Review of the Chronic Exposure Pathway Models in MACCS and Several Other Well-Known Probabilistic Risk Assessment Models

Manuscript Completed: June 1989
Date Published: June 1990

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NRC FIN A1843

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Abstract

The purpose of this report is to document the results of the work performed by the author in connection with the following task, performed for U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research, Division of Systems Research.

MACCS Chronic Exposure Pathway Models: Review the chronic exposure pathway models implemented in the MELCOR Accident Consequence Code System (MACCS) and compare those models to the chronic exposure pathway models implemented in similar codes developed in countries that are members of the OECD.

MACCS has been compared to the following internationally well-known codes:

ARANO	(Finland)
CRAC/CRAC2	(USA)
NECTAR	(United Kingdom)
NUCRAC	(USA)
UFOMOD	(Federal Republic of Germany)

A direct comparison has in many respects proved to be difficult to perform, because of the many basic differences between the approaches chosen. But the report contains comprehensive descriptions of the various approaches and default values of most of the important parameters. It also contains numerous remarks/comments at points where the approach chosen (by MACCS or any of the other codes) may have weaknesses or faults; or where the descriptions/manuals are incomplete, difficult to understand, or not consistent with information given in other documentation.

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PREFACE

When this review was initiated in early summer 1988, published documentation of the MACCS computer code was not available. Two unpublished documents, NUREG/CR-4184 and NUREG/CR-4691, were provided to the author since at the time they represented the best available information on the models and data being utilized by MACCS. These documents have, however, been superseded by three recently published documents containing the most up-to-date and complete descriptions of the MACCS code. These documents are NUREG/CR-4691, Vols. I (MACCS User's Guide), II (MACCS Model Description Document), and III (MACCS Programmers Reference Manual).

The review contained in this document was very beneficial since it pointed out a number of shortcomings in the draft material utilized as its basis. In the intervening period, this information was utilized by the MACCS code developers in order to make significant improvements in the quality of the models and data used in MACCS. These improvements are reflected in the NUREG/CR-4691 documents.

1. INTRODUCTION

The purpose of this report is to document the results of the work performed by the author in connection with the following task, performed for US Nuclear Regulatory Commission, Office of Nuclear Regulatory Research, Division of Systems Research:

MACCS Chronic Exposure Pathway Models: Review the chronic exposure pathway models implemented in the MELCOR Accident Consequence Code System (MACCS) and compare those models to the chronic exposure pathway models implemented in similar codes developed in countries that are members of the OECD.

The chronic exposures concerned are via

- the terrestrial food pathways
- the water pathways
- the long-term groundshine pathway
- the inhalation of resuspended radionuclides pathway

The USNRC has indicated during discussions of the task that the major effort should be spent on the terrestrial food pathways. This has been done.

There is one chapter for each of the categories of chronic exposure pathways listed above. Review of the MACCS models is the core of the task, and hence description and discussion of the MACCS models are placed first in each chapter, together with comments/discussions of unclear points in the available documentation of the MACCS models, misprints, inconsistencies, etc. This is then followed by a separate subchapter for each of the other computer codes examined. To the extent this has been possible, the subchapters are written using similar layout, to facilitate intercomparison. Some codes, however, are so different in structure that they can't have similar subchapter lay-outs. At the end of each chapter there are subchapters containing discussions of similarities and differences between MACCS and the other codes, where e.g. some key quantities are compared. There are also subchapters containing the conclusions at the end of each chapter.

The following documentation on the MACCS computer program was, when the task was undertaken by the contractor (early summer 1988), given to him, and was meant to be the basis for the present review:

Ostmeyer, Robert M. and Helton, Jon C.: Exposure Pathways Models for Accidental Radionuclide Releases. NUREG/CR-4184. SAND85-0520. Sandia National Laboratories. January 1988, (unpublished) available in the NRC Public Document Room. (This unpublished report has been superseded by the MACCS Model Description.)

Chanin, David I., Sprung, Jeremy L. and Ritchie, Lynn T.: MELCOR Accident Consequence Code System (MACCS Version 1.5). User's Guide. (Draft version, last revised 2 June 1988). NUREG/CR-4691. SAND86-1562. Sandia National Laboratories.

Blond, Roger M.: Comments on the Analysis and Results of NUREG-1150. Science Applications International Corporation. 21 December 1987.

Chanin, David I.: Long-Term Mitigating Actions. Changes Implemented May 1988. Sandia National Laboratories. D.C. 26 May 1988, 11:04.

Computer listings of subroutines STPATH, TRFRCT, WTRTRF, DIRDEP, LNGTPH, LTPROJ, LTMACT, CSTEFF, CSTDCN, LTACUM, STOCHR, OXTPT1, CASGET, OXTPT4, OXTPT5, OXTPT6, OXTPT7, OXTPT8, OXTPT9, DOSGET, OXTPT10, ECCGET, OXTPT11, OXTPT12 and GETIMP from the MACCS computer program. Sandia National Laboratories, 10 June 1988, 15:18.

CHRON user input file. Sandia National Laboratories. 10 June 1988, 10:19.

In November 1988 the following documentation was made available:

Chanin, David I., Sprung, Jeremy L. and Ritchie, Lynn T.: MELCOR Accident Consequence Code System (MACCS Version 1.5). User's Guide. (Prepublication review version of 21 September 1988). Sandia National Laboratories.

Rollstin, Judy: Terrestrial Food Pathways Parameters. (Informal communication). Sandia National Laboratories. August and September 1988.

The information contained in the documentation received in November 1988 is based upon a review of the information in the earlier documentation, and when there is conflict, the most recent documentation is valid. The part of the present report in which nutrition pathways in MACCS are described, had already been written when the new documentation was received in November 1988. To save time and cost, it was chosen to only update the values referred to as "taken from the Users Guide", but mostly leaving the descriptions as they had been written before the recent documentation was received. Some of the remarks made by the author of the present report in his first review have been taken into consideration in the Sandia documentation of November 1988, and have also in some cases been implemented in the code and/or data. Later remarks are also said to have been implemented. Whenever possible, later developments will be mentioned together with the remarks in the present report.

June 1, 1989 additional documentation was received:

Chanin, David I., Sprung, Jeremy L., Ritchie, Lynn T. and Jow, Hong-Nian: MELCOR Accident Consequence Code System (MACCS Version 1.5). Volume 1: User's Guide. (Final Draft May 11, 1989). NUREG/CR-4691 (SAND86-1562). Sandia National Laboratories.

MACCS Code Listing dated May 16, 1989. (Listing of input data (dated March 7, 1989) was received separately May 15, 1989).

Summary of the method used to calculate the maximum allowable ground concentrations PSCMLK, PSCOTH, GCMAXR. An informal draft dated May 18, 1989.

Since the funds on this task have by this time almost been completely spent, it has not been possible to examine this documentation thoroughly. It has been used only to find out, where possible, whether specific remarks made by the author of the present report (in the earlier versions of the present report) have been implemented. The subject material of the informal draft dated May 18, 1989 is not part of the present task.

REMARK: If comprehensive documentation of MACCS is meant to be accessible, a complete new set of reports; with all contradictions removed, needs to be prepared to replace the present set of reports. The new MACCS User's Guide, dated May 11, 1989 may be satisfactory. The budget left on this assignment does not allow a proper assessment.

2. SELECTION OF CODES FOR THIS COMPARISON.

An excellent overview of accident consequence assessment codes in the OECD countries is found in (Ref. OE), which is the report from the International Comparison Study on Reactor Accident Consequence Modeling.* In the following table are given the code names, countries, and information on whether or not chronic exposure pathways are treated by the code, for all codes participating in the comparison study.

Country	Name of code	Chronic exposure pathways?
Belgium	IFDM/DOSDIM	Yes
Canada	CONSEQ	No
Denmark	PLUCON2	Yes ¹
Finland	ARANO	Yes
France	ALICE	Yes ¹

*available from Organization for Economic Co-operation and Development, Nuclear Energy Agency, Paris, France, published 1984.

Country	Name of code	Chronic exposure pathways?
FRG	UFOMOD	Yes
FRG	MUSE	Yes ¹
Italy	OTEIB	Yes
Japan	COMOST-II	Yes
Netherlands	RECN	No
Netherlands	MAKRO	No
Norway	CRAC	Yes
Sweden	UNIDOSE	No
Switzerland	CHRONEX/SPAD	Yes
UK	TIRION	Yes ¹
UK	NECTAR	Yes
USA	BADAC1	Yes
USA	CRAC	Yes
USA	CRAC2	Yes
USA	CRACIT	Yes
USA	ADPIC	No
USA	NUCRAC	Yes ²

¹ External exposure only.

² Updates WASH-1400.

The table above presents the status ca. year 1983. A similar, more recent compilation was carried out by the author of the present report in connection with a Technical Committee Meeting arranged by the International Atomic Energy Agency, and presents the status ca. mid-1987. The report from this meeting has not yet been published, but I include the information here, although it may not be quite in its final form. Being assembled for a report from IAEA, the table includes a few countries in addition to the OECD member countries. The survey will contain more information than that presented in the following table, where only information pertinent to the present report is given.

Country	Name of code	Ground-shine?	Resuspension?	No. of nutrition pathways
Belgium	DOSDIM	Yes	Yes	0 ¹
Canada	CONSEQ	No	information received	
Denmark	PLUCON4	Yes	No	0
Finland	ARANO	Yes	No	Variable
Finland	TRADOS	Yes	No	Variable
France	ALICE	Yes	No	0
France	SIMPOL	Yes	No	Variable
FRG	UFOMOD	No	information received	
FRG	MUSE	No	information received	
GDR	METEOR	Yes	No	?

Country	Name of code	Ground-shine?	Resuspension?	No. of nutrition pathways
Israel	REMAND ²	Yes	Yes	0
Japan	OSCAAR	Yes	Yes	Yes
Netherlands	MAKRO	Yes	No	0
Netherlands	NUDOS	Yes	No	2
Norway/ Finland	NOCRAC	Yes	Yes	5
Sweden	UNIDOSE/ BIOPATH	Yes	No	Variable
Switzerland	CHRONEX/SPAD	Yes	Yes	Variable
UK	NECTAR	Yes	No	Yes
UK	CRACUK	Yes	Yes	2
USA	CRAC	Yes	Yes	2
USA	CRAC2	Yes	Yes	2
USA	CRACIT	Yes	Yes	2
USA	MACCS	Yes	Yes	5
USA	NUCRAC	Yes	Yes	Several

¹ Ingestion is not considered by the accident-version of DOSDIM. The routine-version (yearly average) considers 4 ingestion pathways.

² Intended for licensing purposes.

From both lists above it can be seen that roughly half of the codes do not calculate doses via the nutrition pathways. Four of the codes in both lists are versions of CRAC with identical treatment of the nutrition pathways. At least one of the codes utilize an advanced compartment type model, which can not easily be compared to the model used in MACCS. The Finnish models ARANO and TRADOS use the same module for calculation of the nutrition pathways. This module is also used by the Norwegian/Finnish model NOCRAC, as an option to the regular CRAC calculation procedure. OSCAAR from Japan is still under development. Some of the codes in the lists are not widely known or utilized, which leaves them outside the scope of this assignment. These facts severely diminish the number of codes to consider for intercomparing nutrition models. The remaining are:

ARANO	(Finland)
CRAC/CRAC2	(USA)
NECTAR	(United Kingdom)
NUCRAC	(USA)
OSCAAR	(Japan)
UFOMOD	(Federal Republic of Germany)

As the assignment progressed, it was found that documentation for OSCAAR was not available. It was also found that it was difficult to obtain documentation of sufficient level of detail for some of the programs. Given more time, most of the

missing information is obtainable, but at present none of the points of the present report where there are gaps in the information, were judged to be of sufficient importance to warrant additional effort.

3. TERRESTRIAL FOOD PATHWAYS.

In the following descriptions of the different exposure pathways via nutrition, these are presented in an order different from the basically time-sequential order that is usually adopted. Root uptake and related exposure mechanisms are presented before direct deposition on plant exterior, and "green leafy vegetables" is presented first of the crops. The idea behind this choice is to progress throughout the description from the simplest exposure pathways to the more complicated ones.

3.1 MACCS.

The terrestrial food pathways are, in contrast to the other chronic pathways, composed of a number of different pathways. These fall into one of the following categories:

- crop to man
- crop to animal to milk to man
- crop to animal to meat to man
- crop to animal to other animal product (e.g. eggs) to man

Pathways that fall into the last of these categories are not incorporated into the MACCS program.

Six types of crops are considered in MACCS. Some of these are consumed exclusively by humans, some exclusively by animals, and some by both. The following list of these crops also contains the percentage of each crop consumed by man, dairy animals and meat animals, as given in MACCS input data:

Crop name	Percentage of crop consumed by		
	Man	Dairy animals	Meat animals
- pasture		10%	90%
- stored forage		13%	87%
- grains	35%	4%	61%
- green leafy vegetables	100%		
- root vegetables	100%		
- other food crops	100%		
- legumes and nuts	24%	4.6%	71.4%

REMARK: The crop type "root vegetables" does not exist in the earlier documentation on MACCS. It is probably a

subdivision of the crop type "other food crops" into "root vegetables" and "other crops". The crop type "legumes and nuts" was called "legumes and seeds" in the earlier documentation. The values above are from the most recent documentation (Rollstin), and most of the numbers are different from those in the earlier documentation.

The new documentation also contains lists of the major crops in each crop category:

- Pasture (needs no further specification).
- Stored forage: Alfalfa, clover, sorghum.
- Grain: Wheat, oats, barley, rye, corn (including sweet corn), sorghum grain, rice.
- Legumes and nuts: Soybeans, peanuts, snap beans, dried beans, peas, nuts.
- Leafy green vegetables: Lettuce, cabbage, broccoli, spinach, celery, cauliflower, greens.
- Root vegetables and tubers: Potatoes, carrots, beets, sugar beets, onions.
- Other food crops: Apples, grapes, peaches, oranges, grapefruit, lemon, tomatoes, cucumbers, peppers.

3.1.1 Transfer from soil to plants.

3.1.1.1 Leafy green vegetables.

This exposure pathway is the simplest of the nutrition pathways, together with "other crops". The equations e.6, e.7, e.8, e.9 and e.10 in appendix E of NUREG/CR-4184 contain the main expressions upon which calculation of this transfer is based. Important numerical values are contained in tables e.9 and e.10. The manner in which the transfer is incorporated into MACCS is described briefly in chapter 7.1.2, and the numerical values upon which the computations are based are given in table 7.2. All table, equation and chapter references are to the report NUREG/CR-4184.

The important equations are:

The empirical concentration ratio, relating concentration in plant to concentration in soil; both per unit weight, is given by the following equation. It is extremely important, however, to know whether one is referring to dry or wet weight in each specific instance.

$$CR = \frac{\text{Radionuclide activity per unit mass of plant (Bq/kg)}}{\text{Radionuclide activity per unit mass of soil (Bq/kg)}} \quad (e.6)$$

CR is a basic quantity, since it is usually the activity per unit mass plant that is measured, and often the activity per unit mass soil, though it is perhaps more often the activity in soil per unit area.

The following equation gives the radionuclide concentration in soil at time t after deposition, taking radioactive decay and percolation out of the root zone into consideration:

$$SC(t) = SC_0 \exp(-(\lambda_R + \lambda_L)t) \quad (e.7)$$

REMARK: λ_{RU} should really appear in the removal term of equation (e.7) together with λ_R and λ_L , but it is much smaller than these, and can accordingly be disregarded.

The following equation gives the radionuclide transfer factor from soil to plant at time t after deposition, relative to the original soil concentration; taking radioactive decay and percolation out of the root zone into consideration:

$$TF(t) = \lambda_{RU} SC(t)/SC_0 = \lambda_{RU} \exp(-(\lambda_R + \lambda_L)t) \quad (e.8)$$

The following equation gives the radionuclide transfer factor from soil to plant integrated over all time after deposition. It is the fraction of the original soil concentration that is taken up into plants in this nutrition exposure pathway, added over all time (said in a different way: that is not removed by radioactive decay or percolation out of the root zone).

$$ITF = \lambda_{RU} / (\lambda_R + \lambda_L) \quad (e.9)$$

The following equation gives the root uptake fraction as function of the concentration ratio, plant areal mass over a year, and soil areal mass. The root uptake fraction is a quite artificial entity, that describes root uptake as if it is a process taking place at a uniform rate all through the year.

$$\lambda_{RU} = CR \cdot CM/SM \quad (e.10)$$

MISPRINTS: In equation (e.8) of the report the term λ_{RU} is missing in the mid-portion of the equation. In equation (e.10) it says CF where it should say CR.

The following important quantities appear:

CM	dry areal mass of the harvested plant portion ($\text{kg}/\text{m}^2\text{-year}$)
CR	concentration ratio (dimensionless)
ITF	time-integrated root uptake fraction (Bq transf./Bq dep.)
λ_L	percolation loss rate (per year)

REMARK: The percolation loss rate must include the irreversible binding to soil, which does not otherwise appear anywhere in the equations.

IMPORTANT ADDITIONAL COMMENT: In the new documentation on MACCS, that was received after the above was written, irreversible binding to soil is taken into account separately. (So is depletion due to root uptake, although this has little impact upon the rate of reduction of the amount of radioactive materials available for uptake from the root zone.) Irreversible binding, however, appears to be very important, and particularly for Cs-137. For this nuclide the QROOT value is 0.025 in the old documentation, and 0.23 in the new. However, in the new MACCS documentation the expression "depletion due to chemical binding with the soil" is used. The word "irreversible," is very important in this context. If the binding is not irreversible, one more term must be added to the expression, in order to take account of transformation of radionuclides from inaccessible to accessible forms, and this will be a source term.

