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**GARDEC: A COMPUTER CODE FOR ESTIMATING
DOSE-RATE REDUCTION
BY GARDEN DECONTAMINATION**

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GARDEC: A Computer Code for Estimating
Dose-rate Reduction by Garden Decontamination

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Based on studies after the Chernobyl accident, it was found that the greatest contribution to the long-term external dose in the urban environment came from isotopes of radiocaesium deposited onto open areas such as gardens and parks. Cost-benefit analysis on the clean-up of nuclear contaminated urban areas also showed that decontamination of gardens would be the most cost-effective procedure and should be given the highest priority. A computer code, GARDEC, has been developed for estimating the reduction of dose rates by garden decontamination. This code takes account of three methods of decontamination : (i) digging a garden in a special way, (ii) a removal of the upper layer of soil, and (iii) covering with a shielding layer of soil. Sample calculations were carried out to test the performance of the code. There were differences between model predictions and observations for the dose-rate reduction. They might result from the differences of various conditions between calculations and measurements. In spite of the differences, it was confirmed also in the calculations that the garden decontamination had a large effect to reduce the dose rate.

Keywords: Chernobyl Accident, Long-term External Dose, Radiocaesium, Urban Environment, Nuclear Clean-up, Garden Decontamination, Dose-rate Reduction

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庭の除染による線量率低減を推定する計算コード GARDEC

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チェルノブイル事故後の研究によると、都市環境における長期の外部被曝線量に対して、庭や公園という open area に沈着した放射性セシウム同位体が最も大きく寄与していることが明らかになった。放射能で汚染された都市地域の除染に関する費用－便益解析でも、庭の除染は費用を考慮して最も有効な手段であり、最優先で実施すべきであることが示された。計算コード GARDEC は、庭の除染による線量率低減を推定するために開発された。このコードは、3通りの除染手段を考慮している。それらは、(i) 特別な方法による庭の掘削、(ii) 汚染土壌の上部層の除去、(iii) 非汚染土壌による遮蔽、である。計算コードの性能を評価するために、試計算を実施した。線量率低減に関して、モデル予測と実測値には相違が見られた。これらは、計算と測定における様々な条件の相違に起因していると考えられる。このような相違にもかかわらず、庭の除染は線量率を低減するために大きな効果を持つことが計算でも確認された。

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1. Introduction

1.1 Background and objectives

In the event of a severe accident at a nuclear power plant, airborne radioactive materials could reach and contaminate an urban area. Urban contamination would be important in the point of view of a nuclear contingency because the great majority of the population live in the urban and suburban areas. Based on studies after the Chernobyl accident, it was found that the greatest contribution to the long-term external dose in the urban environment came from isotopes of radiocaesium deposited onto open areas such as gardens and parks¹⁾. The calculated results using the URGENT code²⁾, which was developed at Risø National Laboratory in Denmark, also showed that grassed gardens were the main contributors to the long-term external dose from both dry and wet deposition to urban areas^{3),4)}.

After an accident at a nuclear power plant, various kinds of reclamation and decontamination procedures might be taken to reduce the dose rate exposed to the population in urban areas. At Risø National Laboratory, the effect of different decontamination procedures has been experimentally investigated on the contamination in an urban area after the Chernobyl accident⁵⁾⁻⁹⁾. Among the procedures, it was found that decontamination of a garden area had a large effect on reducing the dose rate. Cost-benefit analysis on the clean-up of nuclear contaminated urban areas, calculated with the URGENT code, also revealed that the garden decontamination would be the most cost-effective procedure and should be given the highest priority¹⁰⁾.

The effect of garden decontamination can be investigated not only by experiments in the fields but also by analyses using mathematical models. Such models enable us to make the calculations under various assumed conditions. The effect and practicability of the calculated procedures can be validated by field experiments. Taking these situations into account, a computer code, GARDEC, has been developed for estimating the reduction of dose rates by garden decontamination. This report describes calculation models used in the code, input data to be prepared and sample calculations of the code.

1.2 Decontamination of a garden

At Risø National Laboratory, some methods to reduce the dose rate from a contaminated garden were investigated through *in-situ* experiments. The procedures tested were: 'digging', 'removal' and 'covering' of a garden⁶⁾. These three methods have been modeled in the GARDEC code.

The first method is to dig a garden in a special, but uncomplicated way. The procedure is approximately the same as that performed by a trench plough¹¹⁾, but can be carried out very easily in an urban area, using only a shovel. The principle is schematically illustrated in **Figure 1**. First a two-spit deep trench 1 with two levels is dug. Then the layer 2 is cut loose and placed in the bottom of trench 1, with the turf facing downward. Finally the uncontaminated or less contaminated layer 3 is placed on the top of layer 2, and this procedure is repeated. In the experiment, the procedure was carried out on a 3m×3m area, and the collimated gamma detector was used to assess the decrease in gamma-ray radiation.

The other methods were carried out to compare their effects with that of the first one. The second is a removal of the upper layer of contaminated soil from the garden. The effect of soil layers of 5 cm and 10 cm thick was tested in the experiment. The third is to cover a contaminated garden with a shielding layer of uncontaminated soil. Actually a sand layer of 2.5 cm thick was placed on a contaminated garden.

2. Calculation Models

2.1 Dose-rate reduction by garden decontamination

The dose rate due to external irradiation from radionuclides in garden soil can be estimated using a dose-rate conversion factor for each soil layer. The factor is defined as the external dose rate in air at a given height above the ground from unit concentration of a specified radionuclide in each soil layer. In order to make the dose calculation easy, the garden soil to be assessed is divided into a layer of 1 cm thick, and the influence of grass on the garden is not taken into account in the current version of the code.

Before garden decontamination, the dose rate from a radionuclide in the garden soil can be calculated by:

$$DR_b = \sum_{L=1}^N C_L \cdot DCF_L \quad (1)$$

where DR_b is the dose rate before garden decontamination (Gy/hour), L represents L -th layer of soil from the surface, N is the depth of soil, the contribution of which to the dose rate in air is considered (cm), C_L is the radionuclide concentration in the L -th layer of soil (Bq/m³), and DCF_L is the dose-rate conversion factor for the L -th layer of soil (Gy/hour per Bq/m³).

