine	Milk	2-3 boli per 3	2-3
Bifege ferrocine	Milk	40 g per day	2-4

Table I.LVII. Effectiveness of food processing options.

Row product	Type of processing	Reduction (Bq kg^{-1} per Bq kg^{-1})
Milk	Milk to butter	2.5-15
	Milk to cheese	0.4-2
	Milk to cream	0.5-1.7
	Milk to skimmed milk	1.0-1.1
Meat	Soaking	1.4-2.0
	Salting	2.0-3.3

Tables I.LVIII. Effectiveness of various countermeasures in agriculture.

Groups of protective measures	Reduction factor	
	Range	Best estimates
Amelioration of meadows and pastures	2.5–8.0	3
Application of mineral fertilisers	1.2-2.5	1.5
Liming of acid soil	1.5-2.0	1.7
Technological processing of milk into butter	2.5–15	10
Application of Prussian blue	2–5	3
Crop selection according to ^{137}Cs accumulation	up to 4.5	3

Table I.LIX. Agrochemical measures in the test area (Novozybkov district, agricultural areas), 1986-1989.

Agrochemical Measures	1986	1987	1988	1989
Lime:				
area treated, km^2	271	206	108	105
application, kg m^{-2}	0.73	0.67	0.75	0.84
Phosphorite:				
area treated, km^2	92	100	51	52
application, kg m^{-2}	0.13	0.14	0.16	0.15
Mineral fertilizers active matter), 10^6 kg:				
N	8.1	8.3	7.0	8.1
P	5.1	5.7	4.9	6.7
K	8.3	12.3	10.0	12.2
Total NPK:				
area treated, km^2	460	600	450	600
application, kg m^{-2}	0.033	0.031	0.034	0.034
Organic fertilizers				
area treated, km^2	169	128	145	145
application, kg m^{-2}	7.0	8.5	7.9	7.9

Table I.LX. Radical amelioration of natural forage land in the test area (Novozybkov district, agricultural area AGRO1), 1986-1990.

Year	Cumulative percentage of re-cultivated haylands and pastures
1986	6.4
1987	14.0
1988	35.7
1989	64.6
1990	95.4

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国際単位系（SI）と換算表

表1　SI基本単位および補助単位

量	名称	記号
長さ	メートル	m
質量	キログラム	kg
時間	秒	s
電流	アンペア	A
熱力学温度	ケルビン	K
物質量	モル	mol
光度	カンデラ	cd
平面角	ラジアン	rad
立体角	ステラジアン	sr

表3　固有の名称をもつSI組立単位

量	名称	記号	他のSI単位による表現
周波数	ヘルツ	Hz	s^{-1}
力	ニュートン	N	$m \cdot kg/s^2$
圧力，応力	パスカル	Pa	N/m^2
エネルギー,仕事,熱量	ジュール	J	N·m
工率，放射束	ワット	W	J/s
電気量，電荷	クーロン	C	A·s
電位，電圧，起電力	ボルト	V	W/A
静電容量	ファラド	F	C/V
電気抵抗	オーム	Ω	V/A
コンダクタンス	ジーメンス	S	A/V
磁束	ウェーバ	Wb	V·s
磁束密度	テスラ	T	Wb/m^2
インダクタンス	ヘンリー	H	Wb/A
セルシウス温度	セルシウス度	℃	
光束	ルーメン	lm	cd·sr
照度	ルクス	lx	lm/m^2
放射能	ベクレル	Bq	s^{-1}
吸収線量	グレイ	Gy	J/kg
線量当量	シーベルト	Sv	J/kg

