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REPORT

Urban Contamination and Dose Model

by

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URBAN CONTAMINATION AND DOSE MODEL

A report prepared by E. Robertson and P.J. Barry, AECL Research, Environmental Research Branch, Chalk River Laboratories, under contract to the Atomic Energy Control Board.

ABSTRACT

Nuclear power reactors and other nuclear facilities are being built near or even within urban centres. Accidental releases of radionuclides to the atmosphere in built-up areas result in radiological exposure pathways that differ from those caused by releases in rural environments. Other than inhalation, exposure pathways involve external radiation from the plume while it passes and from radioactivity deposited onto the many and varied surfaces after it has passed. Radiation fields inside buildings are attenuated but many people are potentially exposed so while individual doses may be relatively low, population integrated doses may be high enough to cause concern. It is important, therefore, to assess the potential exposures and to estimate the cost-effectiveness of dose reduction measures in urban environments.

This report describes a model developed to help carry out such assessments. The model draws heavily on experience gained in European cities after their contamination fallout from the Chernobyl accident. Input is time integrated concentrations of specific radionuclides in urban air, obtained either by direct measurement or by prediction using an atmospheric dispersion model. The code includes default values for site specific variables and transfer parameters but the user is invited if desired to enter other values from the keyboard. Output is the time integrated dose rates for individuals selected because of their characteristic living, working and recreational habits.

An accompanying manual documents the technical background on which the model is based and leads a first-time user through the various steps and operations encountered while the model is running.

RÉSUMÉ

Des réacteurs et d'autres installations nucléaires ont été construits à proximité ou même à l'intérieur d'agglomérations urbaines. Les voies de transfert des rejets accidentels de radionucléides dans l'atmosphère des régions habitées sont différentes de celles que suivent les rejets en milieu rural. Outre l'inhalation, les voies de transfert comportent la radioexposition externe causée par le passage du panache et par la radioactivité qui se dépose sur les surfaces nombreuses et variées au cours de son passage. Les champs de rayonnement à l'intérieur des bâtiments sont atténués, mais beaucoup de gens risquent d'être exposés et c'est pourquoi, même si les doses individuelles peuvent être relativement faibles, les doses d'irradiation totale reçues par toute la population peuvent être assez élevées pour inquiéter.

Il importe donc d'évaluer les expositions possibles et d'estimer la rentabilité des mesures de réduction des doses en milieux urbains.

Ce rapport décrit un modèle mis au point pour aider à effectuer de telles évaluations. Le modèle s'inspire beaucoup de l'expérience acquise dans les villes européennes contaminées par les retombées de l'accident de Tchernobyl. Les données d'entrée sont les concentrations intégrées dans le temps de radionucléides particuliers dans l'air urbain, obtenues soit par mesure directe, soit par prévisions basées sur un modèle de dispersion atmosphérique. Le code comporte des valeurs implicites pour des variables spécifiques aux sites et des paramètres de transfert, mais le système invite l'utilisateur à entrer lui-même d'autres valeurs s'il le souhaite. Les données de sortie sont les débits de dose intégrés dans le temps dans le cas d'individus choisis en fonction de leurs habitudes de vie, de travail et de loisirs caractéristiques.

Un manuel d'accompagnement décrit le contexte technique sur lequel s'appuie le modèle et aide le nouvel utilisateur à franchir les diverses étapes et à effectuer les opérations nécessaires pendant l'exécution du modèle.

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PART A - URBAN CONTAMINATION AND DOSE MODEL

INTRODUCTION

Derived release limits for airborne radionuclides (other than noble gases) from nuclear reactors under normal operating conditions have been calculated on the basis that inhalation and ingestion of agricultural foodstuffs are the critical pathways. Similarly for accidents, containment specifications have been based on inhalation of and on external radiation from the passing cloud. In neither case has an urban environment been explicitly considered, though of course, the critical groups inhaling contaminated air or being exposed to external sources could include urban dwellers.

Two factors have arisen lately which suggest that this traditional approach to licensing needs re-appraising. The nuclear generating stations in Southern Ontario are becoming increasingly encroached upon by urban development, while studies in several countries following the Chernobyl accident have shown the urban environment to possess unique and potentially important exposure pathways. For example, Sandalls and Gaudern (1988) report that heavy rainfall while the plume from Chernobyl was passing led to significant deposition of radiocaesium on common urban construction materials in Northwest England. They report furthermore, that 20 weeks later as much as two-thirds was still being retained. Such deposited material is an ongoing source of external exposure to possibly large numbers of people. Sandalls and Gaudern suggest that the need for forced decontamination methods should be considered in nuclear accident contingency planning.

Radionuclides are deposited by wet and dry deposition onto various urban surfaces e.g., roof tops, walls, roads, lawns, trees, etc. There they are retained for variable periods after the plume has passed and contribute to external dose rates. The deposited radionuclides are removed from the contaminated surfaces by

1) radioactive decay
2) wash off
3) weathering
4) infiltration to soil or buildings
5) resuspension

These processes result in a decrease in external dose but, with the exception of radioactive decay, the radionuclides are conserved and transferred to another environmental compartment. For example radionuclides that are washed off roofs or pavement will run off via sewers to surface waters. Those that infiltrate the soil may be returned to the surface when the ground is tilled or excavated, or they may eventually reach the ground water. Radionuclides resuspended by the action of wind, or of vehicles and of mechanical sweepers in spring, may result in inhalation doses prior to their redeposition. Accumulation during a winter followed by spring melt means relatively large amounts of radioactivity become available to surfaces in a short time span.

Studies of run-off from weathering of roof material also have shown that the wash-off process is generally slow for caesium and ruthenium. This highlights the possible need for forced decontamination in a heavily polluted situation (Roed 1987b). Equations and parameters have been developed for use in models designed to describe these processes (Roed 1988a). However, before applying these procedures, the consequent doses arising from the alternate routing of the radionuclides should be known so that the net benefit can be assessed. If chemical decontaminating agents are used, the toxic effects of these, not only on man but on biota as well, must be assessed.

In the urban environment contamination of both indoor and outdoor air must be considered. During passage of the plume, buildings provide shelter from external radiation. They also reduce the concentration of radionuclides in the indoor air relative to that outside because of the relatively slow leakage of outdoor air into the building and the filtration provided by deposition onto the walls of cracks and onto internal surfaces of the building.

This report discusses processes and dosimetry used in the computer code CHERURB which has been written to model the contamination of urban surfaces during passage of a radioactive plume and the resulting inhalation and external doses, as well as external dose rates, after the plume has passed.

In addition, the package consists of a bibliography, a detailed User's Guide, which describes the main features of the model and code, and two 5.25" disks. One contains the executable code for an IBM or IBM compatible machine and sample input data files, and the other contains the source code written in FORTRAN-77. Instructions for running the executable code are in the User's Guide.

BACKGROUND

Estimating the doses to which people would be exposed as a result of radioactive contamination of surfaces was formerly inspired by the threat of nuclear war. Interest in the subject as it might affect urban environments following an accident to a nuclear power generating station was revived in the mid-80's. For example in 1985 one session at a major international workshop on methods for assessing the off-site radiological consequences of nuclear accidents was devoted to the subject.

Further interest was stimulated following the Chernobyl accident in 1986. Levels of activity deposited on a variety of urban surfaces were measured and the subsequent loss by weathering of different isotopes was monitored in several European countries in order to evaluate transfer parameters for the urban environment. At this time, laboratory and field experiments were started to determine the efficiencies of various decontamination procedures.

The MARIA project (Methods for Assessing the Radiological Impacts of Accidents) was started by the European Economic Commission in 1983 to run for 2 years. In March 1985, 1 year before the Chernobyl accident, the original MARIA project was replaced by the enlarged MARIA 2. This consisted of 18 research projects involving 116 man-years of effort at 16 European installations. In MARIA 2 "a great effort is being made in the study of the pathways and systems pertaining to the urban environment. Five research groups are involved". (Finzi et al. 1987). After the Chernobyl accident changes were made to MARIA 2 to include "the improvement of practical countermeasures against nuclear contamination in the urban environment". At the same time it was said "...a more fundamental approach aiming at a better understanding of the processes of deposition and fixation of the contaminants on urban surfaces is believed to be essential". (Finzi et al. 1987). As an example of the response to this initiative, a statistical survey of housing characteristics in the surroundings of nuclear power plant sites has been carried out in France to assess the shielding provided by the building fabric (LeGrand et al. 1987).

In 1988, the International Atomic Energy Agency (IAEA) launched a Coordinated Research Program called Validation of Models for Transfer of Radionuclides in Terrestial, Urban and Aquatic Environments (VAMP). The aim of VAMP is to use the extensive data sets generated following the Chernobyl accident to test or validate biosphere transport models. VAMP has four themes of which contamination of the urban environment is one. With the code developed under this contract it will be possible to participate in this theme.

