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The Program System UFOMOD for Assessing the Consequences of Nuclear Accidents

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The program system UFOMOD for assessing the consequences of nuclear accidents

The program system UFOMOD is a completely new accident consequence assessment (ACA) code. Its structure and modelling is based on the experience gained from applications of the old UFOMOD code during and after the German Risk Study - Phase A, the results of scientific investigations performed within the ongoing Phase B and the CEC-project MARIA, and the requirements resulting from the extended use of ACAs to help in decision-making.

One of the most important improvements is the introduction of different trajecotry models for describing atmospheric dispersion in the near range and at larger distances. Emergency actions and countermeasures modelling takes into account recommendations of international commissions. The dosimetric models contain completely new age-, sex- and time-dependent data of dose-conversion factors for external and internal radiation; the ingestion pathway is modelled to consider seasonal dependencies. New dose-risk-relationships for stochastic and non-stoachastic health effects are implemented; a special algorithm developed for ACA codes allows individual and collective leukemia and cancer risks to be presented as a function of time after the accident. According to the modular structure of the new program system UFOMOD, an easy access to parameter values and the results of the various submodels exists what facilitates sensitivity and uncertainty analyses.

Das Programmsystem UFOMOD zur Abschätzung der Folgen kerntechnischer Unfälle

Das Programmsystem UFOMOD ist ein völlig neuer Rechencode für Unfallfolgenabschätzungen. Sein struktureller Aufbau und seine Modellierung basiert auf den Erfahrungen mit dem alten UFOMOD während und nach der "Deutschen Risikostudie Kernkraftwerke" - Phase A, auf den Ergebnissen wissenschaftlicher Untersuchungen, die im Rahmen der Phase B und dem CEC-Projekt MARIA durchgeführt wurden, sowie auf den Anforderungen die aus dem zunehmenden Einsatz von Unfallfolgenabschätzungen als Entscheidungshilfe resultieren.

Eine der wichtigsten Verbesserungen ist der Einsatz verschiedener Trajektorienmodelle zur Beschreibung der atmosphärischen Ausbreitungsvorgänge im Nahbereich und in größeren Entfernungen. Die Modellierung von Notfallschutz- und Gegenmaßnahmen berücksichtigt Empfehlungen internationaler Gremien. In den Dosismodellen sind völlig neue Datensätze alters-, geschlechts- und zeitabhängiger Dosiskonversionsfaktoren für externe und interne Bestrahlung enthalten; der Ingestionspfad ist unter Berücksichtigung saisonaler Abhängigkeiten modelliert. Neue Dosis-Risiko-Funktionen für stochastische und nicht-stochastische gesundheitliche Schäden wurden implementiert. Ein spezieller für Unfallfolgencodes entwickelter Algorithmus ermöglicht die Berechnung zeitabhängiger Individualrisiken und Kollektivschäden für Krebs und Leukämie. Der modulare Aufbau des neuen Programmsystems UFOMOD erlaubt einen direkten Zugriff zu Parameterwerten und Einzelergebnissen der verschiedenen Unterprogramme, wodurch Sensitivitäts- und Unsicherheitsanalysen erleichtert werden.

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ACA	accident consequence assessment
BSU	Fa. Brenk-Systemplanung, Aachen (FRG)
CCFD	complementary cumulative frequency distribution
DRS-A/B	German Risk Study - Phase A/B
DWD	German Weather Service, Offenbach (FRG)
GRS	Gesellschaft für Reaktorsicherheit mbH, Köln (FRG)
GSF	Gesellschaft für Strahlen- und Umweltforschung mbH, Neuherberg (FRG)
GUW	Gesellschaft für Umweltüberwachung, Aldenhoven (FRG)
ICRP	International Commission on Radiological Protection
ICST	Imperial College of Science and Technology, London (GB)
INR	Institute for Neutron Physics and Reactor Engineering of KfK
KFA	Kernforschungsanlage Jülich (FRG)
KfK	Nuclear Research Centre Karlsruhe (FRG)
MARIA	Methods for Assessing the Radiological Impact of Accidents
NRPB	National Radiological Protection Board, Chilton, Didcot (GB)
RISO	RISO National Laboratory, Roskilde (DK)

Preface

The program system UFOMOD ("Unfallfolgenmodell") is a new accident consequence assessment (ACA) code with models and data based on the present scientific knowledge and the available computational methods. It replaces the computer code of the same name, which was developed and applied in the German Risk Study - Phase A published in 1979/80. In the meantime, various updated versions (B3, B4, B5) were involved in a number of probabilistic consequence assessments of different facilities of the nuclear fuel cycle. The experience gained from these applications, the results of scientific investigations and the extended use of ACA codes to help in decision-making led to a completely new structure and modelling of the program system UFOMOD described in this report.

The new code was developed by members of the accident consequence assessment working group of the "Institut für Neutronenphysik und Reaktortechnik" (INR) at the Karlsruhe Nuclear Research Center (KfK). Part of the work was performed within the German Risk Study - Phase B (DRS-B) and the following institutions participated in upgrading the accident consequence model under that project:

- Gesellschaft für Strahlen- und Umweltforschung (GSF) mbH, Neuherberg

- Gesellschaft für Reaktorsicherheit (GRS), Köln

- Brenk Systemplanung (BSU), Aachen

- Deutscher Wetterdienst (DWD), Offenbach

- Abteilung Sicherheit und Strahlenschutz der Kernforschungsanlage Jülich (KFA), Jülich

- Gesellschaft für Umweltüberwachung (GUW), Aldenhoven

- Institut für Unfallforschung des TÜV Rheinland, Köln.

Important contributions emerged from the international cooperation within the MARIA project (Methods for Assessing the Radiological Impact of Accidents), which is supported by the Commission of the European Communities within its Radiation Protection Programme under contract no. BI6/F/128/D. The close connection to the National Radiological Protection Board (NRPB), UK, where complementary investigations on ACA modelling are performed, ensured a continuous fruitful discussion about modelling requirements and open problems. The RISO National Laboratory, Denmark, and the Imperial College of Science and Technology, UK, made available their atmospheric dispersion models RIMPUFF and MESOS, respectively, for use in UFOMOD.

The purpose of the present report is to give a general overview of the structure of the new program system, the major features of the various submodels and the wide range of results obtainable. More detailed reports on the models, their mathematical formulation and the corresponding parameter values and data sets are being published together with the program description and user's guide /1-6/. Complementary reports on special investigations and program developments are in preparation /7,8/.

The layout of this report reflects, that it is intended for non-specialists, who wish to discover what the new program system UFOMOD has to offer, as well as for those who are more interested in details of the models and their coding. In the introduction (Chap. 1), a general description of the phenomena modelled in ACA computer codes is given together with a summary of the main modelling improvements of UFOMOD. Chap. 2 gives an overview of its layout and modular structure. The first type of readers may then pass on to Chap. 10 on illustrative applications to become acquainted with the results obtainable and their forms of presentation.

Those readers seeking information on modelling improvements should direct their interest to Chaps. 3 to 9, which describe the submodels used, their parameterization and the data sets included. Chap. 11 gives a summary and an overview of improvements planned for the future.

1. Introduction

Despite the elaborate precautions taken in the design, construction and operation of nuclear installations, there will always remain the possibility, however small, of accidents which may lead to the release of radioactive material to the environment. The amounts released may range from the trivial up to a significant fraction of the activity inventory of the facility under consideration. In contrast to the discharges of effluents in normal operation, which occur in a controlled manner and more or less continuously throughout the lifetime of an installation, the occurrence of accidents cannot be pre-determined but only predicted on a probabilistic basis. Similarly, while the exposures (and thus risk) occurring during normal operation can be estimated deterministically, those from postulated accidents can only be estimated probabilistically.

The consequences of a postulated release of radioactive material will vary considerably with the conditions pertaining at the time, in particular with the prevailing meterorological conditions, the season, the location and habits of the population. For any given release, therefore, there will be a spectrum of possible consequences, each having different probabilities of occurrence determined by the environmental characteristics of the release location and its surroundings.

To estimate the spectrum of consequences, accident consequence assessment (ACA) models have been developed in different countries. Broadly, they all have a similar structure but differ at the submodel level. The basic components of an ACA model are schematically shown in Fig. 1.1. The physical processes being important in estimating the exposure of the population are illustrated in the same Figure.

The starting point in each accident consequence assessment is the so-called source term. Besides other information, the source term contains the amount and form of each radionuclide release to the environment, the location of the release in the building complex, the time at which the release occurs and its time dependency and energy content. As among the scenarios known so far releases into the atmosphere are the most important in terms of damage potential, they will be the only ones dealt with here.

Modelling the transfer of radioactive material through the environment following a release to the atmosphere requires an understanding of atmospheric dispersion, the processes of removal of material from the atmosphere leading to deposition on the ground, and the subsequent behaviour in the terrestrial environment. The atmospheric dispersion and deposition model predicts the spatial and temporal distributions of activity, taking account of the meteorological conditions during the release and time of travel of the plume. These determine the direction in which the activity is transported and the rate and extent of dispersion. Mechanisms for removal of activity from the plume are also included, these being radioactive decay and dry and wet deposition processes (including wash-out of radioactive material by rain). Dependent on the release characteristics special features have to be modelled, for example the effect of plume rise due to the buoyancy or momentum of the released activity and the behaviour of plumes released into building wakes.

A large number of different patterns of meteorological conditions will be experienced at any site. To assess the spectrum of consequences for a particular release, a representative sample of meteorological conditions is considered. This statistical sample must, however, be carefully selected to ensure adequate precision over the whole of the estimated distribution of consequences.

Once the spatial and temporal distribution of the radioactive material in the atmosphere and on the ground is estimated, it can be converted to distributions of dose in man. The major

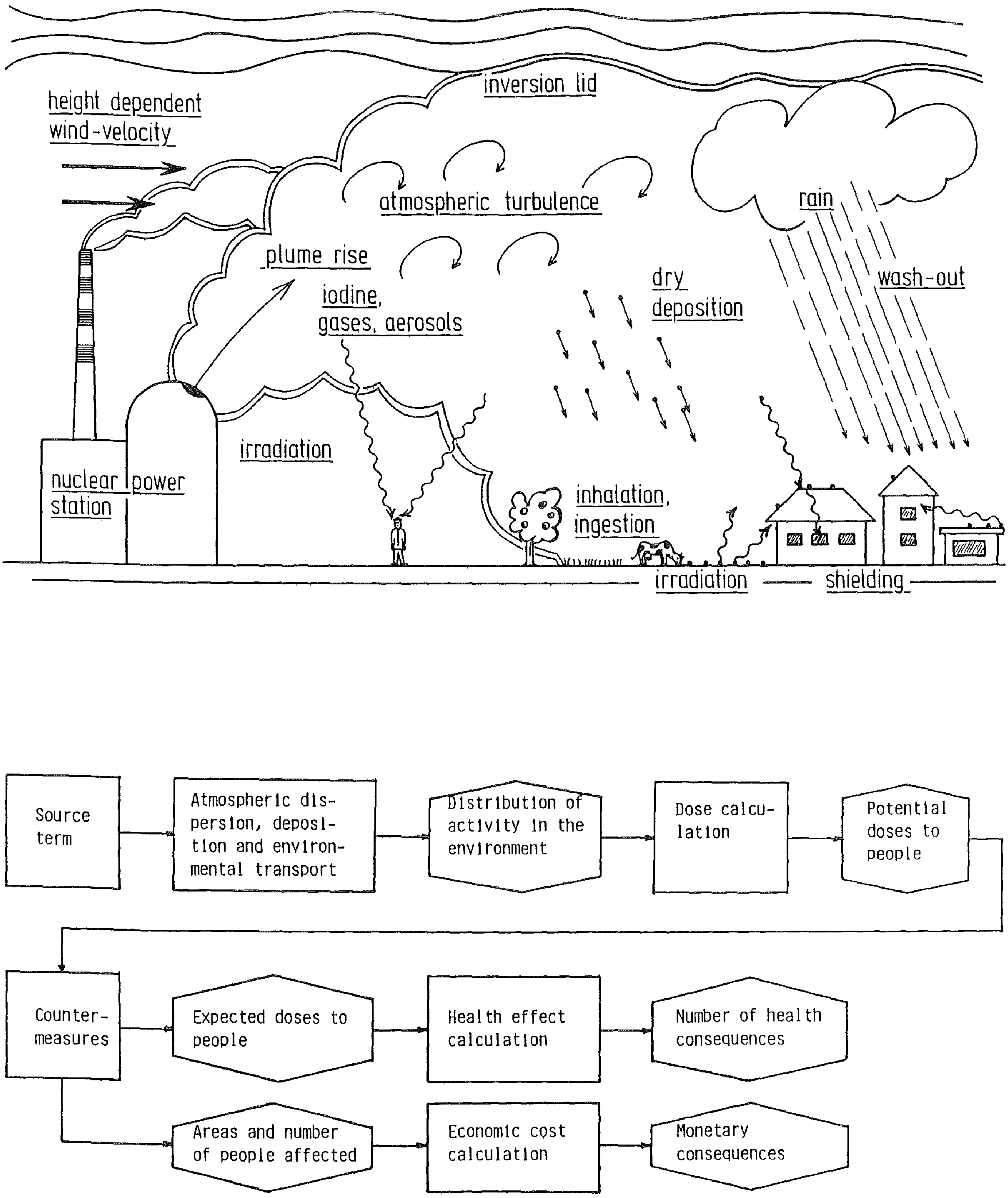

Fig. 1.1: Basic features of an accident consequence assessment

exposure pathways are external irradiation from the plume and from deposited activity, and internal irradiation from radioactive material taken into the body by inhalation and by ingestion of contaminated foods. The external dose from the plume is determined directly from the distribution of activity in the atmosphere; that from deposited activity is a function of both the quantity of material deposited and its subsequent behaviour, such as its rate of migration down the soil column. Since people spend a good deal of their time inside buildings, either at home or at work, and in transport systems, due consideration of shielding by the material between the source of radiation and the individual is necessary. The radiation doses from radioactive material taken into the body depend on the physical and chemical forms of the radionuclides inhaled and ingested. In the evaluation of doses via ingestion, the transfer of the deposited radionuclides as a function of time through the various sectors of the terrestrial environment into each of the significant foodstuffs (both plant and animal) also needs to be described. For some radionuclides, this transfer process may extend over prolonged periods.

A variety of possible countermeasures may be taken following an accidental release, their extent and duration being dependent on the scale of the accident. A realistic estimate of the exposure of the population must therefore take appropriate account of such protective actions.

The major countermeasures affecting people which may be taken in the early phases of an accidental release are sheltering, evacuation and the issue of stable iodine tablets. In the intermediate phase and in the longer term people may be relocated for varying periods pending a reduction in radiation levels by radioactive decay and/or remedial measures such as decontamination. Countermeasures may also be applied to restrict the production and distribution of contaminated foods.

While the application of countermeasures such as evacuation, relocation, decontamination and interdictions on food distribution will result in a reduction of the exposure of the population, they will have an associated economic cost. This will arise from various sources and, in particular, from the areas of land where access is restricted and from which people have been evacuated or relocated.

As the final step of an ACA, the incidence of each of the major types of health effects from the distribution of dose in the exposed population after taking due account of the application of protective actions and interdictions is evaluated. There are two broad categories of effects that need to be considered and they are frequently referred to as "early" and "late" health effects.

Early effects only occur if relatively high threshold doses are exceeded and they may arise within days, weeks or months after exposure. They include death and varying forms of health impairment which may be temporary or more prolonged (e.g. vomiting, sterility, cataracts).

The important late health effects are fatal and non-fatal cancers in the exposed population and hereditary effects in their descendants. Unlike early effects, which occur only if particular levels of dose are exceeded, late effects are primarily stochastic in nature. Late effects are not expressed immediately; there is a delay, or latent period, which may be many years, during which no individual experiences the injury. After this latent period, the expression of the total number of health effects in the population may take place over a period of many years.

Each ACA computer code consists of a sequence of models and data, which describe the various processes mentioned above. The distinct submodels are of varying degrees of complexity, which range from simple numerical relationships to complex descriptions of the movement of radionuclides through parts of the environment. The selection of the most appropriate model is mainly influenced by the often conflicting requirements of minimizing both the computational costs and the uncertainties in the consequences estimated. Because of the complexity of ACA codes and the many repetitive calculations that have to be performed, the reduction of computational costs is an important point often requiring the use of simpler models than might otherwise be adopted.

The ACA codes which have been widely used are e.g. CRAC, MARC and UFOMOD /9,10,11/ in different updated versions. They have been applied /12/ in several areas of nuclear safety including risk assessments of nuclear installations, assessing the merits of different design options, safety goals, siting and emergency planning. In these applications the existing codes have proved to be broadly adequate. However, in the context of their increasing use in a decision-making framework there is a need for further code development with the main objectives of gaining a better understanding of the uncertainties involved and reducing these where appropriate, and enhancing the range of applicability of the existing codes. In addition, new scientific results about the behaviour of radionuclides in the environment, revised dose and dose-risk models as well as modified intervention criteria and emergency plans require adequate consideration in the next generation of ACA codes.

To develop more reliable and more broadly applicable models, research programmes have been installed in the US and Europe. An essential characteristic of these programmes is the organization of an interdisciplinary cooperation to ensure an appropriate selection of the level of model complexity for each of the processes which have to be discribed in an ACA model. Judgements in these areas are complex and require a detailed understanding of the interfaces and dependencies between the many diverse modelling disciplines like atmospheric dispersion, emergency planning, radiobiology, health physics and economics.

The current status and the future aims in establishing ACA methodologies are described in a joint report by KfK and NRPB prepared within the MARIA project /13/. Together with the requirements defined by the task description of the DRS-B, they can be summarized as follows:

- improved treatment of source terms for the various facilities of the nuclear fuel cycle;
- more realistic description of environmental transport processes;
- revision of dose models including shielding;
- detailed modelling of emergency actions, countermeasures and their intervention levels;
- comprehensive estimation of accident consequences and their correlations;
- development of evaluation programs for the problem-oriented numerical and graphical presentation of intermediate and final results;
- program structure suited for easy modification or incorporation of submodels and data coming out from future investigations;
- easy access to parameter values and results of the various submodels to facilitate sensitivity and uncertainty analyses;
- high flexibility and user friendliness of the program system;
- acceptable computing times and storage requirements.

These in some points contradictory demands determined the development of the new program system UFOMOD. One of its most important improvements is the introduction of different trajectory models for describing atmospheric dispersion in the near range and at larger distances. Emergency actions and countermeasures modelling takes into account recommendations of international commissions. The dosimetric models contain completely new age-, sex- and time-dependent data of dose-conversion factors for external and internal radiation; the ingestion pathway is modelled to consider seasonal dependencies. New dose-risk-relationships for stochastic and non-stochastic health effects are implemented; a special algorithm developed for ACA codes allows individual and collective leukemia and cancer risks to be presented as a function of time after the accident. According to the modular structure of the new program system UFOMOD, an easy access to parameter values and the results of the various submodels exists what facilitates sensitivity and uncertainty analyses.

2. Structure of the program system UFOMOD

2.1 General layout

The first process which must be modelled in an ACA computer code is the atmospheric dispersion and deposition of the released radioactive material. The accuracy of the concentration distributions obtained determines the accuracy of the results of all subsequent submodules. Therefore, much effort was invested to substitute the straight-line Gaussian plume model conventionally used in ACA models by more realistic atmospheric dispersion models /8,14/. The most important results of these investigations can be summarized as follows:

- there are Gaussian-like segmented plume and puff trajectory models available which can be applied in ACAs,

- these trajectory models provide much more realistic results of ACAs than straight-line Gaussian models,and

- they increase the applicability of ACA codes (e.g. optimization of protective measures).

In general, the range of validity of these models is limited to the near-to-the-site region, since in most cases the meteorological data are available only from the site or a meteorological station representative for it. A Gaussian dispersion over more than some 10 kilometres based on these data is hard to defend especially in topographically structured areas, and even over flat land, this type of dispersion has never been proven at longer distances.

Therefore, long-range dispersion models are needed to describe the transport of radioactive material over large areas up to thousands of kilometres. The only model available at the time of designing the new program system UFOMOD was the computer code MESOS /15/. It combines the requirement of short computing time with the ability to disperse radioactive material along precalculated windfields derived from meteorological data measured within whole Europe (see Chap. 4). Because of the density of the meteorological stations, a grid size results which does not allow to apply this model in the near range (< 50 km).