λ_R	rate of radioactive decay (per year)
λ_{RU}	root uptake rate (per year)
SC_0	initial concentration in the soil compartment (Bq/kg)
$SC(t)$	time-dependent concentration in the soil compartment (Bq/kg)
t	time since deposition (years)
SM	areal mass of the soil compartment (kg/m^2)

The quantity above depends upon the following two quantities:

DPT	depth of soil compartment (m)
ρ	density of soil (kg/m^3)

Numerical values of some quantities:

DPT = 0.15 m (Depth of mixed soil, tilled) }
 $\rho = 1600 \text{ kg/m}^3$ } (p. E-29)

	λ_R (per year)	λ_L (per year)	λ_{RU} (per year)	ITF (dimensionless)
Sr-89	4.864	0.0096	0.0013	0.00027
Sr-90	0.0247	0.0096	0.0013	0.040
Cs-134	0.3362	0.0021	0.000013	0.000038
Cs-137	0.0230	0.0021	0.000013	0.00052

From the modifications to the Users Guide:

(Whenever there is a reference to the "modifications to the Users Guide" in the present report, the documentation by Judy Rollstin is meant; not the completely new version of the Users Guide dated May 1989.)

	TCROOT	QROOT
Sr-89	0.00017	4.90
Sr-90	0.013	0.065
Cs-134	0.000014	0.54
Cs-137	0.000030	0.23
I-131	-	32.
I-133	-	290.

TCROOT is the same as ITF in the above, and QROOT is the sum of λ_R and λ_L , and the irreversible binding to soil and root uptake. The contribution from the last item, however, is insignificant; and QROOT accordingly has the same set of values for all crops.

REMARK: On p. 104 of the User's Guide it is claimed that QROOT is defined at "the end of this section". It is, however, not in the same section, but in the section on "Protective action data". On p. 109 of the new version of the User's Guide one finds the same claim, which is still just as wrong as before.

REMARK: Almost all values of TCROOT and QROOT have been significantly modified in the new documentation (Roll-

stin). This is mainly due to the introduced values for irreversible binding to the soil. Although most of the root uptake values are also different, they differ for the most part less than a factor two. A marked exception is the root uptake rate for pasture and cesium. This differs by more than a factor of ten (a misprint???). However, for pasture the soil ingestion pathway dominates absolutely, and a factor ten difference in the root uptake rate has no impact whatsoever on the value of TCROOT.

ADDITIONAL REMARK: In the recently received version of the User's Guide from May 1989 some completely insignificant (and un-necessary) modifications have been made to some of the TCROOT-values; like when one value has been changed from 0.00022 to 0.00023. Only for the pasture pathway are there significant differences in the TCROOT-values. Some small (about 10%) modifications have also been made to the QROOT-values for the Cs-nuclides.

The transfer from leafy green vegetables to man is described in chapter 3.1.3.

3.1.1.2 "Other" food crops.

This exposure pathway is treated in exactly the same manner as "leafy green vegetables". For both of these exposure pathways the equations e.6, e.7, e.8, e.9 and e.10 in appendix E of NUREG/CR-4184 contain the main expressions upon which calculation of this transfer is based, and important numerical values are contained in tables e.9 and e.10. The manner in which the transfer is incorporated into MACCS is described briefly in chapter 7.1.2, and the numerical values upon which the computations are based are given in table 7.2.

	λ_R (per year)	λ_L (per year)	λ_{RU} (per year)	ITF (dimensionless)
Sr-89	4.864	0.0096	0.00083	0.00017
Sr-90	0.0247	0.0096	0.00083	0.025
Cs-134	0.3362	0.0021	0.000042	0.00012
Cs-137	0.0230	0.0021	0.000042	0.0017

From the modifications to the Users Guide:

	TCROOT	QROOT
Sr-89	0.0000086	4.90
Sr-90	0.00066	0.065
Cs-134	0.00011	0.54
Cs-137	0.00022	0.23
I-131	-	32.
I-133	-	290.

The transfer from other food crops to man is described in chapter 3.1.3.

3.1.1.3 Legumes and nuts.

This pathway is not mentioned in NUREG/CR-4184, but appears in the User's Guide, where it is called "legumes and seeds". The present name is introduced in the informal report by Judy Rollstin. The pathway is treated in the same manner as leafy green vegetables. In the newest version of the User's Guide, dated May 1989, this pathway is still referred to as "Legumes and seeds".

From the modifications to the Users Guide:

	TCROOT	QROOT
Sr-89	0.00037	4.90
Sr-90	0.028	0.065
Cs-134	0.000093	0.54
Cs-137	0.00020	0.23
I-131	-	32.
I-133	-	290.

There is, however, an important difference between "legumes and nuts" and "other food crops"; namely that this crop is consumed by dairy and meat animals as well as by man.

The transfer from legumes and nuts to man is described in chapter 3.1.3.

The transfer from legumes and nuts to milk and meat producing animals is described in chapter 3.1.3, and from milk and meat producing animals to man in chapter 3.1.4.

3.1.1.4 Grains.

The soil to plant transfer is calculated just like for "leafy green vegetables", and the numerical values upon which the computations are based are:

	λ_R (per year)	λ_L (per year)	λ_{RU} (per year)	ITF (dimensionless)
Sr-89	4.864	0.0096	0.00021	0.000044
Sr-90	0.0247	0.0096	0.00021	0.0064
Cs-134	0.3362	0.0021	0.000021	0.000061
Cs-137	0.0230	0.0021	0.000021	0.00084

From the modifications to the Users Guide:

	TCROOT	QROOT
Sr-89	0.000043	4.90
Sr-90	0.0033	0.065
Cs-134	0.000035	0.54
Cs-137	0.000076	0.23
I-131	-	32.
I-133	-	290.

The transfer from grains to man is described in chapter 3.1.3.

The transfer from grains to milk and meat producing animals is described in chapter 3.1.3, and from milk and meat producing animals to man in chapter 3.1.4.

3.1.1.5 Pasture.

The root uptake from soil to plant is calculated just like for "leafy green vegetables", but in addition soil ingestion by the animals is important for this pathway.

The important equations are:

The following equation gives the radionuclide concentration in the surface soil compartment at time t after deposition, taking radioactive decay and percolation out of the surface soil compartment into consideration:

$$IS(t) = IS_0 * \exp(-(\lambda_{SL} + \lambda_R)t) \quad (e.11)$$

The following equation gives the radionuclide transfer factor from soil to animal via soil ingestion at time t after deposition, relative to the original concentration in the surface soil compartment, taking radioactive decay and percolation out of the surface soil compartment into consideration:

$$SI(t) = \lambda_{IR} * IS(t)/IS_0 = \lambda_{IR} * \exp(-(\lambda_{SL} + \lambda_R)t) \quad (e.12)$$

The following equation gives the radionuclide transfer factor from soil in the surface soil compartment to animal, integrated over all time after deposition. It is the fraction of the original soil concentration that is taken up into animals in this exposure pathway, added over all time (said in a different way: that is not removed by radioactive decay or percolation out of the surface soil compartment).

$$ISI = \lambda_{IR} / (\lambda_{SL} + \lambda_R) \quad (e.13)$$

The following equation gives the radionuclide transfer factor from soil to animal, as the sum of what is transferred via root uptake to plants and via soil ingestion. It is assumed that the amount taken up to plants (pasture) via root uptake is equal to the amount transferred to animals via plants; in other words, that all pasture is consumed.

$$STF_{ik} = RU_{ik} + SI_{ik} \quad (e.22)$$

REMARK: Quite recent experimental evidence indicate that external cesium on plants is less bioavailable than internal cesium. A factor of two difference in bioavailability has been found. If this is indeed the case, simple addition of cesium via root uptake and via soil ingestion will be conservative.

MISPRINT: In equation (e.12) of the report NUREG/CR-4184 the term λ_{IR} is missing in the mid-portion of the equation.

The following important quantities appear:

RU_{ik}	time-integrated root uptake transfer fraction (Bq transf./Bq dep.). (Nuclide i and crop k)
SI_{ik}	time-integrated soil ingestion transfer fraction (Bq transf./Bq dep.). (Nuclide i and crop k)
STF_{ik}	fraction removed from pasture by soil-to-plant transfer (Bq transf./Bq dep.)
λ_{SL}	percolation loss rate (per year)
λ_R	rate of radioactive decay (per year)
λ_{IR}	annual soil ingestion factor (per year)
IS_0	initial surface soil concentration (Bq/kg)
$IS(t)$	time-dependent surface soil concentration (Bq/kg)
ISI	transfer via the soil ingestion pathway integrated over all time (Bq transf./Bq dep.)

REMARK: Both the nomenclature and the choice of symbols for the various quantities gets very confusing here. The quantities ISI and SI_{ik} are evidently identical, a fact which is further disguised by the words used to describe them in report NUREG/CR-4184. RU_{ik} is also evidently identical to the quantity which is called ITF elsewhere in the same report. It appears that ITF and ISI are used in chapter E.1.2.3 of the report, and RU_{ik} and SI_{ik} in chapter E.1.4.

Because the soil compartments pertinent to soil ingestion and to root uptake will usually not be the same, some of the quantities above, which have "twin quantities" in the root uptake pathway, have different names and numerical values for the two pathways.

Numerical values of some quantities:

Relevant to the root uptake exposure pathway:

	λ_R (per year)	λ_L (per year)	λ_{RU} (per year)	ITF (dimensionless)
Sr-89	4.864	0.0096	0.0017	0.00036
Sr-90	0.0247	0.0096	0.0017	0.052
Cs-134	0.3362	0.0021	0.000083	0.00024
Cs-137	0.0230	0.0021	0.000083	0.0033

Relevant to the soil ingestion exposure pathway:

$$\lambda_{IR} = 0.0005 \text{ per year}$$

	λ_R (per year)	λ_{SL} (per year)	ISI (dimensionless)
Sr-89	4.864	0.5	0.000093
Sr-90	0.0247	0.5	0.00096
Cs-134	0.3362	0.25	0.00029
Cs-137	0.0230	0.25	0.0018

The above is table (e.11) in report NUREG/CR-4184.

ERROR: The value of ISI in the above table for Cs-134 is wrong, according to my calculations. It should have been 0.000853, when calculated by equation (e.13). This error may have been corrected in the newest version of the User's Guide, dated May 1989, as the TCROOT-value for Cs-134 has been changed.

From the modifications to the Users Guide:

	TCROOT	QROOT
Sr-89	0.00041	4.90
Sr-90	0.037	0.065
Cs-134	0.0014	0.54
Cs-137	0.0012	0.23
I-131	0.00016	32.
I-133	0.0000017	290.

	TCROOT	QROOT
Sr-89	0.00041	4.90
Sr-90	0.026	0.065
Cs-134	0.0013	0.59
Cs-137	0.0069	0.28
I-131	0.00016	32.
I-133	0.0000017	290.

REMARK: The definition of QROOT in the Users Guide is all right for the other nutrition pathways, where there is no soil ingestion, but it is incomplete or wrong for the pasture pathway. The definition on pages 122 and 123 is "annual depletion rate", and is supposed to take care of both root uptake and soil ingestion. I don't understand how this can be possible, since the soil compartments for root uptake and soil ingestion will be quite different in thickness, as indicated in the report NUREG/CR-4184. Accordingly the depletion rates will also be quite different in the two cases. Said in a different way: Percolation out of the surface soil compartment is not the same as percolation out of the root uptake compartment. Although it is a downward movement, it still has a long way to go before it leaves the root uptake compartment. This remark has not been implemented in the newest version of the User's Guide, dated May 1989. The QROOT-values are still the same.

The transfer from pasture to milk and meat producing animals is described in chapter 3.1.3, and from milk and meat producing animals to man in chapter 3.1.4.

3.1.1.6 Stored forage.

The soil to plant transfer is calculated just like for "leafy green vegetables", and the numerical values upon which the computations are based are given in the following table. It should be noted that for stored forage there is no soil ingestion, which is correct, assuming that the contamination of the forage with soil during harvesting is insignificant. In many agricultural areas stored forage will be hay or silage based upon grass. In MACCS, however, root uptake to stored forage is more than double of that to pasture in the old documentation, and more than four times for strontium and almost sixty times for cesium in the newer documentation, received in November

1988. This might, at least to a certain extent, have been explained by the density difference between grass and hay, if it had not been indicated elsewhere in NUREG/CR-4184 that dry weight is assumed for plants. From the new documentation it appears that the actual explanation is that stored forage in MACCS is other types of plants (alfalfa etc.). Other types of agricultural practices can, however, easily be treated by introduction of the proper numerical values.

	λ_R (per year)	λ_L (per year)	λ_{RU} (per year)	ITF (dimensionless)
Sr-89	4.864	0.0096	0.0042	0.00088
Sr-90	0.0247	0.0096	0.0042	0.13
Cs-134	0.3362	0.0021	0.00021	0.00061
Cs-137	0.0230	0.0021	0.00021	0.0084

From the modifications to the Users Guide:

	TCROOT	QROOT
Sr-89	0.0013	4.90
Sr-90	0.090	0.065
Cs-134	0.00071	0.54
Cs-137	0.0015	0.23
I-131	-	32.
I-133	-	290.

The transfer from stored forage to milk and meat producing animals is described in chapter 3.1.3, and from milk and meat producing animals to man in chapter 3.1.4.

3.1.1.7 Root vegetables.

This exposure pathway was introduced after the contractor had worked on this task for several months. The treatment is just like for leafy green vegetables.

From the modifications to the Users Guide:

	TCROOT	QROOT
Sr-89	0.00011	4.90
Sr-90	0.0084	0.065
Cs-134	0.000056	0.54
Cs-137	0.00012	0.23
I-131	-	32.
I-133	-	290.

The transfer from root vegetables to man is described in chapter 3.1.3.

The transfer from root vegetables to milk and meat producing animals is described in chapter 3.1.3, and from milk and meat producing animals to man in chapter 3.1.4.

3.1.2 Transfer to plants via direct deposition.

The important equations are:

An important quantity for all of these pathways is the interception factor. The observed range of interception factors is wide, from about 0.1 to 0.8 for different conditions, including plant growth density. An interception factor of 0.5 is assumed in MACCS for all pathways, as being a typical value for all agricultural crops and deposition conditions. The interception factor is defined by the following equation:

$$IF = \frac{\text{Radionuclide deposit on plants (Bq/m}^2\text{)}}{\text{Total radionuclide deposit (Bq/m}^2\text{)}} \quad (e.1)$$

The other important effect is retention on vegetation. Deposited radionuclides are gradually removed from vegetation by so-called weathering. The fraction remaining at time t after deposition is described in MACCS by a two-term weathering function. The numerical values of the parameters in the equation will be different for each isotope.

$$R(t) = IF * \sum_i (A_i * \exp(-\lambda_i t)) * \exp(-\lambda_R t) \quad (e.3)$$

The following important quantities appear:

IF	interception factor (Bq/m^2)/(Bq/m^2)
$R(t)$	fraction of radionuclide deposit remaining on vegetation at time t (days) after deposition (dimensionless)
A_i	weathering fractions (dimensionless) ($\sum_i A_i = 1$)
λ_i	weathering rates, coupled with the A -s (per day)
λ_R	radiological decay constant (per day)

3.1.2.1 Leafy green vegetables.

The important equations are:

The following expression is referred to as the direct transfer fraction, and is actually what remains on the green leafy vegetables at time of harvest:

$$\text{DTF}_{ik}(t_d) = 0.5 * \exp(-(0.05 + \lambda_i)t) \quad (\text{e.24})$$

REMARK: In other part of report NUREG/CR-4184 λ_R is used for radioactive decay, and the time unit is per year. Here one suddenly uses λ_i , and the time unit is days.

For leafy green vegetables it is evidently assumed in MACCS that weathering is described by a one-term version of equation (e.4), with weathering rate 0.05 per day; equivalent to a weathering half-life of 13.9 days.

The following important quantities appear:

$\text{DTF}_{ik}(t_d)$	fraction of directly deposited (on day t_d) radionuclide i that is transferred via crop k ($\text{Bq transf./Bq dep.}$)
0.5	interception factor
λ_i	rate of radioactive decay (per day)

t time from day of deposition to end of crop growing
 season (days)

From the modifications to the Users Guide:

Isotope	CTCOEF1	CTHALF1	CTCOEF2	CTHALF2
Sr-89	0.24	1.2096E6	0.06	4.32E6
Sr-90	0.24	1.2096E6	0.06	4.32E6
Cs-134	0.24	1.2096E6	0.06	4.32E6
Cs-137	0.24	1.2096E6	0.06	4.32E6
I-131	0.24	1.2096E6	0.06	4.32E6
I-133	0.24	1.2096E6	0.06	4.32E6

CTCOEF is the product of the interception factor and the weathering fraction, and 1 and 2 respectively refer to the first and second term of the expression for weathering respectively. CTHALF are the short-term (CTHALF1) and long-term (CTHALF2) weathering half-lives in seconds. Transferred into days CTHALF1 is 14 days, and the corresponding lambda-value is 0.0495 per day. CTHALF2 is 50 days, and the corresponding lambda-value is 0.0139 per day.

REMARK: The values given in the Users Guide and in the modifications to the same (Judy Rollstin's paper) do not agree with equation (e.24), and not with each other. The basic condition, that the sum of the weathering fraction for the terms of the weathering function shall be equal to one, is also violated. In term of the quantities used in the Users Guide, we should have:
 $CTCOEFF1 + CTCOEFF2 = 0.5$

REMARK: In the version of the Users Guide from May 1989 the values from Rollstin have largely been adopted. There are only a few diversions, for stored forage and root vegetables. The basic condition, however, is still violated.

REMARK: The term "availability fraction .. in the weathering model", which is used in the Users Guide, may easily give faulty associations. It would be better to refer to the terms in the equation concerned.

Growing season for green leafy vegetables starts at day 150 (May 31) and ends day 240 (August 31).

3.1.2.2 "Other" food crops.