We have been able to find only one model of urban contamination. This is the National Radiological Protection Board (NRPB) code EXPURT (Hill 1989). We understand that several other codes are being written[1] and expect the VAMP program will stimulate additional work by a wide range of groups and institutes.

LITERATURE REVIEW

Most of the literature on urban contamination processes has been written since the Chernobyl accident though the classical papers on external dosimetry are still referenced. Most of the recent literature has originated from work done in Europe. For this reason many parameter values for use in the mathematical descriptions are appropriate to European construction materials and may not be valid for the Canadian urban environment. Some processes of interest in Canada have not been addressed at all. One of these is the effect of snow cover at the time of the accident on the deposition processes and the subsequent fate of

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[1]Since this was written, we have received a report "TACTUS - A code for Simulation of Flow of Caesium-137 in Urban Surroundings". K.G. Andersson, Riso National Laboratory, Denmark. Int. Symp. on Recovery Operations in the Event of a Nuclear Accident of Radiological Emergency. IAEA, Vienna, 6-10 November 1989.

the radionuclides during and after snowmelt. Another hitherto neglected process of possible importance but one not unique to Canada is the tracking indoors of contamination deposited on the streets and lawns.

All the literature found and consulted in the course of this work is referenced in the bibliography. The literature has been searched to obtain:

(a) information about contamination and weathering processes,

(b) values for the various parameters used in the mathematical descriptions,

(c) dosimetric models for use in the urban environment.

For the various parameters, values that seem to be most appropriate have been selected as defaults in the model code. The user may wish to explore the implications of values other than the defaults, and to guide him in selecting these, averages and the ranges of values found in the literature are given, with references, in easily consulted tables in the User's Guide.

MODELLING

1. Objectives. The ultimate objective is to code a model of urban contamination that can be used to:

(a) Calculate the doses to people from inhaling the contaminated air and exposure to the plume.

(b) Calculate the time-integrated external doses to people due to the radioactivity deposited on urban surfaces.

(c) Calculate the time-integrated external doses due to deposited radioactivity after applying forced decontamination procedures. This, combined with the results of (b), will enable the benefits of various decontamination procedures to be assessed.

(d) Calculate the doses arising from the run-off of radioactivity into the storm sewers and the consequent contamination of lakes and rivers. This is particularly important to calculate after the radioactivity is desorbed from surfaces by decontamination procedures.

Only objectives (a) and (b) have been attempted here. The duration of this contract did not allow for the further work to be included. However, it is evident too that relatively little information is currently available in the literature to enable objectives (c) and (d) to be addressed at a useful level. Furthermore, it is useful to determine from the use of the code developed here whether a more detailed and comprehensive model is needed.

2. Limitations. The literature has many gaps. Most of the parameter values to be found are for ^{137}Cs and ^{131}I. For example, the number of deposition velocity measurements found in the literature may be ranked $^{137}Cs > ^{131}I >> ^{103}Ru >> ^{106}Ru >> ^{238}U$.

DOSIMETRY

In the following section three ways of calculating doses due to deposition of radionuclides onto urban surfaces are discussed:

(a) a shielding model based on the point-kernel method and build-up factors

(b) a shielding model using Monte-Carlo simulations of photon absorption and scatter

(c) using measured or calculated shielding factors for representative structures and the dose-rate in air at 1 m above a uniformly contaminated infinite plane.

Three point-kernel shielding models have been found in the literature. They are GRINDS developed by the NRPB in the United Kingdom (Crick & Dimbylow 1988) DEPSHIELD by Riso in Denmark and QAD-CG-E by KfK, F.R.G. (Graf 1985).

In GRINDS, a structure may be specified in three-dimensional space by defining the positions and composition of walls and the size and positions of windows and doors. The dose rate to a point in the XYZ coordinate system is calculated for a given source distribution e.g., contaminated roof or walls or surrounding land surface. A shielding factor is defined as the ratio of the dose rate at the given point inside the building to that outside and in the open. The distribution of dose rates within the building can be calculated by repeatedly running the code. GRINDS is run to obtain shielding factors which are then passed to the urban contamination model - EXPURT.

The point-kernel model tends to under-estimate dose rates. This is particularly so where much of the exposure is to scattered radiation e.g., in the basements of buildings where error can range up to a factor of 10. However, these cases tend to be in low dose rate situations so the error is not too serious.

To overcome the problem, a Monte Carlo simulation model, SAM-CE, has been developed in the U.S. This approach also allows for more realistic but more complex types and arrangements of buildings and their surroundings. However, computing times are long. For a single deposition area and a single mono-energetic photon, 10 hours of CPU time are required on a computer with 3 Mips and 8 MBytes of main-storage.

The third and largely empirical method is simpler and easier to set up. It lacks flexibility in that the shielding factors have only been evaluated for a limited variety of building types and construction. The principal of the method is described by the equation

Dose Rate to Tissue = Reference Dose Rate x
age factor x
roughness factor x
occupancy factor x
shielding factor x
contamination levels on surfaces.

The reference dose is the dose rate to an adult at 1 m above an infinite uniformly contaminated smooth surface. The age factor is a function of age. It has the value 1.0 for adults; for children its value is calculated from the formulae

$$DCF_d = 1.77 - 0.0405A \text{ for deposited activity and} \quad (A.1)$$

$$DCF_{im} = 1.56 - 0.0265A \text{ for exposure to the cloud or plume} \quad (A.2)$$

where A is the age in years ($0 \leq A < 20$).

These formulae were developed for this report from Fig. 6 in Jacob and Meckbach (1987). The average value of the DCF for childhood is 1.39.

The roughness factor takes account of the shielding afforded by roughness elements of real surfaces.

The occupancy factor is the fraction of the time a person spends in a given situation. The total dose rate will be the sum of the rates appropriate to each exposure situation weighted by its occupancy factor.

The shielding factor is the fraction of the outdoor dose rate to which a person in a building would be exposed. Other terms used for this factor are dose reduction factor and location factor. The most commonly used "shielding factor" can be confusing. Thus heavy shielding is associated with a small value of the shielding factor, opposite to the expectation. The terms "dose reduction factor" or "location factor" are to be preferred but shielding factor is so entrenched in the literature it will be used here.

Obtaining shielding factors from the literature has proved more difficult than was expected. While there are many papers giving calculated and measured values, close inspection reveals that the shielding factors are for either "typical" mixtures of radionuclides or the surfaces are assumed to have "typical" contamination levels.

For example, the often quoted values given by Burson and Profio (1977) are for source spectra based on "the PWR category 2 accident, at 10 miles from the plant, under average dry meteorological conditions". Thus these values are for a specific mix of radionuclides and for specific depositions from that mix.

Meckbach et al (1988) using a Monte-Carlo simulation code have given data from which shielding factors can be calculated for specific energies but only for a few European building types in highly specific urban landscapes. The values given would not be appropriate for general use in the present code; but it is useful to see the nature and size of the effects that can occur because of the settings. Tables A.1 and A.2 have been calculated from their Tables 5 and 6. They are for mono-energetic photons of 0.3 Mev and 0.662 Mev respectively.

Table A.1

Shielding factors for a semi-detached house and for various deposition areas

- Source: 0.3 Mev photons.

	Shielding factors - locations				
Deposition Area	Outside (side)	Outside (back)	Ground floor	1st floor	Basement
Ground (without neighbouring buildings)	0.82	0.85	0.072	0.066	$8x10^{-5}$
Ground (with neighbouring buildings)	0.56	0.74	0.048	0.040	$2.7x10^{-5}$
Neighbouring buildings	0.17	0.048	0.0096	0.013	$8x10^{-6}$
Trees	0.08	0.10	0.011	0.008	$1.1x10^{-5}$
Roof	0.002	0.006	0.024	0.069	$2.9x10^{-4}$

The pair of semi-detached houses is 16 m long and 14 m deep. It is separated from neighbouring units, at the side by 7 m, at the front by 19 m, and at the back by 33 m. There are 4 trees at the front, 2 down each side and 6 in the space behind. The effects of the neighbouring buildings are at once evident (compare rows 1 and 2 of the table); though when the contribution from the deposits on the neighbouring buildings is added (Row 2 + Row 3) the effect is relatively small. Hence the effects of setting the house in a typical suburban scene compared to an isolated house in an infinite area (i.e., radius of about 500 m) are relatively small compared to the other uncertainties. Furthermore for the two photon energies shown the value of the shielding factor is not very energy dependent.

Thus for the present purposes, the shielding factors given by Burson and Profio (1977) have been used in the code. Their Fig. 3 showing the logarithm

Table A.2

Shielding factors for a semi-detached house for various deposition areas

- Source: 0.662 Mev photons.