Due to the fact, that

- site-specific characteristics are only relevant in the near range and vanish at farther distances,
- the quality and quantity of consequences in the near range (fast protective measures, early health effects) are different from the far range (long-term countermeasures, stochastic health effects),
- the near range can be modelled much more in detail than the far range, and
- many applications of ACAs refer to only one of both distance ranges,

a separation of the new program system in principally two model parts was a logical conclusion (see Fig. 2.1). According to this concept, different ranges of validity are distinguished and assigned to respective trajectory models:

(1) the near range (< 50 km), where modified versions of the trajectory models MUSEMET /16/ and RIMPUFF /17/, respectively, are used, to calculate the spread of concentrations;

(2) the far range (> 50 km), where the computer code MESOS /15/ is applied, which calculates the dispersion of the radioactive material along precalculated wind fields.

UFOMOD	
Near range model (≲ 50 km)	Far range model (≳ 50 km)
Atmospheric dispersion	
MUSEMET (KFA) RIMPUFF (RISØ)	MESOS (ICST) Windfields in the regions 10°W - 50°E and 36°N - 62°N
10 measuring stations, synoptic data of 1982 and 1983, recorded at 1 h intervals	≈800 measuring stations,synoptic data of 1982 and 1983, recorded at 3 h intervals

Fig. 2.1: UFOMOD: Modelling of atmospheric dispersion

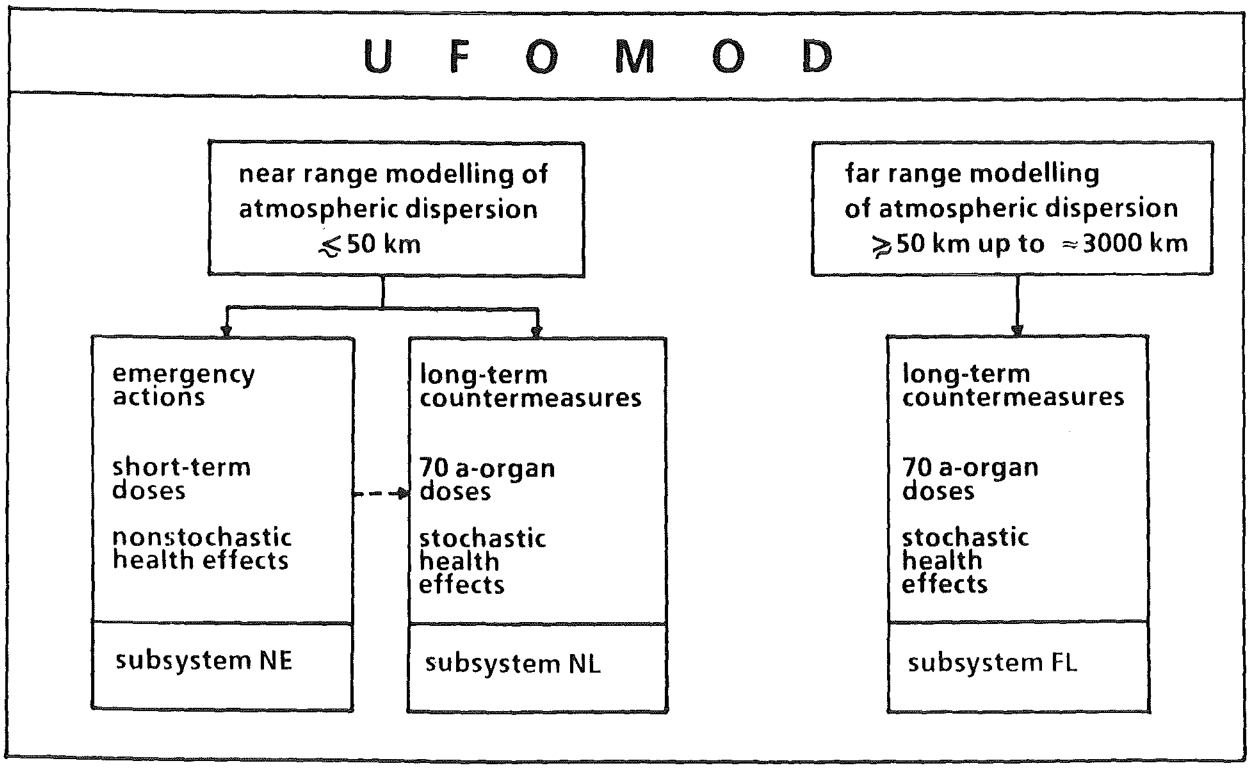

Fig. 2.2: UFOMOD: General structure of the program system

The interface between the atmospheric dispersion models and the subsequent submodels is universal in such a sense, that any arbitrary computer code describing atmospheric transport and deposition processes can be implemented, if it provides time integrated air and ground concentrations in a polar coordinate grid system at single points representative of the corresponding grid element. Therefore, future developments leading to improved trajectory models applicable in complex terrain can be easily taken into account by this modular structure of UFOMOD.

The inclusion of two completely different atmospheric dispersion models, which calculate air and ground concentrations independent of each other in different distance ranges with different grid sizes and for different purposes, consequently leads to the division of the program into more or less independent parts. Together with the requirements defined in Chap. 1, the following structure of the new programm system UFOMOD finally resulted (Fig. 2.2):

- Three subsystems have been built each conceived to assess accident consequences occurring in different time periods or distance ranges.

- Each of the two subsystems of UFOMOD covering the near range up to about 50 km contains models and data to assess only one type of consequences, namely

    - the extent and duration of early protective measures, short-time integrated organ doses and non-stochastic health effects;

    - the extent and duration of long-term counter-measures, long-time integrated organ doses and stochastic health effects.

The two independent computer codes are depicted with UFOMOD/NE and UFOMOD/NL (N for "near", E for "early" and L for "late"). The present versions using MUSEMET are designated as NE 88/1 and NL 88/1, those using RIMPUFF are named NE 88/2 and NL 88/2.

- The subsystem covering the far range from about 50 km up to about 3000 km is designed mainly to estimate long-term countermeasures (esp. food-bans and their withdrawal), long-term doses of individuals and of the population, and the resulting stochastic health effects (version FL 88/1).

When protective measures and non-stochastic health effects are estimated in the near range, these results have to be transferred from UFOMOD/NE to version UFOMOD/NL to assess the correct long-term doses and stochastic health effects also in this range (indicated by an arrow in Fig. 2.2).

The structure of all UFOMOD versions is based on a polar coordinate grid system with the centre point at the location of the nuclear facility. The radial and azimuthal resolution of the near range versions can be preselected, but the default values of 20 radii and 72 azimuthal sectors are recommended. In the far range model, the grid size of 35 radial distance bands and 64 equidistant azimuthal intervals are obligatory by the use of the MESOS code (see Tab. 2.1).

index	radii of the grid system (default values) UFOMOD/NE/NL [km]	UFOMOD/FL [km]
1	0.250	10
2	0.400	20
3	0.625	30
4	0.875	40
5	1.150	50
6	1.550	60
7	2.10	70
8	2.70	80
9	3.70	90
10	4.90	100
11	6.55	125
12	8.75	150
12	11.5	175
14	15.5	200
15	21.0	300
16	27.0	400
17	37.0	500
18	49.0	600
19	65.5	700
20	87.5	800
21		900
22		1000
23		1100
24		1200
25		1300
26		1400
27		1500
28		1600
29		1700
30		1800
31		1900
32		2000
33		2100
34		2200
35		2300

Tab. 2.1: UFOMOD: Radial grid of the subsystems

2.2 Program structure of the subsystems

Each subsystem of UFOMOD has an almost identical modular structure (Fig. 2.3). It consists of several program units, designed to assess subsequently the various types of accident consequences. Each of the program units can be called separately by the steering program MAIN. According to that structure, each of the UFOMOD subsystems can be run as a whole or step by step dependent on the desired results and the mode of application. Especially, sensitivity and uncertainty analyses of single submodels can be easily performed without the repetition of preceeding computational steps.

The intermediate results calculated in each program unit are stored on temporary and/or permanent units. The communication between the program units is organized by reading and writing these data sets. In addition, special evaluation programs have access to these data sets to provide numerical and graphical presentations of the various intermediate and final results and the correlations between them (see Chap. 10).

In the following, the function of each program unit in the corresponding subsystem of UFOMOD is described.

EINLES reads all input data required obligatory or optionally to define the conditions of the ACA run. Especially, the starting times of the weather sequences, the site-specific population data and the source term data are read from the corresponding data sets (see Fig. 2.4). These data sets are generated by the preprocessing programs METSAM, POPGRD and SOURCE, which are not integrated in the program system UFOMOD. As stand-alone codes, they can be run independently of the special UFOMOD application, what enables other algorithms, procedures or data sets to be specified by the user (e.g. for meteorological sampling, population grids or radionuclide release rates).

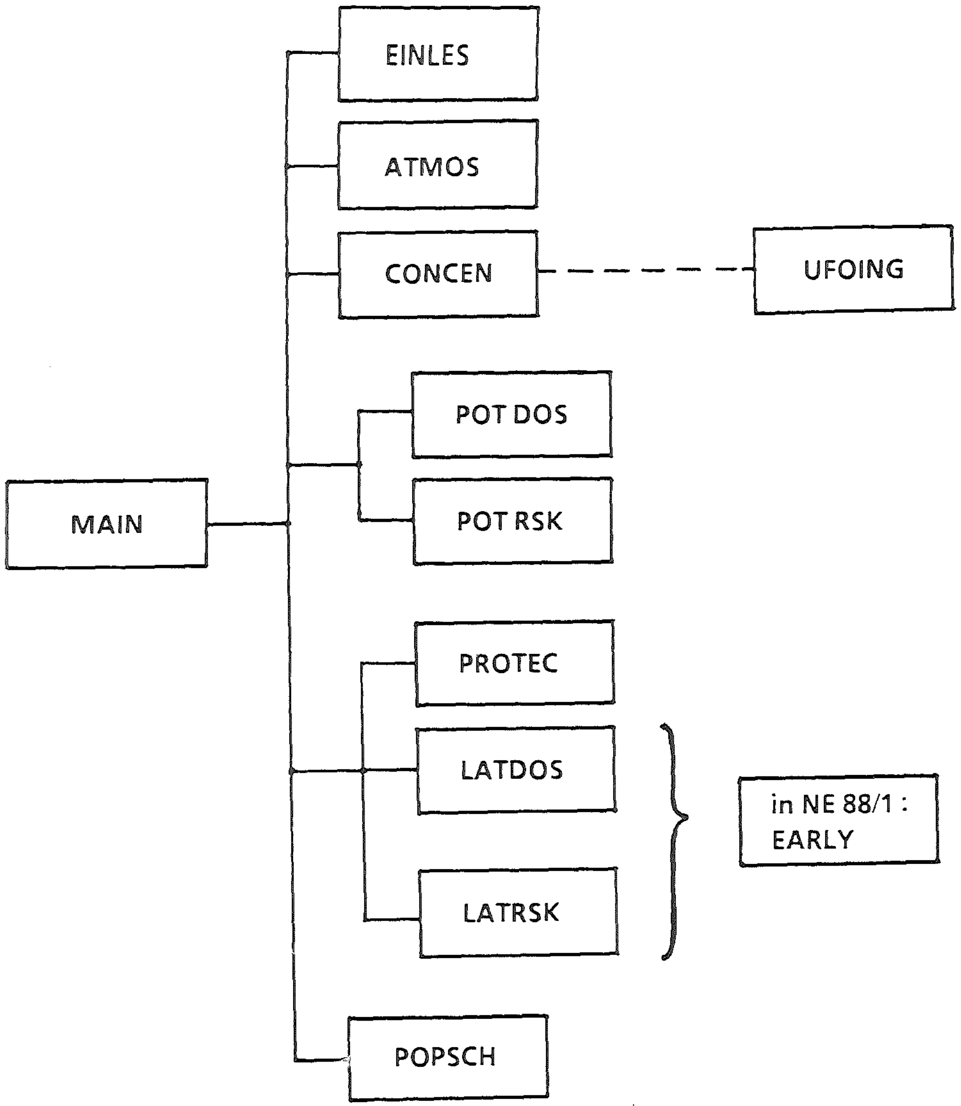

Fig. 2.3: UFOMOD: Structure of each subsystem

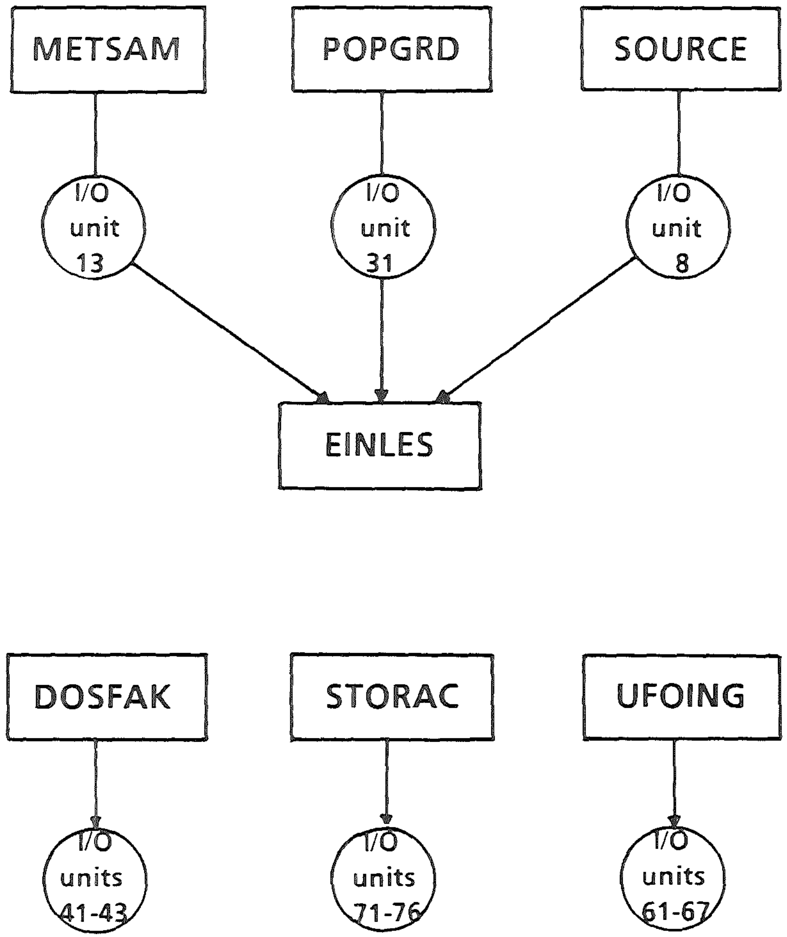

Fig. 2.4: UFOMOD: Preprograms and their linkage to logical I/O-units

ATMOS contains the atmospheric dispersion model. The function of this module is to calculate normalized time-integrated air and ground concentrations of up to five kinds of material with different dry and wet deposition properties (noble gases, aerosols, elemental, organically bound and particulate iodine). In addition, the arrival time of the radioactive plume at a certain grid element and a correction factor for gamma radiation from the cloud in the near range are determined. Dependent on the source term characteristics, buoyant plume rise, building wake effects and lift-off are taken into account. A more detailed description of the modelling, the treatment of time-dependent releases and the selection of weather sequences according to a stratified sampling scheme is given in Chap. 4 and 5.

CONCEN reads the results obtained in ATMOS as mentioned above, calculates the initial air and ground activity concentrations of individual radionuclides at each grid element and corrects for radioactive decay during dispersion and the build-up of radionuclides from radioactive decay chains.

The program unit PROTEC is designed to determine the extent and duration of protective actions, like sheltering, evacuation and relocation, decontamination and food-bans. The areas, which are affected by the different countermeasures, are defined by means of angles and distances or isodose lines resulting from dose criteria. In the latter case, the corresponding action is assumed to take place in the grid element considered, if potential organ doses exceed certain intervention levels.It is withdrawn as soon as the potential organ doses are below a second set of dose thresholds. The imposement of protective measures is oriented at the recommendations of ICRP 40, but all dose levels can be specified by the user. Special cases like evacuation of a disk shaped or sector shaped area, no evacuation of a geometrically defined area etc., are covered by choosing the input data accordingly. (Chap. 8). The results are stored as flags and can be read in by subsequent program units.

POTDOS and POTRSK calculate organ doses and health risks under the condition of absent actions. Dependent on the subsystem, short-time integrated organ doses or 70a-organ doses are estimated with POTDOS together with percentage contributions of nuclides and exposure pathways considered (Chap. 6).

In UFOMOD/NE, the exposure pathways considered are external irradiation from the passing plume and from activity deposited on the ground and internal irradiation from activity incorporated by inhalation. The subsystems UFOMOD/NL and FL additionally evaluate doses from inhalation of resuspended activity from ground deposits and from the ingestion of contaminated foodstuffs at different seasons of the year. To that purpose, the starting times of the weather sequences are linked to the ingestion model. It contains two sets of yearly integrals of specific activity concentrations of 8 foodstuffs and 29 radionuclides up to 200 years after an assumed release in winter and summer (see Sec. 6.3.2).

POTRSK is used to evaluate the potential incidences of each of the major health effects. The fatal non-stochastic effects comprise the effects following the irradiation of the bone marrow (hematopoietic syndrome), the lung (pulmonary syndrome) and the GI-tract (gastrointestinal syndrome). In addition, the mortality of pre- and neonates after exposure in utero are quantified. Of the possible non-fatal effects only the most severe ones are quantified in UFOMOD (impaired pulmonary function, hypothyroidism, cataracts and mental retardation after irradiation in utero). Both fatal and non-fatal stochastic somatic health effects are considered in UFOMOD. The corresponding age-, sex- and time-dependent dose-risk factors for the 10 organs red bone marrow, bone surface, breast, lung, stomach, colon, liver, pancreas, thyroid, and remainder have been provided by GSF. For the hereditary effects, at present only the genetically significant dose is quantified to provide a measure for the overall number of effects.

LATDOS, LATRSK and EARLY calculate organ doses and health effects risk in the subsystems for long-term (UFOMOD/NL and FL) and early phase (UFOMOD/NE) assessments, respectively, taking into account the patterns of dose mitigating actions determined in PROTEC. As in POTDOS and POTRSK, also the percentage contributions of exposure pathways and nuclides are calculated.

EARLY contains a detailed modelling of fast protective actions. After an initial delay, the population is assumed to be partly sheltered and partly evacuating spontaneously. An additional fraction remaining outdoors for whatever reason can be specified. A broad spectrum of shielding factors may be experienced by sheltering persons. EARLY allows for the definition of both 3 shielding factors and 3 fractions of the population staying indoors to be correlated with them. At the end of the sheltering/outdoor period, all remaining persons are evacuated. The spectrum of driving times to leave the evacuation area is approximated by four 3-step distribution functions; each distribution is representative of a certain population density in the evacuation area. The values of the different parameters (delay/response times, fraction of the population taking certain actions, driving times, shielding factors etc.) can be defined by the user. This flexible modelling prevented the subdivision of EARLY into two separate program units for organ dose and health effects risk estimation, since the required storage for all single dose values was unacceptable (see Fig. 2.3).

A special option in POTRSK and LATRSK offers the possibility to calculate the individual risks of stochastic health effects as a function of time after the accident for each type of late effect and their sum.

The dose-conversion factors for external and internal irradiation are read from data sets, which are precalculated by the preprocessing program DOSFAK (see Fig. 2.4). It derives from a large data base provided by GSF age- and time dependent dose-conversion factors for those organs considered in UFOMOD. The data sets of the present versions of UFOMOD contain dose-conversion factors for adults only, but other data sets can be easily prepared with the preprogram DOSFAK.

The assessment of stochastic somatic health effects from irradiation protracted over tens of years requires a complicated algorithm to account for the age- and life expectancy distribution of the population and the continuous incorporation of radioactive material (e.g. ingestion pathway). Therefore, "activity-risk-coefficients" /5,19/ for all stochastic somatic health effects considered were precalculated (see Chap. 7) with the preprocessing program STORAC (see Fig. 2.4). Multiplication of these activity-risk-coefficients with the initial activity concentrations gives the individual health effects risks in each grid element. The stored data are read in POTRSK or LATRSK during the ACA run.

The individual health risks estimates calculated in POTRSK, LATRSK or EARLY are input to POPSCH, which determines the number of health effects in the exposed population by multiplication with the number of persons living in each grid element (Chap. 7). Further evaluation programs enable collective doses to be calculated and correlations between collective doses, the number of health effects and individual doses or health effects risks to be presented. If the stochastic somatic risks calculated in POTRSK or LATRSK are stored as a function of time after the accident, the occurrence of the late health effects in the population can also be estimated time-dependently.

As an important supplement to the long-term exposure subsystems of UFOMOD, the stand-alone program UFOING has been developed /7/. It enables fast and detailed investigations of the accident consequences caused by the ingestion pathways. Dependent on the season of the year, UFOING calculates the contamination of foodstuffs from the deposited activity in each grid element (read from CONCEN), age dependent potential organ doses, the areas over which restrictions of the production and consumption are applied together with the duration of these bans, the organ doses to be expected considering food-bans, and the health effects risk as a function of time after the accident. In addition, the percentage contributions of the foodstuffs and radionuclides to the various results are obtained. A simplified version of UFOING is implemented in UFOMOD for the assessments of the consequences emerging from the foodchain pathways.