The calculations of the dose rate after garden decontamination are different according to the methods of decontamination. In case of digging a garden in a special way:

$$DR_a = \sum_{L=1}^{n_{dl}} C_L \cdot DCF_{n_{d2}+1-L} + \sum_{L=1}^{n_{d2}-n_{dl}} C_{n_{dl}+L} \cdot DCF_L + \sum_{L=1}^{N-n_{d2}} C_{n_{d2}+L} \cdot DCF_{n_{d2}+L} \quad (2)$$

In case of a removal of the upper layer of soil:

$$DR_a = \sum_{L=1}^{N-n_r} C_{n_r+L} \cdot DCF_L \quad (3)$$

In case of covering with a shielding layer of soil:

$$DR_a = \sum_{L=1}^N C_L \cdot DCF_{n_c+L} \quad (4)$$

where DR_a is the dose rate after garden decontamination (Gy/hour), n_{d1} and n_{d2} are the depths of shallow and deep trench ploughs, respectively (cm), n_r is the thickness of the upper layer of contaminated soil which is removed from the garden (cm), and n_c is the thickness of a shielding layer of uncontaminated soil with which the contaminated garden is covered (cm).

Finally the following equation gives the reduction of dose rates, RDR (%), by garden decontamination:

$$RDR = \frac{DR_a}{DR_b} \cdot 100 \quad (5)$$

2.2 Dose-rate conversion factors for soil layers

Dose-rate conversion factors for soil layers are calculated using a computer code, DFSOIL¹²⁾, which was originally developed at Oak Ridge National Laboratory (ORNL) in USA and modified in the present work¹³⁾. DFSOIL computes dose-rate conversion factors to determine the external dose rate in air at 1 m above the ground from photon sources per unit concentration of a specific radionuclide in each soil layer. The dose-rate calculations for soil layers represent an extension of those for photon sources which are confined to the ground surface, namely, the source concentration at a given depth in soil is assumed to be uniform over an infinite plane surface parallel to the ground.

An equation for the dose-rate conversion factor for monoenergetic photon sources which are confined to the ground surface can be expressed by:

$$DCF_{\gamma}^a(z, E_{\gamma}) = \frac{1}{2} K E_{\gamma} (\mu_{en}/\rho)_a \cdot \left[F_1(\mu_a z) - \frac{C_a}{(D_a - 1)} \exp[(D_a - 1)\mu_a z] \right] \quad (6)$$

where DCF_{γ}^a is the photon dose-rate conversion factor (Gy/sec per Bq/m²), z is the height of the receptor location above the ground (cm), E_{γ} is the photon energy (MeV), K is a constant equal to 1.6×10^{-14} (g·Gy·m²/MeV/cm²), $(\mu_{en}/\rho)_a$ is the mass energy absorption coefficient in air (cm²/g), μ_a is the linear attenuation coefficient in air (cm⁻¹), C_a and D_a are the coefficients in the Berger form, B_{en}^a , of the energy absorption buildup factor in air given by:

$$B_{en}^a = 1 + C_a \mu_a r \cdot \exp(D_a \mu_a r) \quad (7)$$

where r is the distance from any point in the source region to the receptor position (cm), and F_1 is the first-order exponential integral:

$$F_1(\mu_a z) = \int_z^{\infty} \frac{1}{r} \exp(-\mu_a r) dr \quad (8)$$

For an exposed individual standing on the ground, the dose-rate conversion factor is usually calculated for the single height $z = 1$ m above the ground.

The dose-rate conversion factors for monoenergetic sources are applied to radionuclides, assuming that the spectrum of photons from radioactive decay consists of γ and X rays of discrete energy. Therefore, the dose-rate conversion factor for ground surface exposure to a particular radionuclide, DCF_{γ}^p , is given by:

$$DCF_{\gamma}^p(z) = \sum_i f_{i\gamma} DCF_{\gamma}^a(z, E_{i\gamma}) \quad (9)$$

where $f_{i\gamma}$ is the intensity of the i -th photon of energy, $E_{i\gamma}$, per decay and the summation includes all photons in the decay spectrum.

The dose-rate conversion factor for monoenergetic sources in soil can be obtained by analogy with Equation (6) by calculating photon attenuation and buildup in soil rather than in air. The dose-rate conversion factor immediately above the soil layer as a function of depth x of the monoenergetic plane source in soil is given by:

$$DCF_{\gamma}^a(x, E_{\gamma}) = \frac{1}{2} K E_{\gamma} (\mu_{en}/\rho)_a \cdot \left[F_1(\mu_s x) - \frac{C_s}{(D_s - 1)} \exp[(D_s - 1)\mu_s x] \right] \quad (10)$$

It is noted that even though the medium between the source and receptor positions is assumed to be in soil rather than in air, the dose-rate conversion factor at a receptor location in air is still calculated. Thus the dose-rate conversion factor itself and the mass energy absorption coefficient on the right-hand side of Equation (10) are values in air and not in soil.

In practice, Equation (10) is to be evaluated at 1 m above the ground, and not immediately above the ground. The effect of the layer of air between the soil surface and the receptor can be approximated by a layer of soil which would provide the same shielding as the layer of air. This equivalent depth of soil, x_a , may be calculated by setting Equation (10) equal to Equation (6) and solving the resulting transcendental equation for x_a . For $z = 1$ m, the resulting value of x_a is less than 1 mm for all photon energies. The dose-rate conversion factor for a receptor 1 m above the soil surface may be then calculated for a plane monoenergetic source at a depth x by evaluating Equation (10) at $x+x_a$ rather than at x .

Radionuclides in soil will be usually distributed throughout a volume rather than confined to a plane surface. The dose rate in air above the ground from a volume source can be obtained by an integration of the plane-source dose-rate conversion factor and the radionuclide concentration over the source volume. Thus the dose rate in air, H_{γ}^a , for energy E_{γ} is given by:

$$H_{\gamma}^a(E_{\gamma}) = \int_{x_1}^{x_2} C(x) DCF_{\gamma}^a(x+x_a, E_{\gamma}) dx \quad (11)$$

where $C(x)$ is the source concentration at depth x (Bq/m^3), x_1 and x_2 are the upper and lower boundaries of the source region, respectively (m), and x_a is the thickness of soil corresponding to 1 m of air (m).