	Shielding factors - locations				
Deposition Area	Outside (side)	Outside (back)	Ground floor	1st floor	Basement
Ground (without neighbouring buildings)	0.79	0.82	0.093	0.081	1.5×10^{-4}
Ground (with neighbouring buildings)	0.53	0.71	0.058	0.048	1×10^{-4}
Neighbouring buildings	0.15	0.044	0.0012	0.013	2.4×10^{-5}
Trees	0.074	0.095	0.013	0.01	4.2×10^{-5}
Roof	0.003	0.006	0.025	0.075	8.8×10^{-4}

of the dose reduction factor as a decreasing function of the mass thickness of the walls and roof of the structure has been approximated by a series of equations of the form

$$SHF = \exp[-(a + bM)] \quad (A.3)$$

where SHF is the shielding factor, a and b are constants that vary with the size of the building and M is the mass thickness of the walls and roof ($g.cm^{-2}$) (see Table A.3).

In very simple models a single shielding factor is used for all situations e.g. 0.4 from CSA Standard (CAN/CSA - N288.1 - M87) and 0.5 for DOSE-MARC from NRPB (UK). When the outputs of EXPURT and DOSE-MARC were compared by Crick, Brown, Hussain and Walmsley (1987) they stated: "We draw the conclusion from this that, at present, at least for this rather limited study, there is no definite benefit to be gained in using EXPURT routinely, compared with the use of the DOSE-MARC methodology assuming SF = 0.1 ".

Table A.3

Values for the constants in the equation for calculating the shielding factor (SHF) from the mass thickness (M) of the walls and roof of a structure [SHF = exp(-(A+BM))]

Size	Deposition	A	B
10'x10'	Roof Only	2.765	0.0433
20'x20'	"	2.040	0.0475
30'x30'	"	1.609	0.0535
40'x90'	"	1.470	0.0523
10'x10'	Roof + Ground	0.315	0.0447
20'x20'	"	0.357	0.0460
30'x30'	"	0.386	0.0484
40'x90'	"	0.511	0.0509

Notes:

Light Construction Wood Frame	$M = 5 - 15\ g \cdot cm^{-2}$	$(10 g \cdot cm^{-2})$
Medium Construction Brick Veneer	$M = 30 - 35\ g \cdot cm^{-2}$	$(32 g \cdot cm^{-2})$
Heavy Construction Stone Block etc. (up to 2 floors)	$M = 35 - 50\ g \cdot cm^{-2}$	
(over 2 floors)	$M = 50 - 70\ g \cdot cm^{-2}$	

To include effects of external contamination of walls treat as ROOF ONLY.

Nevertheless the object here has been to produce a flexible code with which a user can investigate the effects of changing parameter values and release scenarios. Therefore a general formulation for the code has been adopted even though at present limitations in knowledge of parameter values may not seem to justify inclusion of some processes.

Another difficulty that has arisen is the dose to children following inhalation. Dose conversion factors are available only for 1 year-old infants and adults. The code currently gives the same dose, i.e., that for the 1 year-old infant, to all children irrespective of age. The user is asked to state the age of the child, but this information is used only for calculating the dose to children at specific ages from external γ-ray sources.

RECOMMENDATIONS

It is important with any model code to maintain it and keep it updated to the current state-of-the-art. This is particularly important here, where several important pieces of information are missing but some can be reasonably expected to become available in the near future. This is a fast moving field and opportunities for model validation will soon be available in the VAMP program of IAEA. The additional work to include objectives (c) and (d) above should be carried out to complete the code.

It is evident that many parameter values appropriate to Canadian construction materials are missing. The present code should be run systematically to determine to which parameters are the predicted doses most sensitive. It will then be possible to plan a useful program of study to supply the missing information. Options for deposition to, and run-off from, accumulated snow should be included in the next version of the code. Decontamination procedures suitable for the Canadian urban scene should be developed.

A high-quality dosimetric model is needed for better assessment of the doses to which urban dwellers will be exposed if an accidental release of radioactivity occurs. The model should be detailed and flexible enough to handle a wide variety of urban landscapes reliably.

Finally the present code should be modified to include facilities for uncertainty estimation. Time constraints did not allow for this feature to be included in the present code.

PART B - Chalk River Environmental Research Urban Contamination Model (CHERURB)

User's Guide

CHERURB is one of a suite of models designed to assess the doses and dose rates to which people may be exposed following releases of radionuclides to specific compartments of the biosphere, in this case, the urban environment. It does this using as input data real-time concentrations of radionuclides in air and amounts of precipitation. The air concentrations would normally be measured values but may also be obtained using an atmospheric dispersion model.

PROCESSES AND CONCEPTS

The processes and concepts that are included in CHERURB are conveniently considered in two groups, those operating during the contamination phase when a plume is passing and the post-contamination phase after the plume has passed.

A: Contamination Period:

1. Deposition of radionuclides from air to urban surfaces occurs by dry and wet deposition processes.

By definition, daily dry deposition DDEP is

	DDEP	=	$Ca \cdot Vg \cdot 8.64 \times 10^4$
where	Ca	=	air concentration ($Bq \cdot m^{-3}$)
	Vg	=	deposition velocity ($m \cdot s^{-1}$)
	8.64×10^4	=	seconds in a day

The deposition velocity, Vg, is a function both of the radionuclide and of the surface. In this code, a fraction (FM) of the material deposited by dry deposition is assumed to be initially mobile. This part of the deposited material is readily removed by rain but, in the absence of rain, a fraction (FM2FS) becomes fixed each day.

For wet deposition

The daily rate of radionuclide deposition from the air by rain is described by a washout coefficient, which is a function of the radionuclide considered. Thus for wet deposition

	WDEP	=	$Ca \cdot W \cdot P$
where	W	=	washout coefficient (m^3 air/m^3 rain)
	P	=	rain ($mm.d^{-1}$)

The code adopts a concept used in EXPURT (Crick et al. 1987) which assumes that different surface types retain varying amounts of water before run-off occurs. This is defined as a critical amount of precipitation (CAP) which does not run off and deposits all the radionuclide that it holds on to the surface. Precipitation in excess of the critical amount runs off and also washes mobile deposit from the surface. This critical amount may also be a function both of the surface and of the radionuclide. Values of 3 mm and 1 mm have been suggested for pervious and impervious surfaces respectively (Schwartz 1985), but work by Roed (1987b) shows that CAP may approach zero for silicon-treated roofs. Furthermore, Ritchie (1976) and others assume that the concentration of the run-off water is the same as that of the rain, but Roed (1987b) has found that while this is the case for I-131, up to 70% of wet deposited Cs and 50% of ruthenium is retained by roofing materials. The code thus includes a parameter for the fraction of wet deposited isotope that is retained by surfaces (FWRET).

2. Radioactive decay of deposited nuclides is calculated for each step.

	DECAY	=	$DEP \cdot \exp(-T_S \cdot 0.693/thalf)$
where	DEP	=	density isotope deposited by wet and dry deposition ($Bq \cdot m^{-2}$)
	T_S	=	time step (d)
	thalf	=	half life (d)

3. Indoor air concentration is a function of outside air concentration, the volume of the room, the ventilation rate and filter fraction.

Consider a volume V the air in which exchanges with that outside at rate V_R (volume changes/unit time). The rate of change in the internal concentration is

$$\frac{dC_i}{dt} = f \cdot C_o \cdot V_R - V_R \cdot C_i - \frac{V_g \cdot A}{V} \cdot C_i$$

where the first term to the right is the entry rate of activity to the volume, the second term is the rate of loss through the same ventilation process and the third term is the rate of loss of activity from the air in the volume by deposition to the internal surfaces,

C_o and C_i are the activity concentrations in outside and inside air respectively,
f is the fraction of radioactivity penetrating inside the volume,
V_g is the deposition velocity.

Let $D_R = V_g \cdot A/V$ = deposition rate constant.

The equation above then becomes

$$\frac{dC_i}{dt} = f \cdot C_o\, V_R - (V_R + D_R)C_i \qquad (B.1)$$

(it is assumed that radioactive decay can be neglected during the passage of the cloud. If this is not so the decay rate should be added to the two rate constants in parentheses).

A solution of Equation B.1 for the time interval

t_1 to t_2 ($t_2 - t_1$ = time step = T_S) is

$$C_i(n) = \frac{f \cdot C_o V_R}{V_R + D_R}\,(1 - \exp(-(V_R + D_R)T_s) + C_i(n-1) \cdot \exp(-(V_R + D_R)T_s)$$

where $C_i(n)$ and $C_i(n-1)$ are the inside air concentrations at the end of the n^{th} and $(n-1)^{th}$ time step respectively.

The total losses of activity from the volume can be readily deduced from the numbers generated by this equation and the input of $V.f.V_R.C_o.T_s$ during the time step. The proportion of the total that is deposited internally is $D_R/(V_R+D_R)$ enabling the total deposited to be calculated.