The important equations are:

The following equation gives the amount of radioactive materials contained in the edible portion of the plants at time of harvest:

$$DTF_{ik}(t_d) = TF_i * \exp(-\lambda_i t) \quad (e.25)$$

REMARK: The term TF_i is not defined anywhere in report NUREG/CR- 4184. A discussion in the Users Guide, however, indicates that the approach for grain and "other crops" is different from that adopted for the other exposure pathways. In grain, certainly, it is so that the edible portion of the plant is not exposed to the outside environment. The content of radioactive material in the edible portion will build up throughout the growing season. One single constant (for each nuclide) is used to describe the buildup as well as weathering and interception.

ERROR: In equation (e.25) of the report NUREG/CR-4184 the minus-sign is missing in the term for radioactive decay.

The following important quantities appear:

$DTF_{ik}(t_d)$ Fraction of directly deposited (on day t_d)
 radionuclide i that is transferred via crop k
 (Bq transf./Bq dep.)

λ_i rate of radioactive decay (per day)

t time from day of deposition to end of crop growing
 season (days)

From the modifications to the Users Guide:

Isotope	CTCOEF1	CTHALF1	CTCOEF2	CTHALF2
Sr-89	0.2	1.2096E6	0.05	4.32E6
Sr-90	0.2	1.2096E6	0.05	4.32E6
Cs-134	0.2	1.2096E6	0.05	4.32E6
Cs-137	0.2	1.2096E6	0.05	4.32E6
I-131	0.2	1.2096E6	0.05	4.32E6
I-133	0.2	1.2096E6	0.05	4.32E6

CTCOEF is the product of the interception factor and the weathering fraction, and 1 and 2 respectively refer to the first and second term of the expression for weathering respectively. CTHALF are the short-term (CTHALF1) and long-term (CTHALF2) weathering half-lives in seconds. Transferred into days CTHALF1 is 14 days, and the corresponding lambda-value is 0.0495 per day. CTHALF2 is 50 days, and the corresponding lambda-value is 0.0139 per day.

REMARK: After the modifications described in Judy Rollstin's communication, it is evident that equation (e.25) in NUREG/CR-4184 does not any more describe the manner in which "other" food crops are calculated in MACCS. Instead the same approach as for green leafy vegetables has been adopted. The CTCOEf-values have the same weakness pointed out in the chapter on green leafy vegetables.

Growing season for "other" food crops starts at day 150 (May 31) and ends day 240 (August 31).

3.1.2.3 Legumes and nuts.

The treatment of legumes and nuts is as described by equation (e.25) in NUREG/CR-4184, in the chapter on "other" food crops, and which in the earlier versions of MACCS documentation was also used to describe transfer via this pathway. (The exposure pathway "legumes and nuts" is not mentioned in report NUREG/CR-4184).

From the modifications to the Users Guide:

Isotope	CTCOEF1	CTHALF1	CTCOEF2	CTHALF2
Sr-89	0.005	3.1536E13	0.0	1.0
Sr-90	0.005	3.1536E13	0.0	1.0
Cs-134	0.01	3.1536E13	0.0	1.0
Cs-137	0.01	3.1536E13	0.0	1.0
I-131	0.0	1.0	0.0	1.0
I-133	0.0	1.0	0.0	1.0

CTCOEF1 is the same as the quantity TF_i in equation (e.25), and CTHALF1 is set equal to one million years, to get rid of the exponential part of the weathering expression (which is used in the actual calculations by the code). The second term of the weathering expression will be equal to zero. There is no transfer of iodine to the edible portion.

3.1.2.4 Grains.

The treatment of grains is just like for legumes and nuts, but the numerical values are different.

From the modifications to the Users Guide:

Isotope	CTCOEF1	CTHALF1	CTCOEF2	CTHALF2
Sr-89	0.01	3.1536E13	0.0	1.0
Sr-90	0.01	3.1536E13	0.0	1.0
Cs-134	0.05	3.1536E13	0.0	1.0
Cs-137	0.05	3.1536E13	0.0	1.0
I-131	0.0	1.0	0.0	1.0
I-133	0.0	1.0	0.0	1.0

3.1.2.5 Pasture.

The important equations are:

For the pasture exposure pathway, a two-term version of the weathering expression is given. This version, however, is not correct, as mentioned in the following.

$$R(t) = IF * (A * \exp(-(\lambda_w + \lambda_R)t) + (1-A) * \exp(-\lambda_R t)) \quad (e.4)$$

$$\lambda_w = \ln 2 / T_w = 0.693 / T_w$$

$$DTF_i(t_d) = \int_0^t R_i(T) * CR * dT \quad (e.18)$$

$$CR = 1/T_{ps} \quad (e.19)$$

$$R_i(T) = 0.5 * (0.8 * \exp(-0.05T) + 0.2 * \exp(-0.014T)) \dots \dots * \exp(-(CR + \lambda_i)T) \quad (e.20)$$

$$t = t_e - t_d$$

REMARK: It is said that equation (e.20) in NUREG/CR-4184 is derived from equations (e.4) and (e.18). But equation (e.20) contains both long-term and short-term weathering constants, while equation (e.4) only contains a short-term weathering constant. This inconsistency makes it more difficult to understand properly the structure of equation (e.20). The long-term weathering constant, which has been introduced in this "secret" manner, has been given the value of 0.014 per day. Equation (e.20) also contains a "wild mix" of small and capital t-s. They should evidently all have been capital T-s.

The following important quantities appear:

IF	interception factor (Bq/m ²)/(Bq/m ²)
DTF _i (t _d)	fraction of directly deposited (on day t _d) radionuclide i that is "harvested" from the pasture (dimensionless)
R(t)	fraction of radionuclide i deposit remaining on grass at time t (days) after deposition (dimensionless)
A	fraction of deposit that is weathered quickly (dimensionless)
λ _w	short-term weathering constant (per day)
T _w	short-term weathering halflife (days)
CR	"grazing rate" (per day)
T _{ps}	length of pasturing season (days)

t_e end of pasturing season (day)
 t_d day of deposit (day)

REMARK: It is unfortunate that one part of the report uses years as the basic time unit, another part uses days, and the Users Guide uses seconds.

Numerical values of some quantities:

$A = 0.8$

$T_w = 14$ days ($\lambda_w = 0.0459$ per day)

From the modifications to the Users Guide:

Isotope	CTCOEF1	CTHALF1	CTCOEF2	CTHALF2
Sr-89	0.3	1.2096E6	0.076	4.32E6
Sr-90	0.3	1.2096E6	0.076	4.32E6
Cs-134	0.3	1.2096E6	0.076	4.32E6
Cs-137	0.3	1.2096E6	0.076	4.32E6
I-131	0.3	1.2096E6	0.076	4.32E6
I-133	0.3	1.2096E6	0.076	4.32E6

CTCOEF is the product of quantities IF and A, respectively IF and (1-A), in the list of important quantities above.

REMARK: Here also the condition that $A + (A-1) = 1$ is violated.

CTHALF are the short-term (CTHALF1) and long-term (CTHALF2) weathering half-lives in seconds. Transferred into days they are 14 days and 50 days respectively. The corresponding lambda-values are 0.0495 per day and 0.0139 per day respectively.

Growing season for pasture starts at day 90 (March 30) and ends day 270 (September 30).

3.1.2.6 Stored forage.

$$DTF_{ik}(t_d) = 0.5 * (0.8 * \exp(-0.05t) + 0.2 * \exp(-0.014t)) \dots \dots * \exp(-\lambda_i t) \quad (e.20)$$

where t is the time from day of deposition to end of growing season for forage crops.

From the modifications to the Users Guide:

Isotope	CTCOEF1	CTHALF1	CTCOEF2	CTHALF2
Sr-89	0.2	1.2096E6	0.1	4.32E6
Sr-90	0.2	1.2096E6	0.1	4.32E6
Cs-134	0.2	1.2096E6	0.1	4.32E6
Cs-137	0.2	1.2096E6	0.1	4.32E6
I-131	0.2	1.2096E6	0.1	4.32E6
I-133	0.2	1.2096E6	0.1	4.32E6

From the newest version of the Users Guide, dated May 1989:

Isotope	CTCOEF1	CTHALF1	CTCOEF2	CTHALF2
Sr-89	0.2	1.2096E6	0.05	4.32E6
Sr-90	0.2	1.2096E6	0.05	4.32E6
Cs-134	0.2	1.2096E6	0.05	4.32E6
Cs-137	0.2	1.2096E6	0.05	4.32E6
I-131	0.2	1.2096E6	0.05	4.32E6
I-133	0.2	1.2096E6	0.05	4.32E6

CTCOEF is the product of quantities IF and A, respectively IF and (1-A), in the list of important quantities above.

REMARK: In the modified values CTCOEF1 is not the value given in equation (e.20). Nor is the condition that $A + (1-A) = 1$ fulfilled.

CTHALF are the short-term (CTHALF1) and long-term (CTHALF2) weathering half-lives in seconds. Transferred into days they

are 14 days and 50 days respectively. The corresponding lambda-values are 0.495 per day and 0.01386 per day respectively.

Growing season for stored forage starts at day 150 (May 31) and ends day 240 (August 31).

3.1.2.7 Root vegetables.

This exposure pathway was introduced after the contractor had worked on this task for several months. The treatment is just as for legumes and nuts.

From the Users Guide:

Isotope	CTCOEF1	CTHALF1	CTCOEF2	CTHALF2
Sr-89	0.005	3.1536E13	0.0	1.0
Sr-90	0.005	3.1536E13	0.0	1.0
Cs-134	0.01	3.1536E13	0.0	1.0
Cs-137	0.01	3.1536E13	0.0	1.0
I-131	0.0	1.0	0.0	1.0
I-133	0.0	1.0	0.0	1.0

From the newest version of the Users Guide, dated May 1989:

Isotope	CTCOEF1	CTHALF1	CTCOEF2	CTHALF2
Sr-89	0.01	3.1536E13	0.0	1.0
Sr-90	0.01	3.1536E13	0.0	1.0
Cs-134	0.05	3.1536E13	0.0	1.0
Cs-137	0.05	3.1536E13	0.0	1.0
I-131	0.0	1.0	0.0	1.0
I-133	0.0	1.0	0.0	1.0

CTCOEF1 is the same as the quantity TF_i in equation (e.25), and CTHALF1 is set equal to one million years, to get rid of the exponential part of the weathering expression (which is used in the actual calculations by the code). The second term of the weathering expression will be equal to zero. There is no transfer of iodine to the edible portion.

Growing season for "other" food crops starts at day 150 (May 31) and ends day 240 (August 31).

3.1.3 Transfer from plants to milk and meat producing animals.

The model is based entirely upon equilibrium conditions; that is, the daily intake is constant over a time period that is long compared to the biological half-life. The basic equation for content in milk is the following, which gives the fraction of the deposited radionuclide i that is transferred to milk products:

$$MT_i(t_d) = M_i * \sum_{k=1}^n CFT_{ik}(t_d) * f_{Mk} * f_k \quad (e.32)$$

The following is the expression for the crop transfer fraction in the above equation:

$$CFT_{ik}(t_d) = (DTF_{ik}(t_d) + STF_{ik}) * DF_{ik} \quad (e.33)$$

The following is the equation for transfer to milk under equilibrium conditions:

$$M_i = f_{Mi}^* * MP \quad (e.35)$$

where

- $MT_i(t_d)$ fraction of radionuclide i deposited to farmland at time t_d in the year that is transferred to milk products (Bq transf./Bq dep.)
- M_i fraction of daily intake by a cow of radionuclide i that is transferred to average daily amount of milk produced by the cow under equilibrium conditions (dimensionless)
- f_{Mi}^* equilibrium transfer coefficient for milk (Bq/liter)/(Bq/day)
- MP average daily production of milk per dairy animal (liter)
- $CFT_{ik}(t_d)$ crop transfer function for radionuclide i deposited to crop k at time t_d during the year (includes both direct deposition and root uptake). Is (Bq transf.)/(Bq dep.) and corrected for consumption delay
- DF_{ik} consumption delay decay factor, which accounts for radionuclide decay between crop production and consumption by animals (dimensionless)

f_k fraction of farmland used to produce crop k.

f_{Mk} fraction of crop k consumed by dairy animals.

Very similar equations are used to calculate content in beef.

$$BT_i(t_d) = B_i * \sum_{k=1}^n CFT_{ik}(t_d) * f_{Bk} * f_k \quad (e.34)$$

$$B_i = TR * BP * f_{Bi}^* \quad (e.36)$$

REMARK: I have taken some liberties with equation (e.36) to make it consistent with the corresponding milk pathway equation and quantities. In report NUREG/CR-4184 one has at this point suddenly started using M in the meaning "meat", while M up to this point has been reserved for the meaning "milk". To make the distinctions clear, one should always have referred to "beef", symbolized by B, and never to "meat". For this reason I have re-named the quantity M in the report. In the above this quantity is called BP.

where

$BT_i(t_d)$ fraction of radionuclide i deposited to farmland at time t_d in the year that is transferred to beef products. (Bq transf.)/(Bq dep.)

B_i average fraction of a unit intake of radionuclide i that is transferred to beef.

f_{Bi}^* equilibrium transfer coefficient for beef (Bq/kg)/(Bq/day)

BP quantity of beef produced by an animal at slaughter (kg)

TR fraction of animals slaughtered per day (per day)

$CFT_{ik}(t_d)$ crop transfer function for radionuclide i deposited to crop k at time t_d during the year (includes both direct deposition and root uptake).

f_k fraction of farmland used to produce crop k.

f_{Bk} fraction of crop k consumed by beef-producing animals.

Numerical values of some quantities:

Isotope	f_{Mi}^*	f_{Bi}^*	M_i	B_i
Sr-89	1.4E-3	3.0E-4	0.021	-
Sr-90	1.4E-3	3.0E-4	0.021	-
Cs-134	7.1E-3	2.0E-2	0.11	0.005
Cs-137	7.1E-3	2.0E-2	0.11	0.005
I-131	9.9E-3	7.2E-3	0.12	-
I-133	9.9E-3	7.2E-3	0.059	-

Radioactive decay losses within the animal are included in the iodine values.

TR = 0.00085 per day

BP = 280 kg

From the Users Guide:

Values from the Users Guide for the quantities M_i and B_i are listed in the next chapter, since they appear in a data block together with some quantities that belong in that chapter.

3.1.4 Transfer from plant and animal food products to man, and delay in animal consumption of stored forage.

It is assumed in the calculations that all produced food stuffs are consumed.

Before consumption of food products by man, there are two mechanisms that may reduce the content of radioactive materials in the products: consumption delay and food preparation.

Consumption delay losses can be broken down into two types: those that involve consumption after an average delay interval (e.g. leafy green vegetables and beef products) and those that involve continuous ingestion during a period following production (e.g. grain).

A specific type of consumption delay loss, which really does not belong in this chapter, but rather in the previous one, is the delay before stored forage is consumed by animals. However, because the treatment of this problem will be quite similar to the treatment of delay in e.g. grain consumption, it is included in this chapter.

The important equations are:

For the mechanism involving an average delay interval:

$$DF_{ik} = \exp(-\lambda_i T_k) \quad (e.37)$$

For the mechanism that involves continuous ingestion:

$$DF_{ik} = CR_k \int_0^{T_k} \exp(-\lambda_i t) dt = ((1 - \exp(-\lambda_i T_k)) / \lambda_i) / T_k \quad (e.38)$$

and
(e.40)

if we assume that

$$CR_k = 1/T_k \quad (e.39)$$

Reduction due to food preparation and processing is not expressed in the form of any equation. Simple reduction factors, based upon experimental evidence, are applied.

The following important quantities appear:

DF_{ik}	decay factor for consumption delay for nuclide i and crop k (dimensionless)
λ_i	rate of radioactive decay (per day)
T_k	average delay time for consumption of crop k, in equation (e.37), and length of consumption period for crop k, in equations (e.38, 39 and 40) (days)
CR_k	consumption rate for crop k during the consumption period (per day)

Numerical values of some quantities:

Delay times for consumption	Leafy green vegetables 14 days	Produce 14 days	Meat 20 days	Milk 4 days
Continuous consumption period	Grain crops 1 year	Stored forage 365 days minus the length of pasturing season		

In the more recent documentation on input values used in MACCS calculations (Judy Rollstin) these delay times have been modified. In some cases the values previously adopted are considered to be too conservative, and in some cases additional food products or more complicated distribution patterns have been taken into account.

The values for milk have been modified to reflect the fact that the group should contain both milk and milk products like cheese and butter. It was assumed that 50% were products of short shelf life, like fluid milk, ice cream, cottage cheese and condensed milk. These were assumed to have a delay time of 7 days, representative for fluid milk. It was further assumed that 50% were products of longer shelf life, like cheese and butter, and 65 days delay time was assumed for these. Products with very long shelf life, like milk powder have been disregarded, since they are quite a small portion of the total production. It is only possible to enter one value for the reduction factor for each nuclide, which much represent both milk and milk products. This value has been determined by weighted averaging.

The delay time for grain, root vegetables and legumes and nuts is assumed to be 14 days, followed by continuous consumption over the one year to the next harvest.

For green leafy vegetables and "other" food crops it seems that the consumption pattern can be described by three broad categories. Part of the production is delivered fresh, and a delay time of 14 days is assumed. A second part is kept in refrigerated storage for up to six months, with continuous use of the stores over that period. The third part of the production is processed by freezing, canning or drying, and it is assumed that after an initial delay of 14 days, these products are used continuously over the one year till next harvest.

The distribution between these three categories is given in the following table:

Crop	Eaten fresh (14-day delay)	Refrigerated (Eaten over 6 months)	Processed (Eaten over 1 year)
Grain products	0%	0%	100%
Legumes and nuts	0%	0%	100%
Green leafy veg.	70%	25%	5%
Root vegetables	0%	0%	100%
Other food crops	5%	0%	95%

The input data to MACCS is calculated upon the basis of this information as weighed average values.