For most distributions of sources with depth in soil, Equation (11) must be solved numerically. The dose-rate conversion factor for a layer source is obtained by integrating Equation (10) over the vertical extent of the layer. Using the relation for derivatives of the exponential integral:

$$\frac{dF_n(\omega)}{d\omega} = -F_{n-1}(\omega) \quad (12)$$

The result is:

$$\begin{aligned} DCF_{\gamma}^a(x'_1, x'_2, E_{\gamma}) = & \frac{1}{2} K E_{\gamma} (\mu_{en}/\rho)_a \frac{1}{\mu_s} \left[F_2(\mu_s x'_1) - F_2(\mu_s x'_2) \right. \\ & \left. + \frac{C_s}{(D_s - 1)^2} \left[\exp[(D_s - 1)\mu_s x'_1] - \exp[(D_s - 1)\mu_s x'_2] \right] \right] \end{aligned} \quad (13)$$

where the second-order exponential integral is given by:

$$F_2(\omega) = \exp(-\omega) - \omega F_1(\omega) \quad (14)$$

The variables x'_1 and x'_2 are equal to $x_1 + x_a$ and $x_2 + x_a$, respectively. The radionuclide-specific dose-rate conversion factors for layer sources are computed by summing these monoenergetic conversion factors analogously to Equation (9) as:

$$DCF_{\gamma}^p(x'_1, x'_2) = \sum_i f_{i\gamma} DCF_{\gamma}^a(x'_1, x'_2, E_{i\gamma}) \quad (15)$$

For electrons produced by radioactive decay, the electron range in soil is usually less than 2 cm never exceeds 4 cm. Therefore, a nominal penetration of radionuclides into soil with time will provide more effective shielding against electrons than photons. The external dose rates from electron emitters in soil are not considered here, but are transferred to other future research.

3. Code Descriptions

3.1 Input data

Input data to be prepared for the GARDEC code are: definition of input and output data files, conditions of calculations, concentrations of radionuclides in each soil layer, and dose-rate

conversion factors for each soil layer. These input data are read from different data files which have different logical units. **Appendix 1** gives formats of input data.

The user of the GARDEC code has to define logical units and names of four files which are used in the code. These are: (i) input file for calculation conditions, (ii) input file for radionuclide concentrations, (iii) input file for dose-rate conversion factors, and (iv) output file of the GARDEC code. The output file must be installed before the implementation of the code.

The file for calculation conditions includes: (i) option for the methods of garden decontamination, the effect of which is estimated, (ii) depth of soil to which the procedure is taken, (iii) option for preparing radionuclide concentrations in soil layers, and (iv) names of radionuclides to be assessed and their decay chain.

The radionuclide concentrations in each soil layer are prepared by one of three methods as follows: a) to be read from an output file of the MLSOIL code, b) to be read from a file of measurements, and c) to be calculated with exponential functions.

In case of the first option, the radionuclide concentrations at a specified time point after deposition are calculated in advance using the MLSOIL code¹²⁾, which was originally developed at ORNL and also modified in the present work¹³⁾. MLSOIL prepares the concentrations in the unit of Bq/m³ for each soil layer.

The model of radionuclide transport through soil, implemented in MLSOIL, is a five-compartment linear transfer model. The model presents the downward migration into an undisturbed agricultural land. The movement of radionuclides through the soil column is represented by a series of transfers between compartments of various sizes. Within each compartment, radionuclides are assumed to be uniformly mixed. It is noted that there is no upward transfer. The rates of transfer between the various compartments are determined by transfer coefficients k_{ij} . The rate at which the migration takes place is dependent upon several factors, including the compartment thickness, the chemical forms of radionuclides, soil composition and rainfall.

The change rate of the radionuclide concentration in layer 1 is given by:

$$\frac{dC_i(t)}{dt} = Q_i(t) - \lambda_i C_i(t) - k_{i,1} C_i(t) + \sum_m b_{mi} \lambda_i C_m(t) \quad (16)$$

where $C_i(t)$ is the concentration of radionuclide i in layer 1 (Bq/m³), $Q_i(t)$ is the rate at which radionuclide i enters layer 1 (Bq/m³/sec), λ_i is a radiological decay constant for radionuclide i (sec⁻¹), $k_{i,1}$ is the transfer coefficient for radionuclide i from layer 1 to layer 2 (sec⁻¹), and b_{mi} is the branching ratio from radionuclide m to radionuclide i . Analogous equations can be written for the remaining layers of the model. The concentrations of all radionuclides in all layers at time t are obtained by solving the set of simultaneous equations represented by Equation (16).

A model of migration removal rate constant is adopted to calculate the transfer coefficients in MLSOIL. This transfer coefficient is element-specific and is given by:

$$k_{i,j} = \frac{P - E}{\theta d_j \left(1 + \frac{\rho}{\theta} k_d^i \right)} \quad (17)$$

where $k_{i,j}$ is the transfer coefficient for radionuclide i from soil layers j to $j+1$ (sec^{-1}), P is annual average precipitation (cm/year), E is annual average evapotranspiration (cm/year), θ is the volumetric water content of soil (ml/cm^3), d_j is the thickness of soil layer j (cm), ρ is the bulk density of soil (g/cm^3), and k_d^i is the distribution coefficient of radionuclide i (ml/g).

The second option for preparing the radionuclide concentrations in soil layers uses measurements of the vertical distribution of radionuclides in soil. In the third option, the radionuclide concentrations as a function of depth from the surface are represented by exponential functions. The functions to be used here, based on measurements of soil profiles, are:

$$C(x) = AA \cdot \exp(-BB \cdot x) + CC \cdot \exp(-DD \cdot x) \quad (18)$$

or

$$C(x) = AA \cdot \exp(-BB \cdot x) \quad (x \leq X_c) \quad C(x) = CC \cdot \exp(-DD \cdot x) \quad (x > X_c) \quad (19)$$

where $C(x)$ is the concentration of a radionuclide in soil at x cm depth from the surface, AA and CC are initial values of fast and slow attenuation terms, BB and DD are attenuation constants of fast and slow attenuation terms (m^{-1}), and X_c is the abscissa of a crossing point of the two exponential functions described above. In the second and third options, one of Bq/m^3 , Bq/cm^3 , Bq/kg and Bq/g is allowed as the unit of the radionuclide concentration. These units are converted to Bq/m^3 in the code, assuming that density of soil is 1.4 g/cm^3 .

The dose-rate conversion factors for each soil layer are calculated in advance by the DFSOIL code and stored in a data file. The current version of DFSOIL¹³⁾, which was modified in the present work, can deal with 54 radionuclides and their daughters which are considered to be important for a radiological consequence assessment at a nuclear power plant accident. For the GARDEC code, the dose-rate conversion factors which have the unit of $\text{Gy/year per Bq/m}^3$ are provided for each soil layer of 1 cm thick from the ground surface to 1 m depth.