Roed and Cannell (1987) found filter factors in a Danish house of 1.0 for I-131 and 0.53 for Cs-137 for a typical ventilation rate of 0.4 h^{-1}. They have also calculated average indoor deposition rates for a Danish test house.

4. Inhalation doses are a function of the air concentration, the dose conversion factor for the radionuclide in question and the breathing rate. The dose conversion factors and breathing rates are a function of age. Because dose conversion factors are only available for 1 year-old infants and adults, inhalation doses are calculated for these two cases. All children irrespective of age are treated as infants.

If more than one environment is considered, the dose is also a function of the fraction of the time spent in each, i.e., an occupancy factor.

inhalation dose = $Ca_i \cdot DCF \cdot B \cdot OCF_i \cdot T_s$

where				
	Ca_i	=	concentration of nuclide in air in environment i ($Bq \cdot m^{-3}$)	
	DCF	=	dose conversion factor ($Sv \cdot Bq^{-1}$)	(Table B.1)
	B	=	breathing rate ($m^3 \cdot d^{-1}$)	
	OCF_i	=	occupancy factor (fraction of time individual spends in environment i); i can be either indoors or outdoors	

5. External doses are received from immersion in a radioactive cloud and from radionuclides deposited on surfaces.

immersion dose = $Ca_i \cdot DCF(im) \cdot T_s \cdot OCF_i \cdot FAI$

where				
	DCF(im)	=	dose conversion factor ($Sv \cdot a^{-1} \cdot Bq^{-1} \cdot m^3$)	(Table B.1)
	FAI	=	immersion dose correction factor for age	
		=	($1.56 - 0.0265 \cdot AGE$)	
	AGE	=	age in years ($0 < AGE < 20$)	

External doses arise because of activity deposited inside as well as outside a building. A person may be in either location or partly in one and in the other the rest of the time. For a person outside, the shielding factor for activity deposited inside is zero, and that for activity deposited outside is unity.

Indoor contamination is assumed to be uniformly distributed and to give a dose rate equal to that from an infinite plane multiplied by a surface roughness factor and an appropriate occupancy factor.

$$D_{i,i} = C_i \cdot R_D \cdot RF_i \cdot OCF_i \cdot FA$$

where			
	$D_{i,i}$	=	dose rate inside a building from contamination deposited on interior surfaces
	C_i	=	mean density of activity deposited on interior surfaces
	R_D	=	tissue dose rate 1 m from a smooth surface of infinite extent and contaminated uniformly at unit density
	RF_i	=	roughness factor for interior surfaces
	OCF_i	=	fraction of time spent inside the building
	FA	=	external dose correction factor for age due to deposited activity

$$FA = 1.77 - 0.0405 \cdot AGE$$

A similar equation may be used for the dose rates experienced inside and outside a building due to activity deposited on exterior surfaces. Allowance in this case must be made for the shielding provided by the building fabric and for the multiplicity of possible external surface types.

A shielding factor is calculated from the equation

$$SHF = \exp(-(A + BM)) \tag{B.2}$$

where A and B are parameters (see Table A.3 in Part A) and M is the density of the building material in $g \cdot cm^{-2}$.

Several ways of handling the multiple surface types are available. For persons outdoors no problems arise because they will usually only be affected by the activity deposited on one surface type at a time and occupancy factors can specify the fraction of time spent on each. Indoors, however, the doses can arise from two or more surfaces simultaneously. For example one side of a building may be an asphalt parking lot, the other side given to lawn. In this case, the occupancy factor describes how long a person spends in each type of building as defined by the shielding factor. The effect of multiple surfaces is taken care of by specifying the fractions of the surroundings that are covered by each type of surface. Thus, taking the earlier example, the asphalt and grass area factors would each equal 0.5.

This design allows a great amount of flexibility in specifying scenarios, probably more flexibility than the present availability of shielding factors and dose rate factors can justify. Nevertheless, the facility is there when more detailed information becomes available. In the meantime, it shouldn't be exercised too enthusiastically.

The dose, D_o, due to externally deposited activity is given by

$$D_o = \sum_{m=1}^{m=q} \left[\sum_{n=1}^{n=p} (C_o(n) \cdot R_D(n) \cdot R_F(n) \cdot F_s(n)) \cdot SHF(m) \cdot OCF(m) \right] FA$$

where $C_o(n)$	is the density of activity on outdoor surface n
$R_D(n)$	is the reference dose rate 1 m above uniformly contaminated smooth surface per unit density
$R_F(n)$	is the roughness factor for surface n
$F_S(n)$	is the fraction of the surrounding area covered by surface n
p	is the total number of surfaces considered
SHF(m)	is the shielding factor for location m
OCF(m)	is the occupancy factor for location m
FA	is the age factor as before
q	is the number of locations the subject of interest will occupy.

The total external dose rate D_T is then $D_T = D_{i,i} + D_o$

This description may be complex to follow but thorough understanding is essential if the full capabilities inherent in the code are to be realized. It will help to remember that SHF and OCF refer to the locations occupied by people and F_S to the surfaces that the activity resides upon. As a further aid the following table may be useful.

		Location of Activity	
Location of person		Outside	Inside
	Outside	1.0	0
	Inside	exp(-(A+BM))	1.0

The total dose from all sources as a function of time is the important output from the code, but doses from individual surfaces may be of interest when considering remedial actions.

B. Post-Contamination Period

For Cs-137, weathering and decay from pavement and soil are calculated, using Gale's formula (Karlberg 1987), for a period of 5 half-lives in steps of half-life/2 and starting after the end of the contamination period.

$$D(t) = D(0) \cdot (A \cdot \exp(-t \cdot 0.693/T1) + B \cdot \exp(-t \cdot 0.693/T2)$$

where	D(0)	=	density of deposition ($Bq \cdot m^{-2}$) at time zero
	D(t)	=	density of deposition ($Bq \cdot m^{-2}$) at time t
	A and B	=	parameters that are a function of surface type
	T1	=	short term weathering half life
	T2	=	long term weathering half life

The initial amount of Cs-137 on the soil is assumed to be the sum of the amount on grass at the end of the contamination period plus the amount of run-off from the grass. This assumes no removal of grass cuttings and no run-off from other surfaces to the grass.

Radioactive decay is calculated for all isotopes, except U-238, in time steps related to their half lives in the same way as for Cs weathering. External dose rates due to deposition are calculated for the end of each time step.

CODE ORGANIZATION

The code allows scenarios to be developed for urban, suburban and rural areas that are inhabited by adults and children of specific age. Define the urban density by choosing the fraction of the area covered by roofs, pavement, grass or trees, and the lifestyles by choosing the fraction of time spent outdoors, at work, or at home. The construction material may be chosen so that shielding factors can be calculated. Figures B.1a and B.1b show options on lifestyles and building types that can be included in model scenarios.

The code is written to handle 5 isotopes (Cs-137, I-131, Ru-103, Ru-106, and U-238) and 6 surface types (roofs, roads, external walls, grass, trees, building interiors).

Input

1. Contamination data

An input file of daily air concentrations (Bq · m^{-3}) and precipitation (mm) must be created. The FORTRAN format for each daily entry on the file is (5X,2I2,2X,5(E8.2,1X),1X,F4.1) starting on line one. The first 5 spaces are blank, followed by the numeral for the month (2 digits) and the day (2 digits). The radionuclide data are entered in the order Cs-137, I-131, Ru-103, Ru-106, and U-238 in the format d.ddE±dd where d is a digit. If no data are available for a radionuclide the spaces for entries for that nuclide are left blank or are filled with zeros. Finally precipitation in mm is entered using the format dd.d. The newly created data file will have to be named (see section HOW TO RUN CHERURB for how to enter the file).