Reduction factors for food processing and preparation, used in MACCS (Table (e.31)):

Isotope	Sr	Cs	I	Te
Grain products	0.25	0.25	-	-
Leafy green vegetables	0.5	0.5	0.5	0.5
Meat products	1.0	1.0	-	-
Milk products	1.0	1.0	1.0	1.0
Other crops	0.8	0.8	-	-

From the modifications to the Users Guide:

Isotope	DCYPMH	DCYPBH	TFMLK	TFBF
Sr-89	0.66	0.77	0.022	0.00022
Sr-90	1.0	1.0	0.022	0.00022
Cs-134	1.0	1.0	0.11	0.023
Cs-137	1.0	1.0	0.11	0.024
I-131	0.28	0.18	0.13	0.0024
I-133	0.002	0.0	0.062	0.0011

DCYPMH and DCYPBH are said to be transfer factors describing the processing losses and radioactive decay which occur between the production and consumption of milk and meat products respectively. For meat and milk products, however, there are no processing losses in MACCS, and the factors above reflect only radioactive decay.

TFMLK and TFBK are the quantities M_i and B_i in the previous chapter.

	Grains	Green leafy vegetables	Other food crops	Legumes and nuts	Root vegetables
Isotope	DCYPCH	DCYPCH	DCYPCH	DCYPCH	DCYPCH
Sr-89	0.18	0.67	0.21	0.18	0.18
Sr-90	0.99	1.0	0.99	0.99	0.99
Cs-134	0.84	0.96	0.85	0.84	0.84
Cs-137	0.99	1.0	0.99	0.99	0.99
I-131	0.0099	0.21	0.024	0.0099	0.0099
I-133	0.0	0.0	0.0	0.0	0.0

DCYPCH is a reduction factor which corrects for the loss of radioactive material caused by radioactive decay occurring between the time of harvest of plants and of consumption by humans. It is the quantity DF_{ik} in the above.

	Pasture	Stored forage	Grains	Legumes and nuts
Isotope	DCYPCM	DCYPCM	DCYPCM	DCYPCM
Sr-89	1.0	0.37	0.2	0.2
Sr-90	1.0	0.99	0.99	0.99
Cs-134	1.0	0.92	0.85	0.85
Cs-137	1.0	0.99	0.99	0.99
I-131	1.0	0.063	0.032	0.032
I-133	1.0	0.0068	0.0034	0.0034

DCYPCM is a reduction factor which corrects for the loss of radioactive material caused by radioactive decay occurring between the time of harvest of plants and of consumption by milk or meat producing animals. Is the quantity DF_{ik} in the above.

In the Users Guide there are two separate data sets for milk and meat producing animals respectively, and the quantities are called DCYPCM and DCYPCB, but the numerical values in the two data sets are identical.

	Grains	Green leafy vegetables	Other food crops	Legumes and nuts
Isotope	FPLSCH	FPLSCH	FPLSCH	FPLSCH
Sr-89	0.25	0.5	0.8	0.8
Sr-90	0.25	0.5	0.8	0.8
Cs-134	0.25	0.5	0.8	0.8
Cs-137	0.25	0.5	0.8	0.8
I-131	0.33	0.5	0.8	0.8
I-133	0.33	0.5	0.8	0.8

FPLSCH is a reduction factor which corrects for loss of radioactive material by washing, peeling, cooking etc. of food.

3.1.5 Logical structure of nutrition calculations.

It may be difficult to see from the equations in the preceding subchapters exactly how the calculation of doses via the nutrition exposure pathways are performed. This subchapter contains a simplified verbal description of the logical flow of these calculations, as described in report NUREG/CR-4184. The description is not based on examination of the actual computer program listing.

MACCS calculates collective doses, without going via individual doses. The basic assumption is that all food produced, and not interdicted, is consumed.

For a specific section of the spatial grid (a specific geographical location) the line of thought in the following paragraphs is followed. All sections of the spatial grid are treated in this manner, each contributing part of the collective dose, and the collective doses are summed.

The first step in the logic of the calculations is to determine the area within the section upon which a specific type of crops is grown. The size of the area is then multiplied by the area concentration of deposited materials, to give the starting point for the calculations: the amount of radioactive materials that has been deposited upon the land where this type of crops is grown (within the specific spatial section).

Root uptake or interception factor combined with weathering or translocation gives the amount of radioactive material entering the particular nutrition pathway. It is integrated over all time. It is transfer to the edible parts only.

The next step is the reduction in the amount of radioactive materials due to radioactive decay during the time delay between harvest and consumption.

And the last step is the reduction in the amount of radioactive materials due to loss of radioactive materials during food processing and preparation.

The nutrition exposure pathways involving animals are almost like described above, except that the time between harvest and consumption by animal is involved instead of between harvest and consumption by humans. And of course, radioactive materials entering animals are "channeled" into three different "streams": milk, meat and the parts of the animal that are not used for food. And there is an additional delay period, between milk production and consumption or between slaughtering and consumption. It is assumed that all pasture, stored forage and the fractions of grains and legumes and seeds that are used for fodder, are consumed by the animals.

What has been calculated now is the fraction of the radioactive materials that have deposited upon land, where one specific type of crops are grown, that is consumed by man, via any nutrition pathway involving this type of crops. And then it is summed over all types of crops.

3.2 CRAC, CRAC2.

In CRAC and CRAC2 there are really only two nutrition pathways; milk and "other", and only the milk pathway is actually estimated. For the "other" nutrition pathway it is simply assumed that the intake is directly proportional to intake via the milk pathway. Based upon weapons fall-out measurements, the following proportionality factors are used: For direct deposition the intake via "other" is slightly less than that via milk for Sr and double that via milk for Cs. For root uptake the intake via "other" is double that via milk for Sr and three times that via milk for Cs.

As input data CRAC and CRAC2 use concentration factors that relate Curies (or Bq) ingested to Curies/m² (or Bq/m²) deposited. CRAC and CRAC2 use exactly the same input data in this data subgroup (CHRONIC), and the CRAC2 Model Description refers to Appendix VI of WASH-1400 for a detailed description of the nutrition pathways.

3.2.1 Transfer from soil to plant.

Soil ingestion by grazing animals is not taken into account in CRAC and CRAC2, so that the only mechanism here is root uptake.

Relevant quantities from WASH-1400:

Percolation rate:	{	Sr: $2.89 \cdot 10^{-4}$ per day
		Cs: $2.60 \cdot 10^{-3}$ per day

These percolation rates are equivalent to half-lives of 2398 days for Sr and 266.5 days for Cs.

CRAC uses time-integrated concentration factors, but with the parameter values above, the integration really covers only a few years.

Since only the milk pathway is actually calculated, there is only one crop; namely grass.

Uptake rate to pasture grass:	{	Sr: $1.41 \cdot 10^{-4}$ per day
		Cs: $6.31 \cdot 10^{-6}$ per day

3.2.2 Transfer to man via root uptake.

The root uptake calculations are performed using a simple compartment model, consisting of five compartments: Soil sink, pasture soil, pasture grass, milk, man. This system is described by the flow diagram on the following page and the following equations:

In WASH-1400 the symbol T is used to denote the transfer rates. I have chosen to use λ , because of the parallel to rate of radioactive decay, which is routinely denoted by this symbol.

REMARK: This "compartment model", however, is rather shaky. A compartment model should show how the material is transported through the system, and R , D , G , C and I ought to mean the content in the separate compartments, and be coupled by the transfers. It is OK for R , D and C , which can be regarded as the content in the root zone of one square meter, in the soil below the root zone underneath one square meter, and in the grass growing on one square meter. But the trouble starts when C is not the content in the amount of milk produced from grazing the grass from one square meter, but the content in one liter of milk. This means that part of the flow out of the grass compartment is not followed through the system. The transfer from the milk to the man compartment is also illogical. These shortcomings may have been corrected for, but it seems that they have not. Accordingly the calculated concentration factors, and all nutrition doses are may be incorrect.

$$\begin{aligned} dR/dt &= -(\lambda_R + \lambda_{RU} + \lambda_L) * R \\ dG/dt &= -(\lambda_R + (V/AD)) G + \lambda_{RU} * R \\ dC/dt &= \lambda_{gc} G - (\lambda_R + \lambda_{milk}) * C \end{aligned}$$

$$I = \lambda_{cm} C$$

where

- λ_R rate of radioactive decay (per day)
- λ_{RU} root uptake rate (per day)
- λ_L percolation loss rate (per day)
- λ_{gc} rate of transfer from one m^2 of pasture land to one liter of milk (m^2 /liter-day)
- λ_{milk} is defined as the "rate of loss of milk from the cow's udder" which really means the rate of transfer from the milk to the man compartment, just like λ_{gc} is the rate of transfer from the grass to the milk compartment (per day)

"Rate of loss of milk from the cow's udder" is said to be 2.0 per day, which is equivalent to loss of about 86.5% of the activity in the milk compartment per day.

- λ_{cm} is defined as the daily average consumption of milk for an individual (which is 0.7 liter/day). But in the figure showing the compartment structure it is shown as the rate of transfer from the milk to the man compartment (per day)

The two definitions of λ_{cm} given in WASH-1400 are contradictory. In a proper compartment model λ_{cm} should be the rate of transfer from the milk to the man compartment, and λ_{cm} should be equal to λ_{milk} in the above. As far as I can see, this error has been brought all the way through the calculations in WASH-1400, and makes all concentration factors (and all intakes and nutrition doses calculated) a factor $2.0/0.7 = 2.86 (\lambda_{milk}/\lambda_{cm})$ too low. This error may have been counter-acted by other, conservative assumptions, e.g. that the cow can always go to a fresh lot of pasture, and never returns to one lot from which most of the deposited activity has been removed by previous grazing. In addition there is the possible error in going from the grass to the milk compartment, as pointed out above.

R activity content in pasture soil compartment

G activity content in grass compartment
 C activity content in milk compartment
 I activity intake per day to man
 V dry weight of grass consumed by a cow per day
 A pasture area used by one cow (8500 m²)
 D dry weight grass density (kg/m²)
 V/AD the fraction of all the grass available to the cow
 that is consumed per day (per day)

Numerical values of the quantities above:

In WASH-1400 the following values are given for these quantities:

λ_{milk} = 2.0 per day

All values in the following table are given in (per years) to make comparison with MACCS easier, except λ_{gc} which is m²/liter-day.

Nuclide	λ_R	λ_L	λ_{RU}	λ_{gc}
Sr-89	4.864	0.10	0.05	0.0378
Sr-90	0.0247	0.10	0.05	0.0378
Cs-134	0.3362	0.949	0.0023	0.566
Cs-137	0.0230	0.949	0.0023	0.566

V = 11.8 kg/day

A = 8500 m²

D = 0.25 kg/m²

From the Users Guide:

Nuclide	Concentration factors, root uptake ((Bq ingested)/(Bq/m ²))	
	via crops	via milk
Sr-89	0.0136	0.0068
Sr-90	1.340	0.669
Cs-134	0.164	0.0547
Cs-137	0.250	0.0835

The integration time for the values in this table is 10 years, probably meaning that all nutrition doses via root uptake in CRAC and CRAC2 are for integrated intake over 10 years. However, as already pointed out in this chapter, with percolation rates as fast as the ones above, there will be no more activity available for uptake after 10 years. The integration in MACCS, as a contrast, is not cut at any specific time. It goes to infinite time, and with the MACCS percolation rates, only about 20% of the total root uptake takes place in the first 10 years (see the comparisons chapter).

A quantity which in the Users Guide is called weathering half-life is assumed to be 2400 days. But in connection with root uptake it must mean percolation half-life. It is given the same value for Sr and Cs, although in WASH-1400 there is a factor 10 difference between these two percolation rates (see chapter 3.2.1).

3.2.3 Transfer to man via direct deposition.

Interception factor	50%
Weathering half-life	14 days

The transfer to man of deposited activity is calculated in a straightforward manner, using an equation of the form

$$I(t+d) = C * R * L * A * S * V$$

where

$I(t+d)$	intake to man at a time which is the sum of the time since start of activity intake by the cow (t) and delay before consumption by man (d) (Bq)
C	first day's intake by the cow (Bq)
R	factor accounting for radioactive decay up till the time of intake by cow (dimensionless)
L	factor accounting for weathering (dimensionless)
A	fraction of daily intake that is in 1 liter of milk (per liter)
S	factor accounting for radioactive decay from intake by cow to intake by man (dimensionless)
V	daily consumption of milk by man (liter)

From the Users Guide:

Nuclide	Concentration factors, direct deposition ((Bq ingested)/(Bq/m ²))	
	via crops	via milk
Sr-89	0.397	0.402
Sr-90	0.505	0.588
Cs-134	8.44	4.22
Cs-136	2.84	1.42
Cs-137	8.44	4.22
I-131	1.00E-8	0.692
I-133	1.00E-8	0.00486

These concentration factors are integrated over one year.
Weathering half-life is assumed to be 14 days.

3.2.4 Transfer from grass to milk.

Density of grass	0.25 kg dry weight/m ²
Average consumption of grass by cow	11.8 kg dry weight/day
Average area grazed by cow	45 m ² /day

The three quantities above are only roughly in agreement. The first and third are the ones actually used.

Pasture area utilized per cow	8500 m ²
-------------------------------	---------------------

The fraction of daily intake that is in 1 liter of milk at day t after start of the intake is

$$\text{for strontium } A(\text{SR}) = 0.0013 * \exp(0.017t) * (1 - \exp(-0.45t))$$

$$\text{for cesium } A(\text{I}) = (0.0138 + 0.000073t) * (1 - \exp(-0.3t))$$

$$\text{for iodine } A(\text{I}) = 0.0091 * \exp(0.021t) * (1 - \exp(-0.292t))$$

3.2.5 Transfer from milk to man.

Delay before milk consumption by man	3 days
Milk consumption by man	0.7 l/day

3.3 ARANO.

The ACA/PRA computer program ARANO is developed in Finland, and the nutrition pathway portion of the program is called AGRID. The description in the following is taken from reference:

Kakko, Rhea and Partanen, Jouni: Assessment of doses from ingestion of contaminated agricultural products due to radioactive deposition. Technical Research Centre of Finland. Research Report 292. Espoo, Finland, 1985.

Because it was planned to be an integral part of a PRA computer program, AGRID had to treat the nutrition pathways in a simplified manner, but the original intention was to use the dynamic nutrition pathway program DETRA, also developed in Finland, to calculate various quantities to be used by AGRID. The development of DETRA, however, was delayed, and another approach had to be adopted. It was chosen to base AGRID upon the British program FOOD-MARC, described in:

Linsley, G.S., Simmonds, J.R. and Haywood, S.M.: FOOD-MARC; The foodchain transfer module in the methodology for assessing the radiological consequences of accidental releases. NRPB-M76. Chilton, United Kingdom, 1982.

Six types of crops are considered in ARANO:

- green vegetables
- grains
- root vegetables
- pasture
- hay
- forage

The first three are assumed to be consumed exclusively by man, and the last three exclusively by dairy and meat animals. Hay and forage are basically processed pasture, so for the exposure pathways involving these, the uptake from soil to plant is just like for pasture, and the difference is in the harvesting and consumption pattern.

3.3.1 Transfer from soil to plants.

3.3.1.1 Green vegetables, grain and root vegetables.

The important equations are:

The empirical concentration ratio, relating concentration in plant to concentration in soil; both per unit weight, is given by the following equation. In ARANO the mass of plant is wet weight and the mass of soil is dry weight.

$$CR_i = \frac{\text{Radionuclide activity per unit mass of plant (Bq/kg)}}{\text{Radionuclide activity per unit mass of soil (Bq/kg)}}$$

COMMENT: To the extent possible I will attempt to use the MACCS nomenclature and symbols for the various quantities. Nomenclature and symbols vary much between different reports. By trying to translate everything into "MACCS-language" it will be easier to compare the approaches adopted for the different programs. It is, however, not always possible to do this, and furthermore the "MACCS-language" is not quite consistent.

The following equations give the radionuclide concentration in soil at time t after deposition, taking radioactive decay and percolation out of the root zone into consideration:

$$SC(t) = SC_0 \exp(-(\lambda_i + \lambda_L)t)$$

$$SC_0 = A_i / (DPT * \rho)$$

Just like in MACCS, although the equations above are said to represent percolation, they must also include irreversible binding to soil and root uptake, all "baked into" the so-called percolation rate.

The following important quantities appear:

CR_i concentration ratio for nuclide i (dimensionless)

λ_L	percolation loss rate (per day)
λ_i	rate of radioactive decay (per day)
SC_0	initial concentration in the soil compartment (Bq/kg)
$SC(t)$	time-dependent concentration in the soil compartment (Bq/kg)
t	time since deposition (days)
DPT	depth of soil compartment (m)
ρ	density of soil (kg/m^3)
A_i	deposited activity at time of depos. per unit area (Bq/m^2)

Numerical values of some quantities:

$DPT = 0.30 \text{ m}$ (Depth of mixed soil, tilled)

$\rho = 900 \text{ kg/m}^3$

$\lambda_L = 0.00693 \text{ per year}$ (equivalent to 100 years "half-life" for percolation). Is assumed to be the same for all nuclides.

CR_i has the values shown in the following table. These values are taken from calculations with the computer program FOOD-MARC.

Concentration ratio, CR_i (Bq/kg wet weight plant)/(Bq/kg dry weight soil)			
	Green vegetables	Grain	Root vegetables
Sr	0.7	0.02	0.06
Cs	0.02	0.006	0.005
I	0.02	0.02	0.02

The actual calculation of uptake from soil to plant in ARANO is an integral part of the dose calculation, and is described in chapter 3.3.4.