The current version of MLSOIL¹³⁾ also can deal with the same radionuclides as DFSOIL. In MLSOIL, default values are prepared for all input parameters. If available, however, the user of the code can provide the site-specific data for the distribution coefficient of an element, annual average precipitation and evapotranspiration, bulk density and volumetric water content of soil.

Appendix 2 shows sample input data for the GARDEC code. The sample treats with ^{137}Cs - $^{137\text{m}}\text{Ba}$ which is the greatest contributor to the long-term external dose following an accident at a nuclear power plant. This sample is for the calculation that the effect of digging a garden is estimated, and that the radionuclide concentrations in soil layers are calculated from exponential

functions given by Equation (19). Only parts of the data for the dose-rate conversion factors (^{137}Cs - ^{137m}Ba) are shown because of its large volume.

3.2 Outputs

Appendix 3 shows a sample output of the GARDEC code, which is written on the logical unit 1. This sample output was calculated using the sample input data given in **Appendix 2**. In the sample output, the radionuclide concentrations in soil layers were calculated from exponential functions given by Equation (19), and the effect of digging a garden was estimated. Generally the output file contains:

(i) input data

- a) radionuclides to be assessed (including daughter radionuclides), their half lives and branching ratios from parent radionuclides
- b) method for preparing radionuclide concentrations in soil layers. In case that the concentrations are calculated with exponential functions, the form and constants of the functions are also given here.
- c) radionuclide concentrations for each soil layer (Bq/m^3)
- d) dose-rate conversion factors for each soil layer ($\text{Gy/year per Bq/m}^3$)

(ii) calculated results

- a) method of garden decontamination, the effect of which is estimated
- b) depth of soil to which the procedure is taken (m)
- c) dose rates before and after the decontamination (Gy/hour)
- d) reduction of the dose rates by the decontamination (%)

The dose rates and their reduction are calculated not only for each radionuclide but also for the sum total of all radionuclides.

4. Sample Calculations

Sample calculations were carried out to test the performance of the GARDEC code. The predictions were done for ^{137}Cs - ^{137m}Ba , ^{134}Cs and ^{106}Ru - ^{106}Rh , the concentrations of which in soil were available at the present work. In the calculations, the radionuclide concentrations in each soil layer were calculated with two exponential functions given by Equation (19). The least square method gave the functions by fitting them with the vertical distribution of the radionuclides in soil. The radionuclide concentrations were measured at the Chernobyl site by Risø National Laboratory¹⁴⁾. **Table 1** shows the constants of the exponential functions used here. The data for daughter radionuclides, ^{137m}Ba and ^{106}Rh , are not given here but calculated in the code, assuming that the radioactive equilibrium is attained.

Table 2 shows the calculated results for the reduction of dose rates by three kinds of garden decontamination, together with experimental data. The experiments were also conducted at the Chernobyl site by Risø National Laboratory⁶⁾⁻⁸⁾. The effects of three methods calculated here are larger than those obtained by experiments. The differences between model predictions and observations might result from several reasons as follows:

- (i) Dose-rate conversion factors used here are calculated under the assumption that the radionuclide concentration in soil is uniformly distributed over each of an infinite layer parallel to the ground. The use of these dose-rate conversion factors means that the dose-rate reduction by garden decontamination are estimated for an infinite area. The experiments, on the other hand, were carried out for a limited area (for example, a $3\text{m} \times 3\text{m}$ area for digging), and the collimated gamma detector was used to assess the decrease in gamma-ray radiation.
- (ii) The vertical distribution of radionuclides in soil which is used for the calculations was measured in 1990. The measurements were performed for soil layers of about 10 cm depth, and the radionuclide concentrations below 10 cm up to 1 m are estimated by extrapolating the measured data. On the other hand, the experiments on the garden decontamination were carried out in 1993 at different points from those where the concentrations were measured (but the same area).
- (iii) The calculations are performed under realized conditions, namely, the radionuclide concentration is uniformly distributed in each soil layer and the characteristics of soil is also uniform over the depth to be assessed. The concentration and the characteristics, however, might be not uniform actually. Moreover it seems to be difficult to carry out digging, a removal and covering of the garden soil in a realistic manner like the calculations.
- (iv) Some situations for calculations are different from those for experiments. In case of covering with a shielding layer of soil, the covering soil is assumed to be the same type as garden soil in the calculation. In the experiment, however, the garden soil was covered with sand. The influence of grass on the garden is not taken into account in the calculations, either.

Although there are differences between model predictions and observations, it has been confirmed also in the calculations that garden decontamination has a large effect to reduce the dose rate from radionuclides retained in the garden soil. The calculation also shows that ^{137}Cs - $^{137\text{m}}\text{Ba}$ is the most important contributor to the total dose rate, whereas the contributions of ^{134}Cs and ^{106}Ru - ^{106}Rh are approximately 30 % and 1% of that of ^{137}Cs , respectively.

5. Concluding Remarks

A computer code, GARDEC, was developed for estimating the reduction of dose rates by garden decontamination. The code takes account of three methods of decontamination: (i) digging a garden in a special way, (ii) a removal of the upper layer of soil, and (iii) covering with a shielding layer of soil.

Sample calculations were carried out to test the performance of the code. There were differences between model predictions and observations for the dose-rate reduction. They might result from the differences of various conditions between calculations and measurements. Among them, the main contributors would be the garden area where the decontamination is taken and the distribution of radionuclides in soil. In spite of the differences, it was confirmed also in the calculations that garden decontamination had a large effect to reduce the dose rate from radionuclides in the garden soil.

Both of digging a garden in a special way and a removal of the upper layer of soil are more effective methods to reduce the dose rates. Taking into account the practicability of the methods, however, the removing procedure generates rather amounts of radioactive wastes (contaminated soil) which must be disposed of. The digging method, on the other hand, can reduce the dose rates as sharply as the removing method with producing no or little radioactive waste.

To improve the accuracy of model predictions, comparisons between calculations and measurements should be carried out under the condition that the vertical distribution of radionuclides and the dose-rate reduction by garden decontamination are measured at the same point and time. Concerning the models used in the code, further research is needed on: (i) preparation of dose-rate conversion factors for a finite area, (ii) prediction of the radionuclide distribution in soil from limited measurements, and (iii) estimate of the influence of grass on the garden to the dose rates.