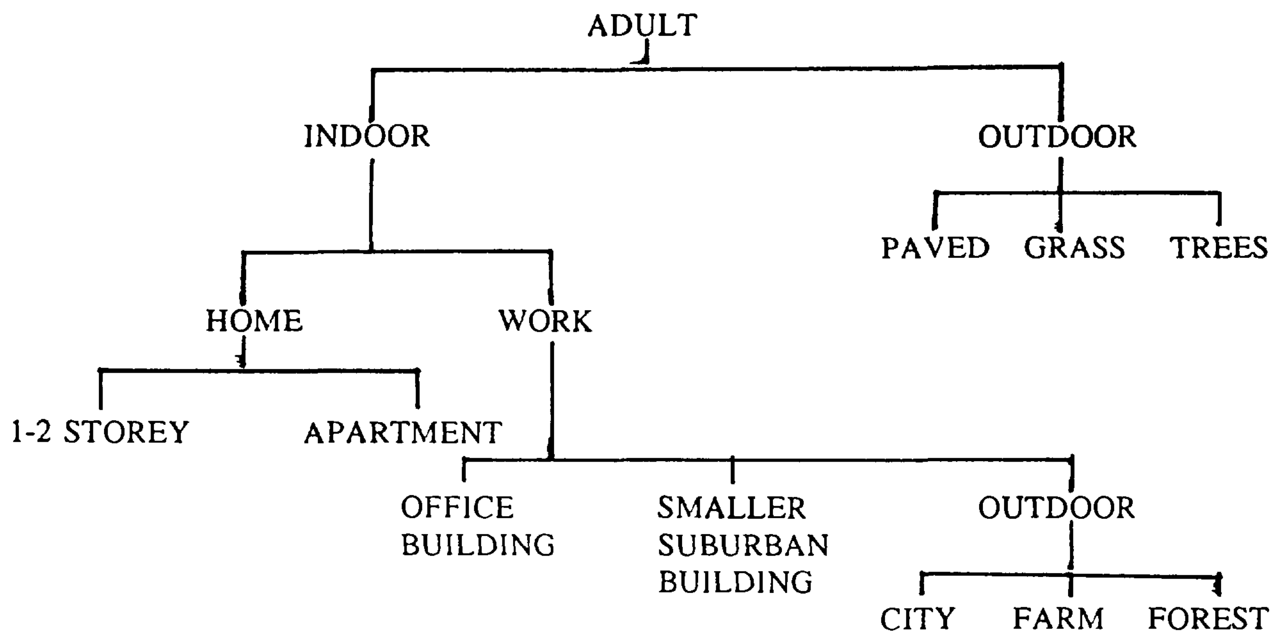

Figure B.1a: Chart showing lifestyle and building characteristics that may be included in model scenario for adults.

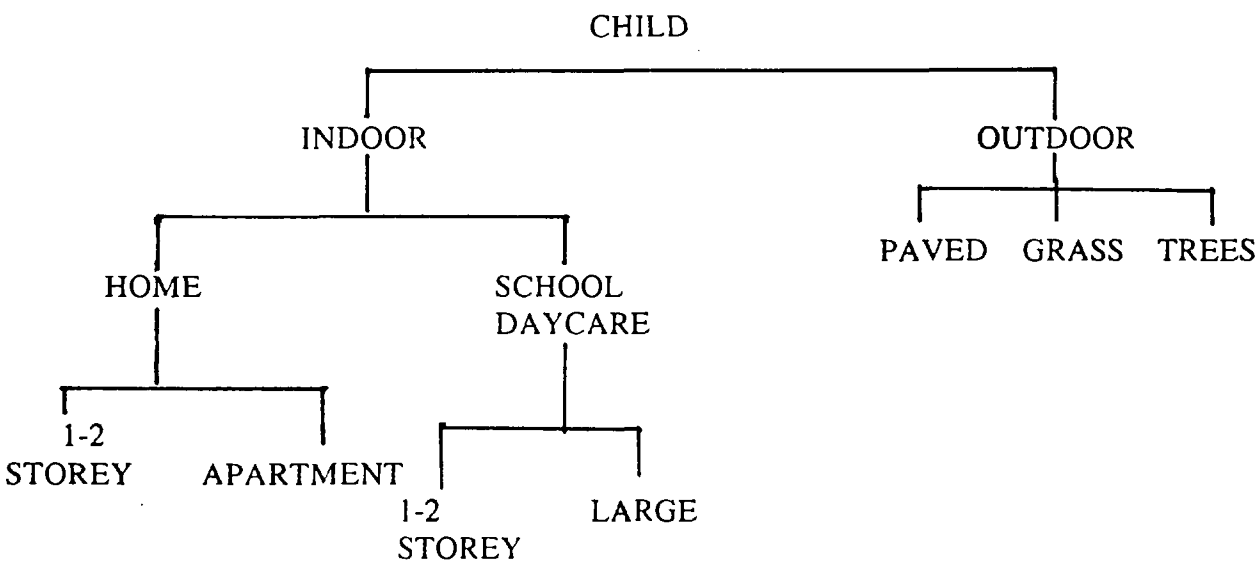

Figure B.1b: Chart showing lifestyle and building characteristics that may be included in model scenario for children.

When the code is run with concentrations in air as the starting point, these are assumed to be daily averages. If the averaging time is longer or if the times of collection do not coincide with the times of collecting precipitation, it will be necessary to interpolate to provide a continuous sequence of values for each day during the incident. Model predictions will be less reliable when this is done, especially if non-linear processes, such as rain occurring during the period, intervene.

CHERURB can be run with a file (PPTN_A.DAT) which is included in the code as an example of input as described above. The data for ^{137}Cs and ^{131}I air concentrations are from the Chernobyl release; the concentrations from the other three isotopes are the same as for ^{137}Cs to allow the user to test the code.

If air concentrations are not provided, the code can be run starting from levels of surface contamination, bypassing the deposition calculations. The file SURF_C.DAT is included as an input example. Each record in the file contains the deposition (in Bq/m^2) to the different surface types for a particular isotope.

2. Values of the model parameters

Default values for nuclide-specific parameters and parameters determined by lifestyle, buildings and terrain are found within the code. These same default values are found in Tables B.1, B.2, B.3 and B.4. Table B.1 lists dose conversion factors, washout coefficients and average indoor deposition velocities for the 5 isotopes considered. Table B.2 lists the default values for deposition velocities and other deposition parameters. Additional deposition velocities taken from the literature, along with ranges and references are given in Table B.3(a-d). Default roughness factors are listed in Table B.4.

As you run the code, you are given the option to change any of the parameter values from the keyboard. Parameter descriptions and default values are presented in groups. Unless otherwise stated, as is the case for parameters that are isotope specific, you must type in each value within a group if you want to change only one of them. The FORTRAN format given should be followed for input.

After choosing up to 5 isotopes, you will have the following opportunities to change the default parameter values (to help you access the source code, subroutine names are given in parentheses):

a. Fraction of total surface area covered by each surface type. This describes density of buildings, paved areas and vegetation in the urban or suburban area modelled.

b. Roughness factors for each surface type.

c. Building parameters that affect indoor contamination. (Subroutine BLDGFAC)

TABLE B.1
ISOTOPE SPECIFIC PARAMETERS

INHALATION DOSE CONVERSION FACTORS ($Sv \cdot Bq^{-1}$)*

	Adult	Infant
Cs-137	6.9E-09	7.3E-09
I-131	1.1E-08	8.7E-08
Ru-103	2.8E-09	1.1E-08
Ru-106	1.5E-07	5.5E-07
U-238	3.8E-05	1.8E-04

	REFERENCE DOSE* FOR DEPOSITION ($Sv \cdot a^{-1} \cdot Bq^{-1} \cdot m^2$)	IMMERSION DOSE* CONVERSION FACTOR ($Sv \cdot a^{-1} \cdot Bq^{-1} \cdot m^3$)
Cs-137	1.65E-08	8.27E-07
I-131	1.09E-08	5.17E-07
Ru-103	1.35E-08	6.55E-07
Ru-106	5.63E-09	2.85E-07
U-238	6.00E-10	2.70E-08

	WASHOUT COEFFICIENT (m^3 air/m^3 rain)	INDOOR DEPOSITION ($m \cdot s^{-1}$)
Cs-137	6.0E+05	6.4E-05
I-131	4.0E+05	1.1E-04
Ru-103	6.0E+05	2.0E-04
Ru-106	6.0E+05	1.7E-04
U-238	6.0E+05	1.7E-04

* Canadian Standards Association, CAN/CSA-N 288.1-M87. Guidelines for Calculating Derived Release Limits for Radioactive Material in Airborne and Liquid Effluents for Normal Operation of Nuclear Facilities.

TABLE B.2
ISOTOPE AND SURFACE SPECIFIC PARAMETER VALUES

	ROOF	ROAD	WALL	GRASS	TREE
Cs-137					
Vg (m · s^{-1})	.60E-03	.10E-03	.20E-03	.60E-03	.70E-03
FM	0.5	0.5	0.5	0.5	0.5
FM2FS	0.1	0.1	0.1	0.1	0.1
CAP(mm)	3.0	3.0	1.0	2.0	2.0
FWRET	0.5	0.5	0.5	0.5	0.5
I-131					
Vg (m · s^{-1})	.30E-02	.50E-03	.30E-03	.20E-02	.80E-02
FM	0.5	0.5	0.5	0.5	0.5
FM2FS	0.1	0.1	0.1	0.1	0.1
CAP (mm)	3.0	3.0	1.0	2.0	2.0
FWRET	0.0	0.0	0.0	0.0	0.0
Ru-103					
Vg (m · s^{-1})	.35E-03	.40E-03	.20E-03*	.60E-03*	.30E-02
FM	0.5	0.5	0.5	0.5	0.5
FM2FS	0.1	0.1	0.1	0.1	0.1
CAP (mm)	3.0	3.0	1.0	2.0	2.0
FWRET	0.5	0.5	0.5	0.5	0.5
Ru-106					
Vg (m · s^{-1})	.35E-03	.40E-03	.20E-03*	.60E-03*	.30E-02
FM	0.5	0.5	0.5	0.5	0.5
FM2FS	0.1	0.1	0.1	0.1	0.1
CAP (mm)	3.0	3.0	1.0	2.0	2.0
FWRET	0.5	0.5	0.5	0.5	0.5

* value not found in the literature - value for Cs-137 used.