3.3.1.2 Pasture.

In ARANO the pasture calculations are performed in a manner which makes it difficult to describe uptake to grass via roots and direct deposition upon grass separately. Both mechanisms are described in chapter 3.3.2.2.

3.3.2 Transfer to plants via direct deposition.

An important quantity for transfer after direct deposition is the interception factor:

$$IF = \frac{\text{Radionuclide deposit on plants (Bq/m}^2\text{)}}{\text{Total radionuclide deposit (Bq/m}^2\text{)}}$$

$$IF = \begin{array}{ll} 0.3 & \text{for green vegetables} \\ 0.05 & \text{for grain} \\ 0 & \text{for root vegetables} \end{array}$$

The interception factor for grass is not given. It is probably taken into account in calculation of the activity integrals (see chapter 3.3.2.2), but this is not evident. If it is not taken into account, it would result in overestimation of a factor about two for doses from pasture, hay and forage.

3.3.2.1 Green vegetables, grain and root vegetables.

In ARANO weathering of radioactive materials deposited upon the plant surface as a function of time is not calculated. Nor is translocation of the materials. These phenomena are presumably accounted for in a reduction factor which also accounts for reduction in radioactivity intake to man due to processes like washing, milling etc.

The dose calculations, the plant uptake calculations and the human intake calculations are interwoven in a manner which makes it impossible to fit the description properly into a chapter structure used to describe MACCS. For this reason the way in which descriptions of the various processes has been placed in the ARANO subchapters in the present report, is sometimes illogical.

Further description of the direct deposition exposure mode is found in chapter 3.3.4.

3.3.2.2 Pasture.

In ARANO there is a clear distinction between calculations performed when deposition takes place during the pasturing season and when deposition takes place during the dormant season.

Deposition during the pasturing season:

The manner in which transfer via pasture is treated in ARANO is rather different from the manner in which it is treated in MACCS. The difference is largely explained by differences in agricultural practices. In Finland pasture is ploughed after some years and used for other crops for a period. Accordingly the calculations will be different in the years after deposition when the pasture fields are not ploughed, and in the years when pasture is grown in fields where ploughing has been performed.

In ARANO it is assumed, since it represents the worst case, that the fields at time of deposition are in the beginning of the customary three year period when they are used to grow pasture. This applies, of course, not to all farm-land, but to the fraction customarily used for growing pasture. In these fields the radioactive materials will be in the top layer of the soil only. After three years the growing of pasture is moved to other fields. These fields have been ploughed in the intervening years since deposition, and the radioactive materials are mixed in the soil.

In the fields used to grow pasture it is assumed that all radioactivity is initially in the top 1 cm of soil, uniformly distributed. Downward movement of the radioactive materials is calculated using a three-compartment model for soil with the second and third compartments being 4 and 10 cm thick respectively. The removal rate assumed from the top compartment is 0.243 per year. Removal rates from the other two compartments are not given, but may not be so important, since very little activity will probably leave the second compartment during a time period as short as three years.

After three years pasture is grown in fields where the soil has been ploughed, and the activity is assumed to be uniformly distributed in the top 30 cm of soil.

Harvesting of grass:

In Finland grass is harvested as pasture, hay and forage.

Pasture is consumed by the animals at a uniform rate over the pasturing season, which in ARANO is assumed to be 100 days.

Hay is harvested during a short period in the early mid-part of the pasturing season; in ARANO assumed to be from day 26 to day 40 (both included), when the beginning of the pasturing

season is day 1. Consumption of the hay is at a uniform rate throughout the part of the year outside the pasturing season (265 days).

Forage is assumed in ARANO to be harvested at a uniform rate over the pasturing period, and consumed at a uniform rate during the part of the year outside the pasturing season.

Consumption by animals:

During the pasturing season the animals consume only pasture.

Outside the pasturing season it is assumed that half of the foodstuff consumed by the animals is hay and half is forage. It is not defined what is meant by "half of". It evidently does not refer to weight. The equations seem to imply that only half the activity that could have reached the animals via hay from a unit area of farm land, actually does so; and likewise for forage. But the corrections introduced to account for this mix of foodstuffs are not well defined, and probably not strictly correct, although the errors are probably insignificant.

Basic aspects of calculations in ARANO:

The equations given in the ARANO report include both direct deposition upon pasture and root uptake, when deposition takes place during the pasturing season.

The equations contained in this part of the ARANO report are based upon activity integrals reported in the previously mentioned FOOD-MARC report. The actual assumptions concerning interception, weathering etc. are not described. For direct deposition and pasture and forage it is assumed that deposition takes place on the first day of the 100 day pasturing season; but it seems that at the same time the grass is, rather illogically, assumed to be full grown. But in this manner a conservative solution is assured. The assumption for hay is different. Deposition is assumed to take place at the first day of the hay harvesting period, but the result is divided by two, since deposition might also have taken place after hay harvesting.

The equations from this part of ARANO do not have direct counterparts in MACCS, and are better explained verbally. The following equation, however, illustrates some basic aspects of the approach:

$$D_{ie} = A_i * DC_{ie} * I_{ie}$$

where

- D_{ie} dose to man via exposure mode e from nuclide i (Sv)
- DC_{ie} is called the dose factor, and is the dose to man due to intake of 1 Bq via exposure mode e. It is based upon the ICRP dose factors, but corrected for radioactive decay due to aspects of the human consumption pattern (Sv/Bq).
- A_i initially deposited activity (Bq)
- I_{ie} activity integral for exposure mode e. Here is taken into account the harvesting and consumption by the animals for the particular exposure mode (dimensionless).

I will not attempt to explain the activity integral in detail, but the activity integral above is the sum of separate activity integrals for pasture, hay and forage, where radioactive decay by the different modes of harvesting and consumption by animals described in the above are taken into account.

The year after deposition took place, and the third year, there is only root uptake to grass, but still from untilled soil. For these years doses via meat and milk are calculated using equilibrium content in meat and milk one and two years after deposition (calculated with FOOD-MARC), and in addition imposing radioactive decay integrated over a year.

After the first three years, pasture is grown on fields that have been plowed, and the transfer from soil to grass is only by root uptake. The calculations are similar to the calculations for root uptake to other crops (green vegetables, grain and root vegetables), and an integration over 30 years is performed. This, at least, is what is said in the description, although it then adds up to 33 years for pasture.

3.3.3 Transfer from plants to milk and meat producing animals.

The transfer to the animals is not calculated separately. But it is interesting to note that for the first year, when deposition takes place in the pasturing season, calculations via milk and meat are not performed in the same way. The reason is that the pasturing season is long enough for milk to reach equilibrium conditions, while meat does not. Milk is calcula-

ted in a rather detailed manner, while meat over the first year is calculated by application of a factor of proportionality relative to milk, derived from the FOOD-MARC report.

For the second and third years the content in both milk and meat are assumed to be constant over each year, except for the reduction due to radioactive decay. In other words, the seasonal variation, mainly due to whether the diet consists of pasture or hay and forage, are disregarded. The numerical values used in the calculations are taken from the FOOD-MARC report. Unfortunately it has not been possible within the limited time available for preparation of this report to obtain this additional numerical information.

3.3.4 Transfer from plant and animal food products to man.

Just like in MACCS it is assumed that all produced food is consumed.

Dose via root uptake:

The dose to man via root uptake is calculated in ARANO by the following equation:

$$D_{ik} = DC_i * CR_i * \sum_{j=1}^{30} SC((t_e - t_d) + (j-1)*1a)$$

The dose factor in the above equation is based upon dose factors from ICRP, but are corrected for radioactive decay between the time of harvest and the time of consumption. The ICRP dose factors are for substances that are already in the body. If the whole harvest had been consumed immediately, they could have been applied. But that is, of course, not the case. In ARANO it is assumed that the harvested food stuffs are consumed at a constant rate during the year till next harvest. It is assumed that there is a certain delay after harvest before consumption begins. The corrected dose factors are:

$$DC_i = DC_i^0 * \int_{t_n}^{t_n+1a} \exp(-\lambda_i t) dt$$

D_{ik} dose to man from soil activity due to root uptake during 30 years, including the year of deposition (Sv) (nuclide i and crop k)

DC_i	is called the dose factor, and is the dose to man due to intake of 1 Bq via harvested vegetables or grains from one harvest (Sv/Bq). It is assumed that consumption occurs at a uniform rate during the subsequent year, after a minimum delay time t_n .
DC_i^0	dose factors according to ICRP (Sv/Bq)
t_d	day of deposition (date)
t_e	day of end of growing season (date)
t_n	time delay from harvest until consumption starts (days)

The above is for crops other than grass. When it comes to exposure via pasture, hay, forage, milk and meat, the situation is more complicated. One reason for this is that it is assumed that the vertical distribution of radioactive materials in soil changes abruptly between the third and the fourth year, due to plowing. Another reason is that pasture, hay and forage have different harvesting and consumption (by animals) patterns. In all cases (including green vegetables, grain and root vegetables) root uptake to an exposure pathway is limited to the growth season. But the length of the growth seasons differs; and the way in which harvesting takes place differs also. For hay and all other vegetative agricultural products harvesting takes place at the end of the growth season - except for pasture and forage, which are harvested all through the growth season.

From the fourth year on these differences between pasture, hay and forage seem to be disregarded. Calculations for these years are performed much in the same way as for green vegetables, grain and root vegetables; with the use of two additional quantities: the amount of grass consumed by a cow per day, and transfer factors that describe the fraction of activity ingested by a cow that is transferred into 1 kg of milk or meat.

Dose via direct deposition:

The dose is calculated using the following expression:

$$D_{ik} = DC_i * A_i * C * P * \exp(-\lambda_i(t_e - t_d))$$

where

D_{ik}	dose to man from soil activity due to directly deposited activity (Sv) (nuclide i and crop k)
DC_i	is called the dose factor, and is the dose to man due to intake of 1 Bq via harvested vegetables or grains from one harvest (Sv/Bq). It is assumed that consumption occurs at a uniform rate during the subsequent year, after a minimum delay time t_n .
A_i	initially deposited activity (Bq)
λ_i	rate of radioactive decay (per day)
t_d	day of deposition (date)
t_e	day of end of growing season (date)
P	fraction transferred from plant to man (dimensionless)

P is said to be "what is left after 90 % of the plant surface activity is removed during different treatment processes, such as washing, threshing and milling". But it must also include weathering, since removal processes by weather are not included in any other manner. Nor are translocation processes accounted for.

The above is for crops other than grass. When it comes to exposure via pasture, hay, forage, milk and meat, there is not much to add here to what has been said in chapter 3.3.2.2.

Numerical values of some quantities:

$$P = 0.1$$

Yield of green vegetables over one season is 1 kg/m^2 .

Yield of grain over one season is 0.4 kg/m^2 .

Delay time for consumption of grain is 2 months.

The yield of root vegetables is not given, and the yield of grass (pasture, hay, forage) is not given. The latter,

however, is implicit in the so-called activity integrals.

Individual consumption of food stuffs per year are given in input data. However, these are irrelevant when it comes to calculation of collective doses. Values given in the report are:

Individual consumption of green vegetables is 35 kg/year.

Individual consumption of grain products is 70 kg/year.

Individual consumption of root vegetables is 30 kg/year.

Individual consumption of milk is 250 kg/year.

Individual consumption of meat is 35 kg/year.

Delay time for consumption of green vegetables is 1 day.

Delay time for consumption of root vegetables is 1 day.

Delay time for consumption of milk is 3 days.

Delay time for consumption of meat is 4 days.

A cow consumes 50 kg grass per day.

Transfer via root uptake from soil to grass. Concentration ratios. (Bq/kg grass wet weight)/(Bq/kg soil dry weight)

Nuclide	
Sr	0.05
Cs	0.02
I	0.02

The grass - cow - milk and grass - cow - meat pathways. Transfer factors (fraction of activity intake transferred)

Nuclide	Milk	Meat
Sr	0.001	0.0003
Cs	0.007	0.03
I	0.01	0.007

3.4 NECTAR.

The PRA/ACA computer program NECTAR has been developed at the Berkeley Nuclear Laboratories of the Central Electricity Generating Board of the United Kingdom. The description given in the present report is based upon the following two reports:

Nair, S.: Models for the evaluation of ingestion doses from the consumption of terrestrial foods following an atmospheric radioactive release. RD/B/5200/N84. Berkeley, United Kingdom. 1984.

Nair, S.: A user's guide for the foodweb transfer module NECTAR-FOODWEB. RD/B/5195/N82. Berkeley, United Kingdom. 1982.

The module calculates food contamination levels and individual doses and/or population doses, as requested.

The model for use in NECTAR for accident conditions is a dynamic compartment model, and may as such be difficult to compare to MACCS. Furthermore the equations for solving a compartment model do not say much about the processes involved, but simply relate inventory, inflow and outflow to/from the compartment.

The compartments in NECTAR, however, are almost the same as the different parts of the environment considered in MACCS, and accordingly many of the transfer factors from one compartment to another in NECTAR are equivalent to percolation rates, various transfer factors etc. in MACCS.

An equilibrium model is also included in NECTAR-FOODWEB, but is meant to be used for continuous releases only.

The maximum number of different crops is ten. NECTAR also considers a standard set of agricultural products:

- Cereals	- Beef and veal
- Root vegetables	- Pork
- Green vegetables	- Bacon and ham
- Fruit	- Mutton and lamb
- Liquid milk	- Eggs
- Manufactured milk	- Poultry

The sample problem given in the Users Guide is for a very limited case, containing only two agricultural products: root vegetables and milk. It is further simplified by setting soil loss (loss of activity from the soil compartment by percolation) and soil fixation equal to zero. The nuclides included in the sample problem (Pb, Bi and Po) are also not among the ones that are most important in connection with a nuclear accident, and which we are concerned with in the present report.

3.4.1 Transfer from soil to plants.

In NECTAR the ploughed soil layer is, according to the model description, assumed to be 15 cm thick, but it appears in input data, and any value can accordingly be chosen.

Numerical values of some quantities given in sample problem:

Depth of ploughed layer	0.15 m
Resuspension factor for grass	0.002 (Bq/kg dry weight soil)/(Bq/.. ..kg dry weight plant)
Resuspension factor for hay	0.00002 (Bq/kg dry weight soil)/.. ..(Bq/kg dry weight plant)
Resuspension factor for silage	0.001 (Bq/kg dry weight soil)/(Bq/.. ..kg dry weight plant)

It should be noted that the "resuspension factors" above have a different definition from the traditional one, which refers to air concentration above a contaminated surface.

Soil density	1900 kg/m ³ wet weight
Soil dry matter content	84%
Dry matter content of grass	17%
Dry matter content of hay	83%
Dry matter content of silage	30%
Herbage density of grass	2.97 kg/m ²
Herbage density of silage	2.5 kg/m ²

The herbage density for hay is not requested in this part of input data. It is possibly assumed to be the same as for grass or for silage, probably the last.

Root uptake rates for the three sample problem nuclides (per sec):

Root vegetables:	$1.5 \cdot 10^{-10}$	$1.2 \cdot 10^{-8}$	$2.9 \cdot 10^{-10}$
Grass:	$1.5 \cdot 10^{-10}$	$1.2 \cdot 10^{-8}$	$3.2 \cdot 10^{-10}$

3.4.2 Transfer to plants via direct deposition.

The interception factor is expressed as a function of growth density, according to the following reference:

Chamberlain, A.C.: Interception and retention of radioactive aerosols by vegetation. Atmospheric Environment 4, pp. 5 - 78. 1970.

$$IF = 1 - e^{-\mu * DW}$$

where

μ "Chamberlain" factor (m^2/kg)

DW dry matter herbage yield (kg/m^2)

NECTAR uses a quantity called field loss, which is equivalent to weathering rate in MACCS, if weathering is described by one exponential term.

3.4.2.1 Root vegetables.

This is the only crop included in the sample problem. The only data given there that may be of interest in connection with this report are the ones concerned with weathering and interception, although it is difficult to see how they are relevant to root vegetables.

Numerical values of some quantities given in sample problem:

Interception factor 0.8 (the quantities given are actually the "Chamberlain" factor = 2.8, yield = 2.36 kg wet weight per m^2 , and dry matter = 25%)

It undoubtedly seem peculiar to have an interception factor for root vegetables, but there is probably an explanation.

Field loss (weathering rate) 9.259E-7 per second (corresponds to a weathering half-life of 8.7 days)

Although these data are for Pb, Bi and Po, the same values would probably be used for other elements also, although probably not for iodine.

3.4.2.2 Grass.

Numerical values of some quantities given in sample problem:

Field loss (weathering rate) for grass	4.629E-7 per second (corresponds to a weathering half-life of 17.3 days)
---	---

Field loss (weathering rate) for silage	9.259E-7 per second (corresponds to a weathering half-life of 8.7 days)
--	--

The difference between the two above is probably explained by differences in harvesting procedure. When harvesting for the grass is cut some centimeters above ground, while cattle eating grass even takes in some soil with the grass.

Interception factor	0.8 (the quantities given are actually the "Chamberlain" factor = 2.8, yield = 2.36 kg wet weight per m ² , and dry matter = 25%)
---------------------	--

Dry matter content of grass	17%
-----------------------------	-----

Dry matter content of hay	83%
---------------------------	-----

Dry matter content of silage	30%
------------------------------	-----

Herbage density of grass	2.97 kg/m ²
--------------------------	------------------------

Herbage density of silage	2.5 kg/m ²
---------------------------	-----------------------

Although these data are for Pb, Bi and Po, the same values would probably be used for other elements also, although probably not for iodine.

3.4.3 Transfer from plants to milk and meat producing animals.

Numerical values of some quantities given in sample problem:

Storage time for hay	180 days
----------------------	----------

Storage time for silage	180 days
-------------------------	----------

There is no activity loss during feed processing for these products.