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Table 1 Constants of two exponential functions
which represent the radionuclide concentrations in soil

Radionuclides	Fast attenuation term ($x \leq X_c$)		Slow attenuation term ($x > X_c$)		X_c (cm)
	AA (Bq/g)	BB (cm^{-1})	CC (Bq/g)	DD (cm^{-1})	
Cs-137	215	1.67	6.69	0.419	2.77
Cs-134	24.1	1.61	1.01	0.456	2.75
Ru-106	1.94	0.752	0.678	0.454	3.53

Table 2 Calculations of dose-rate reduction by garden decontamination
and comparison with experimental data at the Chernobyl site

Methods of decontamination	Calculations		Experiments	
	Reduction of Dose rate (%)	Conditions	Reduction of dose rate (%)	Conditions
Digging	0.11	$d_{n1} = 30 \text{ cm}$ $d_{n2} = 60 \text{ cm}$	25.6	$d_{n1} \approx 30 \text{ cm}$ $d_{n2} \approx 60 \text{ cm}$
Removal	1.11	$d_r = 5 \text{ cm}$	21.7	$d_r = 5 \text{ cm}$
	0.13	$d_r = 10 \text{ cm}$	15.1	$d_r = 10 \text{ cm}$
Covering	56.9	$d_c = 2 \text{ cm}$	81.5	$d_c = 2.5 \text{ cm}$
	47.6	$d_c = 3 \text{ cm}$		

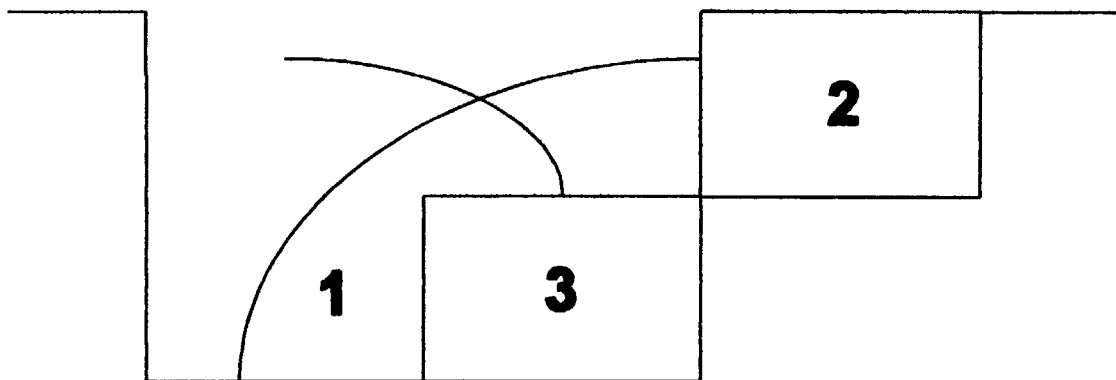


Figure 1 Sketch showing the plinciple of the special method
which was followed for digging a grassed garden

Appendix 1 Formats of Input Data

Logical unit 1

Definition of input and output data files

The card #1 is repeated 4 times.

#1 IFNUM,FILEN (I2,3X,A40)

IFNUM : logical unit of an input or output data file

=5 : input file for conditions of calculations

=10 : input file for concentrations of radionuclides in each soil layer

=11 : input file for dose-rate conversion factors for each soil layer

=1 : output file of the GARDEC code

FILEN : name of the file

Logical unit 5

Conditions of calculations

#1 DECON (A6)

#2 DN1,DN2 (2F10.3)

#3 SCONC (A6)

#4 NUC (I5)

The cards from #5 to #7 are repeated NUC times.

#5 ICHN (I5)

The card #6 is repeated ICHN times.

#6 NAME,HLF,NNIT,NBRA,(IBRA(K),K=1,5),(BRAT(K),K=1,5)
(A6,E10.3,A1,I2,5I2,5F5.2)

#7 IDAUT (4X,I4)

DECON : option for methods of garden decontamination

= 'DIG' : digging a garden in a special way

= 'REMOVE' : removal of the upper layer of soil

= 'COVER' : covering with a shielding layer of soil

DN1 : depth of a shallow trench plough (m) when DECON='DIG'

thickness of the removed soil layer (m) when DECON='REMOVE'

thickness of the covering soil layer (m) when DECON='COVER'

DN2 : depth of a deep trench plough (m), used when DECON='DIG'

SCONC : option for preparing radionuclide concentrations in soil layers

= 'MLSOIL' : to be read from an output file of the MLSOIL code

= 'MEASUR' : to be read from a file of measurements

= 'EXPNTL' : to be calculated with exponential functions

NUC : number of radionuclides to be assessed

ICHN : number of radionuclides included in this decay chain

NAME : name of the radionuclide

HLF : half life of the radionuclide

NNIT : unit of the half life

= 'Y' : year

= 'D' : day

='H' : hour
 ='M' : minute
 ='S' : second
 NBRA : number of radionuclides in the decay chain which have this radionuclide as an immediate daughter ($NBRA \leq 5$)
 IBRA : index of radionuclides in the decay chain which have this radionuclide as an immediate daughter
 BRAT : branching ratio from the parent radionuclides to this radionuclide
 IDAUT : option for preparing concentrations of daughter radionuclides in soil layers
 =0 : the data for daughter radionuclides are prepared by the user.
 =1 : the data for daughter radionuclides are calculated in the code, assuming that the radioactive equilibrium is attained.

Logical unit 10

Concentrations of radionuclides in each soil layer

If SCONC='MLSOIL',

#1 TA,TB (8X,E10.3,1X,E10.3)
 #2 (SLAY(L),L=1,5) (19X,4(F10.2,12X),F10.2)

The card #3 is repeated as many as the number of radionuclides.

#3 NAME,(CONC(L),L=1,5) (A7,12X,4(E10.3,12X),E10.3)

If SCONC='MEASUR',

#1 UNIT,NLAY (A10,I5)
 #2 (SLAY(L),L=1,NLAY) (10X,7F10.2)

The card #3 is repeated as many as the number of radionuclides.

#3 NAME,(CONC(L),L=1,NLAY) (A6,4X,7E10.3/10X,7E10.3)

If SCONC='EXPNTL',

#1 UNIT,IOSM (A10,I5)

The card #2 is repeated as many as the number of radionuclides.

#2 NAME,AA,BB,CC,DD (A6,4X,4E10.3)

TA : time at which the assessment is performed (year)

TB : time for radionuclide deposition onto soil (year)

SLAY : lower boundary of each soil layer (m)

NAME : name of a radionuclide

CONC : radionuclide concentration in each soil layer

UNIT : unit of radionuclide concentrations in soil layers

One of 'BQ/M**3', 'BQ/CM**3', 'BQ/KG' or 'BQ/G' is allowed.