N.B. Since no values for U-238 have been found to date, parameter values for Cs-137 are used as default values in the code.
Parameter names are those defined for the code.

TABLE B.3a

DEPOSITION VELOCITIES Cs-137 $m \cdot s^{-1}$ ($x10^{-4}$)

Surface	Material	Ref #	n	mean	range
Roof	Clay tile	1	10	7.6	5.0-12
	concrete	1	4	5.3	4.7-5.8
	eternite	2	1	2.8	
	clay tile	2	2	3.1	2.7-3.5
	all		17	6.2	
Road	asphalt	2	3	0.9	0.5-1.1
	concrete	2	4	0.6	0.5-0.8
	all		7	0.7	
Wall	plastered	2	4	0.1	0.1-0.2
		3	11	1.9	0.4-4.3
	brick	3	14	2.0	0.2-5.2
	all		29	1.7	
Trees	Yew	2	2	9.0	5.0-13
	Juniper	2	1	3.0	
	Spruce	2	1	7.3	
	all		4	7.1	
Grass		2	10	5.8	1.5-9.9
		4		7.0	3.0-15
Indoor		5		0.64	
	wallpaper	6	2	0.02	0.01-0.02
	vinyl floor	6	2	0.11	0.09-0.13
	wood floor	6	2	0.07	0.05-0.08

TABLE B.3b

DEPOSITION VELOCITIES I-131 m · s^{-1} ($x10^{-4}$)

Surface	Material	Ref #	n	mean	range
Roof	Clay tile	2	1	43	
	cement tile	2	1	32	
	eternite	2	1	20	
	all		3	32	
Road	asphalt	2	5	5.4	3.0-7.7
	concrete	2	4	3.7	2.2-7.3
	all		9	4.6	
Trees	Yew	2	2	105	100-110
	Juniper	2	1	32	
	Spruce	2	1	89	
	all		4	83	
Grass		2	5	68	22-120
	total iodine	4		20	
	elemental	4		80	
	particle	4		10	
Indoor	particulate	5		1.1	
	total				
	wallpaper	6	2	0.09	0.08-0.09
	vinyl floor	6	2	0.22	0.20-0.23

TABLE B.3c

DEPOSITION VELOCITIES Ru-103 m · s^{-1} ($x10^{-4}$)

Surface	Material	Ref #	n	mean	range
Roof	clay tile	2	1	2.9	
	cement	2	1	4.1	
	eternite	2	1	3.3	
	all		3	3.4	
Road	asphalt	2	5	3.9	1.2-5.7
	concrete	2	4	3.0	1.2-5.8
			9	3.5	
Trees	Yew	2	2	32	28-36
	Juniper	2	1	13	
	Spruce	2	1	28	
	all		4	26	
Indoor		5		2.0	
	wallpaper	6	2	0.01	0.01
	vinyl floor	6	2	0.10	0.10
	wood floor	6	2	0.08	0.07-0.08

TABLE B.3d

DEPOSITION VELOCITIES Ru-106 m · s^{-1} ($x10^{-4}$)

Surface	Material	Ref #	n	mean	range
Road	concrete	2	2	11.8	5.6-18
Trees	Yew	2	1	47.	
	Juniper	2	1	28.	
	Spruce	2	1	53.	
	all		3	43.	
Indoor		5		1.7	

References:
1. Nicholson (1987)
2. Roed (1987a)
3. Gjorup et al. (1985)
4. Maqua et al. (1987)
5. Roed and Cannell (1987)
6. Roed and Cannell (1988)

TABLE B.4

ROUGHNESS FACTORS*

Surface	Preferred Value	Range
Infinite smooth	1.0	
Paved area	0.92	0.85 - 1.0
Lawn	0.8	0.75 - 0.85
Gravelled area	0.7	0.65 - 0.75
Ploughed field		
normal depth	0.6	0.55 - 0.65
deep	0.5	0.47 - 0.55

* Values are summarized from Burson and Profio (1977)

d. Life-style parameters. Default values are based on the assumption that adults spend 90% of the time indoors (Kelly 1987). (Subroutine LIFSTYL)

e. Shielding factors. There are three options: accepting the default value (Burson and Profio 1977), entering another choice or having one calculated from a range of building sizes and construction material densities.

f. Parameters that are specific to the isotope being considered. Default values are read from the file PARAM.DAT.

Output for each isotope

1. All parameter values used in the current scenario.

2. Input air concentrations and precipitation, cumulative wet and dry deposition, run-off and total deposition for each time step and total run-off amounts and volume for the period of contamination for each surface type.

3. Mean contamination of the urban area weighted for each of the five surface types.

4. Indoor air concentration and cumulative indoor deposition for each time step.

5. Daily inhalation doses to adults and children while in the home, outdoors, and at work or school.

6. Daily immersion doses to adults and children while in the home, outdoors, and at work or school.

7. Daily external doses to adults at home and at work and to children at home and school. Daily external doses to adults and children due to time spent on grass and on pavement.

8. Accumulated inhalation, immersion and external doses to adults and infants for contamination period.

9. Daily external dose rates for a period of 5 half-lives in time steps of half-life/2 for the post-contamination period.

HOW TO RUN CHERURB

The code requires an IBM or similar computer having one or two floppy disk drives and a hard disk. Before running the program, a directory named CHERURB has to be created on your hard disk. The output file generated by the program is written on that directory under the name CHERURB.OUT.

Insert the flexible disk including the executable code and data files (default parameters, example of air concentration and precipitation data, example of surface contamination data) into drive A and type A: CHERURB

You are first asked to choose one of the two primary inputs:

- daily air concentrations and amounts of precipitation
- levels of surface contamination.

The first set of instructions and parameter values will then appear on the screen. If the prompt is answered "YES", you will be prompted to enter a value for each parameter in the group that was shown. The values must be entered in the same format as the default values appearing on the screen. When all the values have been entered, the screen will clear and the next set of parameters will appear. If the answer was "NO", the screen will clear and the next set of parameter values will be shown.

Choices of input to be made in order as they appear on the screen are:

Choices (a) to (h) inclusive (below) will remain constant for a run involving 2 or more radionuclides.

Choices (i) and (j) (below) are isotope specific and can be changed by the user before calculations begin on the next nuclide.

a. Fraction of total surface area covered by each surface type.

b. Roughness factors, used in dose calculations, for each surface type.

c. Air concentration and precipitation data file. The code will access a user defined file (see Input under CODE ORGANIZATION) or the default file (PPTN_A.DAT) that is part of this package. If a file is ready (answer Yes) you will be given appropriate instructions. You will then be prompted by DOS to enter the file access path and name in the usual manner.

d. 1 or more of the 5 isotopes.

e. Building parameters that affect indoor contamination.
   1) for the home: room volume
      room area
      ventilation rate and
      filter fraction

   2) for the workplace and school, which is assumed to have the same characteristics as the workplace.

f. Life-style parameters for an adult.
   1) fraction of time spent outdoors,
   2) fraction of time spent at work,
   3) fraction of time spent at home,
   4) fraction of time spent on pavement,
   5) fraction of time spent on grass,
   6) fraction of time spent under or near trees.
   (1-5 should add to 1.0, but the time near trees is extra and may make the total greater than 1.0 because trees can add to dose while a person is on grass, pavement or even indoors)

g. Life-style parameters for a child.
   1) age of child (0 < age < 20)
   2) fraction of time spent outdoors,
   3) fraction of time spent at school or in any building of different size or

construction than home,
4) fraction of time spent at home,
5) fraction of time spent on pavement,
6) fraction of time spent on grass,
7) fraction of time spent under or near trees.
(2-6 should add to 1.0, but the time near trees is extra and may make the total greater than 1.0 because trees can add to dose while a person is on grass, pavement or even indoors)

h. Shielding factors for home and school/workplace. Values may either be entered directly or calculated according to building size and type of construction.

i. Parameters that are specific to the isotope being considered. These include parameters that are also a function of surface type e.g., deposition velocity, fraction of mobile deposits, rate that mobile deposits become fixed and critical precipitation amounts. Other parameters that are isotope specific are washout coefficients and dose conversion factors. The default values listed in Tables B.1 and B.2 are shown on the screen and can be accepted by typing 0. The user may also consult Table B.3 for alternate values for the deposition velocities.