3. Interface between in-plant and off-site accident analysis

A comprehensive probabilistic safety study of a nuclear installation leads to the identification of a wide spectrum of conceivable accident sequences derived from event tree analysis. Limitations of time and resources, as well as the complexity of the computer codes for in-plant and off-site radionuclide transport calculations, make it impossible to perform a complete risk assessment based on all conceivable event sequences for which radionuclide releases can be identified. To circumvent this difficulty, accident sequences which lead to similar source terms are grouped together to form a limited number of categories. Each category is characterized by one release term, which includes data on the frequency of occurrence and parameters which affect the radiological consequences. The set of release terms representing the relevant accident sequences forms the release matrix of the plant under consideration.

Sorting of accident sequences into categories usually requires expert judgement, as it is based on the predicted behaviour of radionuclides inside the plant and during release to environment, with emphasis on the off-site radiological consequences. The selection of radionuclides and the time dependency of their release are important as well. It should be pointed out that variations in the release characteristics can considerably influence the results of an ACA, since non-linear dependencies in the different models may cause unexpected changes.

3.1 Procedures presently used

Risk studies performed with established ACA codes (CRAC, UFOMOD, MARC) mainly refer to nuclear power stations. The interface between in-plant and off-site accident consequence calculations is described by two data sets, namely (Fig 3.1):

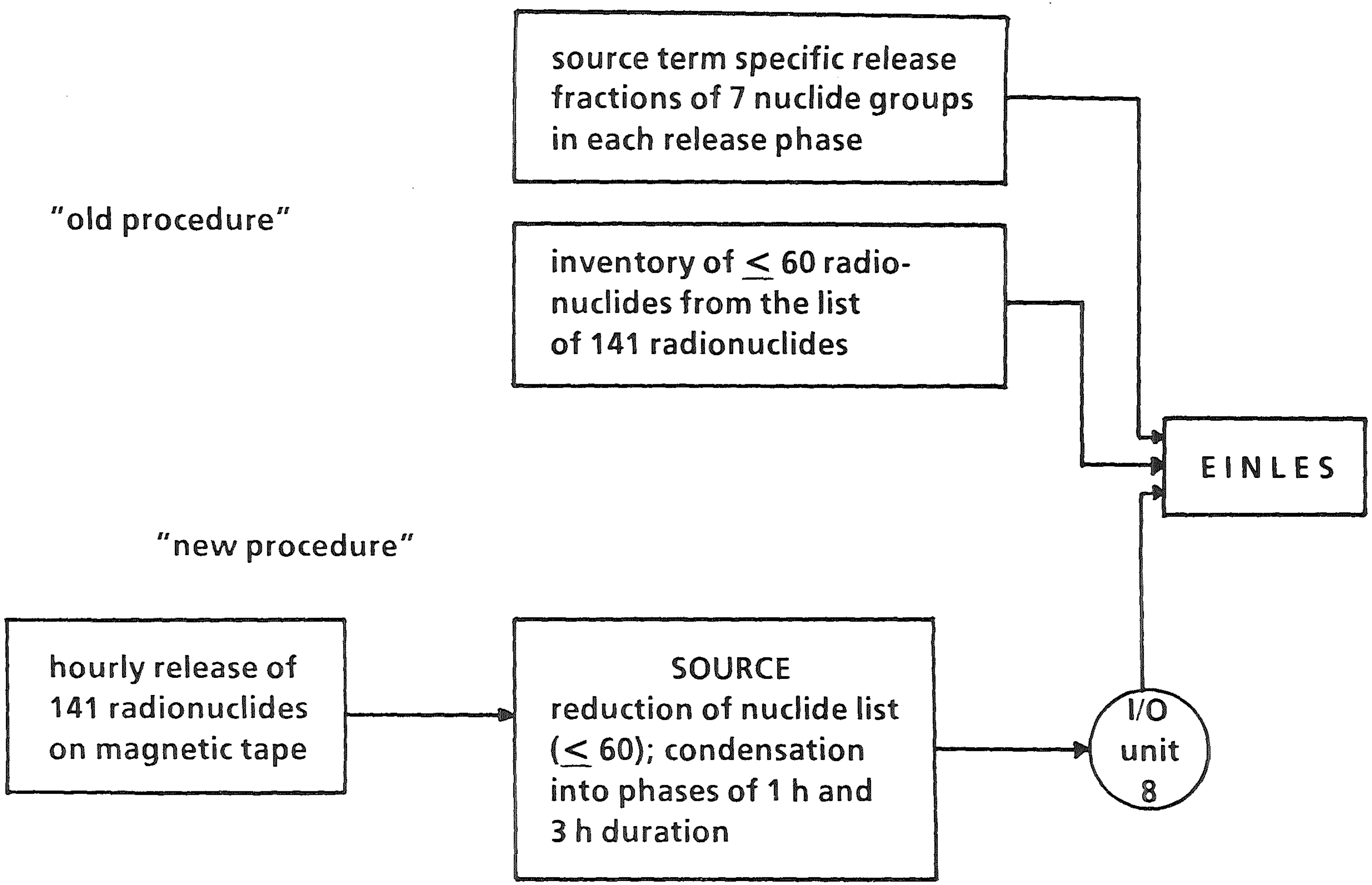

Fig. 3.1: UFOMOD: Source term interface

- the radioactive inventory of the radionuclides present in the reactor core at the time of the accident, and

- the release term for each category which provides the radionuclide release fractions and additional parameters describing the particular release characteristics.

The radioactive inventory of the reactor core describes the condition of the reactor prior to the accident and is dependent on the thermal power of the reactor and - in particular for the long-lived radionuclides - the fuel burn-up. The response of the nuclear power plant to the accident scenario and the capability of its containment system to retain the radioactive inventory is reflected in the magnitude and the time characteristics of the radionuclide release fractions. The release fractions denote the relative amount of the total activity inventory released to the environment due to either malfunction of various reactor safety systems or total plant failure.

To reduce the calculational effort, the radionuclides are sorted into 7 groups mainly based on their volatility:

- noble gases (Kr, Xe)
- iodine
- alkali metals (Cs-Rb-Na)
- tellurium-group (Te-Sb)
- alkaline earth metals (Ba-Sr)
- noble metals
- metal oxides of low volatility.

The noble metal group includes Fe, Co, Zn, Se, Mo, Tc, Ru, Rh, and Ag, the low volatile metal oxide group comprises Mn, Ni, Y, Zr, Nb, La, Ce, Pr, Nd, Pm, Eu, Ra, U, Np, Pu, Am, and Sm.

The time dependency of the release is calculated for each of the 7 element groups, but the ACA codes can only treat this information in a simplified manner. As an example the old UFOMOD program was designed to approximate the time behaviour by up to 5 release phases of one hour duration, which can be separated from each other by an arbitrary time interval of several hours. Within each release phase a constant release rate is assumed.

To aid realistic modelling of the dispersion and the impact of accidentally released radionuclides, the following parameters are included in the release term of each category in addition to its release fractions and its frequency:

- the time delay between reactor shutdown and release of radioactive material to the environment, which reduces activity by radioactive decay and also may influence the introduction of countermeasures before the release;

- the duration of the release, which influences the dispersion of released material;

- the height of release which influences the exposure of individuals near to the source;

- the thermal energy associated with the release which may lead to plume rise thus reducing the exposure over significant down-wind distances.

Other parameters of the release, which are important for ACA calculations are assumed to be constant in all release cases. These include the physical form and the chemical properties of the radionuclides. It is assumed, that they are released in oxide form as aerosol particles with 1 μm AMAD (activity median aerodynamic diameter), except noble gases, which are in elemental form, and iodine, which may appear in elemental, organically bound and aerosol-type forms. The presence of moisture during release and its influence on plume rise and deposition of radioactive material has been neglected.

3.2 New procedure in the program system UFOMOD

Recently published results of new investigations on accident sequences in PWRs and the behaviour of the radionuclides released into the containment indicate, that the time of release as well as the duration of the releases tend to larger values. In addition, risk studies of other nuclear facilities came to the result, that prompt releases with extremely low frequencies as well as delayed releases ranging over days up to some weeks are contained in the spectrum of possible source terms. Therefore, the new program system UFOMOD has been improved to meet requirements resulting both from short-term and long-term releases:

1. Releases of long duration cannot be described by condensing them into one or a few release phases with constant release rates, because of the non-linear functional dependencies between activity concentrations and accident consequences.

2. The atmospheric dispersion model of the old UFOMOD code assumes a straight-line transport of the radioactive plume. Changes of wind direction during the release and the dispersion are neglected. This simplification can be justified under certain restrictions if short-term releases are considered. In the case of long-term releases the modelling of constant wind direction during the whole release and dispersion process leads to inaccurate results for the contamination of land areas and the radiation doses to the population (see Chap. 4).

3. The radioactive decay calculation should be continued up to the time of release to guarantee that decay products are taken into account adequately.

From the accident analysis of the plant, time dependent hourly release rates are provided on magnetic tape for 141 radionuclides including radioactive daughter production up to the time of release. In addition, the time dependent relationship between elemental, organically bound and aerosol-type iodine is stored. The source terms of the German Risk Study - Phase B will be prepared in this form by GRS.

A special program called SOURCE has been developed to read the source term data and to reduce them to a UFOMOD-compatible form (see Fig. 2.4). To that purpose, SOURCE contains algorithms

- to condense the hourly recorded release data into a limited number of release phases, and

- to select specific for each exposure pathway those nuclides which contribute most to the radiation dose.

Dependent on the subsystem, the duration of one phase is one hour (UFOMOD/NE and NL) and three hours (UFOMOD/FL), respectively. The phases can be separated from each others by multiples of the phase length. The present maximum number of phases is 17 in UFOMOD/NE and NL, and 10 in UFOMOD/FL, but these dimensions can be changed.

The selection of nuclides is performed for each exposure pathway relevant for short-term and chronic exposure separately. Only those radionuclides are considered in the accident consequence calculations, whose overall percentage contribution to the potential dose is below a certain maximum value (e.g. 99%).

The list of nuclides, which have to be considered in the subsequent UFOMOD runs, the release rates of these nuclides in each release phase and the contribution of the 3 iodine species are stored as a data set. Dependent on the choice of the corresponding input parameter, the source term data will be read from this data set or prepared in UFOMOD-compatible form according to the "old" procedure described in the previous section.

4. Atmospheric dispersion and deposition

Any probabilistic evaluation of the consequences of nuclear accidents with radioactive releases must be based on predictions of the distribution of the radioactive material throughout the environment.

Therefore, the first submodel ATMOS of the program system UFOMOD models the dispersion of radioactive material in the atmosphere and the processes of removal of material from the atmosphere leading to deposition on the ground. Thereby the meteorological conditions prevailing during the release and time of travel of the radioactive plume are taken into account, which determine the dispersion and the direction in which the activity is transported. Removal mechanisms by dry and wet deposition are included, while the radioactive decay will be considered in a subsequent program unit. Dependent on the release characteristics plume rise due to the buoyancy of the released activity and the influence of the turbulent building wake are modelled.

4.1 The atmospheric dispersion models

Most of the computer programs for ACAs developed in the last ten years use the straight-line Gaussian model to describe the atmospheric dispersion, e.g. CRAC /9/, MARC /10/, UFOMOD /11/ and their modified versions. This model is derived from a simplified theoretical treatment of dispersion which assumes that the atmospheric flow- and turbulence fields are homogeneous and stationary. These idealized situations occur rather seldom under real atmospheric conditions and, therefore, the application of the straight-line Gaussian model might predict the accident consequences unrealistically.

Recently, a benchmark study compared the probabilistic results of an ACA resulting from the application of the straight-line Gaussian model and more improved dispersion models which describe the physical conditions in the atmosphere more realistically /8,18/. This study demonstrated that significant differences in the consequences might be calculated if dispersion models of different complexity are applied. With respect to the demands "high flexibility, user friendliness and acceptable computing time" (see Chap. 2) for an ACA program system, the benchmark study revealed that only Gaussian-like trajectory models are applicable. Although these models use the Gaussian formula to calculate time integrated concentration fields, the ability to consider changes of wind direction during the release and the dispersion led to more realistic consequence assessments compared to the straight-line Gaussian model.

The conclusion from the comparitive study was to apply trajectory models in ACAs what led to the completely novel concept of the new program system UFOMOD (see Chap. 2).

For the application in the near range (≤ 50 km) modified versions of the Gaussian-like trajectory models MUSEMET /16/ and RIMPUFF /17/ are available. Their basic characteristics and one of their principle differences are illustrated in Figure 4.1. The segmented plume model MUSEMET transports the radioactive material along one single trajectory which is divided into several straight-line segments. The direction and the length of each of these segments are determined by the meteorological conditions prevailing at a single meteorological station which is regarded as representative for the source site. In the multiple-puff model RIMPUFF all puffs released experience a change of wind direction instantaneously so that each puff will follow its own trajectory. Therefore, utilizing the puff model, the contaminated area gets larger.

The second difference concerns the meteorological input data. MUSEMET, as already mentioned, uses data of one meteorological station representative for the source location. During one timestep homogeneous meteorological conditions are

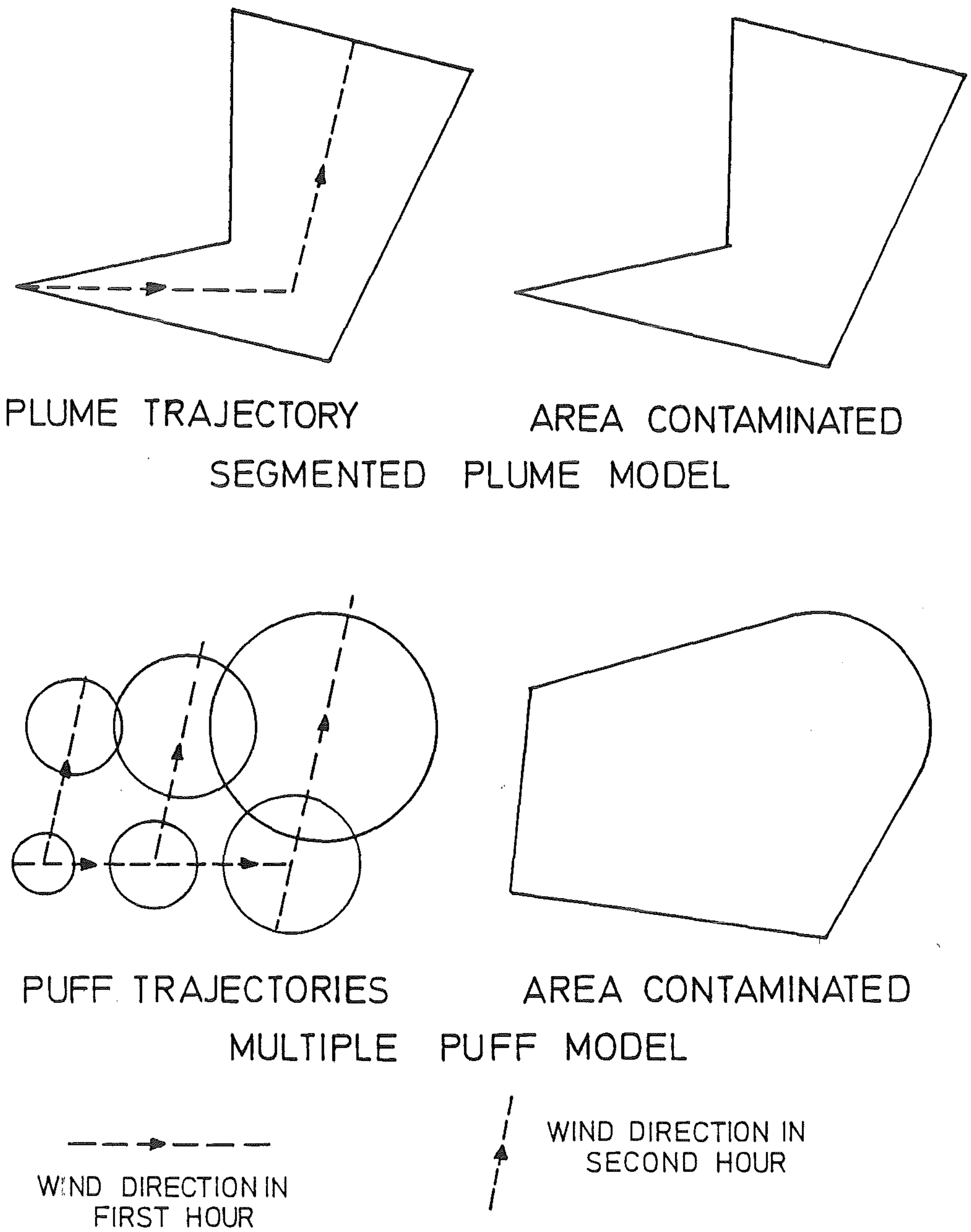

Fig. 4.1: Illustration of plume and puff models

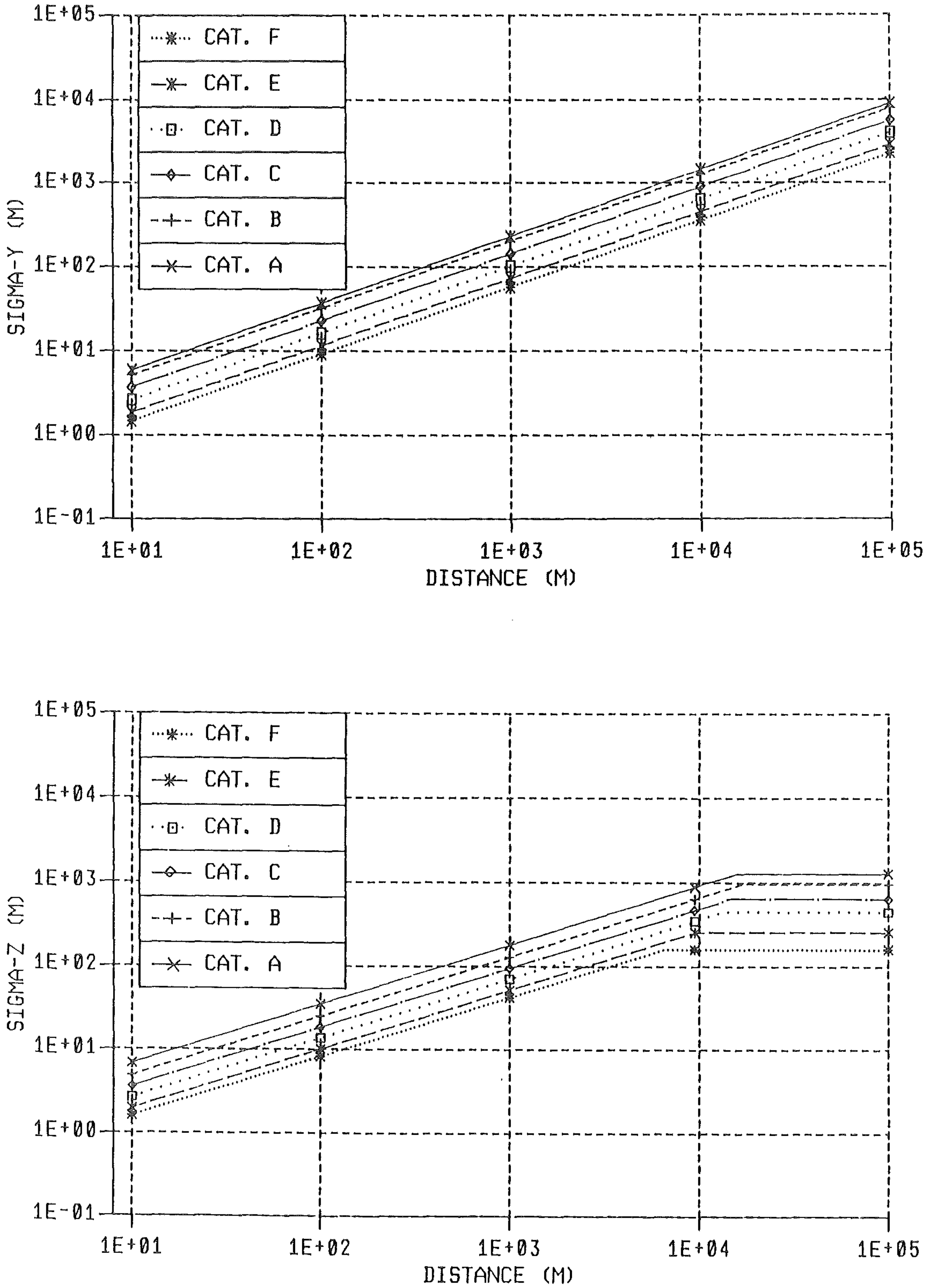

Fig. 4.2: Horizontal (σ_y) and vertical (σ_z) dispersion parameters as a function of distance for different stability categories and smooth terrain (release height 50 m)

assumed. In contrast to this the data of several stations can be considered in RIMPUFF. Spatial varying windfields and precipitation patterns are generated on a user-defined rectangular grid by a simple interpolation method. The spatial range of validity for the stability classes has to be defined by the user for each station, ideally taking into account the topographical characteristics of the surroundings.