表2　SIと併用される単位

名称	記号
分，時，日	min，h，d
度，分，秒	°，′，″
リットル	l，L
トン	t
電子ボルト	eV
原子質量単位	u

1 eV=1.60218×10^{-19}J

1 u=1.66054×10^{-27}kg

表4　SIと共に暫定的に維持される単位

名称	記号
オングストローム	Å
バーン	b
バール	bar
ガル	Gal
キュリー	Ci
レントゲン	R
ラド	rad
レム	rem

1 Å=0.1nm=10^{-10}m

1 b=100fm^2=$10^{-28}m^2$

1 bar=0.1MPa=10^5Pa

1 Gal=1cm/s^2=$10^{-2}m/s^2$

1 Ci=3.7×10^{10}Bq

1 R=2.58×10^{-4}C/kg

1 rad=1cGy=10^{-2}Gy

1 rem=1cSv=10^{-2}Sv

表5　SI接頭語

倍数	接頭語	記号
10^{18}	エクサ	E
10^{15}	ペタ	P
10^{12}	テラ	T
10^9	ギガ	G
10^6	メガ	M
10^3	キロ	k
10^2	ヘクト	h
10^1	デカ	da
10^{-1}	デシ	d
10^{-2}	センチ	c
10^{-3}	ミリ	m
10^{-6}	マイクロ	μ
10^{-9}	ナノ	n
10^{-12}	ピコ	p
10^{-15}	フェムト	f
10^{-18}	アト	a

（注）

1．表1－5は「国際単位系」第5版，国際度量衡局1985年刊行による。ただし，1 eVおよび1 uの値はCODATAの1986年推奨値によった。

2．表4には海里，ノット，アール，ヘクタールも含まれているが日常の単位なのでここでは省略した。

3．barは，JISでは流体の圧力を表わす場合に限り表2のカテゴリーに分類されている。

4．EC閣僚理事会指令ではbar，barnおよび「血圧の単位」mmHgを表2のカテゴリーに入れている。

換算表

力	N(=10^5dyn)	kgf	lbf
	1	0.101972	0.224809
	9.80665	1	2.20462
	4.44822	0.453592	1

粘度　1 Pa·s($N \cdot s/m^2$)=10 P（ポアズ）(g/(cm·s))

動粘度　1m^2/s=10^4St（ストークス）(cm^2/s)

圧力	MPa(=10bar)	kgf/cm^2	atm	mmHg(Torr)	lbf/in^2(psi)
	1	10.1972	9.86923	7.50062×10^3	145.038
	0.0980665	1	0.967841	735.559	14.2233
	0.101325	1.03323	1	760	14.6959
	1.33322×10^{-4}	1.35951×10^{-3}	1.31579×10^{-3}	1	1.93368×10^{-2}
	6.89476×10^{-3}	7.03070×10^{-2}	6.80460×10^{-2}	51.7149	1

エネルギー・仕事・熱量	J(=10^7 erg)	kgf·m	kW·h	cal(計量法)	Btu	ft·lbf	eV
	1	0.101972	2.77778×10^{-7}	0.238889	9.47813×10^{-4}	0.737562	6.24150×10^{18}
	9.80665	1	2.72407×10^{-6}	2.34270	9.29487×10^{-3}	7.23301	6.12082×10^{19}
	3.6×10^6	3.67098×10^5	1	8.59999×10^5	3412.13	2.65522×10^6	2.24694×10^{25}
	4.18605	0.426858	1.16279×10^{-6}	1	3.96759×10^{-3}	3.08747	2.61272×10^{19}
	1055.06	107.586	2.93072×10^{-4}	252.042	1	778.172	6.58515×10^{21}
	1.35582	0.138255	3.76616×10^{-7}	0.323890	1.28506×10^{-3}	1	8.46233×10^{18}
	1.60218×10^{-19}	1.63377×10^{-20}	4.45050×10^{-26}	3.82743×10^{-20}	1.51857×10^{-22}	1.18171×10^{-19}	1

1 cal= 4.18605J（計量法）
= 4.184J（熱化学）
= 4.1855J（15℃）
= 4.1868J（国際蒸気表）

仕事率　1 PS（仏馬力）
= 75 kgf·m/s
= 735.499W

放射能	Bq	Ci
	1	2.70270×10^{-11}
	3.7×10^{10}	1

吸収線量	Gy	rad
	1	100
	0.01	1

照射線量	C/kg	R
	1	3876
	2.58×10^{-4}	1

線量当量	Sv	rem
	1	100
	0.01	1

（86年12月26日現在）

OSCAAR Calculations for the Iput Dose Reconstruction Scenario of BIOMASS Theme 2