Output Options

j. You will be asked whether you want to print the details of isotope accumulation and deposition. If the answer is "NO", only dose predictions will be printed.

k. After computations and output for the first isotope considered are complete, you will be asked to choose parameters that are specific to the next isotope you have chosen to model (i.e. the operation goes back to i).

DEFINITIONS

Definitions of variables used in CHERURB are presented below. They have been divided into integers, characters, parameter groups, variables used in deposition and run-off calculations and finally variables used in dose calculations. Variable names used in the subroutines are the same as in the main program in almost every case.

SUBROUTINES

BLDGFAC
INTER
EXTDOSE
LIFSTYL
PARAM
WEDECAY

INTEGERS

I	
IS	
J	
JJ	dimension for isotope
K	
KT	
LA	
N	dimension for time step
NDA	day
NM	dimension for surface type
NML	
NPREDS	number of input data sets
NS	
MO	month

CHARACTERS

ISOT(JJ)	ISOT	isotope name
NTYPE(JJ)	NTYPE	surface type
REP	REP1	reply

BUILDING FACTORS

AREA	area of home
AW	area of workplace or school
FIF	filter fraction of home
FIFW	filter fraction of workplace
RCD	deposition rate
RCV	ventilation rate of home
RW	ventilation rate of workplace
VOL	volume of home
VW	volume of workplace

LIFESTYLE PARAMETERS

AGE	age of child
FH	fraction of time adult spends in home
FHI	fraction of time child spends in home
FHS	fraction of time child spends in school
FIO	fraction of time child spends outdoors
FOUT	fraction of time adult spends outdoors
FR(NM)	fraction of time adult spends on surface of type NM
FRI(NM)	fraction of time child spends on surface of type NM
FRNS(NM)	fraction of area that is of surface type NM
FW	fraction of time adult spends at work
SHFH	shielding factor of home
SHFW	shielding factor of workplace

ISOTOPE SPECIFIC PARAMETERS

CAP(JJ)	critical amount of precipitation before rain runs off
DCFA(JJ)	inhalation dose conversion factor for adults for isotope JJ
DCFI(JJ)	inhalation dose conversion factor for infants for isotope JJ
DIM(JJ)	immersion dose conversion factor
FF(JJ,NM)	fraction of dry deposit of isotope JJ that is initially fixed on surface NM
FM(JJ,NM)	fraction of dry deposit of isotope JJ that is initially mobile on surface NM
FM2FS(JJ,NM)	the fraction of mobile dry deposit JJ that becomes fixed in each step
FWRET(JJ,NM)	the fraction of wet deposit that is retained
RDOSE(JJ)	reference dose rate for deposited radionuclide
VGI(JJ)	indoor deposition velocity for isotope JJ

VGS(JJ,NM)	deposition velocity for isotope JJ on outdoor surface NM
WOCS(JJ)	washout coefficient

DEPOSITION AND RUN-OFF

AM2FS	amount of mobile deposit that becomes fixed in each step
AMDDS(N,NM)	amount of mobile dry deposit
CA(N,JJ)	air concentration of isotope JJ in step N
CAIR	air concentration (dummy value)
CIN(N)	air concentration in home
CIW	air concentration in workplace (dummy value)
CW(N)	air concentration in workplace
DDLOSS(N,NM)	mobile deposit moved to run-off
FDDS(N,NM)	amount of fixed dry deposit
FWDS(N,NM)	amount of wet deposit
P(N)	daily precipitation amount
PR(NM)	cumulative precipitation that runs off surface NM
ROFF(N,N)	run-off (volume)
TCONTAM(JJ)	total contamination of urban area by isotope JJ weighted by the relative areas of each surface type
TD(N,NM)	total deposition of surface NM at start of weathering period (end of contamination period)
TDEP(JJ,N,NM)	total deposit of isotope JJ on surface NM at the end of step N
TOTPR(JJ)	total loss to run-off of isotope JJ from permeable surface
TOTPRI(JJ)	total loss to run-off of isotope JJ from impermeable surface
TOTROF(JJ,NM)	total run-off of isotope JJ from surface NM during the contamination period
TROFF(JJ)	total run-off volume during contamination period
TROFI(JJ)	total run-off (Bq) during contamination period

DOSE CALCULATIONS

BA	breathing rate of adult
BDAI(N,JJ)	inhalation dose to adults while at home
BDAO(N,JJ)	inhalation dose to adults while outdoors
BDAW(N,JJ)	inhalation dose to adults while at work
BDII(N,JJ)	inhalation dose to infants while at home
BDIO(N,JJ)	inhalation dose to infants while outdoors
BDIW(N,JJ)	inhalation dose to child while at school
BI	breathing rate of infant
DDOSE(JJ,N,NM)	dose to adult while on surface NM
DDOSI(JJ,N,NM)	dose to child while on surface NM

DECAY	radioactive decay constant
DIMA(JJ,N)	immersion dose to adults
DIMI(JJ,N)	immersion dose to child
FAGE	age factor for children's dose
HAD(JJ,N)	external dose to adult at home
HID(JJ,N)	external dose to infant at home
RUF(NM)	roughness factor
SCD(N,JJ)	dose to child while at school
SST	time step for weathering and decay
STEP	time step for contamination period
STP	time step for weathering and decay
TADD	total external dose to adults from all isotopes chosen
TAID	total inhalation dose to adults from all isotopes chosen
TBAW(JJ)	total inhalation dose to adult at work due to isotope JJ
TBDAI(JJ)	total inhalation dose to adult at home due to isotope JJ
TBDAO(JJ)	total inhalation dose to adult while outdoors
TBDII(JJ)	total inhalation dose to child at home
TBDIO(JJ)	total inhalation dose to child outdoors
TBIW(JJ)	total inhalation dose to child at school
TDA(JJ)	total external dose to adult due to isotope JJ during the contamination period
TDAP(JJ)	total external dose to adult due to isotope JJ during the post-contamination period
TDI	initial density of isotope in home
TDII(JJ)	total external dose to child due to isotope JJ during the contamination period
TDIP(JJ)	total external dose to child due to isotope JJ during the post-contamination period
TDIMA(JJ)	total immersion dose to adult
TDIMI(JJ)	total immersion dose to child
TDIN(N)	accumulated density of deposited isotope in home
TDIW	initial density of deposited isotope in workplace
TDOS	total indoor external dose to adult due to outdoor deposition
TDOSI	total indoor external dose to child due to outdoor deposition
TDW(N)	accumulated deposit of isotope in work place
THALF(JJ)	half life of isotope
TIID	total inhalation dose to infants from all isotopes chosen
TIDD	total external dose to children from all isotopes chosen
TIMA	total immersion dose to adults from all isotopes chosen
TIME(K)	total time after contamination period
TIMI	total immersion dose to infants from all isotopes chosen
WAD(JJ,N)	dose to adults while at work
X	total inhalation dose to infants from isotope JJ
Y	total inhalation dose to adults from isotope JJ

REFERENCES AND ADDITIONAL BIBLIOGRAPHY

Alley, W.M., Estimation of impervious area washoff parameters. Water Resour. Res. 17 (1981) 1161-1166.

Beck, H. and G. de Planque, The radiation field in air due to distributed gamma-ray sources on the ground. HASL-195 (1968).

Brenk, H.D. and H. De Witt, Indoor inhalation exposure after nuclear accidents. Rad. Prot. Dos. 21(1/3) (1987) 117-123.

Brown, J., Effectiveness of sheltering. NRPB Radiological Prot. Bull. No. 97 (1988) November.

Brown, J., M.J. Crick, and M.D. Hill, The effectiveness of various decontamination techniques for reducing external radiation doses to people living in an urban environment. Workshop on recent advances in reactor accident consequence assessment. Joint CEC/OECD (NEA) workshop. Rome, EUR 11408 (1985).

Brown, L., National radiation survey in the U.K. indoor occupancy factors. Rad. Prot. Dos. 5(4) (1984) 203-208

Bunzl, K. and W. Kracke, Cumulative deposition of ^{137}Cs, ^{238}Pu, $^{239+240}Pu$ and ^{241}Am from global fallout in soils from forest grassland and arable land in Bavaria. J. Environ. Radioactivity 8 (1988) 1-14.

Burson, Z.G., Environmental and fallout gamma radiation protection factors provided by civilian vehicles. Health Physics 26(Jan) (1974) 41-44.

Burson, Z.G. and A.E. Profio, Structure shielding in reactor accidents. Health Physics 33 (1977) 287-299.

Charles, D., M.J. Crick, T.P. Fell, and J.R. Greenhalgh, DOSE-MARC The dosimetric module in the methodology for assessing the radiological consequences of accidental releases. NRPB-M74 (1982).

Christensen, G.C. and R. Mustonen, Filtering effect of buildings on airborne particles. Rad. Prot. Dos. 21(1/3) (1987) 125-128.

Crick, M.J., J. Brown, Z. Hussain, and A. Walmsley, Identification of important parameters in urban dose assessment. Rad. Prot. Dos. 21(1/3) (1987) 181-188.