NLAY : total number of soil layers

IOSM : option for exponential functions

=1 : $CONC = AA * \exp(-BB * x) + CC * \exp(-DD * x)$ =2 : $CONC = AA * \exp(-BB * x)$ ($x \leq X_c$) $CONC = CC * \exp(-DD * x)$ ($x > X_c$)

AA,CC : initial values of fast and slow attenuation terms in the exponential functions

BB,DD : attenuation constants of fast and slow attenuation terms in the exponential functions (m^{-1})

Logical unit 11

Dose-rate conversion factors for each soil layer

The cards #1 and #2 are repeated 20 times ($n=0,1,\dots,19$).

#1 (SLDCF(L), $L=5n+1,5n+5$) (20X,5F10.2)

The card #2 is repeated as many as the number of radionuclides.

#2 ZAS,(DCF(L), $L=5n+1,5n+5$) (3X,I7,10X,5E10.3)

SLDCF : lower boundary of each soil layer (m)

ZAS : index for identifying a radionuclide
(atomic number, mass number and the state of isomer)

DCF : dose-rate conversion factor for each soil layer (Gy/year per Bq/m³)

Appendix 2 Sample Input Data

Logical unit 1

Definition of input and output data files

```

5   C:\GARDEC\DATA\COND\REPORT.DAT
10  C:\GARDEC\DATA\SCON\EXPNTL\REPORT.DAT
11  C:\GARDEC\DATA\DOSE\REPORT.DAT
6   C:\GARDEC\GDOUT\REPORT.DAT

```

Logical unit 5

Conditions of calculations

```

DIG
      0.3      0.6
EXPNTL
  1
  2
CS137   30.0   Y
BA137M   2.552 M 1 1      .946
FILE    1

```

Logical unit 10

Concentrations of radionuclides in each soil layer

```

BQ/G      2
CS137      2.15E+02  1.67E+02  6.69E+00  4.19E+01

```

Logical unit 11

Dose-rate conversion factors for each soil layer

	0.01	0.02	0.03	0.04	0.05
551370. CESIUM	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
561371. BARIUM	1.698E-10	1.163E-10	9.291E-11	7.743E-11	6.592E-11
	0.06	0.07	0.08	0.09	0.10
551370. CESIUM	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
561371. BARIUM	5.685E-11	4.945E-11	4.327E-11	3.805E-11	3.357E-11
	0.11	0.12	0.13	0.14	0.15
551370. CESIUM	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
561371. BARIUM	2.970E-11	2.634E-11	2.341E-11	2.083E-11	1.856E-11
	0.16	0.17	0.18	0.19	0.20
551370. CESIUM	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
561371. BARIUM	1.656E-11	1.479E-11	1.322E-11	1.182E-11	1.058E-11
	0.21	0.22	0.23	0.24	0.25
551370. CESIUM	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
561371. BARIUM	9.478E-12	8.493E-12	7.613E-12	6.828E-12	6.126E-12
	0.26	0.27	0.28	0.29	0.30
551370. CESIUM	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
561371. BARIUM	5.498E-12	4.937E-12	4.433E-12	3.982E-12	3.578E-12
	0.31	0.32	0.33	0.34	0.35
551370. CESIUM	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
561371. BARIUM	3.216E-12	2.891E-12	2.599E-12	2.337E-12	2.102E-12

	0.36	0.37	0.38	0.39	0.40	
551370. CESIUM	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
561371. BARIUM	1.891E-12	1.701E-12	1.531E-12	1.377E-12	1.240E-12	2.532E-08
	0.41	0.42	0.43	0.44	0.45	
551370. CESIUM	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
561371. BARIUM	1.116E-12	1.004E-12	9.042E-13	8.141E-13	7.330E-13	2.532E-08
	0.46	0.47	0.48	0.49	0.50	
551370. CESIUM	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
561371. BARIUM	6.601E-13	5.944E-13	5.354E-13	4.822E-13	4.344E-13	2.532E-08
	0.51	0.52	0.53	0.54	0.55	
551370. CESIUM	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
561371. BARIUM	3.913E-13	3.525E-13	3.176E-13	2.861E-13	2.578E-13	2.532E-08
	0.56	0.57	0.58	0.59	0.60	
551370. CESIUM	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
561371. BARIUM	2.323E-13	2.093E-13	1.886E-13	1.700E-13	1.532E-13	2.532E-08
	0.61	0.62	0.63	0.64	0.65	
551370. CESIUM	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
561371. BARIUM	1.381E-13	1.244E-13	1.121E-13	1.011E-13	9.111E-14	2.532E-08
	0.66	0.67	0.68	0.69	0.70	
551370. CESIUM	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
561371. BARIUM	8.213E-14	7.403E-14	6.674E-14	6.016E-14	5.424E-14	2.532E-08
	0.71	0.72	0.73	0.74	0.75	
551370. CESIUM	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
561371. BARIUM	4.890E-14	4.408E-14	3.974E-14	3.583E-14	3.231E-14	2.532E-08
	0.76	0.77	0.78	0.79	0.80	
551370. CESIUM	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
561371. BARIUM	2.913E-14	2.626E-14	2.368E-14	2.135E-14	1.925E-14	2.532E-08
	0.81	0.82	0.83	0.84	0.85	
551370. CESIUM	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
561371. BARIUM	1.736E-14	1.566E-14	1.412E-14	1.273E-14	1.148E-14	2.532E-08
	0.86	0.87	0.88	0.89	0.90	
551370. CESIUM	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
561371. BARIUM	1.035E-14	9.336E-15	8.419E-15	7.593E-15	6.847E-15	2.532E-08
	0.91	0.92	0.93	0.94	0.95	
551370. CESIUM	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
561371. BARIUM	6.175E-15	5.569E-15	5.023E-15	4.530E-15	4.086E-15	2.532E-08
	0.96	0.97	0.98	0.99	1.00	
551370. CESIUM	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
561371. BARIUM	3.685E-15	3.323E-15	2.997E-15	2.703E-15	2.438E-15	2.532E-08