Both models evaluate the time integrated air concentrations and the ground contamination in a variable polar grid system.

For the application in the far range (> 50 km) the computer code MESOS /15/ is available. MESOS is a trajectory - puff model for the transport, dispersion and deposition of material released to the atmosphere up to distances of thousands of kilometres. It considers temporal and spatial changes of the meteorological conditions during the transport: "In MESOS a 3 hour release is simulated by tracing the histories and development of puffs released at the beginning and end of the period, and assuming that a continuous release over the 3 hours leads to a continuous sequence of puffs following intermediate trajectories, thus leading to contamination of the whole area along and between the calculated trajectories. Longer releases are treated as a sequence of 3 hour releases" /15/. The resulting time-integrated air and ground concentrations are available on a fixed polar grid system.

4.2 Dispersion parameters

In MUSEMET and RIMPUFF the horizontal and vertical dispersion parameters σ_y and σ_z are assumed to be power functions of the distance from the source /20/. The appropriate dispersion coefficients depend on the atmospheric stability, the surface roughness and the release height. Both models distinguish between two different sets of dispersion coefficients valid for two different surface roughnesses. Those determined

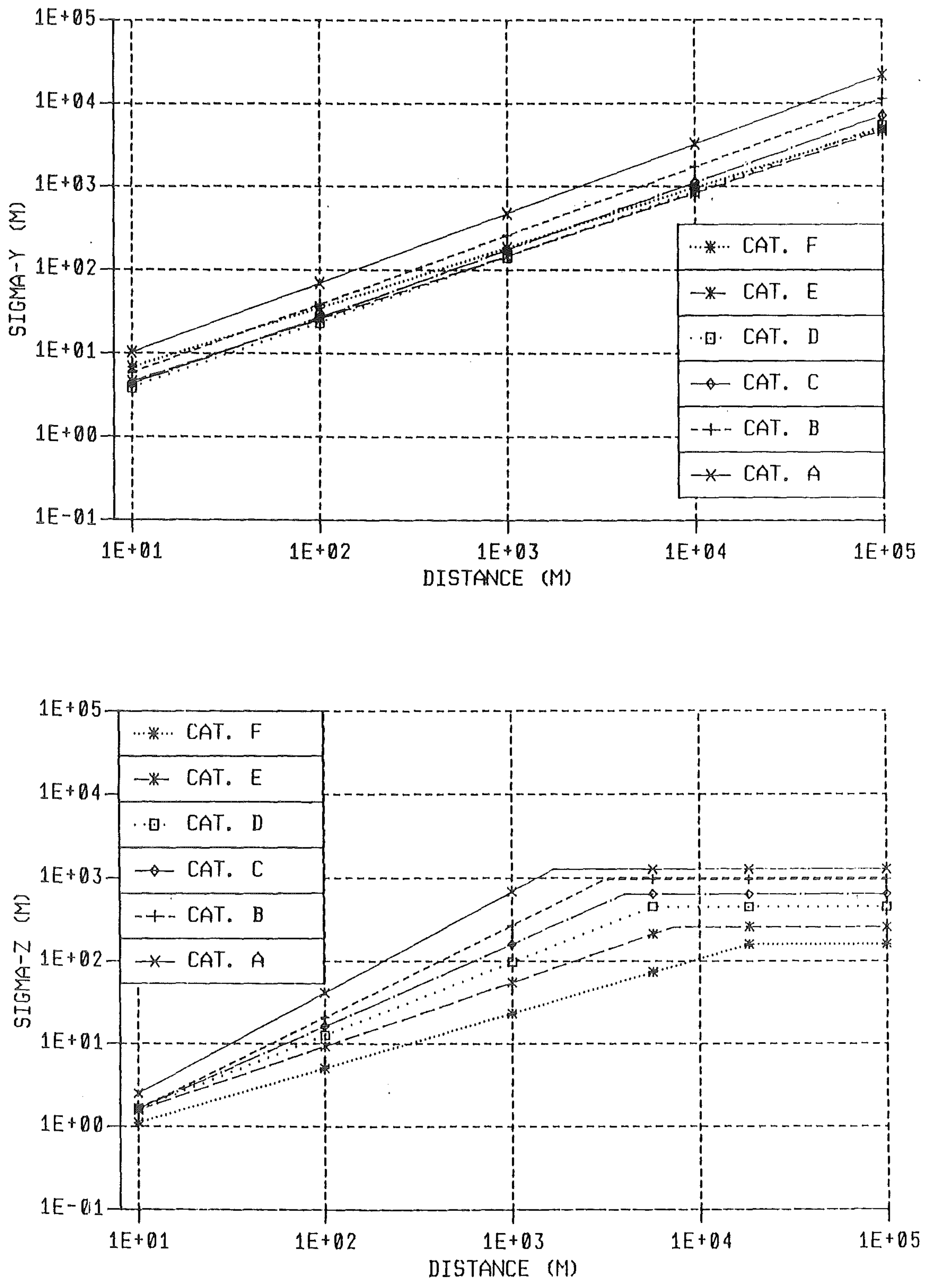

Fig. 4.3: Horizontal (σ_y) and vertical (σ_z) dispersion parameters as a function of distance for different stability categories and rough terrain (release height 50 m)

experimentally at the S.C.K / C.E.N., MOL/Belgium, are used for dispersion calculations over rather smooth terrain (0.1 m $\leq Z_o < 1$m) /21/ (see Fig. 4.2). Over rough terrain ($Z_o \geq 1$m) the height dependent Karlsruhe - Jülich sigma parameter system will be applied /22/ (see Fig. 4.3).

In the MESOS model the horizontal dispersion parameter σ_y is assumed as proportional to the travel time of a puff according to Doury's system /23/. The vertical dispersion parameter σ_z is a power function of source distance; it is derived for a surface roughness of 0.3 m /24/.

4.3 Height of mixing layer

The height of the mixing layer varies with stability. In MUSEMET and RIMPUFF this height must be preselected by the user dependent on the stability class. During the dispersion process, it is not allowed to decrease. Neither the final rise height nor the vertial diffusion are allowed to exceed the mixing height chosen, as it defines the position of a lid which cannot be penetrated by the plume.

In MESOS the daily variation of the height of the mixing layer is calculated and taken into account during the dispersion process. Therefore it might be possible that parts of the plume will be isolated in the stable layer above if the height of the mixing layer decreases during the course of the day. These parts of the plume can only be diffused again after a subsequent increase of the mixing layer height (fumigation).

4.4 Dry and wet deposition

Dry and wet deposition parameters depend on the physical and chemical form of the isotopes released: noble gases, which will neither be deposited by dry nor by wet deposition, particulate material (aerosols), elemental and organically bound iodine. For a given form of isotope the dry deposition parameter also depends on the characteristics of the underlying surface. The values used for dry deposition velocities have been evaluated and summarized in /25/.The removal process of activity from the plume due to dry deposition is taken into account by using the source depletion model /20/.

The washout coefficients describing the amount of activity depletion by rain falling through the plume and the rate of wet deposition on the ground are, in addition, functions of precipitation intensity. In MUSEMET and RIMPUFF values of the washout coefficients are used which have been evaluated for iodine and aerosols for three different precipitation intensity classes /26/. A characteristic duration of rainfall is linked to each intensity class, which is derived from a ten years record of rain intensity.

MESOS models the washout-coefficient as the well known power function of precipitation intensity /20/ with the appropriate coefficients taken from /27/. This modelling of wet deposition can optionally be chosen also in MUSEMET and RIMPUFF.

4.5 Lift-off and plume rise

Dependent on the release characteristics the thermal rise of a buoyant plume out of the source is taken into account by all three models. MUSEMET and RIMPUFF utilize a plume rise model which has been adopted to Briggs' plume break up model /28/, considering also the rising phase.

Due to the coarse horizontal grid resolution the rising phase is not considered in MESOS. A puff will be started above the source at the final release height; it can be estimated using empirical formulas, e.g. taken from /29/.

The lift-off criterion, modelled only in MUSEMET and RIMPUFF, decides whether a buoyant plume really rises or whether it is caught in the turbulent wake downwind of a building /30/. The criterion, which depends on the thermal energy of the release, the prevailing windspeed and the dimensions of the building, has been formulated by Briggs /31/ and it has been confirmed recently by laboratory experiments /32/.

4.6 Building wake effects

Aerodynamic downwash due to the mechanical turbulence around a building can significantly alter the effective release height of a pollutant and, if the pollutant is caught in the turbulent wake downwind of the building, it is rapidly distributed within this turbulent zone.

In MUSEMET and RIMPUFF only the effect of aerodynamic downwash in the wake of a building is considered; the downwash effect in the wake of a stack is neglected compared to the stack height. In the model stack releases can be influenced by the turbulent zone around a building in the vicinity of the stack.

It is assumed that the whole building complex of a nuclear facility can be represented by a single building of simple geometric form with appropriate building dimensions. The model equations describing the aerodynamic downwash are taken from /20/.

To account for the mixing in the turbulent wake the virtual image source method is used /20/. It is assumed that the plume has an initial size at the real source with initial horizontal and vertical dispersion parameters which are related to the width and the height of the building, respectively. The virtual image source concept guarantees mass conservation of the released material.

Due to the coarse horizontal grid resolution building wake effects are not considered in MESOS because the influence of the building vanishes with increasing distance from the source.

4.7 Plume correction factors for gamma dose calculations

The calculation of γ-dose from the radioactive cloud in principle is performed by multiplying the time-integrated air concentrations near ground with dose-conversion factors for a semi-infinite cloud of uniform activity concentration (see Sec. 6.2). To take account of the finite extent of the plume in the near range (up to about 20 km), dose correction factors are calculated in MUSEMET for each grid point. To that purpose, basic correction factors evaluated by GSF /33/ have been implemented, which are expressed as functions of the location of the target with respect to the centre-line of the plume, of the spread over the vertical and horizontal direction of the plume and of stability class for 4 different heights of the plume and two different types of surface roughness.

4.8 Meteorological input data

All three models have been devised with the requirement that they should use real meteorological data, extracted from routine observations recorded and reported from meteorological stations.

Generally, for MUSEMET and RIMPUFF, hourly meteorological data are used, but shorter temporal resolutions are also possible. The necessary data input consists of windspeed, wind direction, informations on precipitation intensity and the Pasquill-Gifford stability classification which can be derived by several methods, e.g. the Klug-Manier scheme /34/. These data have been made available by the German Weather Service for several meteorological stations in the FRG as continuous hourly synoptic records of the years 1982/1983.

The MESOS model needs three hourly recorded synoptic data. They are available from synoptic stations distributed nearly over the whole area of Europe (36°N-62°N, 10°W-50°E) and they also cover the 1982/1983 period. The MESOS data consist of surface pressure, air temperature, relative humidity, cloud cover and height of cloud level and informations on precipitation intensity. Other parameters necessary for modelling a dispersion process like wind speed, wind direction, stability class, height of mixing layer are derived from the input data by several submodels.

4.9 Output of the submodule

The output of the ATMOS submodule are normalized time integrated air and ground concentrations for each grid element. These are then processed by CONCEN to calculate the actual initial activity concentrations of the invidual radionuclides (Sec. 2.2). Both normalized and actual concentrations and the areas contaminated with concentration levels can be presented as CCFDs and statistical quantities by using special evaluation programs. A list of the possible presentations is given in Tab. 4.1.

type of result	presentations
time integrated concentrations in air and on ground surface	• CCFDs, expectation values, percentiles as a function of distance for each radionuclide
areas contaminated with concentration levels	• CCFDs, expectation values, percentiles for a preselected concentration interval, radionuclide and distance band

Tab. 4.1: UFOMOD: Atmospheric dispersion part. Possible presentation of results.

5. Meteorological sampling

In probabilistic accident consequence assessments, it is necessary to repeat the atmospheric dispersion calculations with several hundreds of weather sequences to predict the full distribution of consequences which may occur following a postulated accidental release. Ideally, the ACA should be performed with every possible sequence of weather conditions, that means dispersion calculations starting every hour. In practice, time and computer constraints prevent this because the number of possible different sequences of weather conditions is large. However, many of the sequences would result in similar dispersion of activity and consequently in similar accident consequences. Therefore, it is desirable to select a representative sample of weather sequences from a meteorological record which is typical of the area over which the released radionuclides will disperse and which spans a sufficiently long period.

Generally, the meteorological record will include windspeed, wind direction, rainfall and atmospheric stability category. The procedure used to select the sample of weather sequences should ensure that the full range of weather conditions which might occur is included. Especially infrequent sequences which might lead to a larger number of early health effects should not be overlooked. In order to present the consequences probabilistically, the procedure should also be capable of determining the probability with which each chosen sequence occurs.

5.1 Choice of meteorological data

The assignment of meteorological stations with continuous longterm records of meteorological conditions to the nuclear site considered in an ACA should take into account the topographical and regional climatological characteristics of the areas where they are located. For risk assessments of sites within the FRG, the required meteorological parameters are available from 10 meteorological stations as hourly records from two years. Each of these can be regarded as representative for one or more locations of nuclear facilities. The assignment of meteorological stations to nuclear sites under the requirements mentioned above has been carried out by the German Weather Service.

5.2 Sampling techniques

A meteorological sequence within a database of continuous records is defined by specifying the time at which it starts. The most straightforward methods of sampling these times are the random and cyclic sampling techniques, respectively /13/. Both methods tend to sample similar sequences frequently, whilst overlooking the more unusual (and potentially more serious) ones and neither of these sampling schemes is adequate for predicting the probabilities of severe consequences. Despite of these disadvantages cyclic sampling can be selected optionally in UFOMOD. Each weather sequence then has the same probability.

A more refined method is called stratified sampling. This technique is potentially capable of selecting meteorological sequences from the full spectrum of weather situations and associating more realistic probabilities of occurrence to them. The intention is to group together all weather sequences present in the meteorological database, which give rise to the same consequences. By categorizing the recorded weather sequences, the probabilities of occurrence of each category may be determined directly. Meteorological sequences, identified by the time of their start, are then selected randomly from each category, thus ensuring that the full range of possible weather situations is covered. A more comprehensive discussion of stratified sampling, especially of grouping weather sequences with rainfall, is given in /13/.

5.3 Outline of sampling scheme of UFOMOD

As already mentioned in the beginning of this chapter, a sampling scheme has to be designed in such a way that the numbers and frequencies of (acute) health effects is predicted as comprehensively as possible. Besides on the weather situation, these health effects are also dependent on the distribution of the population in the surroundings of the site. Therefore, meteorological sampling schemes used for instance in CRAC2 /9/ or MARC /10/ select weather sequences for site-specific ACAs in correlation with population distributions.

The weather sampling procedure presently used in UFOMOD is more aiming at generic ACAs which consider a larger number of sites. Therefore, the correlation with population distributions is not taken into account. The method for grouping weather sequences in UFOMOD has been adopted from /35/. For every possible sequence of weather situations the travel time of the plume is determined depending on the distance out to which early health effects are to be expected (e.g. 20 km) and the windspeed in each time interval of measurement. Additionally, the total amount of rainfall occurring within the travel time of the plume is calculated and the initial wind direction is registered. Then defining certain categories characterized by the initial wind direction, the total rainfall and the travel time, several hundreds of groups may be obtained. From each of these groups at least one weather sequence is selected randomly. The bounds chosen for the categories and thus the number of groups depend upon the application of the ACA.

As an illustration of the sampling method currently used in UFOMOD, Tab. 5.1 shows one part of the whole classification scheme of the meteorological data of Karlsruhe (FRG). The initial wind directions are grouped into twelve 30° sectors. The dispersion calculations are performed out to a distance of 20 km and the resulting travel times of the plume are categorized in three groups:

$0 < T \leq 3h \qquad 3\ h < T \leq 6\ h \qquad T > 6\ h$

Additionally, four classes of the total amount of precipitation are distinguished:

$I = 0$ mm/h $\qquad 0$ mm/h $< I <$ 1mm/h;
1 mm/h $\leq I <$ 3 mm/h $\qquad I \geq 3$ mm/h

In this way 12 x 3 x 4 = 144 different classes of weather conditions are obtained. Tab. 5.1 shows the precipitation intensity/travel time classification for the most frequent initial wind direction sector with the numbers of weather situations per category. The probability of occurrence of each categorized sequence can be determined from the known total number of weather sequences.

travel time T [h]	precipitation intensity I [mm/h] I=0	0<I<1	1≤I<3	I≥3
0<T≤3	2976	610	303	22
3<T≤6	146	20	12	3
T>6	79	13	6	6

Tab. 5.1: Classification scheme of stratified sampling and results obtained with synoptic recordings of 1982/83 for a 30° sector

6. Exposure pathways and dose assessment

In this chapter the broad features of the dose submodules of the program system UFOMOD are outlined, a more detailed description can be found in /3/. In the first two sections a general view of the models and the data bases for the dose conversion factors is given. In Sec. 6.3 and Sec. 6.4 the calculation of the doses resulting from the various external and internal exposure pathways is briefly explained.

6.1 General features of the models

The exposure pathways currently taken into account in UFOMOD are summarized in Tab. 6.1. They are those which have been shown to be the most important ones for releases to the atmosphere from nuclear power plants. Some other possible routes of exposure, e.g. ingestion of drinking water, fresh water fish and seafood or irradiation by radioactive material deposited onto skin and clothes are not included at present, since they are not expected to contribute significantly to the doses of members of the general public, given the current source-terms. The inclusion of these or other additional exposure pathways into UFOMOD may be subject for future improvements.

Due to the threshold nature of nonstochastic effects, only high doses delivered over a relatively short timespan ("acute exposure") can lead to these effects. Such doses can occur only within a few tens of kilometers around the site and are therefore assessed with the near range model UFOMOD/NE. For acute exposure it is assumed that the doses from ingestion of contaminated food do not contribute to the acute dose since this exposure pathway can - for a brief time - be completely avoided by restricting the distribution of freshly produced foodstuffs. The acute doses from inhalation of resuspended activity are also not taken into account, since at present the short term exposure from this pathway is considered to be

Exposure pathways		Considered for	
		acute exposure[a)]	lifetime exposure[b)]
external irradiation from the cloud as it passes overhead		X	X
external irradiation from activity deposited on the ground		X	X
internal irradiation by inhalation	from activity during the passage of the cloud	X	X
	of deposited activity resuspended in the air		X
internal irradiation from ingestion of contaminated food			X

a) the dose accumulation times for acute exposure are given in Tab. 7.1
b) integrated over 70 a after the accident

} the times may be modified by the countermeasures model

Tab. 6.1: UFOMOD: Dose part. Exposure pathways considered

	acute exposure
organ doses for:	red bone marrow, lung, remainder (as representative for the GI-tract), thyroid, uterus, skin (as representative for the eye lens)
	lifetime doses
organ doses for:	red bone marrow, bone surface, breast, lung, stomach, colon, liver, pancreas, thyroid, gonads (averaged over males and females)
remainder:	organ or tissue not specified above receiving the highest dose
effective dose:	weighted organ dose due to ICRP 26

Tab. 6.2: UFOMOD: Dose part. Types of doses considered

negligible. So for the acute doses only the external exposure from the passing radioactive cloud and from activity deposited onto the ground and the internal exposure from radionuclides inhaled from the cloud are taken into account.

For stochastic effects, the dose accumulated over the lifetime of an individual provides some measure for the individual risk. Lifetime doses [1)] are calculated for all the exposure pathways specified in Tab. 6.1 with the UFOMOD-subsystems NL and FL in the near and in the far range, respectively.

All doses are calculated for an adult average member of the general public. However, in the separate program UFOING /7/, also age dependent doses and doses for members of critical groups can be calculated for the ingestion pathway. Optionally, either doses with or without countermeasures can be calculated. The interface to the countermeasures model is the PROTEC submodule of UFOMOD, which supplies all necessary information of type and duration of the countermeasures predicted for each spatial grid element.