Input data includes fraction of daily intake appearing in 1 kg of animal product (for equilibrium conditions??), and biolo-

gical removal rate constant (per second). But the elements included in the sample problem are not of interest in connection with the present report, so there is no sense in giving the numerical values here.

Daily intake of grass	23 kg
Daily intake of hay	3 kg
Daily intake of silage	12.3 kg
Soil intake with grass	0.02 (kg dry weight soil)/ (kg dry weight grass)

3.4.4 Transfer from plant and animal food products to man.

Numerical values of some quantities given in sample problem:

Storage time for milk	1 day before consumption
-----------------------	--------------------------

There is no activity loss during food processing for milk or for root vegetables.

Daily consumption of milk	0.8219 kg
---------------------------	-----------

Daily consumption of root veg.	0.3288 kg
--------------------------------	-----------

In NECTAR it is not automatically assumed that all produced food is consumed. The fraction of each specific type of food that is consumed is specified in input data.

Fraction of milk production that is consumed	50%
---	-----

Fraction of root vegetables production that is consumed	51%
--	-----

The sample problem contains no information on meat.

3.5 NUCRAC.

NUCRAC is a version of CRAC, but the nutrition pathways have been thoroughly modified. The approach, however, is quite similar to MACCS. As a matter of fact, it is so similar that it is found un-necessary to list the equations used etc. in NUCRAC, except in the instances where MACCS and NUCRAC differ.

The quick analysis performed in this report shows that the

approach used in NUCRAC to the nutrition pathways is a large improvement over the approach taken in CRAC/CRAC2, and does as a matter of fact have little in common with the approach in CRAC/CRAC2. The approach in NUCRAC, however, has some clear weaknesses, and is clearly inferior to the one developed for MACCS. Of particular importance may be the absence of the soil ingestion pathway.

Seven types of crops are considered in NUCRAC. Some of these are consumed exclusively by humans, some exclusively by animals, and some by both. The following list of these crops also contains the percentage of each crop consumed by man and by cattle:

Crop name	Percentage of crop consumed by	
	Man	Cattle
- pasture		100%
- green leafy vegetables	100%	
- wheat	78%	15%
- corn	3%	85%
- grains	21%	62%
- hay		100%
- other crops	91%	0%

It is also assumed that 8.7% of the cattle are dairy cows.

For most of the crops the percentage consumed by man plus that consumed by cattle do not add up to 100%. The difference between this sum and 100% is actually lost from the calculations. This portion of the crops is presumably fed to other animals (chickens, pigs etc.), and part of the radioactivity contained in this portion will also eventually reach man, and ought really to have been included in the calculations; although this contribution will probably be small compared to the contribution via the other exposure pathways.

3.5.1 Transfer from soil to plants.

The empirical concentration ratio, relating concentration in plant to concentration in soil; both per unit weight, is used in NUCRAC, just as in MACCS, except it is called "concentration factor". It is defined by the following equation (using MACCS symbols):

$$CR = \frac{\text{Radionuclide activity per unit mass of plant (Bq/kg)}}{\text{Radionuclide activity per unit mass of soil (Bq/kg)}}$$

CR is a basic quantity, since it is usually the activity per unit mass plant that is measured, and often the activity per unit mass soil, though it is perhaps more often the activity in soil per unit area.

The following equation gives the root uptake fraction as function of the concentration ratio, plant areal mass over a year, and soil areal mass. In NUCRAC this equation is quite different from in MACCS.

In MACCS it is:

$$\lambda_{RU} = CR \cdot CM/SM \quad (e.10)$$

In NUCRAC it is:

$$\lambda_{RU} = \frac{\ln(1 + (CR \cdot CM/SM))}{t_o}$$

However, when it is remembered that, if $(CR \cdot CM/SM)$ is small compared to one, we also have that $(\ln(1 + (CR \cdot CM/SM)))$ is almost equal to $(CR \cdot CM/SM)$; and then the two equations are almost the same. The only difference then is that in MACCS uptake is "smeared" over the whole year, while in NUCRAC it is assumed to take place uniformly over the growing season.

The quantities above are explained in the following:

CM	dry areal mass of the harvested plant portion (kg/m^2 - year)
CR	concentration ratio (dimensionless)
λ_{RU}	root uptake rate (per year)
t_o	length of the growing season (fraction of year)
SM	areal mass of the soil compartment (kg/m^2)

The quantity above (SM) depends upon the following two quantities:

DPT	depth of soil compartment (m)
ρ	density of soil (kg/m^3)

Numerical values of some quantities:

SM = 240 kg/m² (in MACCS exactly the same)

The depth of the soil compartment is not given in NUCRAC.

Rate of loss of activity to soil sink is given in the following table. It is the sum of percolation and irreversible chemical binding to the soil.

	NUCRAC (per year)	MACCS (per year)	MACCS modified (per year)
Sr-89	0.04	0.0096	0.0396
Sr-90	0.04	0.0096	0.0396
Cs-134	0.04	0.0021	0.202
Cs-137	0.04	0.0021	0.202

In NUCRAC is used a very strickt division between grazing/ growing seasons and non-grazing/growing seasons. There is a very detailed treatment of uptake during subsequent periods and between the periods (although uniform within each period or between periods). A simpler approach has been adopted in MACCS, where the uptake is "smeared" over the whole year. The NUCRAC approach is of course more correct, but results in very complicated equations. It may be doubted whether the increased accuracy of the more detailed treatment is sufficient to justify these complications.

3.5.1.1 Pasture.

Most information on the pasture pathway is contained in chapter 3.5.2.1.

Root uptake rate to pasture is 0.01 per year.

3.5.1.2 Crops other than pasture.

The production of crops other than pasture is 2 kg/m² per year, presumably dry weight, so as to make sense in connection with the concentration factors.

All crops other than pasture are treated in the same manner in NUCRAC, except regarding length of growth season and consump-

tion pattern. For length of growing season and consumption pattern see chapter 3.5.2.2.

From the report it seems that this even applies to hay; in other words that the concentration and interception factors applied to hay are the same as those applied to the other crops, and not the same as for pasture. If this is so, it is certainly wrong.

The concentration factors via root uptake to crops used in NUCRAC are given in the following table. Concentration factors are actually given for 23 elements in NUCRAC, but only strontium, cesium and iodine are included here. The table also contain the root uptake rates these concentration factors correspond to.

Nuclide	Concentration factor	Root uptake rate (per year)
Sr	0.2	0.0017
Cs	0.01	0.000083
I	0.02	0.00017

In calculating the root uptake rates it is also assumed that the yield of crops is 2 kg/m^2 annually, as stated in the NUCRAC appendix on the nutrition pathways. This yield, however, is specified in input data. One single value is used for the whole area for which calculations are performed. In the NUCRAC sample problem this value is 2.4 kg/m^2 per year.

3.5.2 Transfer to plants via direct deposition.

The treatment of interception and weathering is just like in MACCS, even though the equations look rather different. The interception factor is 0.5 for pasture and 0.2 for all other types of crops. Weathering is expressed as a one-term exponential with a half-life of 14 days, both for pasture and for all other types of crops.

3.5.2.1 Pasture.

The use of pasture is based upon a utilization area factor of 45 m^2 per day and cow.

The flow of the calculation is:

- Daily intake of radioactive material by one cow, resulting from grazing of 45 m^2 .

- The resulting concentration in one liter of milk as function of time (see remarks below).
- Daily milk production (presumably in total by all cows in the area) multiplied by content per liter, gives content of radioactive material in all milk consumed, at time of production.
- This is multiplied by reduction due to radioactive decay during 3 days delay between milk production and consumption.

This is somewhat different from the approach in MACCS, where the assumption simply is that all pasture is eaten by cows, and is reduced by a factor to account for the fact that only part of the cow's intake of radioactive materials goes to milk. The remainder goes to other parts of the cow's body or is simply not taken up. Then there are reductions due to radioactive decay during delay between harvest of fodder and intake by cow (none for pasture), and delay between milk production and consumption by man. In this scheme, all activity on pasture, after application of these reduction factors, is consumed by man. The same type of approach is used for the soil ingestion pathway and pathways involving other types of fodder.

A number of remarks can be made to the approach chosen in NUCRAC and the specific manner in which it is applied:

On daily intake based upon grazing of a specific area per day: The intake should rather have been based upon intake of a certain amount of grass. The grass density may vary much from one climate to another. However, when the grass density is low, the interception factor will also be lower. These two effects do counteract; perhaps (but probably not quite) so that one cow's intake per day is roughly independent of the grass density. But the amount of radioactive material contained in all pasture growing on an area of a certain size, will obviously be lower if the grass density is lower. This reduction, however, is presumably taken care of in a "secondary" manner; namely in the way that the number of cows grazing on a certain area is chosen so that there is sufficient pasture for all.

On concentration in milk as function of time: These calculations are based upon a three-term expression to describe the reduction of activity content in milk with time from a one-time intake of activity. The three terms have the following half-lives for Cs-137: 0.93 days, 4.6 days and 35 days. No other nuclides have longer half-lives. It therefore seems strange that the calculation is carried two years into the future, for the activity taken up during the first pasturing season.

On daily milk production: From the Users Guide there appears to be two quantities that specify the milk production; PROMLK

and FACMLK. It is difficult to understand why two quantities should be needed.

FACMLK is defined as "milk production factor (liter/m² per year)", and can only have one value for the whole calculation. However, when combined with the "fraction of habitable land", "fraction of land devoted to farming" and "fraction of farmland devoted to milk production" (all these three are defined for each type of geographical area, which in CRAC/CRAC2/NUCRAC is referred to as "states"), this gives total milk production per year for each part of the spatial grid.

PROMLK is defined as "whole milk production (lb/year)", and is specified for each "state". The "total state area (km²)" is also specified in input. These two quantities divided and multiplied by "fraction of land devoted to farming" and "fraction of farmland devoted to milk production" will also give milk production per m² and year, but referring to each state separately, while FACMLK is for the whole area.

On concentration in beef as function of time: The calculations are very similar to those for milk, but the expression describing the reduction of activity content in beef with time from a one-time intake of activity, has only one term, and the half-life for Cs of 5.5 days. For some other nuclides it is considerably longer, with the highest value for Sb, of more than 10 years. This does not, however, seem to be a measured, but a calculated quantity; and furthermore a calculation where both single intakes and continuous daily intakes are involved. It may be all right, but there is parts of the information given here that looks peculiar. But I have chosen not to spend more time on this in the present report.

On beef production: Beef production is specified in input data. One value is given for each "state" (kg/year). As in the paragraph for PROMLK (on this or the previous page) yearly production per square meter is obtained by division with the quantity "total state area", and multiplication with the proper "land fractions", except that the "fraction of farmland devoted to beef production" does not seem to be specified anywhere.

Length of pasturing season is defined by the quantities "seeding month for state" and "harvesting month for state" in input data. The values specified in input are used for all crops (including pasture), except leafy green vegetables.

3.5.2.2 Crops other than pasture.

The growing seasons are defined by the quantities "seeding month for state" and "harvesting month for state" in input

data. The values specified in input are used for all crops except leafy green vegetables. In NUCRAC sample input the seeding month is May and harvesting month September for most states. It is April and October for the states where the climate is warmer.

Leafy green vegetables can be grown in 90 days in any of the four seasons. The choice of seasons is controlled by the input quantities "fresh vegetable area (km²) for spring", "....for summer" etc. These quantities are specified for each state separately. If no green vegetables are grown during winter in a certain state, the area is set equal to zero.

For consumption patterns, it is assumed that leafy green vegetables are consumed uniformly over a 90 day period directly following the end of the growing season. All other crops, except pasture, are consumed uniformly over a period of one year following the end of the growing season.

3.5.3 Transfer from plants to milk and meat producing animals, and from plant and animal food products to man, and delay in animal consumption of stored forage.

In NUCRAC the transfer from plants to animals is treated separately for the following pathways:

- Contaminated milk resulting from direct deposition on pastureland.
- Contaminated milk resulting from direct deposition on feedcrops.
- Contaminated milk resulting from root uptake by pasture grass.
- Contaminated milk resulting from root uptake by feedcrops.
- Contaminated beef resulting from direct deposition on pastureland.
- Contaminated beef resulting from direct deposition on feedcrops.
- Contaminated beef resulting from root uptake by pasture grass.
- Contaminated beef resulting from root uptake by feedcrops.

In NUCRAC the transfer from plants to animals and the transfer from animal products to man are coupled into the same set of equations. For this reason the NUCRAC-information equivalent to the MACCS-information contained in chapters 3.1.3 and 3.1.4 is contained in one single chapter here.

Transfer from plant products directly to man is subdivided into the following pathways:

- Crops contaminated by direct deposition.
- Crops contaminated by root uptake.

In NUCRAC it is not as easy as in MACCS to break the description into the "plant part" and the "animal part". For this

reason much of the information on uptake by animals is found in the previous chapters, under the separate "plant headings".

The typical calculation flow for the plant-animal-man pathways is described in the beginning of chapter 3.5.2.1, and the direct deposition and root uptake aspects are described in the respective chapters.

Radioactive decay during the time period between animal product production and consumption by man are based upon the following assumptions:

Delay period from milk production to consumption is 3 days.

Delay period from beef production to consumption is 20 days.

3.6 UFOMOD.

The nutrition pathway part of the UFOMOD code is called UFO-MOD-IG, and it actually exists in two versions; one which is part of the UFOMOD code, and one which is a separate computer program, called UFOING. The two versions are very similar, and most of the differences between them are not important in relation to the present report. When I refer to UFOMOD in the remainder of this chapter, I mean UFOMOD-IG.

The basic calculations in UFOMOD are now individual dose calculations. The present model for calculation of collective doses goes via individual intakes and food consumption rates. This may easily lead to faulty estimates of collective doses. Intake of radioactive nuclides are much more strongly coupled to food production than to food consumption, and a new model for use in UFOMOD is under development, which will calculate collective doses based upon predicted food concentrations and agricultural production data.

The nutrition pathway calculations performed in UFOMOD are really rather schematic, as they are based upon a type of quantity called "the yearly time integral of the specific activity in the foodstuff normalized to unit initial ground deposit" ($\text{Bq}\cdot\text{a}/\text{kg}/(\text{Bq}/\text{m}^2)$). These integrals have been calculated in advance, using the computer program ECOSYS, which is capable of treating nutrition pathways in great detail, but which is too complicated to be incorporated into a probabilistic risk model.

One very important peculiarity of the nutrition pathway part of UFOMOD is that only two release times per year are considered: The release must take place either at 1 January or 1 July. Said in a different way: The data files used in the

nutrition pathway calculations in UFOMOD contain the activity integrals for releases at these two dates only. In ECOSYS it is possible to make these calculations for any release time throughout the year, but each single day will give a different result for the activity integral, and it is not practical to attempt to handle such an amount of data in UFOMOD, which is a probabilistic risk model, and these two release times have been chosen as representative of "winter" and "summer" conditions.

UFOMOD contains eight foodstuffs:

- milk and milk products
- beef
- meat from pork
- grain products
- potatoes
- leafy vegetables
- non-leafy vegetables
- root vegetables

ECOSYS contains seven types of crops:

- pasture grass
- grain
- potatoes
- root vegetables
- leafy vegetables
- other vegetables
- maize

A few additional pieces of information: The animal feedstuffs are pasture, maize, grain and potatoes. Grain and potatoes are also consumed by humans. "Other vegetables" evidently is the same as "non-leafy vegetables".

3.6.1 Transfer from soil to plants.

Percolation and root uptake is calculated in a manner very similar to that in MACCS. Irreversible binding to the soil is not included explicitly, but it must be assumed that it is implicit in the quantity "migration half-life", which in UFOMOD is used to describe these processes. In UFOMOD one uses a compartment model to calculate transfer from soil to plants. It is used in two versions; one for pasture and one for all other crops.

Root uptake in ECOSYS is treated as a dynamic process, within the limits imposed by availability of data. The basic data, as in MACCS, are the empirical concentration ratios. And the

basic assumption is that these concentration ratios are reached at the time of harvest. In addition to this assumption, the following assumptions are adopted:

- the increase in biomass during growth is a linear function.
- the uptake rate to a plant during growth is an exponential function (fast uptake in early growth, leveling off towards time of harvest).

Using these assumptions, the time-dependency of uptake of radionuclides can be modeled. However, in most calculations one will only be interested in the content of radionuclides at the time of harvest, and time-dependency is of no concern. The obvious exception is pasture, where there is continuous grazing of grass of all ages. It is not clear, however, how this problem is treated in ECOSYS. The concentration ratios are given in the following table, and in the following subchapters are given the corresponding root uptake rates, calculated by the MACCS equations linking concentration ratios and root uptake rates, from chapter 3.1.1.1, and using the value for areal mass of soil of 240 kg/m² as in MACCS, and crop yields from the new MACCS documentation (Rolstin). These crop yields (with some reservations, since the crop types do not exactly match) are also given in the following table:

Type of crop	Experimental concentration ratios			Crop yields (kg/m ²)
	Sr	Cs	I	
Pasture grass	0.5	0.1	0.02	0.175
Grain	0.15	0.05	0.02	0.25
Potatoes	0.1	0.05	0.02	0.26 (?)
Root vegetables	0.25	0.01	0.02	0.26
Leafy vegetables	0.5	0.03	0.02	0.10
Other vegetables	0.3	0.03	0.02	0.22
Maize	0.2	0.01	0.02	0.25 (?)

3.6.1.1 Leafy green vegetables.

The version of the compartment model used for all crops other than pasture has only two compartments: the upper soil layer of 25 cm, and a soil sink. Distribution of radioactive materials appears to be assumed to be uniform in the upper soil layer, whether deposition has taken place 1 January or 1 July. This is strictly not correct for the latter date, and probably not for the first; since plowing would certainly not take place during summer, and often not during spring.