Appendix 3 Sample Outputs

RADIONUCLIDES TO BE ASSESSED

NUCLIDE	HALF LIFE	BRANCHING RATIO
CS137	3.000E+01 Y	
BA137M	2.552E+00 M	0.946

CONCENTRATIONS AND DOSE-RATE CONVERSION FACTORS FOR EACH SOIL LAYER

CONCENTRATIONS IN SOIL LAYERS WERE CALCULATED WITH EXPONENTIAL FUNCTIONS

FUNCTION USED; $Y=AA*EXP(-BB*X)$ $X<XC$
 $Y=CC*EXP(-DD*X)$ $X>XC$

NUCLIDE	AA (BQ/G)	BB (/M)	CC (BQ/G)	DD (/M)	XC (M)
CS137	2.15E+02	1.67E+02	6.69E+00	4.19E+01	2.77E-02
BA137M	2.03E+02	1.67E+02	6.33E+00	4.19E+01	2.77E-02

NUCLIDE		CS137		BA137M	
SOIL LAYER		CONCENT.	DOSE FAC.	CONCENT.	DOSE FAC.
LOWER	UPPER	(BQ/M**3)	(GY/YEAR)	(BQ/M**3)	(GY/YEAR)
0.00	0.01	1.463E+08	0.000E+00	1.384E+08	1.698E-10
0.01	0.02	2.754E+07	0.000E+00	2.606E+07	1.163E-10
0.02	0.03	8.782E+06	0.000E+00	8.308E+06	9.291E-11
0.03	0.04	2.177E+06	0.000E+00	2.059E+06	7.743E-11
0.04	0.05	1.432E+06	0.000E+00	1.354E+06	6.592E-11
0.05	0.06	9.417E+05	0.000E+00	8.908E+05	5.685E-11
0.06	0.07	6.193E+05	0.000E+00	5.859E+05	4.945E-11
0.07	0.08	4.073E+05	0.000E+00	3.853E+05	4.327E-11
0.08	0.09	2.679E+05	0.000E+00	2.534E+05	3.805E-11
0.09	0.10	1.762E+05	0.000E+00	1.667E+05	3.357E-11
0.10	0.11	1.159E+05	0.000E+00	1.096E+05	2.970E-11
0.11	0.12	7.622E+04	0.000E+00	7.211E+04	2.634E-11
0.12	0.13	5.013E+04	0.000E+00	4.742E+04	2.341E-11
0.13	0.14	3.297E+04	0.000E+00	3.119E+04	2.083E-11
0.14	0.15	2.169E+04	0.000E+00	2.051E+04	1.856E-11
0.15	0.16	1.426E+04	0.000E+00	1.349E+04	1.656E-11
0.16	0.17	9.381E+03	0.000E+00	8.874E+03	1.479E-11
0.17	0.18	6.170E+03	0.000E+00	5.837E+03	1.322E-11
0.18	0.19	4.058E+03	0.000E+00	3.839E+03	1.182E-11
0.19	0.20	2.669E+03	0.000E+00	2.525E+03	1.058E-11
0.20	0.21	1.755E+03	0.000E+00	1.661E+03	9.478E-12
0.21	0.22	1.154E+03	0.000E+00	1.092E+03	8.493E-12
0.22	0.23	7.593E+02	0.000E+00	7.183E+02	7.613E-12
0.23	0.24	4.994E+02	0.000E+00	4.724E+02	6.828E-12
0.24	0.25	3.285E+02	0.000E+00	3.107E+02	6.126E-12
0.25	0.26	2.160E+02	0.000E+00	2.044E+02	5.498E-12
0.26	0.27	1.421E+02	0.000E+00	1.344E+02	4.937E-12
0.27	0.28	9.345E+01	0.000E+00	8.840E+01	4.433E-12
0.28	0.29	6.146E+01	0.000E+00	5.814E+01	3.982E-12
0.29	0.30	4.042E+01	0.000E+00	3.824E+01	3.578E-12
0.30	0.31	2.659E+01	0.000E+00	2.515E+01	3.216E-12
0.31	0.32	1.749E+01	0.000E+00	1.654E+01	2.891E-12
0.32	0.33	1.150E+01	0.000E+00	1.088E+01	2.599E-12
0.33	0.34	7.564E+00	0.000E+00	7.156E+00	2.337E-12
0.34	0.35	4.975E+00	0.000E+00	4.706E+00	2.102E-12
0.35	0.36	3.272E+00	0.000E+00	3.095E+00	1.891E-12
0.36	0.37	2.152E+00	0.000E+00	2.036E+00	1.701E-12
0.37	0.38	1.415E+00	0.000E+00	1.339E+00	1.531E-12
0.38	0.39	9.309E-01	0.000E+00	8.806E-01	1.377E-12
0.39	0.40	6.123E-01	0.000E+00	5.792E-01	1.240E-12
0.40	0.41	4.027E-01	0.000E+00	3.809E-01	1.116E-12
0.41	0.42	2.648E-01	0.000E+00	2.505E-01	1.004E-12
0.42	0.43	1.742E-01	0.000E+00	1.648E-01	9.042E-13
0.43	0.44	1.146E-01	0.000E+00	1.084E-01	8.141E-13
0.44	0.45	7.535E-02	0.000E+00	7.128E-02	7.330E-13
0.45	0.46	4.956E-02	0.000E+00	4.688E-02	6.601E-13