The organs considered in UFOMOD for acute and lifetime doses are summarized in Tab. 6.2. For the calculation of the doses, dose conversion factors have been made available by GSF (Tab. 6.3). This primary data base contains data for a large number of radionuclides, organs, age groups and integration times. These data are preprocessed by stand-alone programs summarily called DOSFAC (Sec. 2.2) to derive the dose conversion factors for the organs listed in Tab. 6.2 and the integration times, age groups and nuclides actually used in UFOMOD.

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1) These doses are calculated to study the individual dose ranges only; they are not used to assess the stochastic somatic effects (see Chap. 7.2).

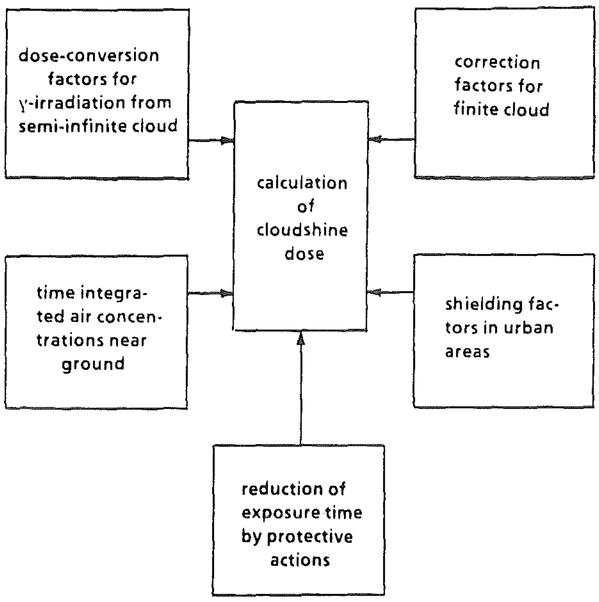

Fig. 6.1: Important quantities influencing the calculation of external radiation doses from the passing cloud

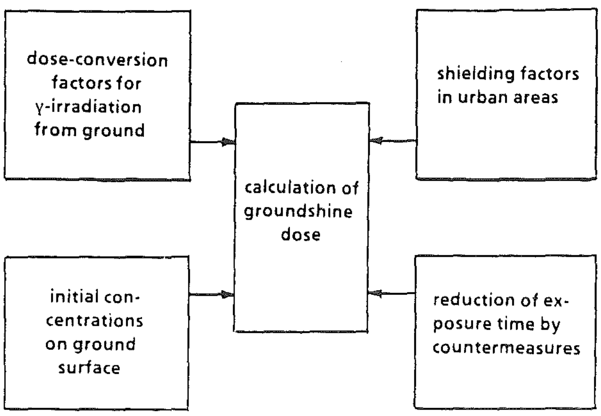

Fig. 6.2: Important quantities influencing the calculation of external radiation doses from ground surface

Output of the program are organ doses calculated for each grid point. Further evaluation programs allow a multitude of graphical presentations of the doses, including statistical quantities (e.g. expectation values, percentiles) as a function of distance, pie diagrams for contributions of exposure pathways and radionuclides etc.. A list of the possible presentations is given in Tab. 6.4.

6.2 External exposure pathways

Fig. 6.1 and 6.2 show the quantities which are important for the calculations of the radiation doses due to external exposure to γ-radiation from the passing cloud or for material deposited onto the ground from the cloud, respectively. The radiation doses are calculated by multiplication of the corresponding time-integrated activity concentrations with dose conversion factors which give the dose to an individual irradiated from external volume - or area sources, and with factors to allow for influences of geometry and shielding.

Completely new data for dose conversion factors (Tab. 6.3), correction factors for geometry and shielding factors were evaluated and made available by GSF /33, 36-41/.

The dose conversion factors for exposure from the cloud have been calculated under the assumption of immersion in a semi-infinite cloud of uniform activity concentration with inclusion of anisotropy of the irradiation field and the influence of the ground surface. In assessing the doses with UFOMOD, the finite extension of the plume is taken into account by the application of the correction factors for geometry (see Sec. 4.7).

The dose conversion factors for exposure from the ground have been calculated under the assumption of an infinite plane source and of an initial contamination in a depth of 2-4 mm.

exposure pathway	organs 1) A	B	C	D	E	Number of age groups	integration times	nuclides
external cloud 2)	x	x	x	x		1 4)	–	826
external ground	x	x			x	1 4)	26	141
internal inhalation 3)	x	x	x	x		6	11	126
internal ingestion 3)	x	x	x	x		6	11	126

1) A = bone marrow, bone surface, lung, thyroid
B = breast, gonads, ovaries, uterus
C = adrenals, bladder wall, brain, kidneys, stomach wall, SI + cont., LLi wall, ULI wall, spleen, thymus
D = skin
E = ICRP-remainder

2) averaged over males and fermales (besides for organs of group B)

3) averaged over males and females

4) age dependent correction factors available

Tab. 6.3: UFOMOD: Primary data base of dose conversion factors

type of result	presentations
individual organ doses	• expectation values and percentiles as a function of distance • CCFDs for each distance band • contributions of exposure pathways • contributions of nuclides for each exposure pathway • ingestion pathway: contributions of foodstuffs } for each distance band
collective organ doses	• CCFDs, expectation values, percentiles (opt. as a function of distance) • projected number of people vs. individual doses • expectation values or percentiles vs. individual doses

Tab. 6.4: UFOMOD: Dose part. Possible presentations of results

Effects of surface roughness and of the diffusion into deeper layers of soil are included in the dose conversion factors.

The shielding factors are applied to allow for people staying outdoors or inside buildings with different shielding properties against exposure from the cloud and from ground. In UFOMOD, five classes of shielding are considered; the fraction of the population associated with each class can be defined by the user (see Sec. 8.2.4).

6.3 Internal exposure pathways

6.3.1 Inhalation

Intake of radionuclides by inhalation can occur either directly from the radioactive cloud as it passes overhead or following the resuspension of radioactive material deposited onto the ground surface. The former pathway is of interest only during the stay in the radioactive cloud whereas resuspension is a process which may be active for longer time periods. Fig. 6.3 and 6.4 show the factors which are of importance in estimating the doses resulting from both pathways.

Direct inhalation of radionuclides is generally modelled by multiplying the time integrated air concentration and an inhalation rate. This inhalation rate is mainly dependent on the age of the individual and its engagement in physical activity during cloud passage. UFOMOD uses for dose calculations only one inhalation rate; it can be chosen by the user, the default value for adults is $3{,}33 \cdot 10^{-4}$ m^3/s. [1)]

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1) The stochastic somatic health effects risks are estimated taking into account the age-dependency of the inhalation rate.

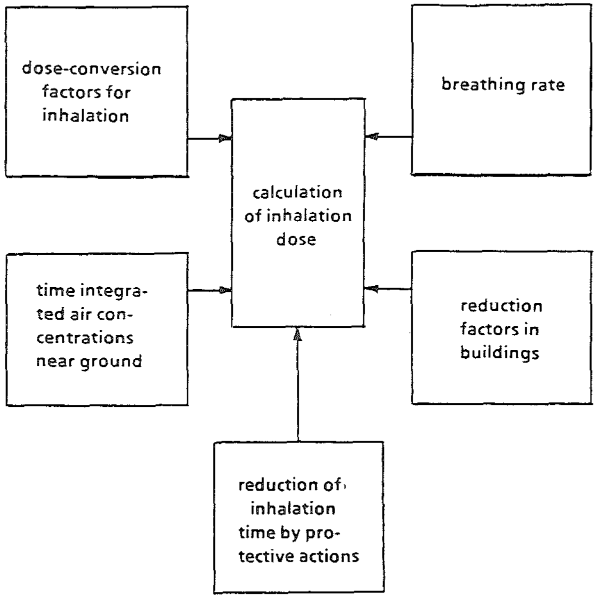

Fig. 6.3: Important quantities influencing the calculation of internal radiation doses by inhalation from the radioactive cloud

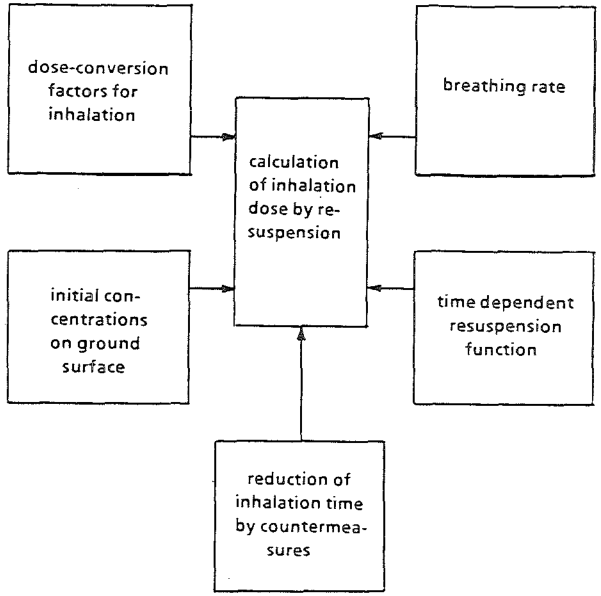

Fig. 6.4: Important quantities influencing the calculation of internal radiation doses by inhalation of resuspended radioactive material

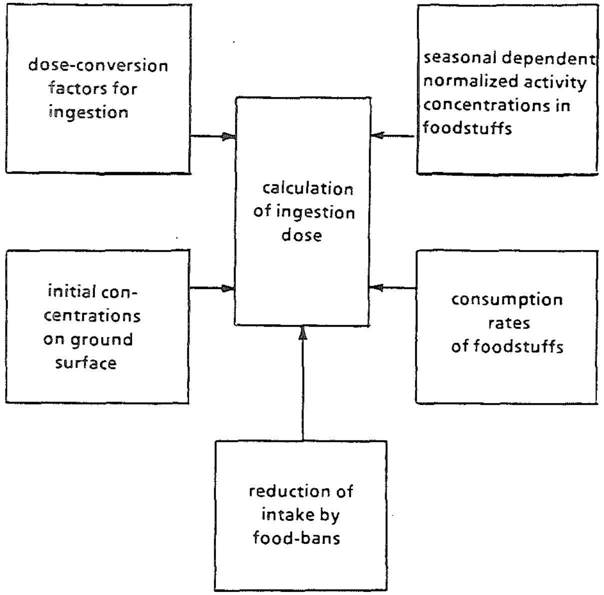

Fig. 6.5: Important quantities influencing the calculation of internal radiation doses by ingestion of contaminated foodstuffs

The air concentrations indoors and outdoors may be different during and after the passage of the radioactive cloud, depending on the ventilation and air exchange rates of buildings. UFOMOD provides the possibility of introducing 3 reduction factors for locations with different shielding properties (see Sec. 8.2.4).

Resuspension of radioactive material deposited on the ground can be caused by wind or human activities (e.g. traffic, digging or ploughing). The amount of radionuclides resuspended in the air and therefore available for inhalation depends on many factors, such as the time-dependent physical-chemical properties of the radioactive material and its fixation on the surface as well as the climatic and the atmospheric conditions. Owing to the lack of detailed reliable experimental data, simple models are applied which make use of empirical factors. In UFOMOD, an exponential law together with a constant is included to describe the time dependence of resuspension processes after the deposition. The parameters can be chosen by the user.

6.3.2 Ingestion

In Fig. 6.5 the factors which influence the calculation of the individual dose due to the consumption of contaminated foodstuffs are summarized. To estimate the individual dose it is necessary to know the activity levels in those foodstuffs which are major contributors to the diet of the individual. Together with the consumption rates the incorporated activity can be determined, and, with the corresponding dose conversion factors, the resulting dose. Previous investigations have shown that in regions with pronounced seasonality of climate the time of year when an accidental release may occur has a marked influence on the subsequent transfer of radionuclides through the terrestrial foodchains. Therefore, in realistic accident consequence assessments, the influence of seasonal variations have to be at least approximately included for the ingestion pathways.

To cope with these requirements, a completely new ingestion model is now implemented in UFOMOD. Eight foodstuffs are considered according to German consumption habits, namely milk (including milk products), beef, meat from pork, grain products, potatoes and three types of vegetables (leafy-, nonleafy-, root). For these foodstuffs, age dependent consumption rates have been derived /7/. Local production and consumption of the foodstuffs is assumed for the dose calculations.

The transfer of radioactive material through the various components of the ecosystem into the foodstuffs has been calculated by GSF with the dynamic terrestrial foodchain transport model ECOSYS /42/. The processes considered in ECOSYS are direct deposition, root uptake, translocation, agricultural practice, washing of the foodstuffs etc. In UFOMOD, yearly integrals of the activity per unit mass of foodstuff up to 200 years after an assumed accident are used for 29 radionuclides (including 9 actinides).

In principle, ECOSYS can calculate the activity of foodstuffs for an assumed single deposition at any day of the year. Such an amount of data cannot reasonably be handled in an ACA code. Therefore, to approximate seasonal effects, in UFOMOD two data sets are implemented, one for a release at 1st of January to represent an accident in winter ("November-March") and one for a release at 1st of July to represent an accident in summer ("April-October"). For each weather sequence from the two time periods the corresponding foodchain data set is selected by the program.

The individual dose is calculated by multiplication of the time integral of the activity deposited onto the ground with an "activity-dose-coefficient" /3/, taking into account the duration of foodbans from the countermeasures model (Chap. 8) and the time of the accident. The activity-dose coefficients are taken from precalculated datasets /3/. They were obtained by multiplying for each year the yearly integral of the normalized activity of the foodstuff, the consumption rate and the dose conversion factor for exposure from the current year to the end of life of the individual /43/, and then summing up the dose contributions from each year starting with the end of foodbans.

7. Health effects

The exposure of individuals to nuclear radiation can lead to health detriments. Such radiation - induced detrimental effects are called "somatic", if they become manifest in the irradiated individual, and "hereditary" if they affect his or her descendants. The somatic effects may be either "stochastic" or "nonstochastic". Nonstochastic effects can occur shortly after exposure to high levels of radiation and are those for which the severity of the effect varies with the dose and for which a threshold may exist. Stochastic effects generally appear long after irradiation and are those for which the probability of the effect occurring, rather than its severity, is taken to be a function of dose without threshold. At levels of dose encountered in accidental situations after the imposition of counter- and protective measures, hereditary effects are regarded as being stochastic /44/. Nonstochastic and stochastic effects are calculated with different subsystems of UFOMOD (Chap. 2). The main features of the models underlying the computer code are described in the following sections, and, in somewhat more detail, in /5/.

7.1 Nonstochastic effects

The model for the assessment for nonstochastic effects is based on the "Health Effects Model for Nuclear Power Plant Accident Consequence Analysis" (HEM) /45/ developed for the accident consequence model MACCS /46/ of the program package MELCOR /47/.

All fatal effects specified in this model are also considered in UFOMOD. They comprise the effects following the irradiation of the red bone marrow (hematopoietic syndrome), the lung (pulmonary syndrome) and the GI-tract (gastrointestinal syndrome). Mortality by the gastrointestinal syndrome after severe external irradiation of the GI-tract is included for completeness, but for nuclear accidents it is likely that the other fatal effects will be more limiting. In addition to these fatal effects the mortality of pre- and neonates after exposure in utero are quantified.

Of the possible non-fatal effects only such are taken into account in UFOMOD which will lead to a severe disability of the affected individual for the rest of his or her life or which require continuous medical treatment and/or social care. The effects considered are the impaired pulmonary function, hypothyroidism, cataracts and mental retardation after irradiation in utero. Non-fatal effects which are of transitory nature and leave no permanent health detriment are not quantified, e.g. prodromal vomiting, temporary erythema, transitory depilation etc.

The probability r that an individual will exhibit a non-stochastic effect is modelled using hazard functions. Mathematically a hazard function has the form:

(7.1) $$r = 1-e^{-H}$$

The cumulative hazard H and is a function of dose. For acute exposure, H is taken to be a Weighbull function. Such functions are characterized by two parameters, which in the following are called D_{50} and S:

(7.2)

$$H = \ln 2 \cdot \left(\frac{D}{D_{50}}\right)^{S}$$

D is the mean dose in the organ of interest. D_{50} is the median dose at which 50% of the exposed individuals whould be expected to exhibit the effect (mortality or clinical symptoms of illness in case of morbidity). The parameter S characterizes the slope of the dose-risk function. The ratio D/D_{50} represents a dimensionless dose (normalized) in units of the D_{50}.

dose in organ/tissue: external irradiation	internal irradiation	effect	slope parameter S	median dose D_{50} [Sv][a) upper end of exposure interval [d]: 1	7	14	21	30	200	365	threshold for exposure during time interval: 1	2	3	4
		mortality												
lung	lung	pulmonary syndrome	7.0	9.3	–	94.0	–	–	220.0	540.0	5.0	47.0	110.0	270.0
red bone marrow	red bone marrow	hematopoietic syndrome	6.0	4.7	–	8.5	–	17.1	–	–	2.3	4.2	8.5	–
remainder[b)]	–	gastrointestinal syndrome	10.0	15.0	35.0	–	–	–	–	–	10.0	23.0	–	–
ovaries	uterus	pre- and neonatal death[c)]	3.0	1.0	–	–	–	–	–	– –	0.1	–	–	–
		morbidity												
lung	lung	lung function impairment	7.0	4.6	–	47.0	–	–	110.0	270.0	2.3	23.0	55.0	135.0
thyroid	thyroid	hypothyroidism	1.3	60.0	–	–	–	external exposure			2.0	–	–	–
				–	–	–	300.0	iodine inhalation			10.0	–	–	–
skin	–	cataracts	1.5	3.1	–	6.2	–	–	–	9.3	1.0	3.0	4.5	–
ovaries	uterus	mental retardation[c)]	1.0	4.1							0.1	–	–	–

a) In accidents involving releases of α-emitters, the absorbed dose should be multiplied by a factor to account for the relative biological effectiveness of acute α-irradiation

b) Since the dose conversion factors for the GI-tract were not included in the GSF-data (Chap. 6), the calculations are based on the dose to the remaining organs and tissues.

c) Risks predicted using these parameters would have to be multiplied by 0.01 to be applicable to the general population.

Tab. 7.1: UFOMOD: Health effects part. Nonstochastic effects considered and model parameters

To account for protracted exposure the approach is made to express the cumulative hazard as sums of the normalized doses received within various time intervals:

(7.3)

$$H = \ln 2 \cdot \left(\sum_i \frac{D^i}{D^i_{50}}\right)^S$$

where D^i is the dose accumulated in some time interval i and the normalization parameter D^i_{50} is the dose at which 50% of the individuals are likely to develop the effect when continually exposed in this time interval. The slope parameter S is assumed to be independent of the dose rate for all effects. To determine the overall mortality risk from exposure of several organs, the cumulative hazard is calculated as the sum of the hazards of each effect.

The default values for S and D^i_{50} currently used in UFOMOD/NE are given in Tab. 7.1, but they can be changed by the user. As an illustrative example, Fig. 7.1 shows the dose-risk-function of the hematopoietic syndrome for the three time intervals of dose accumulation considered for this effect.

Mathematically, the risk predicted by a hazard function is positive for any non-zero level of dose. Because of the threshold nature of the nonstochastic effects, it is assumed that acute doses below a certain threshold do not cause any early health risk. The dose thresholds presently used in UFOMOD are included in Tab. 7.1 for each time interval i and each effect. They can also be modified by the user.

Revised versions of the "Health Effects Model" (HEM) presently under publication /48/ contain new dose-rate dependent parameter combinations of D^i_{50}, S and threshold values, especially for the pulmonary syndrome. Currently, it is considered to implement this modelling into the health effects module of UFOMOD.