Crick, M.J. and P.J. Dimbylow, GRINDS - A computer program for evaluating the shielding provided by buildings from radionuclides deposited on ground and urban surfaces. NRPB-M119 (1985).

Crick, M.J., A review of models to assess exposure from deposited material and future needs. Workshop on Methods for Assessing the off-site radiological consequences on nuclear accidents, Luxembourg, April (1985) 426-437.

Dorner, R. and H.G. Vogt, Comparative standard-house calculations with the Monte-Carlo code SAM-CE and the point-kernel code QAD-CG-E. Proceedings of Workshop on Methods for Assessing the off-site radiological consequences of nuclear accidents, Luxembourg, April (1985) 451.

Duftschmid, K., K. Muck, F. Steger, P. Vychytil, and J. Zechner, Exposure of the Austrian population due to the Chernobyl accident. Rad. Prot. Dos. 19(4) (1987) 213-222.

Finzi, S., M. Olest, and J. Sinnaeve, Opening address (CEC Radiation Protection Program). Rad. Prot. Dos. 21(1/3) (1987) 9-11.

Garland, J.A. and R.S. Cambray, Deposition resuspension and the long term variation of airborne radioactivity from Chernobyl. 4th Int. Sym. on Radioecology, Cadarache, March (1988).

Garnier, A., Data Base on: A) Land use agricultural produce and B) housing in some E.C. countries. Proceedings of Workshop in Methods for Assessing the off-site radiological consequences of nuclear accidents, Luxembourg, April (1985) 615-646.

Gjorup, S.L., P. Hedemann Jensen, B. Lauridsen, J. Roed, and L. Warming, Deposition retention and decontamination of radioactive material on urban surfaces - the Danish program. Proceedings of Workshop on Methods for Assessing the off-site radiological consequences of nuclear accidents, Luxembourg, (1985) 463.

Graf, O., Intercomparison of three shielding codes for external radiation from deposited material. Proceedings of Methods for Assessing the off-site radiological consequences of nuclear accidents, Luxembourg, April EUR 10397 (1985) 439-450.

Helton, J.C., The proposed development of a radionuclide washoff model for the German reactor safety study. KfK 3421.

Hill, M.D., Verification and validation of NRPB models for calculating rates of radionuclide transfer through the environment. NRPB-R233 January (1989).

Huddleston, C.M., Q.G. Klingler, Z.G. Burson, and R.M. Kincaid, Ground roughness effects on the energy and angular distribution of gamma radiation from fallout. Health Physics 11 (1965) 537-548.

Huibregtse, K.R., Secondary impacts due to run-off from urban area. EPA- 600/2-82-045 (1982).

Jacob, P., R. Meckbach, and J.M. Müller, Reduction of external exposure from deposited Chernobyl activity by run-off, weathering, street cleaning and migration in soil. Rad. Prot. Dos. 21(1/3) (1987) 51-57.

Jacob, P. and R. Meckbach, Shielding factors and external dose evaluation. Rad. Prot. Dos. 21(1/3) (1987) 79-85.

Karlberg, O., Weathering and migration of Chernobyl fall-out in Sweden. Rad. Prot. Dos. 21(1/3) (1987) 75-78.

Kelly, G.N., The importance of the urban environment for accident consequences. Rad. Prot. Dos. 21(1/3) (1987) 13-20.

Koch, J. and J. Tadmor, Sheltering - A protective measure following an accidental atmospheric release from a nuclear plant. Health Physics 54(6) (1988) 659-667.

Kocher, D.C., Dose rate conversion factors for external exposure to photon and electrons. Health Physics 45 (1983) 665-686.

Kocher, D.C. and A.L. Sjoreen, Dose rate conversion factors for external exposure to photon emitters in soil. Health Physics 48 (1985) 193-205.

Le Grand, J, J.C. Croizi, T. de Dorlodot, and Y. Roux, Statistical survey of the housing characteristics and evaluating shielding factors in the surroundings of French nuclear sites. Rad. Prot. Dos. 21(1/3) (1987) 87-95.

Maqua, M., H. Bonka, and H-G. Horn, Deposition velocity and washout coefficient of radionuclides bound to aerosol particles and elemental radioiodine. Rad. Prot. Dos. 21(1/3) (1987) 43-49.

Meckbach, R., P. Jacob, H.G. Paretzke, Gamma exposures due to radionuclides deposited in urban environments Part I: Kerma rates from contaminated urban surfaces. Rad. Prot. Dos. 25(3) (1988) 167-179.

Meckbach, R., P. Jacob, Gamma exposures due to radionuclides deposited in urban environments Part II: Location factors for different deposition patterns. Rad. Prot. Dos. 22(5) (1988) 181-190.

Nicholson, K.W., Deposition of Cs to surfaces of buildings. Rad. Prot. Dos. 21(1/3) (1987) 37-42.

Nicholson, K.W., The deposition, resuspension and weathering of Chernobyl derived material in the U.K. J. Rad. Prot. 9(2) (1989) 113-119.

Poston, J.W. and W.S. Snyder, A model for exposure to a semi-infinite cloud of a photon emitter. Health Phys. 26 (1974) 287-293.

Paretzke, H.G., The impact of the Chernobyl accident on radiation protection. Health Physics 55(2) (1988) 139-143.

Reineking, A., K.H. Becker, J. Porstendorfer, and W. Wicke, Air activity concentrations and particle size distributions of the Chernobyl aerosol. Rad. Prot. Dos. 19 (1987) 159-163.

Ritchie, L.T., W.D. Brown, and J.R. Wayland, Effects of rainstorms on consequences of atmospheric releases from nuclear reactor accidents. Nucl. Safety 19 (1978) 220-238.

Roed, J., Reduction in inhalation dose by staying indoors. Proceedings of Workshop on Methods for Assessing the off-site radiological consequences of nuclear accidents, Luxembourg (1985) 559-589.

Roed, J., Dry deposition in rural and in urban areas in Denmark. Rad. Prot. Dos. 21(1/3) (1987a) 33-36.

Roed, J., Run-off from and weathering of roof material following the Chernobyl accident. Rad. Prot. Dos. 21(1/3) (1987b) 59-63.

Roed, J., Parameters used in consequence calculations for an urban area. Joint Workshop on Advances in Reactor Accident Consequence Assessment, Rome, January (1988a). EUR 11408.

Roed, J., The distribution on trees of dry deposited material from the Chernobyl accident. Joint Workshop on Advances in Reactor Accident Consequence Assessment, Rome, January (1988b). EUR 11408.

Roed, J. and R.J. Cannell, Relationship between indoor and outdoor aerosol concentration following the Chernobyl accident. Rad. Prot. Dos. 21(1/3) (1987) 107-110.

Roed, J. and R.J. Cannell, The deposition of Beryllium-7 marked particles on surfaces in unfurnished and furnished rooms. Joint Workshop on Advances in Reactor Accident Consequence Assessment, Rome, January (1988). EUR 11408.

Sandalls, F.J., Radiocaesium on urban surfaces after Chernobyl. Rad. Prot. Dos. 21(1/3) (1987a) 65-68.

Sandalls, F.J., Removal of radiocaesium from urban surfaces. Rad. Prot. Dos. 21(1/3) (1987b) 137-140.

Sandalls, F.J. and S.L. Gaudern, Radiocaesium on urban surfaces in West Cumbria five months after Chernobyl. J. Environ. Radioactivity 7 (1988) 87-91.

Schwartz, G., Deposition and post-deposition radionuclide behaviour in urban environment. Proceedings of Workshop on Methods for Assessing the off-site radiological consequences of nuclear accidents, Luxembourg (1985) 533-600.

Steinhaüsler, F., The effect of fall-out deposition on indoor gamma radiation levels in single family dwellings. Rad. Prot. Dos. 21(1/3) (1987) 103-105.

Strand, T. and E. Stranden, Indoor gamma radiation in Norwegian dwellings during the 1st 3 months after the Chernobyl accident. Rad. Prot. Dos. 18 (1987) 13-17.

Strand, T., E. Stranden, and A.L. Rudjord, External radiation doses to the Norwegian population from the Chernobyl fall-out. Rad. Prot. Dos. 20 (1987) 231-236.

Toly, J.A. and D. Tenchine, Effect of heat island on dispersion. EUR--9213 (1984).

Underwood, B.Y., Dry deposition to an urban complex. Rad. Prot. Dos. 21(1/3) (1987) 21-32.

Wilkins, B.T., The retention behaviour of radiocaesium on common building materials under natural outdoor conditions. Rad. Prot. Dos., 21(1/3) (1987) 69-73.

Yaziz, M.I. and W.P. Yen, Effects of ventilation and air temperature on pollution levels in underground car parks. Water, Air and Soil Pollution 44 (1989) 375-385.