0.46	0.47	3.259E-02	0.000E+00	3.083E-02	5.944E-13
0.47	0.48	2.144E-02	0.000E+00	2.028E-02	5.354E-13
0.48	0.49	1.410E-02	0.000E+00	1.334E-02	4.822E-13
0.49	0.50	9.273E-03	0.000E+00	8.773E-03	4.344E-13
0.50	0.51	6.099E-03	0.000E+00	5.770E-03	3.913E-13
0.51	0.52	4.011E-03	0.000E+00	3.795E-03	3.525E-13
0.52	0.53	2.638E-03	0.000E+00	2.496E-03	3.176E-13
0.53	0.54	1.735E-03	0.000E+00	1.642E-03	2.861E-13
0.54	0.55	1.141E-03	0.000E+00	1.080E-03	2.578E-13
0.55	0.56	7.506E-04	0.000E+00	7.101E-04	2.323E-13
0.56	0.57	4.937E-04	0.000E+00	4.670E-04	2.093E-13
0.57	0.58	3.247E-04	0.000E+00	3.072E-04	1.886E-13
0.58	0.59	2.136E-04	0.000E+00	2.020E-04	1.700E-13
0.59	0.60	1.405E-04	0.000E+00	1.329E-04	1.532E-13
0.60	0.61	9.238E-05	0.000E+00	8.739E-05	1.381E-13
0.61	0.62	6.076E-05	0.000E+00	5.748E-05	1.244E-13
0.62	0.63	3.996E-05	0.000E+00	3.780E-05	1.121E-13
0.63	0.64	2.628E-05	0.000E+00	2.486E-05	1.011E-13
0.64	0.65	1.729E-05	0.000E+00	1.635E-05	9.111E-14
0.65	0.66	1.137E-05	0.000E+00	1.076E-05	8.213E-14
0.66	0.67	7.478E-06	0.000E+00	7.074E-06	7.403E-14
0.67	0.68	4.918E-06	0.000E+00	4.652E-06	6.674E-14
0.68	0.69	3.235E-06	0.000E+00	3.060E-06	6.016E-14
0.69	0.70	2.127E-06	0.000E+00	2.013E-06	5.424E-14
0.70	0.71	1.399E-06	0.000E+00	1.324E-06	4.890E-14
0.71	0.72	9.203E-07	0.000E+00	8.706E-07	4.408E-14
0.72	0.73	6.053E-07	0.000E+00	5.726E-07	3.974E-14
0.73	0.74	3.981E-07	0.000E+00	3.766E-07	3.583E-14
0.74	0.75	2.618E-07	0.000E+00	2.477E-07	3.231E-14
0.75	0.76	1.722E-07	0.000E+00	1.629E-07	2.913E-14
0.76	0.77	1.133E-07	0.000E+00	1.071E-07	2.626E-14
0.77	0.78	7.449E-08	0.000E+00	7.047E-08	2.368E-14
0.78	0.79	4.899E-08	0.000E+00	4.635E-08	2.135E-14
0.79	0.80	3.222E-08	0.000E+00	3.048E-08	1.925E-14
0.80	0.81	2.119E-08	0.000E+00	2.005E-08	1.736E-14
0.81	0.82	1.394E-08	0.000E+00	1.319E-08	1.566E-14
0.82	0.83	9.168E-09	0.000E+00	8.672E-09	1.412E-14
0.83	0.84	6.030E-09	0.000E+00	5.704E-09	1.273E-14
0.84	0.85	3.966E-09	0.000E+00	3.751E-09	1.148E-14
0.85	0.86	2.608E-09	0.000E+00	2.467E-09	1.035E-14
0.86	0.87	1.715E-09	0.000E+00	1.623E-09	9.336E-15
0.87	0.88	1.128E-09	0.000E+00	1.067E-09	8.419E-15
0.88	0.89	7.421E-10	0.000E+00	7.020E-10	7.593E-15
0.89	0.90	4.881E-10	0.000E+00	4.617E-10	6.847E-15
0.90	0.91	3.210E-10	0.000E+00	3.037E-10	6.175E-15
0.91	0.92	2.111E-10	0.000E+00	1.997E-10	5.569E-15
0.92	0.93	1.389E-10	0.000E+00	1.314E-10	5.023E-15
0.93	0.94	9.132E-11	0.000E+00	8.639E-11	4.530E-15
0.94	0.95	6.006E-11	0.000E+00	5.682E-11	4.086E-15
0.95	0.96	3.950E-11	0.000E+00	3.737E-11	3.685E-15
0.96	0.97	2.598E-11	0.000E+00	2.458E-11	3.323E-15
0.97	0.98	1.709E-11	0.000E+00	1.617E-11	2.997E-15
0.98	0.99	1.124E-11	0.000E+00	1.063E-11	2.703E-15
0.99	1.00	7.392E-12	0.000E+00	6.993E-12	2.438E-15

REDUCTION OF GAMMA DOSE RATE BY GARDEN DECONTAMINATION

DIGGING OF THE GARDEN IN A SPECIAL WAY

DEPTH OF A SHALLOW TRENCH PLOUGH ; 0.30 (M)

DEPTH OF A DEEPER TRENCH PLOUGH ; 0.60 (M)

NUCLIDE	HALF LIFE	DOSE RATE BEFORE DECON. (GY/HOUR)	DOSE RATE AFTER DECON. (GY/HOUR)	DOSE RATE REDUCTION (%)
CS137	3.000E+01 Y	0.000E+00	0.000E+00	0.000E+00
BA137M	2.552E+00 M	3.157E-06	3.286E-09	1.041E-01
TOTAL		3.157E-06	3.286E-09	1.041E-01

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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 ー 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·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	°C	
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

$$1 \text{ eV} = 1.60218 \times 10^{-19} \text{ J}$$

$$1 \text{ u} = 1.66054 \times 10^{-27} \text{ kg}$$

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 ム	rad
レ ム	rem

$$1 \text{ Å} = 0.1 \text{ nm} = 10^{-10} \text{ m}$$

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

$$1 \text{ bar} = 0.1 \text{ MPa} = 10^5 \text{ Pa}$$

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

$$1 \text{ Ci} = 3.7 \times 10^{10} \text{ Bq}$$

$$1 \text{ R} = 2.58 \times 10^{-4} \text{ C/kg}$$

$$1 \text{ rad} = 1 \text{ cGy} = 10^{-2} \text{ Gy}$$

$$1 \text{ rem} = 1 \text{ cSv} = 10^{-2} \text{ Sv}$$

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)

- 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。
- 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。
- 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。
- 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 ⁵ dyn)	kgf	lbf
	1	0.101972	0.224809
	9.80665	1	2.20462
	4.44822	0.453592	1

$$\text{粘 度 } 1 \text{ Pa} \cdot \text{s} (\text{N} \cdot \text{s} / \text{m}^2) = 10 \text{ P (ポアズ)} (\text{g} / (\text{cm} \cdot \text{s}))$$

$$\text{動粘度 } 1 \text{ m}^2 / \text{s} = 10^4 \text{ St (ストークス)} (\text{cm}^2 / \text{s})$$

圧	MPa (=10 bar)	kgf/cm ²	atm	mmHg (Torr)	lbf/in ² (psi)
	1	10.1972	9.86923	7.50062 × 10 ³	145.038
力	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

$$1 \text{ cal} = 4.18605 \text{ J (計量法)}$$

$$= 4.184 \text{ J (熱化学)}$$

$$= 4.1855 \text{ J (15 °C)}$$

$$= 4.1868 \text{ J (国際蒸気表)}$$

$$\text{仕事率 } 1 \text{ PS (仏馬力)}$$

$$= 75 \text{ kgf} \cdot \text{m/s}$$

$$= 735.499 \text{ W}$$

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)

GARDEC: A COMPUTER CODE FOR ESTIMATING DOSE-RATE REDUCTION BY GARDEN DECONTAMINATION