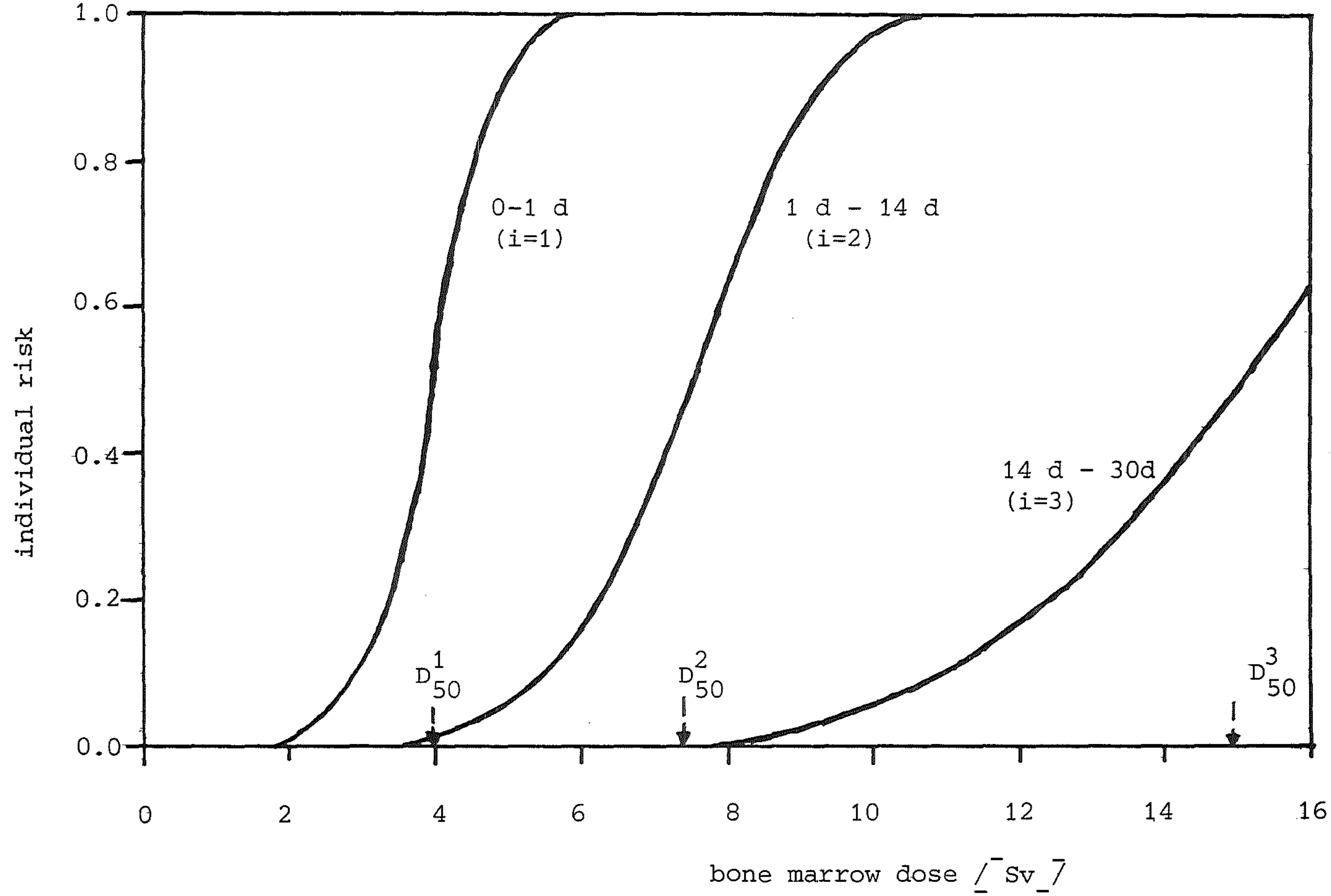

Fig. 7.1: Dose-risk relationships of hematopoietic syndrome

In assessing the nonstochastic effects, three exposure pathways are taken into account, namely the external exposures from the passing plume and from activity deposited on the ground and the internal exposure from activity inhaled during the passage of the cloud.

Internal irradiation from the ingestion of contaminated foodstuffs or from the inhalation of resuspended activity are assumed not to contribute as they can be easily avoided by counter- and protective measures in the short time span after the accident which is relevant for the early effects.

Output of the model are the individual risk and the projected number of affected individuals for each grid element. The various possible presentations of these results are given in Tab. 7.2.

7.2 Stochastic effects

The stochastic effects that may occur are the late somatic and the hereditary effects. The principal late somatic effect is the increased incidence of cancers, both fatal and non-fatal in the irradiated population, the appearance of which is likely to spread over several decades following an accidental release /44/.

The ten late somatic effects considered in UFOMOD are listed in Tab. 7.3. Both mortality and morbidity is assessed in a normal UFOMOD run. For the hereditary effects at present only the genetically significant dose is quantified to provide a measure for the overall number of effects.

Estimates of the radiation induced incidences of cancers are generally based on the assumptions of a linear or a linear-quadratic [1] dose response function. Both approaches are intended to reflect assumptions that are reasonbly consistent with available evidence. In UFOMOD, principally a linear dose

type of results	possible presentations
individual risk a)	• expectation values and percentiles as a function of distance • CCFDs for each distance band
projected number of people a)	• expectation values and percentiles • CCFDs of the numbers

a)for each effect or overall mortality or morbidity

Tab. 7.2: UFOMOD: Health effects part. Possible presentations of the results of the nonstochastic effects model

organ/tissue	effect	model1)	correction factors for cancer incidence (BEIR III)	fatal cancers per 10^6 persons and 10^{-2} Sv (GSF) (LQ)2)	(L)2)
red bone marrow	leukemia	A	1.0	21	52
bone surface	cancers	A	1.0	1	1
breast4)	cancers	R	0.4	80	80
lung	cancers	R	0.75	36	90
stomach	cancers	R	0.85		
colon	cancers	R	0.55	903)	2243)
liver	cancers	R	1.0		
pancreas	cancers	R	0.9		
thyroid	cancers	R	0.1	17	17
remainder	cancers	R	0.6	15	38

1)A: absolute risk model. R: relative risk model
2)L: linear dose-risk relationship. LQ: linear quadratic dose-risk relationship
3)summarily for the GI-tract
4)averaged over males and females

Tab. 7.3: UFOMOD: Health effects part. Stochastic somatic effects considered and model parameters response function without threshold is used. Optionally an approximate consideration of a linear-quadratic [1] dose response function is possible by a reduction of the risk coefficient in the low dose range ($\leq 5 \times 10^{-2}$ Sv).

Risk coefficients for fatal cancers have been provided by the GSF /49, 50/. They give the cumulative numbers of radiation induced effects per unit dose equivalent as a function of time after a single radiation exposure and are parameterized with respect to the age at exposure and sex. This data base has been developed by GSF in the frame of a study carried out on the data currently available from Hiroshima and Nagasaki. The coefficients for leukemia and bone cancer are based on the assumption of an absolute risk model, for all other coefficients, relative risk models have been used. As an example, dose-risk-coefficients from GSF integrated over time and demographic data for a linear and linear-quadratic dose-response relationship are given in Tab. 7.3. The values for both assumptions differ by a factor of about two.

To derive risk coefficients for cancer incidences, GSF recommended the use of correction factors from the BEIR-III study /51/; these factors are included in Tab. 7.3. The risk coefficient for cancer incidences is obtained by dividing the corresponding coefficient for mortality by the correction factor.

The risk coefficients mentioned above allow to predict the risk for an individual of some age and sex as a function of time after a single exposure. The time distribution of cancerincidences in the general population, however, is made up from many different time distributions of individual risks by the following reasons:

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1) only for low LET radiation

- the exposed population includes members of both sexes and a wide distribution of ages;

- the exposure can be protracted in time as for instance for the internal exposure by inhaled or ingested radionuclides or by external exposure from activity deposited on the ground, provided that the radionuclides are present in the environment or inside the body for a sufficiently long time;

- the necessity to introduce countermeasures may locally lead to the interruption of exposure pathways for some time after the accident.

To estimate the number of cancer incidences as a function of time in UFOMOD the new concept of "activity-risk coefficients" has been introduced /5,19/. These coefficients contain all information of age and lifetime distributions in the population, the time and age dependence of the intake of activity for internal exposure pathways [1]), the time and age dependence of irradiation for all exposure pathways, and of the individual risk.

To save computing time the coefficients are precalculated with the preprocessing program STORAC (Chap. 2.2). They are tabulated in a data file as pathway dependent coefficients normalized to unit concentrations in air and on ground and parameterized with respect to the considered radionuclides,

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1) For the ingestion pathways, local production and consumptions of the foodstuffs is assumed.

organs and up to 10 time steps each for the time after the accident, and assumed ends of countermeasures. Two different sets of coefficients are distinguished for the population alive at the time of the accident (living generations), and summarily for all subsequent generations (following generations). A comprehensive description of the formalism and the numerical solution is given in /5/.

The activity-risk coefficients quantify the risk as a function of time of an individual which is representative for the general population. The risk for such an individual is then simply obtained by multiplication of the activity-risk coefficient with the initial activity concentration, and the number of cancer incidences by multiplication of this risk with the number of affected individuals. Thereby, all acute and long-term exposure pathways are taken into account together with the information from the countermeasures models about the estimated duration of the measures.

The "individual" risk and the number of incidences of cancer injury and fatality in each grid element is calculated separately for each cancer type together with the overall risk for morbidity and mortality (excluding individuals already affected by early fatalities). In routine calculations, individual risks and the number of cancer cases are calculated separately for the living generations, the following generations, and their sum. Optionally, individual and collective results can be generated as a function of time after the accident for demonstration or other special applications (see Sec. 10.4).

The various forms of graphical and tabular presentations possible for the different types of results are summarized in Tab. 7.4. They include CCFDs, pie diagrams, and functions of distance of statistical quantities. Several two-dimensional diagrams of the projected number of incidences or collective dose against individual risk or dose may be helpful to

type of result	presentations
individual risk a) b)	• expectation values, percentiles as a function of distance[d)] • CCFDs for each distance band • contributions of exposure pathways • contributions of nuclides for each exposure pathway } for each distance band[d)]
projected number of people b)	• CCFDs, expectation values, percentiles[d)] • projected number of health effects vs. individual risk or dose (2-dim.) • contributions of generations living at time of accident and all subsequent generations
genetically significant dose c)	– as above for individual and collective dose –

a)individual representing the general population (for details see text)
b)for each effect or overall morbidity or mortality
c)in the current version of UFOMOD, the risk for hereditary effects is not quantified
d)optionally as a function of time

Tab. 7.4: UFOMOD: Health effects part. Possible presentations of the results of the stochastic effects model demonstrate that the major part of the stochastic effects is usually accumulated at low levels of dose and personal risk (see Sec. 10.4).

8. Countermeasure models

8.1 Introduction

In case of an uncontrolled release of radionuclides, the exposure of members of the public can only be limited by actions usually termed "intervention". The different forms of intervention are called "protective actions", "countermeasures", or simply "measures". Depending on type and amount of release, dispersion conditions, distance to the source, and time, the countermeasures may cover the whole range between minor important restrictions, almost without any impact on the average citizen, and disruption of normal living due to evacuation or relocation. Countermeasures are implemented with the aim of reducing either acute exposure during and shortly after the accident or continuing and long-term exposure due to deposited or incorporated radionuclides. In ACA codes countermeasures are modelled in order to obtain realistic predictions of the consequences of an accidental release of radionuclides.

There are several types of countermeasures and each of them may exhibit a large variety of possible features characterized by parameters in the program system UFOMOD.

The types of countermeasures are

Sheltering
Evacuation
Interdiction of areas

as immediate actions against high short-term exposure and

Ban of food, feed and water
Land decontamination
Relocation

as subsequent or continuing actions against long-term exposure. The types of parameters are given by the program system, their values, however, may be defined by the user of the code at run-time (intervention levels, delay/response times, shielding factors, fractions of the population taking certain actions etc.). The initial delay chosen by the user, e.g., determines whether an evacuation is prophylactic or in response to an ongoing or already finished release. Thus UFOMOD is a flexible tool for investigation of alternatives in emergency response planning and emergency management, and for studies about the influence of the behaviour of the population on the efficiency of countermeasures.

As already mentioned in preceding chapters, UFOMOD is subdivided into a near range and a far range part. In the area covered by the near range subsystems, protective actions against both short-term and chronic exposure may be required, whereas in the far range countermeasures against chronic exposure are sufficient. The submodel of fast protective actions is described in Sec. 8.2, the countermeasures against chronic exposure are presented in Sec. 8.3. A detailed description and a complete list of input data and their default values can be found in /6/.

8.2 Countermeasures in the near range subsystems of UFOMOD

8.2.1 General features

The area covered by the near range subsystems is chosen in such a manner that exclusively in this area fast protective actions may be necessary and early health effects may occur.

As alternative or sequential countermeasures in the near range, evacuation of a keyhole shaped area (A) determined by 2 radii (r,R) and an angle and/or evacuation of an area (B) determined by an isodose line are modelled (Fig. 8.1). Since radii and angles are easier to be established than isodose lines, evacuation of area A is modelled to take place first. If areas A and B are overlapping, the common part is assigned to A.

Sheltering, unintended reactions of the population, like spontaneous evacuation (flight) and disregard or misinterpretation of alarm signals and requests of the authorities, and the possible existence of unattainable persons, are taken into account as explained below.

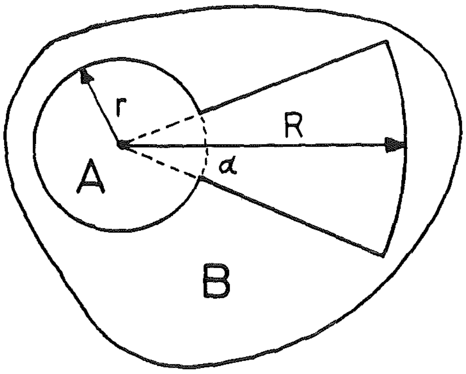
Countermeasures against chronic exposure in the near range are modelled as described in Sec. 8.3.

8.2.2 Evacuation of a keyhole shaped area

Modelling of a keyhole shaped area of evacuation (A) allows for consideration of this countermeasure even in cases when isodose lines are not (yet) determined or available. Area, features, sequence of actions and input parameters are presented in Figs. 8.1 and 8.2 and in Tabs. 8.1 and 8.2.

After an initial delay (TINA), the population in area A is assumed to be partly sheltered and partly evacuating spontaneously. An additional part remaining outdoors for whatever reason may be determined. The end of the sheltering/outdoor period is given by the source term parameter "end of release" (TREND) plus an additional delay (TDELA) for initiation of the subsequent evacuation requested by the authorities. All remaining persons are then evacuating.

The spectrum of individual driving times TDRA for leaving area A is approximated by four 3-step distribution functions; each distribution function is representative of a certain range of the population density in area A (see Tab. 8.3). The default values of the driving times have been derived for two distance bands of the keyhole: up to 6 km and up to 10 km /52,53/. Dependent on the outer radius of the area A, the



long-term
countermeasures

area A:

actions: sheltering and/or evacuation

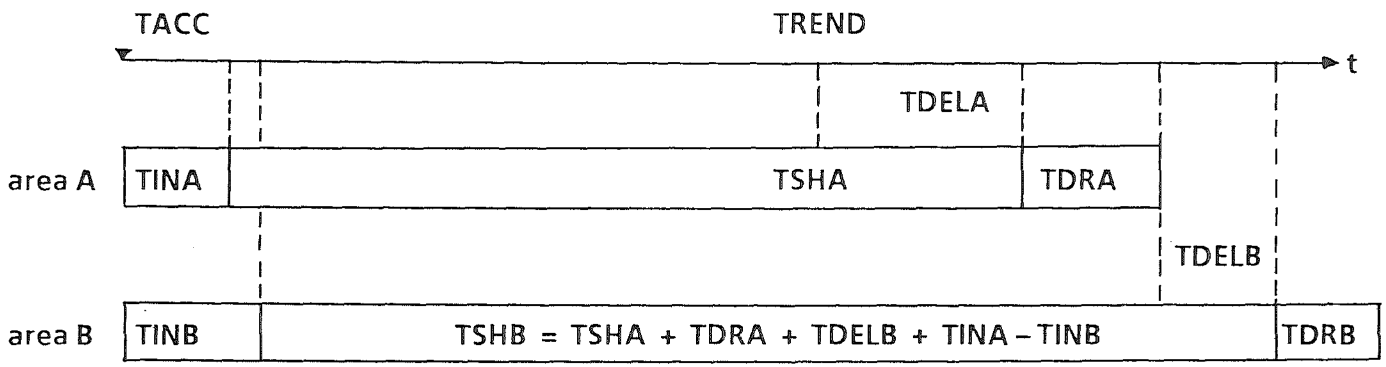
definition: keyhole shaped area with inner radius r, outer radius R and sector angle α
($r = 2.4$ km, $R = 5.6$ km, $\alpha = 60^{o}$)

area B:

actions: sheltering, evacuation

definition: acute dose to lung, bone marrow or GI-tract > 500 mSv

Fig. 8.1: UFOMOD: Modelling of protective actions in the early phase and current default intervention levels



TACC = time of accident (end of chain reaction)

TREND = time of end of release (≈ 95 %)

TINA, TINB = initial delay, area A, B

TSHA, TSHB = duration of sheltering period, area A, B

TDELA = delay time between end of release and end of sheltering period, area A

TDELB = delay time between end of evacuation in area A and begin of evacuation in area B

TDRA, TDRB = driving time to leave area A, B

Fig. 8.2: UFOMOD: Timing of early protective actions

corresponding data set is used. All parameter values can be replaced by the user. Exposure during evacuation is taken into account in the dose calculations.

Special cases like prophylactic evacuation (V), evacuation of a disk shaped or sector shaped area, no evacuation of a geometrically defined area etc. are covered due to the possibility of choosing the input data accordingly (e.g. 100% spontaneous evacuation or R = r, R = r = o, respectively). Shielding factors are discussed in Sec. 8.2.4.

8.2.3 Evacuation based on dose criteria

Another area of (subsequent) evacuation is defined by a dose intervention level for short-term exposure of the red bone marrow, the lung or the gastrointestinal tract. The acute exposure pathways considered in the dose calculations can be preselected. Default assumptions and values may be used or chosen by the user (see Tab. 8.2). All grid elements where any of the 3 criteria is exceeded are assigned to area B (if not belonging to A).

Evacuation of area B is modelled in a way similar to that of area A, but the value of the parameters may be substantially different. After an initial delay (TINB) fractions of the population are sheltering, remaining outdoors or evacuating spontaneously. In contrast to A, the starting time of evacuation of area B is not related to the development of the release but to the end of the evacuation of area A. Again, evacuation is characterized by 4 triplets of driving times, dependent on the population density and the outer radius of the area B (see Sec. 8.2.2).

In all areas outside A and B normal activity of the population during the first phases of an accident is assumed. Countermeasures against chronic exposure are discussed in Sec. 8.3.

	Limit(s) or shape of the area	Sequence of measures/behaviour of the population
V	Keyhole consisting of a full disk + forecast downwind sector	Initial delay, evacuation in 3 groups with different speed, evacuation speeds depending on population density
A	Keyhole consisting of a full disk + downwind sector	Initial delay, spontaneous evacuation of a part of the population (0-100%), sheltering of the remaining part of the population, evacuation after the passage of the plume. Disregarding or misinterpreting persons see B.
B	Isodose line of exposure to bone marrow, lung or GI-tract, whichever is more restrictive	Initial delay, sheltering, evacuation after passage of the plume but not before the end of evacuation in area A. % of persons disregarding or misinterpreting alarm or advice or being unattainable.
C	Isodose line IL * DF_{max}	Normal activity, subsequent relocation in daily rates
D	Isodose line IL	Normal activity, subsequent decontamination in daily rates
E	Effective equivalent dose <IL	No countermeasure modelled, ban of foodstuffs if appropriate

Tab. 8.1: Correlation between areas, countermeasures and behaviour of the population in UFOMOD (IL = intervention level of effective equivalent dose, DF_{max} = maximum decontamination factor)

8.2.4 Shielding factors

Sheltering persons may stay in various parts of houses differing by size, shape, design, construction material, ventilation rate etc.. Thus a broad spectrum of shielding factors and a complex correlation between these shielding factors and the corresponding fraction of the population exists in reality. UFOMOD allows for the definition of both 3 shielding factors and 3 fractions of the population to be correlated with them. In addition an average shielding factor for cars used to leave the areas A and B is required. Each of the above-mentioned shielding factors must be defined for both radiation from the plume (cloudshine) and from deposited material (groundshine). Since shielding factors are defined as the ratio of indoor to outdoor dose, the doublet of shielding factors for persons remaining outdoors is (1.00/1.00) by definition. A classification scheme and the default values provided by UFOMOD are presented in Tab. 8.4. Shielding due to ground roughness is taken into account implicitly in the dose factors (see Sec. 6.2). During the initial delay an average shielding factor for cloud- and groundshine is applied, except the population group remaining outdoors during sheltering.

8.3 Countermeasures against chronic exposure and latent effects

As already mentioned, relocation, land decontamination, and ban of food, feed and water are suitable countermeasures against long-term exposure. Depending on the source term and on the dispersion conditions, such countermeasures may be necessary in areas covered by the near range or by the far range subsystems of UFOMOD. Therefore in UFOMOD/NL and UFOMOD/FL the following countermeasures are modelled.