A two-compartment model of this type is identical to the calculation method adopted in MACCS, and the parameters used in

the calculations can be compared directly. In UFOMOD we have (using MACCS nomenclature) the following parameter values describing percolation, including irreversible binding to soil, and root uptake:

	Migration half-life (years)	λ_L (per year)	λ_{RU} (per year)
Sr	22	0.0315	0.00021
Cs	140	0.00495	0.0000063
I	11	0.063	0.0000041

The growth season for leafy green vegetables starts at 1 April and harvest takes place over the time period from 20 May to 15 October. The growth period is 50 days.

3.6.1.2 Potatoes.

	λ_{RU} (per year)
Sr	0.00011
Cs	0.000054
I	0.000022

The growth season for potatoes starts 15 April and harvest takes place 15 September. The growth period is 150 days.

3.6.1.3 Non-leafy vegetables.

	λ_{RU} (per year)
Sr	0.00028
Cs	0.000028
I	0.000018

The growth season for non-leafy vegetables starts 1 April and harvest takes place from 1 August to 15 October. The growth period is 120 days.

3.6.1.4 Grains.

	λ_{RU} (per year)
Sr	0.00016
Cs	0.000052
I	0.000021

The growth season for grains starts 15 March and harvest takes place 15 August. The growth period is 150 days.

3.6.1.5 Pasture.

The version of the compartment model used for pasture has three compartments: the top soil layer of 1 cm, a lower soil layer from 1 to 10 cm, and a soil sink. Distribution of radioactive materials is assumed to be uniformly distributed within each compartment. The top 1 cm layer is considered in connection with resuspension, and the 9 cm beneath for root uptake.

For this compartment model there are two sets of values for percolation rates. In UFOMOD we have (using MACCS nomenclature) the following parameter values describing percolation, including irreversible binding to soil, and root uptake:

	0 - 1 cm layer		1 - 10 cm layer		
	Migration half-life	λ_L	Migration half-life	λ_L	λ_{RU}
	(years)	(per year)	(years)	(per year)	(per year)
Sr	0.87	0.797	7.8	0.0888	0.00036
Cs	5.5	0.126	50	0.0139	0.000073
I	0.43	1.61	3.9	0.178	0.000015

The growth season for pasture starts 1 April and harvest takes place from 15 May to 1 November. The growth period is 45 days.

3.6.1.6 Stored forage.

Root uptake is as for pasture. Stored forage is harvested mainly in May, June and July.

3.6.1.7 Root vegetables.

λ_{RU}
(per year)

Sr	0.00027
Cs	0.000011
I	0.000022

The growth season for root vegetables starts 1 April and harvest takes place from 1 August to 15 October. The growth period is 120 days.

3.6.1.8 Maize.

λ_{RU}
(per year)

Sr	0.00021
Cs	0.000010
I	0.000021

The growth season for maize starts 15 April and harvest takes place 15 September. The growth period is 150 days.

3.6.2 Resuspension to plants and soil ingestion.

In UFOMOD, or rather ECOSYS, resuspension of soil and settling of this resuspended soil on plant surfaces is included in the calculations. It is simulated by estimating what fraction of plant mass is resuspended soil, after cleaning and other food processing. This fraction is given in the following table. For potatoes and root vegetables the value in the table evidently has a different meaning, although the implications are more or less the same.

The resuspension data below are said to include soil ingestion by animals, for pasture. There is also a general remark that it is assumed that 4% of the dry matter intake by cattle (which will be more than pasture) is soil. However, it is also assumed (chapter 3.6.3.3) that there is no actual grazing in fields. All pasture grass is harvested and fed to the cattle soon after harvesting (then it is called pasture) or outside the pasture season (then it is called hay and silage, and in the present report "stored forage"). It therefore seems strange to include soil ingestion. It is not clear whether the plant mass in the following table is dry or fresh weight.

Type of crop	(kg resuspended soil)/(kg plant mass)
Pasture grass	0.008
Grain	0.0001
Potatoes (human food)	0.0001
Potatoes (animal feed)	0.01
Root vegetables	0.0001
Leafy vegetables	0.0001
Other vegetables	0.0001
Maize	0.001

By comparing these values with the concentration ratios it is evident that resuspension is of little importance compared to root uptake, with the following exceptions: Pasture grass and iodine, where the amount of resuspended radio-iodine on the plant might be 40% of the content in the plant via root uptake. Potatoes for animal feed and iodine, where the amount of resuspended radio-iodine on the plant might be 50% of the content in the plant via root uptake. Potatoes for animal feed and cesium, where the amount of resuspended radio-cesium on the plant might be equal to the content in the plant via root uptake.

There are some reservations to above conclusions. First of all, the concentration ratios for iodine are not well known, as they have been given the same value for all crops. Secondly, it is not strictly correct to use the concentration ratios in these comparisons in the case of pasture. The concentration ratios are the ratios between concentration in plant and concentration in soil in the root zone, while the resuspended soil is from the top soil, which for pasture will have a higher concentration than soil in the root zone. It is, accordingly, possible that resuspension (with soil ingestion included) is important for all nuclides where pasture is concerned.

3.6.3 Transfer to plants via direct deposition.

The treatment of these exposure pathways in UFOMOD, or rather in ECOSYS, is somewhat more detailed than in MACCS.

The elements have been classified into two groups according to translocation behaviour; mobile (iodine and cesium are in this group) and immobile (strontium is in this group).

With the exception of leafy vegetables and pasture grass, ECOSYS does not use an explicit interception factor or weathering half-life. And both interception factors and weathering half-lives, whether used explicitly or implicitly, are functions of plant growth, or time since deposition, respectively.

3.6.3.1 Leafy green vegetables.

Contamination of leafy vegetables due to direct deposition is calculated using the following assumptions:

- The yield of leafy vegetables is 2 kg/m^2 (fresh weight).
- The time between two croppings is 50 days (growth period lasts 50 days).
- The fraction of soil area covered by plants increases linearly from zero at time of planting to one at time of cropping.
- The interception factor is directly proportional to the fraction of ground covered by the plants; which is zero at time of planting and one at time of cropping (applies to dry deposition or wet deposition with little moisture. If heavier rain, interception will be less. It is not described how this will be treated.)
- The activity initially retained is lost due to weathering with a half-life of 14 days.

With these assumptions (and using MACCS terminology) the initially intercepted activity on plants harvested at time t after deposition took place, is given by the following equation:

$$IF(t) = (1 - t/50)$$

(In this equation is implicit that all leafy vegetables are harvested at the end of the 50 days growth period. In reality harvest takes place more evenly over much of the growth period.)

The contamination of plants harvested at time t (days) after deposition is given by the following equation:

$$R(t) = IF(t) * \exp(-(\lambda_i + \lambda_R)t)$$

ECOSYS uses a one-term expression to describe weathering. The quantities in the equations are defined in the following:

$IF(t)$ interception factor (at time zero; time of deposition) for leafy vegetables harvested at time t (days) after deposition (Bq/m^2)/(Bq/m^2)

$R(t)$	fraction of radionuclide deposit remaining on vegetation at time t (days) after deposition (dimensionless)
λ_i	weathering rate (per day)
λ_R	radiological decay constant (per day)

Translocation is of no importance for leafy vegetables.

3.6.3.2 Potatoes, non-leafy vegetables, grains, root vegetables, and maize.

For all crops, except pasture and leafy vegetables, so-called "contamination factors" are used for calculation of the direct-deposition-upon-plant pathways in ECOSYS. The contamination factors are defined as the ratio of activity found in the edible part of the crop per unit land area relative to the total deposited activity per unit land area, at time of harvest. The contamination factors have been derived from experiments. Weathering is implicit in the contamination factors, and they do not distinguish between what is on the plant surface and what is incorporated into the plant at time of harvest.

For all the crops for which contamination factors are used, harvest takes place at the end of the growing season. The contamination factor will depend upon the time when deposition took place. If it takes place at the beginning of the growing season, the contamination factor will be zero, since there was no plant material upon which deposition could have taken place. And throughout the growing season it will depend upon the growth processes, more or less as described in chapter 3.6.1 for root uptake. In ECOSYS two values of the contamination factor (for mobile and immobile elements) are given for each month within the growing season and for each type of relevant crop. In UFOMOD calculations deposition during summer can only take place at the 1 July, so that only the July values are relevant. In this report, however, I will give the values for all the months.

Crop		Contamination factor (%)					
		April	May	June	July	August	September
Potatoes	mobile	1.0	3.5	7.5	9.0	5.5	1.5
	immobile	0	0	0	0	0	0
Non-leafy veg.	mobile	0.5	2.0	4.5	6.0	4.5	2.5
	immobile	-	0.25	0.75	1.25	1.75	2.0
Grains	mobile	0.5	2.0	4.5	4.5	2.5	-
	immobile	0.1	0.4	0.75	1.5	2.0	-
Root vegetab.	mobile	0.75	3.0	7.5	9.0	5.5	1.5
	immobile	0	0	0	0	0	0
Maize	mobile	-	0.5	2.0	6.5	15.0	35.0
	immobile	-	0.5	2.0	6.5	15.0	35.0

For potatoes and root vegetables translocation is the only important process in connection with radioactive materials deposited upon the plant. For the immobile elements, on the other hand, there is no translocation, and all activity is on the surface. This is evidently also true for maize, both for mobile and immobile elements. The "-"s show that the month is outside the growing season for that particular type of crop. But in the case of non-leafy vegetables (tomatoes, cucumber, cauliflour etc) it rather shows that the edible part of the plant has not yet started to develop in April.

3.6.3.3 Pasture.

Regular grazing is not included in the UFOMOD or ECOSYS calculations. The agricultural practice in Germany is evidently to harvest pasture after a growing period of about 45 days. There are three to four consecutive growing periods in a season. The grass that is fed to the cattle soon after harvest is considered as pasture in this connection.

The interception factor for pasture is a function of the time in the growing season. The interception factor when deposition takes place a time interval t (days) before harvest is described by the following equation, which is a well-known expression by Chamberlain:

$$IF(t) = \mu * (CM - g*t)$$

When it is considered that the daily increase in plant material (g) multiplied by the length of the growing period (45 days) must equal the crop yield per harvest (CM), it is seen that the equation above is quite similar to the one in chapter 3.6.3.1, and could have been written in much the same manner.

The contamination of plants harvested at time t (days) after deposition is given by the following equation:

$$R(t) = IF(t) * \exp(-(\lambda_i + \lambda_R)t)$$

The quantities in the equations are defined in the following:

IF(t)	interception factor (at time zero; time of deposition) for pasture harvested at time t (days) after deposition (Bq/m^2)/(Bq/m^2)
R(t)	fraction of radionuclide deposit remaining on vegetation at time t (days) after deposition (dimensionless)
μ	absorption coefficient (m^2/kg). The value $3.3 m^2/kg$ is used.
CM	crop yield, dry weight (per harvest). The value $0.2 kg/m^2$ is used.
g	daily increase plant material, dry weight ($kg/m^2 day$)
λ_i	weathering rate (per day). This part is somewhat different from the other computer programs. There are two weathering half-lives involved, but it is not a two-term expression. During the first 14 days the weathering has half-life 14 days and from day 15 till day 45 (harvest) it has half-life 28 days. The equation above is really valid only for periods up 14 days. For longer periods it must be multiplied by a correction factor of 0.705.
λ_R	radiological decay constant (per day)
t	time between deposition and harvest (days)

3.6.3.4 Stored forage.

Stored forage is harvested mainly in the months May, June and July. Monthly averaged contamination values are calculated for these months. Deposition, of course, can take place in only one of the consecutive growing periods, and after 45 days only root uptake is assumed.

3.6.4 Transfer from plants to milk and meat producing animals.

Dairy cattle is assumed to feed exclusively on pasture during that season, and stored forage outside the pasturing season. The feeding rate is assumed to be 65 kg (fresh weight) per day.

Beef cattle are fed stored forage (15 kg fresh grass-weight/day), grain (2 kg/day) and maize (12.5 kg/day).

Pigs are fed grain (1.5 kg/day) and potatoes (4 kg/day).

The activity concentration in milk and meat is calculated using time-dependent compartment models, but relatively simple ones. For the elements strontium and cesium simple transfer coefficients from intake to milk and meat are used, and it is assumed that the biological half-life is 1 day in milk and 30 days in muscle tissue. With these half-lives and the reductions assumed for weathering and dilution due to plant growth, maximum concentrations are reached at 7 and 30 days respectively. For iodine a more complicated model is used, with compartments for thyroid, blood and GI-tract, as well as separate compartments for organic and inorganic iodine. For iodine the biological half-life is assumed to be 0.8 days in milk, 105 days in beef and 70 days in pork.

The transfer coefficients used are given in the following table:

Nuclide	Transfer coefficient (d/kg or d/liter) to		
	Milk	Beef	Pork
Sr	0.0014	0.0003	0.003
Cs	0.0071	0.03	0.3
I	0.01	0.0072	0.027

3.6.5 Transfer from plant and animal food products to man.

In UFOMOD consumption rates are age-dependent, divided into six age-groups. The rates given in the reference material for Germany are given in the following table (Units: kg/year):

Food product	Age-groups (years)					
	0-1	1-4	5-9	10-14	15-19	≥20
Milk and milk products	210	80	90	100	110	115
Beef	5	10	10	15	15	20
Pork	0	35	45	55	60	70
Grains	10	35	55	65	80	95
Potatoes	5	15	20	30	40	70
Leafy vegetables	10	10	15	15	20	20
Non-leafy vegetables	10	20	25	25	25	25
Root vegetables	10	10	10	10	15	15

4 INHALATION OF RESUSPENDED RADIONUCLIDES.

Resuspension is the phenomenon of earlier deposited activity at some later time once more becoming air-borne. Most commonly this is assumed to be caused by weather, mainly wind. But it may also be caused by mechanical or human disturbance of the surface. The "resuspension" referred to in connection with the nutrition pathways is a somewhat different phenomenon; but mainly because of the difference in height above ground of the "receptor", which is various types of crops for the nutrition pathways, and the human respiratory system in the present connection.

The resuspension pathway is routinely calculated in quite a straightforward manner, in which it is assumed that there is a certain ratio between ground concentration and concentration in the air above the area. This factor is called the "resuspension factor". It is usually considered to be timevariant. Experiments show that resuspension is larger shortly after a deposition, and the reasons for the decrease, in addition to radioactive decay, are fixation of the radioactive materials to soil particles (or other ground materials like asphalt, concrete) and percolation out of the surface soil compartment. The inhalation phase of this exposure pathway may or may not take into account the respirability of the radioactive materials, which is the fraction of inhaled materials that actually reach the lungs; and reduction in concentration of radioactive materials in the air, caused by the fact that the larger part of the population spends most of the time indoors.

Inherent in the definition of the resuspension factor is the assumption that resuspension is a local phenomenon. Recent research indicates that this may not always be so.

The descriptions of reduction in resuspension factor with time always refer to soil. There may be other types of surfaces that are more important in connection with population doses, as the larger part of the population inhabit urban areas, where the surfaces to a large extent are different materials.

4.1 MACCS.

The manner in which the amount of inhaled activity via the resuspension exposure pathway is calculated in MACCS is: The initial ground concentration (Bq/m^2) is corrected for weathering and radioactive decay, then multiplied by a "resuspension factor", breathing rate and "inhalation protection factor". These are discussed in the following subchapters.

4.1.1 Resuspension factor.

The resuspension factor is defined as the ratio between the airborne resuspended radionuclide concentration (Bq/m^3) and the surface radionuclide concentration (Bq/m^2). The concentration of resuspended radionuclides in air must evidently be a function of the height above ground, and in connection with inhalation the interesting height will be some 170 cm for adults, and considerably less, of course, for children. This reference height is not, as far as I can see, mentioned anywhere in the MACCS documentation, and it must just be assumed that it is referred to a sensible height.

The resuspension factor is given as a function of time, since there is evidently an aging effect, caused by weathering and other processes. In MACCS the resuspension factor is defined by the following expression, which consists of a short-term (days), intermediate-term (weeks to months) and long-term (years) component.

$$\text{RF}(t) = 10^{-3} \exp(-250t) + 10^{-5} \exp(-0.68t) + 10^{-9} \exp(-0.007t)$$

The half-lives of these components are 1 day, 1 month (according to the Users Guide, but 1 year according to report NUREG/CR-4184) and 100 years respectively. t in the equation is measured in years.

In the Users Guide the term in front of the short-term component is 10^{-4} instead of 10^{-3} . This change and the change in intermediate-term half-life appear to have been made April 1988.

4.1.2 Breathing rate and inhalation protection factor.

For long-term inhalation of resuspended radioactive materials is used the average breathing rate, which is $2.66 \cdot 10^{-4}$ m³/sec.

Respirability of resuspended particles is discussed in report NUREG/CR-4184. This term refers to the impact of particles size on the distribution of radioactive materials in the respiratory system. The larger resuspended particles may not be expected to reach the lungs, but to be trapped in the nose, throat etc. However, the report concludes from experimental evidence that more than 50% of the particles in question would reach the lung, and MACCS does accordingly not use any correction factor to account for respirability in connection with resuspension.

The filtering effect of houses gives a reduction of particles in indoor air. In MACCS this inhalation protection factor is set equal to 0.5, but is used only for the short-time doses via this exposure pathway, according to report NUREG/CR-4184. This is somewhat strange, since the filtering effect should be equally relevant in the intermediate to long term. People mostly stay indoors, at least during the week. Filtering effect can, however, not be considered without also considering indoor deposition and indoor resuspension. New information on these phenomena has recently become available. In the Users Guide the following values for the inhalation protection factor are given:

Evacuation: 1.0 Normal activity: 0.75 Sheltering: 0.5

4.2 CRAC, CRAC2.

The resuspension pathway in CRAC and CRAC2 is calculated exactly as in MACCS, except that neither any correction for respirability of particles, nor any "inhalation protection factor", due to the filtering effect of houses, are considered.