Protective action	Current default intervention levels
Early phase: Sheltering, evacuation	Acute dose to lung, bone marrow or GI-tract ≥500 mSv
Intermediate Phase:	
Relocation	Effective dose equivalent in the first year ≥50 mSv•DFMAX disregarding exposure due to ingestion (DFMAX = 3)
Resettlement	Effective dose equivalent in one of the following years ≤25 mSv•DFMAX disregarding exposure due to ingestion (DFMAX = 3)
Ban of foodstuffs	Committed effective dose equivalent ≥5 mSv due to ingestion in the first year
Withdrawal of bans	Committed effective dose equivalent due to ingestion in one of the following years ≤0.5 mSv

Tab. 8.2: Current default values of intervention levels for protective actions in UFOMOD

8.3.1 Land decontamination (area D)

If the effective dose equivalent D_{eff} in the first year is within the range

$$IL < D_{eff} < IL \bullet DFMAX,$$

land decontamination is modelled. To calculate D_{eff} the pathways of exposure except ingestion can be preselected by the user. IL is the intervention level for decontamination, DFMAX is the maximum decontamination factor applicable to large areas. IL and DFMAX are determined by the user, IL = 50 mSv/a and DFMAX = 3 are present default values in UFOMOD.

At doses $D_{eff} > IL \bullet DFMAX$ in the first year, decontamination is considered to be not feasible.

8.3.2 Relocation (area C)

If the effective dose equivalent in the first year is above the range for decontamination but the short-term doses are below the criteria for evacuation, relocation is modelled. If the intervention level for relocation is exceeded in evacuated areas, it is assumed that the evacuated persons remain outside the affected areas.

As soon as local doses have decreased to a level below IL' • DFMAX, decontamination and recovery of the area are supposed. IL' may be lower than IL by a reduction factor RF:

$$IL' = \frac{IL}{RF}$$

The present default value of RF in UFOMOD is 2 (Tab. 8.2). Exposure of the returning population and its offsprings is taken into account in the assessment of lifetime doses and stochastic health effects.

Population density PD (P/km^2)	Percentage of population	Driving time [min] for R = 6 km	Driving time [min] for R = 10 km
PD ≤ 100	10	13	14
	40	11	12
	50	6	6
100 < PD ≤ 500	10	25	50
	40	18	35
	50	8	12
500 < PD ≤ 1000	10	70	125
	40	50	85
	50	15	15
1000 < PD	10	160	500
	40	110	290
	50	25	60

Tab. 8.3: Parameterization of driving time

Percentage of population	residence	shielding factor cloudshine	shielding factor groundshine 1)
30 %	in cars (spontaneous evacution)	1.00	0.70
30 %	in cellars	0.05	0.03
15 %	in buildings with low shielding	0.30	0.10
15 %	in buildings with high shielding	0.01	0.01
10 %	outside, rural area	1.00	1.00

1) normalized to external radiation from ground surface with shielding factor of about 0.7

Tab. 8.4: Probabilistic treatment of population behaviour in areas A and B and corresponding shielding factors

8.3.3 Ban of foodstuffs

The area for ban of foodstuffs is determined by an isodose line based on the committed effective dose equivalent and the thyroid dose due to ingestion in the 1st year. The withdrawal of the bans is assumed as soon as another criterion based on the committed effective dose equivalent due to ingestion in one (subsequent) year is no more exceeded.

The organs (or effective dose) on which the decisions on food-bans are to be based and the intervention levels for introduction and withdrawal of food-bans can be chosen by the user via run-time options. In the same way, it can be selected, on which organs (or effective dose) the calculations and thus decisions shall be based, which foodstuffs or groups of foodstuffs are to be taken into account and for which age-groups of the population (characterized by different dose-conversion factors and consumption rates) the doses are to be considered. The default values for implementation and withdrawal of the ban of foodstuffs are presented in Tab. 8.2.

8.4 Presentation of results

Possible results of UFOMOD calculations related to all types of countermeasures are shown in Tab. 8.5. All long-term countermeasures can be presented as a function of time up to 70a after the accident.

type of result	presentations
areas and number of persons affected by emergency actions	• CCFDs, expectation values and percentiles for each type of action
areas and number of persons affected by long-term counter-measures	• CCFDs, expectation values and percentiles as a function of time for each type of measure

Tab. 8.5: UFOMOD. Countermeasures part. Possible presentation of results

9. Population grid

To estimate the impact on the population of an accidental release of radioactive material, the spatial distribution of population is combined with the distributions of individual radiation doses and health effects risks, respectively. The spatial resolution with which information is required is less detailed at large distances from the site, compared with the level of detail required in the near range. This is mainly because the doses received at large distances are significantly lower and vary less with distance than those received closer in and because the environmental concentrations calculated at large distances are less certain than those calculated close to the site. The polar grid established in the program system UFOMOD directly reflects these facts (see Sect. 2.1, Tab. 2.1).

The basic data of the UFOMOD population grid consist of three data sets:

(1) population data on a 500 m x 500 m grid up to about 25 km distance from 28 sites of nuclear facilities existing or planned within the FRG /54/ (see Tab. 9.1);

(2) population data of the FRG on a 5 km x 5 km grid /54/;

(3) population data outside the FRG on a 5 km x 5 km grid.

The 5 km x 5 km grid outside the FRG has been derived from the 10 km x 10 km grid of EC /55/. For all countries outside the EC, population data were derived from special maps up to those distances prescribed by the calculational limits of the MESOS code (10° W up to 50° E and 36° N up to 62° N).

In general, UFOMOD reads the population data from a file, which was generated by the stand-alone preprogram POPGRD
In POPGRD (see Sec. 2.3), the above-mentioned population data sets are used to calculate the number of persons living in

each element of the polar grid used in the UFOMOD subsystems for each of the 28 sites shown in Tab. 9.1. Optionally, UFOMOD can be run with an artificial homogeneous population distribution or a combination of site specific and homogeneous distribution in differing distance ranges. In addition, the population data can be written directly by the user into the input file of UFOMOD.

site no.	site name
01	Brokdorf
02	Brunsbüttel
03	Esenshamm
04	Hamm-Schmehausen
05	Krümmel
06	Stade
07	Vahnum
08	Biblis A
09	Neupotz
10	Philippsburg
11	Wyhl
12	Grafenrheinfeld
13	Gundremmingen
14	Isar-Ohu
15	Borken
16	Grohnde
17	Mülheim-Kärlich
18	Neckarwestheim
19	Würgassen
20	Emsland
21	Pfaffenhofen
22	Obrigheim
23	Kalkar
24	Hanau-Alkem
25	Exxon-Lingen
26	Gronau
27	Dragahn
28	Wackersdorf

Tab. 9.1 Sites of nuclear facilities with 500 x 500 m population grid

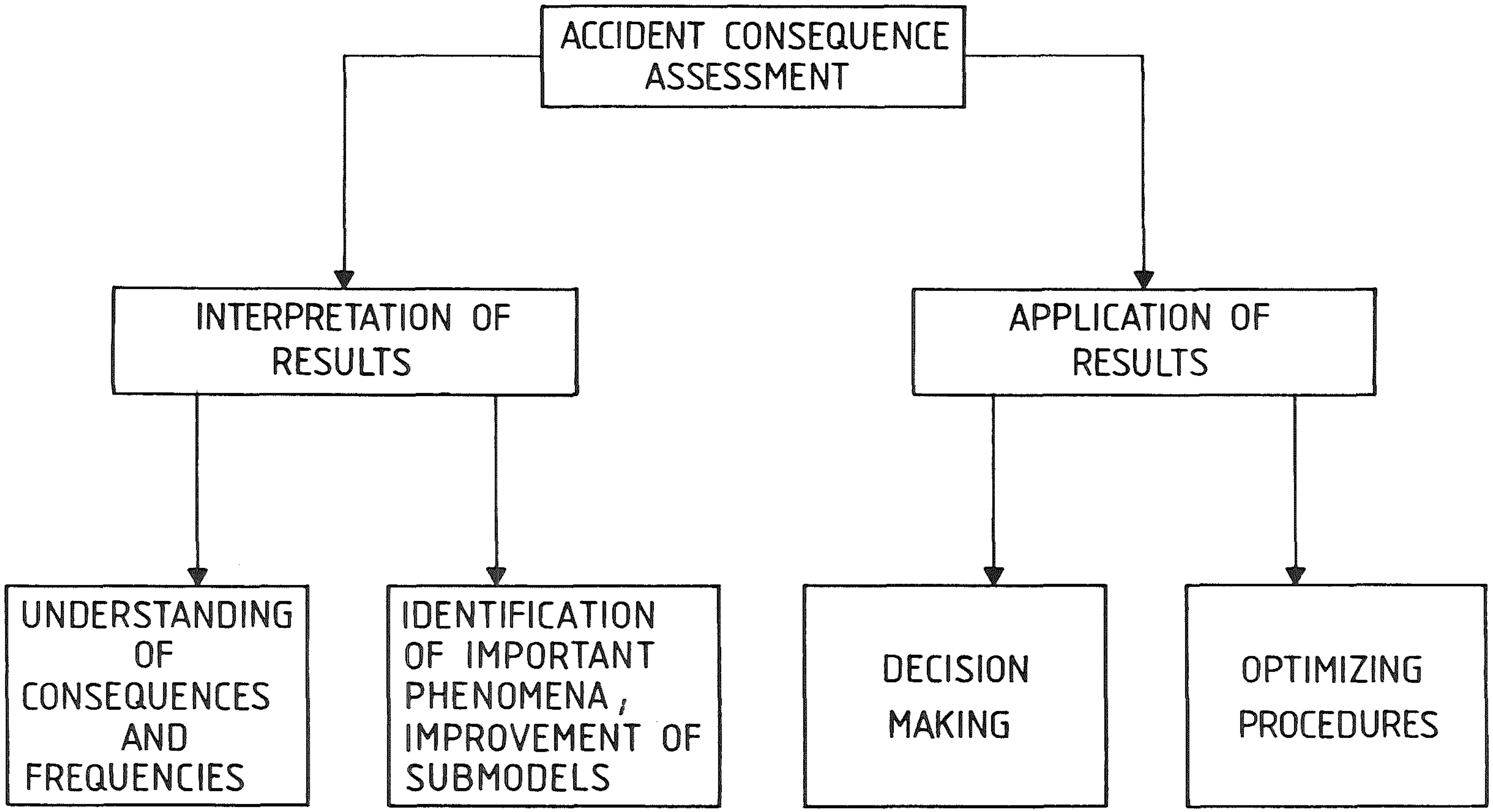
10. Output and illustrative applications

10.1 Introduction

As described in the previous chapters, large quantities of data are transferred during an ACA calculation with the program system UFOMOD through the various modules to produce the final output. Initially the activity concentrations are estimated as space-dependent values in the plume, near the ground and on the underlying ground surface, for each released radionuclide. These data are input to the modules describing the behaviour of the radionuclides in the environment and in the human body. To save computer time, these modules are not implemented concurrently within the UFOMOD subsystems, but are run separately, and the resulting set of data provide the input for the corresponding modules of UFOMOD.

The radiation doses are input to the countermeasures and health effect modules. Accordingly two data sets exist: space-dependent potential organ doses taking into account the needs of the criteria included in the countermeasures model (see Chap. 8) and space-dependent actual doses received by individuals experiencing the mitigating effect of protectice measures. The actual doses resulting from each exposure pathway are calculated for inclusion in the health effects models and are therefore time-integrated with respect to the time intervals prescribed by the dose-risk relationships.

The results of the health effects calculations are available as space-dependent individual risks and - after multiplying with the population distribution - collective detriment. Since each accident consequence situation is calculated separately, the space-dependent dose distributions and the resulting health effect distributions can be linked by additional evalulation programs to show the relationships between the organ doses and the number of health effects associated with them.



<u>Fig. 10.1:</u> Evaluation of accident consequence assessment

The potential doses and the countermeasures model define the areas and number of persons affected by protective actions. The space- and time-dependent patterns of these mitigating actions form the data base for non-health effect consequence assessments. In particular the economic module currently under development needs these results as basic input for the estimation of the monetary impact. By coupling non-health effect consequences with the results of the health effects module, the interrelation of countermeasures, costs and collective health effects can be demonstrated.

Nearly all risk studies document more or less comprehensively frequency distributions of early and late health effects with some information on areas and number of persons affected by countermeasures and on economic costs. Limiting the presentation to these final results may lead to a pure enumeration of fatalities, as the experiences with risk studies in Europe and overseas have shown. But moreover, this top heavy presentation of ACA results completely suppresses the large variety of details which can be extracted from the intermediate results of the various submodels. The complexity of the ACA model vanishes and no feedback is possible with the experts of the different disciplines, which contributed to the overall model.

It is obvious, that presenting only final results, is completely inadequate with respect to the complexity of the codes and the applicabilities offered by an ACA model. Neither enough information is available for interpretation and understanding of the results, nor the recognition of dependencies between submodels and parameters is possible.

A detailed presentation of intermediate and final results is an important task in view of the two principle fields "interpretation" and "application" (Fig. 10.1).

The interpreation of results is a fundamental necessity first of all to understand the results, i.e. the sources of accident consequences and their dependence on certain model assumptions and parameters. This analysing procedure may lead to the detection of model weakpoints, which significantly influence the accuracy of the ACA results.

Application of ACAs is a term, which has differing importance in the countries with nuclear industries. The largest experience exists in the USA, where ACAs have been broadly used as help both in decision making and in optimizing procedures.

Besides the original task to assess the individual and societal risks resulting from the operation of nuclear facilities, ACAs have been applied

- direct or in parallel to regulatory and licensing procedures,
- as help in decision making on improved or alternative plant concepts,
- as an important source of information for optimizing emergency plans,
- in the development of siting criteria and in decisons on sites,
- in defining safety goals to achieve quantitative acceptance criteria,
- as aid in decision-making on research priorities.

However, independent of the details of application, it becomes obvious from this list, that different intermediate and final results, different interdependencies between these results and different forms of presentation are required to adequately fit with the special problem.

For example, information on radionuclide-specific activity concentrations may be helpful to answer questions about the equipment needed for emergency response and in connection with the efficiency and feasibility of decontamination methods in rural and urban areas. The evaluation of radiation doses can be an important input to medical and administrative emergency planning, the development of siting criteria and safety goals or in setting research priorities.

It rather seems, that at present, the increasing application of ACA is handicaped by the fact that the evaluation and presentation of ACA results is not oriented at the special problem. There could be some more fields of application which are not recognized so far, because the various information, which can be extracted from an ACA, have not been demonstrated till now.

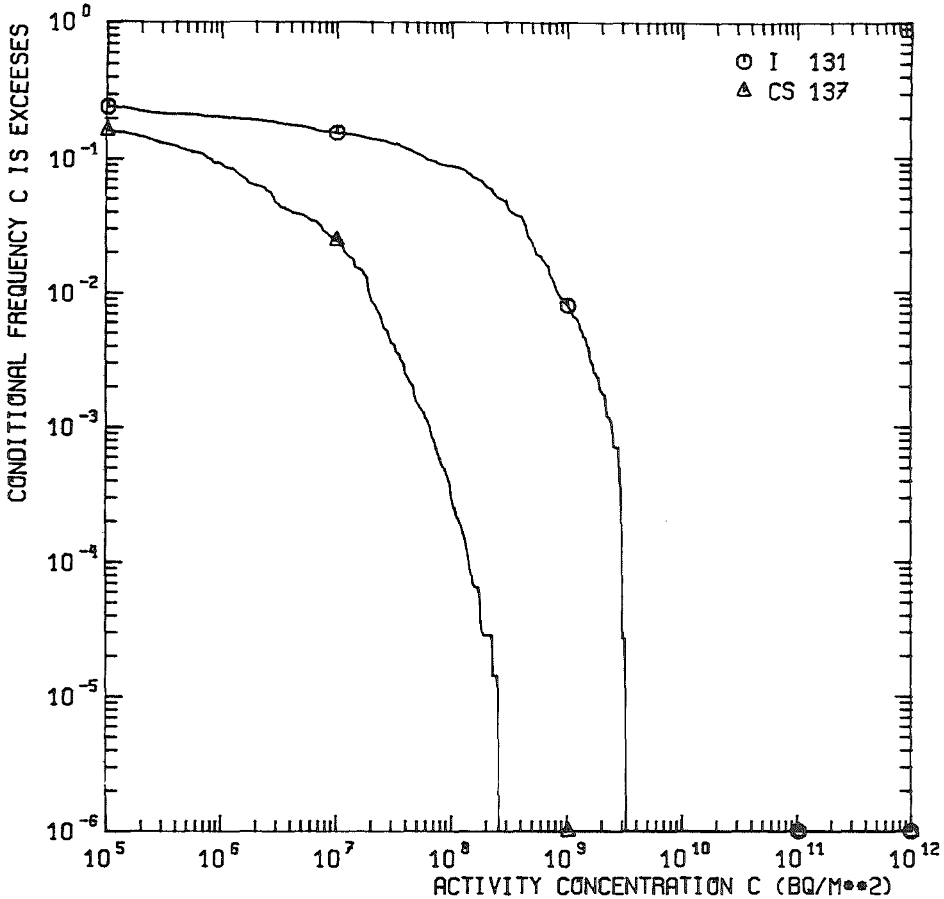
Therefore, the increasing application of ACA requires, that, before starting the program system UFOMOD, the following questions must be answered:

- What is the aim of the investigation ?

- Which kinds of consequences are relevant for the problem ?

- How should the results be presented ?

Proper answers to these questions indicate, which UFOMOD subsystem should be used and at which levels of intermediate findings the ACA can be stopped or whether a complete assessment must be performed. Great importance was attached to the development of evaluation programs (including plot software), which have access to the results stored during an UFOMOD run. Therefore, a variety of forms of presentation can be chosen



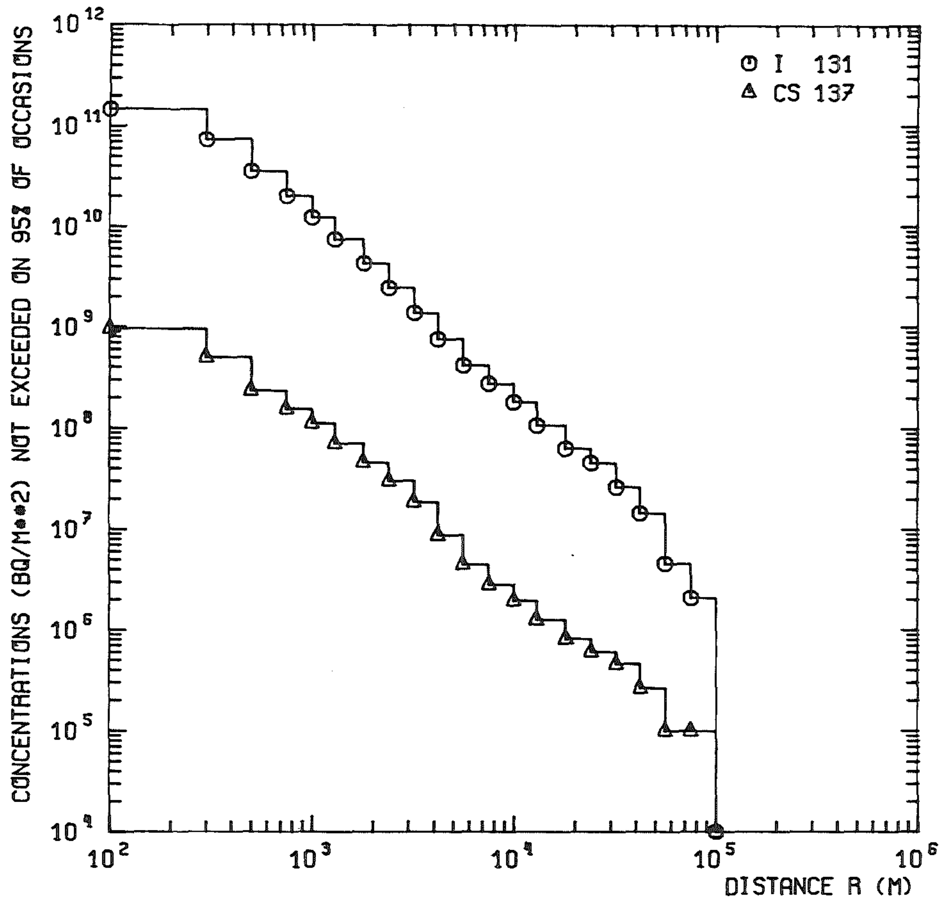


FIG. 10.2: ILLUSTRATIVE CONDITIONAL CCFDS OF ACTIVITY CONCENTRATIONS ON GROUND SURFACE AT 8.75 KM DISTANCE (RELEASE ASSUMED)

FIG. 10.3: EXAMPLES OF THE 95TH PERCENTILES OF THE ACTIVITY CONCENTRATIONS ON GROUND SURFACE

which are appropriate for a large number of special applications.

At the end of the previous chapters, the possible forms of presenting intermediate and final results are listed. In the next sections, some illustrative examples will be given together with complementary presentations correlating results obtained in subsequent calculational steps. As source term, a near-ground 3-hour release of 100% noble gases, 8% elemental iodine, 6% cesium, and 4% tellurium of a typical PWR inventory was assumed. The population distributions stem from 5 representative sites in the FRG. The figures and tables are not intended to be discussed quantitatively but qualitatively as possible and typical results of an ACA with the program system UFOMOD.