4.2.1 Resuspension factor.

The resuspension factor is defined as the ratio between the airborne resuspended radionuclide concentration (Bq/m³) and the surface radionuclide concentration (Bq/m²). In CRAC and CRAC2 the resuspension factor is defined by the following

expression, which consists of a intermediate-term time-variant component, and a long-term constant component:

$$RF(t) = 10^{-5} \exp(-0.677t) + 10^{-9}$$

The half-life of the intermediate-term component is 1 year, and t in the equation is measured in years.

4.2.2 Breathing rate.

The value used for the average breathing rate in CRAC and CRAC2 is $7300 \text{ m}^3/\text{year}$, which is equivalent to $2.31 \cdot 10^{-4} \text{ m}^3/\text{sec.}$

4.3 ARANO.

ARANO does not contain models for calculation of inhalation of resuspended radioactive materials.

4.4 NECTAR.

NECTAR does not contain models for calculation of inhalation of resuspended radioactive materials.

4.5 NUCRAC.

The approach in NUCRAC to inhalation of resuspended radioactive materials is identical to the one used in CRAC and CRAC2.

4.6 UFOMOD.

The resuspension pathway in UFOMOD is calculated in much the same manner as in MACCS or CRAC and CRAC2. But no correction for respirability of particles, nor any "inhalation protection factor", due to the filtering effect of houses, are considered. In addition to reduction built into the definition of the resuspension factor, UFOMOD also applies a factor to account for leaching of deposited activity to deeper layers in the ground. This factor and the resuspension factor are multiplied.

4.6.1 Resuspension factor and leaching factor.

The resuspension factor is defined as the ratio between the airborne resuspended radionuclide concentration (Bq/m^3) and the surface radionuclide concentration (Bq/m^2). In UFOMOD the resuspension factor is defined by the following expression, which consists of a short-term time-variant component, and a long-term constant component:

$$\text{RF}(t) = 10^{-5} \exp(-1.62 \cdot 10^{-7} t) + 10^{-9}$$

The half-life of the short-term component corresponds to 50 days, and t in the equation is measured in seconds.

The leaching factor is given by the expression:

$$\text{F}(t) = 0.63 \exp(-1.5 \cdot 10^{-8} t) + 0.37 \exp(-2.38 \cdot 10^{-10} t)$$

Here also t is in seconds, and the half-life of the short-term component corresponds to 1.46 years, and of the long-term component to 93.6 years.

4.6.2 Breathing rate.

In UFOMOD the value $3.333 \cdot 10^{-4} \text{ m}^3/\text{sec}$ is used for the average breathing rate, and this is the same as the value used for inhalation from the passing cloud.

5 GROUNDSHINE.

At present all probabilistic risk assessment programs use basically the same approach to this exposure pathway. In this approach it is always assumed that the deposited radioactive materials are evenly distributed upon an infinite smooth, flat surface, representing the ground. Exposure to an individual is calculated using standard expressions, routinely used in radiation shielding. The ground concentration all over this surface is assumed to be the same as in the position of the individual.

Subsequently shielding factors are applied, partly to account for the fact that the surface in reality is not smooth, and partly to take the shielding effect of houses into account.

Groundshine is reduced with time, and not only because of radioactive decay. Percolation of the radioactive materials

into ground will give additional shielding, although this movement is very slow. This is not quite the same as percolation like it is described in connection with the nutrition pathways; which may also include irreversible binding to the soil and root uptake. In connection with groundshine it is the radiation field above ground that is important, and binding to the soil will not reduce this field. The best description of this reduction is still the one derived from the experiments described the following reference. As far as I know, this expression is still used in all consequence assessment codes.

Gale, H.J., Humphreys, D.L.O. and Fisher, E.M.R.: Weathering of Cesium-137 in Soil. *Nature*, 201, pp 257 - 261. 1964.

Long-term groundshine is dominated by the nuclide Cs-137, and the data given in this chapter refers to this nuclide only.

The conditions described in the preceding may be proper in rural areas. In urban areas, however, the surfaces are different, and the geometry is different. There is new evidence that the infinite surface may be far from reality even in rural areas. In many cases trees may actually contribute the larger portion of "groundshine", and not materials deposited upon ground.

5.1 MACCS.

The long-term groundshine dose commitment in the position (x,y) in the spatial grid, and from a specific nuclide, is in MACCS calculated from an expression of the form:

$$DLTG(x,y) = SF * \int_{t_b}^{t_e} GDF * GCL(x,y,t) * dt$$

where

$$GCL(x,y,t) = GC_0(x,y) * (A_1 * \exp(-\lambda_1 t) + A_2 * \exp(-\lambda_2 t)) * \exp(-\lambda_R t)$$

DLTG(x,y) probably is an abbreviation for Dose Long-Term Groundshine (Sv)

SF shielding factor (dimensionless)

GDF groundshine dose-rate factor (Sv/sec)/(Bq/m²)

GC₀(x,y) initial radionuclide concentration at position (x,y) (Bq/m²)

t_b and t_e	times for beginning and end of groundshine exposure
A_1 and A_2	fraction of deposit that is weathered quickly and slowly, respectively (dimensionless). Sum of these should be one.
λ_1 and λ_2	short-term and long-term weathering rates (per time unit)
λ_R	rate of radiological decay (per time unit)

The groundshine dose-rate factor is the dose-rate 1 meter above an infinite smooth plane contaminated with 1 Bq per square meter. This simplification can be used, since under most relevant conditions the size of the radioactive plume causing the contamination is large compared to mean-free-path of gamma radiation in air.

From the Users Guide:

The values used in the MACCS sample problem to calculate weathering are:

$A_1 = 0.65$	$A_2 = 0.35$
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Instead of the lambda-values are given the corresponding half-lives:

$T_{half_1} = 219$ days	$T_{half_2} = 32850$ days
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The shielding factor used is: $SF = 0.33$

REMARK: The parameter values used in MACCS differ slightly from the ones in CRAC/CRAC2. This easily gives the impression that new information upon this point has become available since development of CRAC/CRAC2, but this is not the case. It is better to stick to the old values until there is a real reason for changing them.

5.2 CRAC, CRAC2.

The approach is identical to the one used in MACCS, including the use of the infinite smooth plane approach, corrected by a shielding factor to account both for surface roughness and shielding provided by houses.

The parameter values are:

$$A_1 = 0.63 \qquad A_2 = 0.37$$

Instead of the lambda-values are given the corresponding half-lives:

$$T_{half_1} = 224 \text{ days} \qquad T_{half_2} = 33726 \text{ days}$$

$$\text{The shielding factor used is:} \qquad SF = 0.33$$

5.3 ARANO.

Groundshine is included in the ARANO code in much the same manner as in MACCS. Detailed information on this aspect has not been received.

5.4 NECTAR.

Groundshine is included in the NECTAR code, but the received documentation contains no information on this aspect.

5.5 NUCRAC.

The approach in NUCRAC to groundshine is identical to the one used in CRAC and CRAC2.

5.6 UFOMOD.

In UFOMOD long-term groundshine exposure is calculated by the following expression:

where

DGR(o,n,IZINT)	groundshine dose for organ o, nuclide n (Sv)
IZINT	upper end of integration time (years)
AG(n)	initial concentration of activity deposited upon ground (Bq/m^2)
DCFGR(o,n,IZINT)	doseconversion factor for the groundshine exposure pathway ($\text{Sv}/(\text{Bq/m}^2)$)
AFLATE(GR)	average shielding factors for the groundshine exposure pathway (dimensionless)

The description of this pathway is very brief, and contains no numerical information. It is assumed that the initial contamination is at a depth of 2-4 mm, and effects of surface roughness and of diffusion into deeper layers of soil are included in the dose conversion factors. The population can be divided into five classes, and each of three of these classes can be assigned its own shielding factor to account for the shielding effect of houses etc. (The last two classes are reserved for people evacuating the two defined evacuation areas by cars, and are not relevant in the present connection.)

6 WATER PATHWAYS.

6.1 MACCS.

It is assumed that the strontium and cesium isotopes are likely to dominate exposure via the water pathways, and only these isotopes are included in the model. MACCS always assumes that release is to the atmosphere. Direct liquid release to water bodies are not considered.

In the model used in MACCS radioactive materials can be introduced into water bodies by direct deposition or by wash-off from surrounding land areas. Only fresh-water bodies are considered.

Human exposure is via drinking water or via aquatic food.

In this model each watershed is treated separately, and each watershed must belong to a "watershed class". For each watershed class the parameters needed in the calculations are defined in the Site Data File. Each interval in the spatial grid must be assigned to one of the watershed classes. For each of these intervals is also given the "fraction of land", which is used in the wash-off calculations (but also in the nutrition pathway calculations). One minus the "fraction of land" is used in the direct deposition upon waterbodies calculations. There are potential problems here when the part of a grid element that is not land, is ocean and there should be no exposure via the water pathways. However, it can be managed by assigning artificial values to the watershed class parameters.

The water pathways model is quite simple, and described (for a specific nuclide and watershed class) by the equations:

$$LPPD = ST * TF$$

$$ST = GC(x,y) * A(x,y) * (LF(x,y) * WF + (1-LF(x,y)))$$

$$TF = IGDF * (PE_{dw} + PE_{af})$$

where

LPPD	liquid pathway population dose (Sv)
ST	source term for the particular nuclide and watershed (Bq)
TF	transfer factor (Sv/Bq)
GC	ground concentration (Bq/m ²). (x,y) refer to the spatial grid element
A	area of the grid element (m ²)
LF	land fraction (dimensionless)
WF	wash-off fraction (dimensionless) (see chapter 6.1.2)
PE _{dw}	drinking water exposure per "unit deposition into the water body" (Bq ingested/Bq deposited)
PE _{af}	aquatic food exposure per "unit deposition into the water body" (Bq ingested/Bq deposited)

6.1.1 Direct deposition.

The part of the source term to the watershed that is direct deposition upon the water surfaces, is simply the ground concentration times the size of the grid element times the fraction of this area that is water. Here is the inherent assumption that deposition upon water and land surfaces are identical. This is true for wet deposition, but not for dry deposition. A significant overestimation of this part of the source term may result.

The only input parameters needed are the area of each spatial grid element and the fraction of each element that is water.

6.1.2 Wash-off.

The part of the source term to the watershed that is wash-off is calculated just like the direct deposition component, but in addition the term is multiplied by a wash-off fraction. The wash-off fraction is given by the following equation:

$$WF = (\lambda_a \lambda_R + \lambda_b) X_O / (\lambda_R + \lambda_b)$$

where

λ_a	initial wash-off fraction (dimensionless)
λ_b	long-term wash-off rate (per year)
λ_R	radionuclide decay rate (per year)
X_O	atmospheric deposit to land (Bq)

REMARK: I don't think the quantity "atmospheric deposit to land" should be included in the expression for WF. It must really mean the same as "ground concentration" multiplied by "area of grid element" multiplied by "land fraction", and this is already in the expression for the source term in chapter 6.1. As it is written now, the amount of deposited radioactive materials is multiplied by itself for the wash-off component.

The expression for the wash-off fraction is derived from two assumptions:

- An initial fraction (described by λ_a) is washed off "immediately".

- The remainder is washed off with a constant rate (described by λ_b).

One weakness of this approach is that it is assumed to be independent of the deposition conditions. It is certain that at least the initial fraction will differ significantly between dry deposition conditions and heavy rain.

In the description it is said that the approach is conservative, since only radioactive decay is taken into consideration in addition to the wash-off processes. Chemical binding to the soil is neglected in this connection. Chemical binding may, however, not be very important, as much of the long-term wash-off is displacement of soil particles.

In the Users Guide the initial fraction for wash-off is set equal to 0.02, and the rate of long-term wash-off is 0.005 per year.

6.1.3 Drinking water.

Population exposure via drinking water is described by the equation:

$$PE_{dw} = IWC * WT * WC * POP_{dw}$$

where

IWC	average integrated radionuclide concentration for the waterbody per "unit deposition of radionuclide" (Bq-year/m ³ per Bq deposited)
WT	water treatment factor (dimensionless)
WC	water consumption per person and year (liter/year)
POP _{wc}	size of the population receiving drinking water from the water body

From the Users Guide it is apparent that in designing the program one has chosen a much simpler approach than the one described in the above, and in the following chapter for aquatic food. The parameter "Ingestion factor" (WINGF) is used to describe the combined impact of drinking water and aquatic food. WINGF is (Bq ingested)/(Bq entering water). Water treatment factors, water consumption, concentration of radionuclides in water, concentration factor to fish, annual production of fresh-water fish etc are not part of input to the computer program, but are presumably used in calculating WINGF. In the problem in the Users Guide $WINGF = 10^{-6}$.

6.1.4 Aquatic food.

Population exposure via aquatic food is described by the equation:

$$PE_{af} = IWC * CR * FP$$

where

IWC average integrated radionuclide concentration for the waterbody per "unit deposition of radionuclide" (Bq-year/m³ per Bq deposited)

CR concentration factor for fish relative to water (Bq/kg)/(Bq/m³)

FP annual production of fresh-water fish from the waterbody (kg/year)

See chapter 6.1.3 for the approach described in the Users Guide.

6.2 CRAC, CRAC2.

There are no water pathways in CRAC or CRAC2.

6.3 ARANO.

There are no water pathways in ARANO.

6.4 NECTAR.

The received documentation on NECTAR contains no information about water pathways, and I am rather certain that no such pathways are included in the code.

6.5 NUCRAC.

There are no water pathways in NUCRAC.

6.6 UFOMOD.

There are no water pathways in UFOMOD.

7 COMPARISONS.

Originally the plan was that the differences between the numerical values used in the different programs should be summarized in this chapter, and used to compare the different programs. As the assignment progressed, it became apparent that this would not be so simple, because of the many basic differences between the programs. It was also found that differences in numerical values for selected parameters could say little about the differences to be expected in the end results.

Qualitative comparisons of the types of models used in the different programs are found throughout the text of the report. Some weaknesses and strengths of the various models are pointed out. It is clear from the text that the models vary much in degree of complexity. And it is natural to have more trust in the more complex programs, since it is generally expected that a more complex model is closer to reality. It is not possible, however, just from reviewing the models to have any certain opinion of whether one program will over- or under-estimate doses or risks relative to another program. The ideal manner in which to compare different programs would be to run a couple of sample problems with all, but this is clearly outside the scope of the present assignment.

A few interesting aspects of some of the programs are summarized in the following:

Percolation rates and root uptake rates for pasture, Cs:

	MACCS	CRAC/CRAC2	NUCRAC	UFOMOD	ARANO
Percolation rate (per year)	0.0021	0.949	0.04	0.0139	0.00693
Root uptake rate (per year)	0.000083	0.0023	0.000083	0.000073	-

Percolation rates and root uptake rates for pasture, Sr:

	MACCS	CRAC/CRAC2	NUCRAC	UFOMOD	ARANO
Percolation rate (per year)	0.0096	0.105	0.04	0.0888	0.00693
Root uptake rate (per year)	0.0017	0.0515	0.0017	0.00036	-

In ARANO the root uptake rates are built into the "activity integrals", which contain both root uptake and direct deposition. In the NECTAR documentation are given root uptake rates for Pb, Bi and Po only.

Similar tables could be put together for other crops.

The time distribution of root uptake in MACCS and CRAC/CRAC2:

The time-integrated transfer factor via root uptake over the time period t_1 to t_2 is:

$$\begin{aligned} \int_{t_1}^{t_2} TF(t) dt &= \int_{t_1}^{t_2} (\lambda_{RU} \exp(-(\lambda_R + \lambda_L)t)) dt \\ &= \frac{\lambda_{RU}}{\lambda_R + \lambda_L} [\exp(-(\lambda_R + \lambda_L)t_1) - \exp(-(\lambda_R + \lambda_L)t_2)] \end{aligned}$$

In MACCS, for Cs-137 (this comparison is based upon the information that was given with the original documentation. It has since been changed):

$$\lambda_R = 0.023/\text{year}, \quad \lambda_L = 0.0021/\text{year}, \quad \lambda_{RU} = 0.000031/\text{year}$$

$$\int_{t_1}^{t_2} TF(t) dt = 0.000518 (e^{-0.0251t_1} - e^{-0.0251t_2})$$

t_a	$e^{-0.0251t_a}$	$0.000518 e^{-0.0251t_a}$	$\int_{t_1}^{t_2} TF(t) dt$	
0	1	0.0005180	0.0000129	2.5%
1	0.9752	0.0005051	0.0000124	2.4%
2	0.9510	0.0004927	0.0000123	2.4%
3	0.9275	0.0004804	0.000235	4.5%
5	0.8821	0.0004569	0.0000539	10.4%
10	0.7780	0.0004030	0.0000895	17.3%
20	0.6053	0.0003135	0.0000695	13.4%
30	0.4710	0.0002440	0.0000963	18.6%
50	0.2851	0.0001477	0.0001056	20.4%
100	0.0813	0.0000421	0.0000387	7.5%
200	0.0066	0.0000034		
				99.4%

In CRAC and CRAC2, for Cs-137:

$$\lambda_R = 0.023/\text{year}, \quad \lambda_L = 0.949/\text{year}, \quad \lambda_{RU} = 0.0023/\text{year}$$

$$\int_{t_1}^{t_2} TF(t) dt = 0.002366 \left(e^{-0.972t_1} - e^{-0.972t_2} \right)$$

t_a	$e^{-0.972t_a}$	$0.002366 e^{-0.972t_a}$	$\int_{t_1}^{t_2} TF(t) dt$	
0	1	0.002366	0.001471	62.2%
1	0.3783	0.000895	0.000556	23.5%
2	0.1431	0.000339	0.000211	8.9%
3	0.0541	0.000128	0.000110	4.6%
5	0.0078	0.000018	0.000018	0.8%
10	0.000006	0.00000001		
				100.0%

The large difference in time distribution is apparent.