10.2 Activity concentrations

The contamination of air and ground surface is the first physical process in the course of environmental transport. The activity concentrations may be presented for single or groups of radionuclides (see Tab. 4.4 in Sec. 4.9).

The most detailed information is provided in CCFDs of radionuclide-specific activity concentrations estimated in radial distance bands. Fig. 10.2 shows as an example the I-131 and Cs-137 concentration on the ground surface at 8.75 km distance under the condition, that the release described in Sec. 10.1 has occurred. The variation of concentrations is caused by the number of weather sequences considered and the azimuthal distribution of the concentrations in the radioactive plume. From these CCFD curves, the probability that a certain concentration value is exceeded can easily be derived. For example, an I-131 concentration greater than $2 \cdot 10^{9}$ Bq/m^{2} is predicted with a probility of 10^{-3} at a distance of 8.75 km assuming the release has occurred.

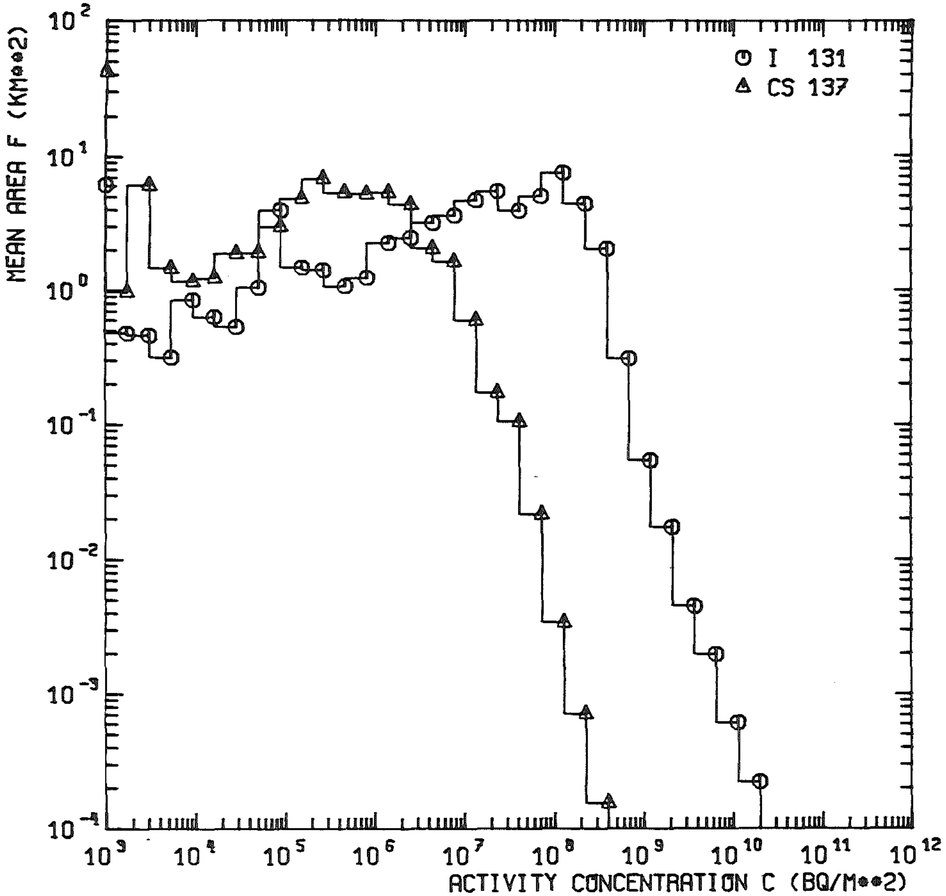


FIG. 10.4: ILLUSTRATION OF THE MEAN LAND AREAS UP TO 32 KM WITH ACTIVITY CONCENTRATIONS OF A GIVEN LEVEL (RELEASE ASSUMED)

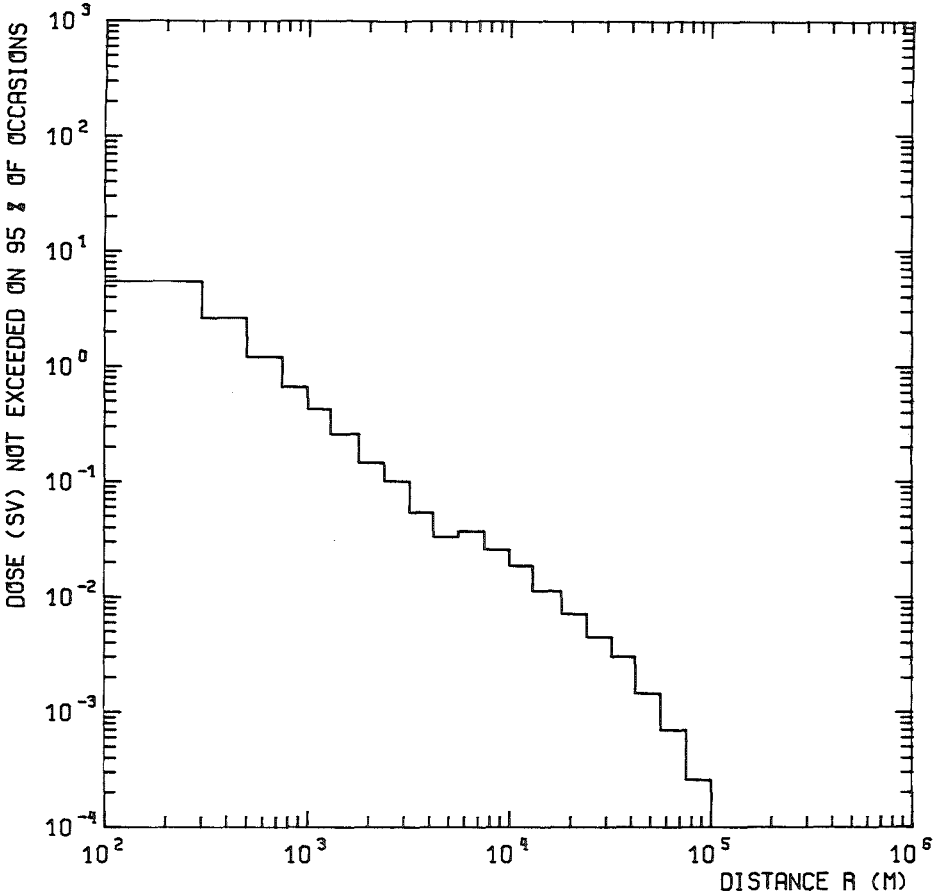


FIG. 10.5: EXAMPLES OF THE 95TH PERCENTILES OF THE INDIVIDUAL BONE MARROW DOSE DISTRIBUTIONS

From the set of CCFDs in all distance bands, characteristic quantities like expectation values and percentiles can be derived and presented as a function of distance. The expectation value gives the activity concentration averaged over all weather sequences and azimuthal grid elements, and the percentiles give the concentration levels that are not exceeded in a given percentage of the situations. Fig. 10.3 shows the 95th percentiles of the I-131 and Cs-137 activity concentrations on the ground surface. Due to higher deposition velocities for iodine than for aerosols, the iodine concentration within the plume is reduced much quicker with growing distance, which leads to a faster decline of the I-131 curve. Curves like these may help to assess the distances up to which certain concentration levels occur with the indicated confidence.

In connection with the detection and the measurement of contamination in the aftermath of a nuclear accident it may be of importance to know the expected activity concentrations as well as the size of the areas with certain contamination levels. Both quantities can be linked in various types of distributions. One example is given in Fig. 10.4.

It shows the mean land areas contaminated up to 32 km with activity concentrations in certain concentration intervals. The abszissa is divided into 4 logarithmically equidistant concentration intervals per decade. The interpretation of the curves is as follows: averaged over all weather situations, e.g. land areas of about 3 km^2 are to be expected with initial activity concentrations of I-131 between $4 \cdot 10^6$ and $2 \cdot 10^8$ Bq/m^2. The distributions are nearly identical in shape but are shifted on the concentration scale. This is due to the fact that the area under the passing plume is independent of the particular radionuclide considered.

10.3 Radiation doses

The space- and time-dependent behaviour of the radionuclide concentrations determines the radiation doses of individuals and in the population and the need for countermeasures like interdictions or decontamination.

The radiation doses and their corresponding frequencies may be presented for the various radionuclides contributing to the exposure, the organs, which are considered in the dosimetric calculations, and the relevant exposure pathways (see Tab. 6.4 in Sec. 6.1). They can be presented with and without protective actions or countermeasures. A further important information may be, how many people are expected with certain radiation dose levels and in which distances or areas they occur. Organ doses integrated over certain periods may be of interest to judge the duration of severe health risks for the population.

The complete spectrum of radiation doses is also completely presented in the form of distance dependent CCFDs. From these distributions, again characteristic quantities like expectation values or percentiles can be derived.

As an example, Fig. 10.5 shows the distance-dependent 95th percentiles of the acute and 70a-bone marrow doses including countermeasures under the condition of the release described in Sec. 10.1. They can be interpreted as doses to individuals at any azimuthal position, which are not exceeded in 95% of the considered accident consequence situations. In particular, acute bone marrow doses above 0.5 Gy are to be expected in a small area around the site up to a distance of about 1 km in most of the situations.

To facilitate the understanding of the sources of radiation and to judge the effectiveness of emergency plans and countermeasures and to identify areas for improvement, the significance of the exposure pathways and radionuclides as a

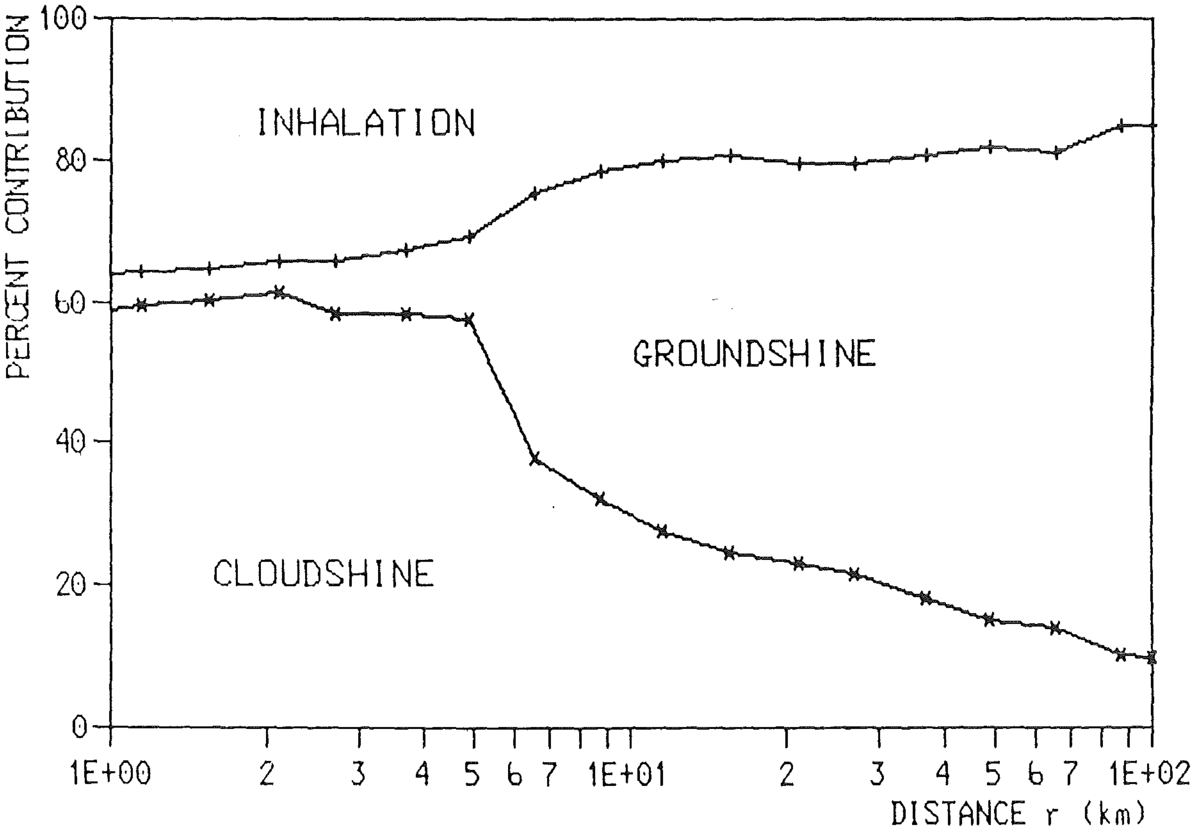


Fig. 10.6: Illustration of the contribution of various exposure pathways to acute bone marrow dose

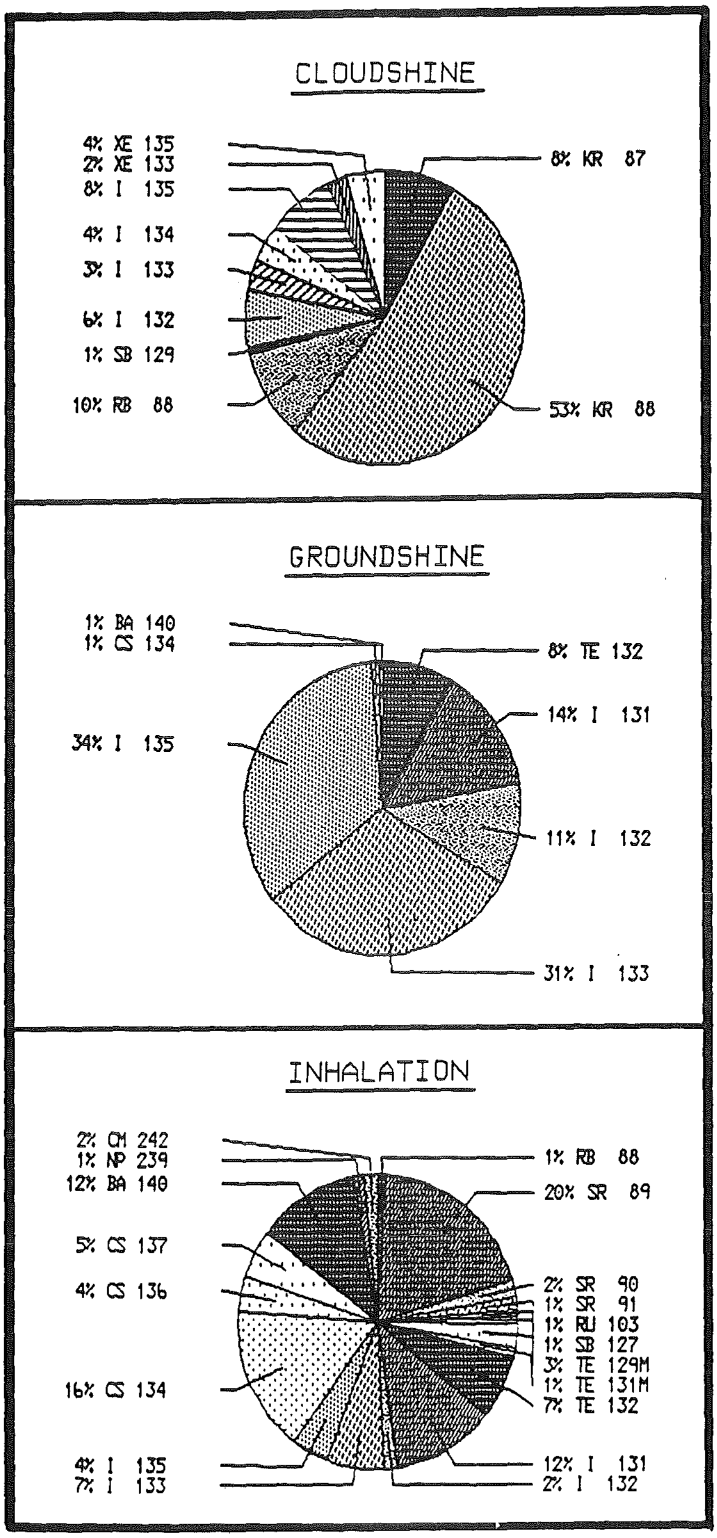


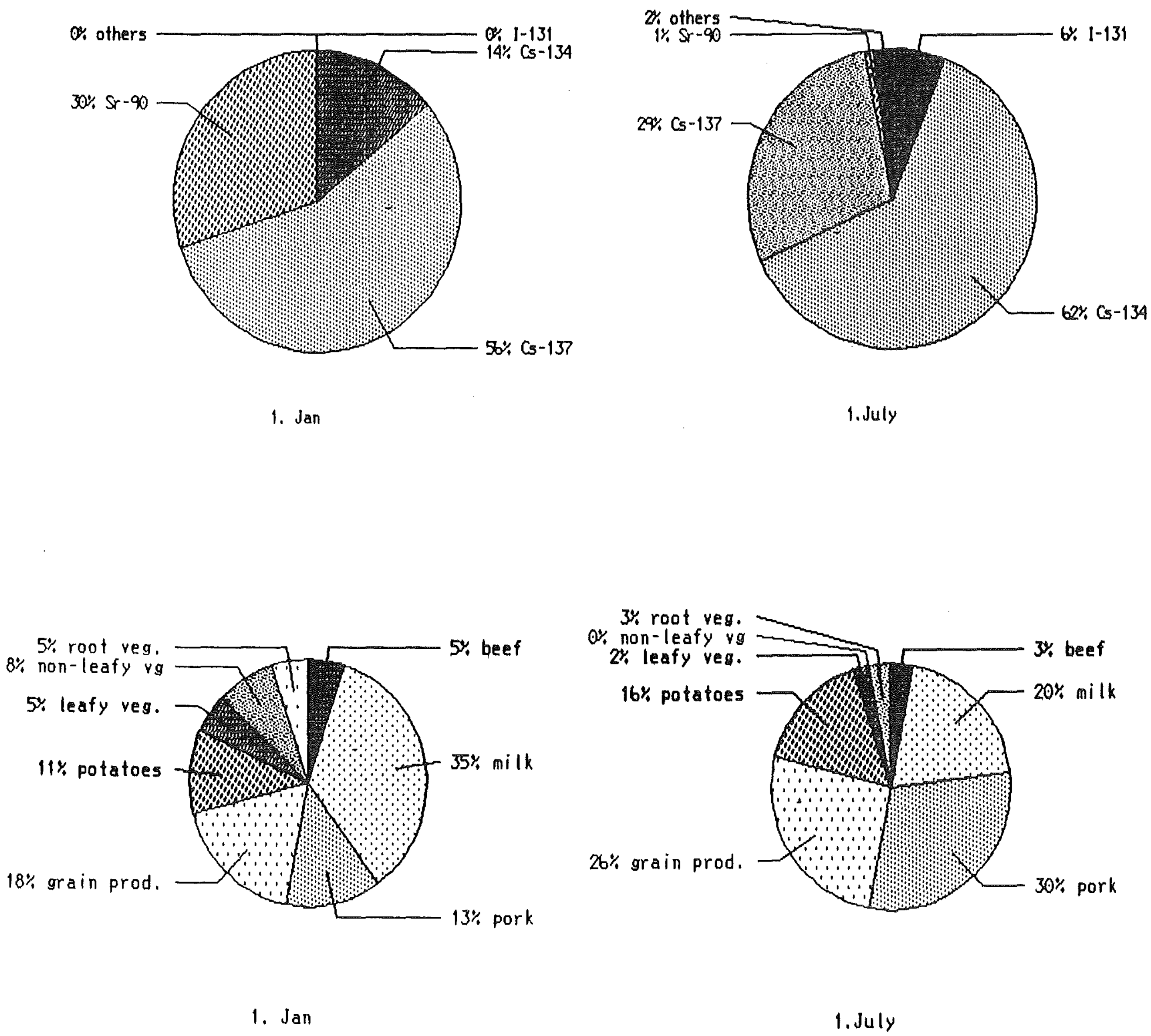
Fig. 10.7: Illustrative breakdown by nuclide of individual acute bone marrow dose at 0.875 km distance

function of distance may be an important source of information. Figs. 10.6 and 10.7 give illustrative examples of the contributions of the different exposure pathways to the acute bone marrow doses and the breakdown of bone marrow doses from every exposure pathway by the relevant radionuclides at about 1 km distance.

The acute bone marrow doses accumulate from short-time exposure (see Chap. 6). Consequently only the pathways "inhalation" and "external radiation from ground and passing plume" are relevant. In the countermeasures model of UFOMOD, evacuation of the population is presumed after sheltering up to about 5 km in each accident situation. Therefore, the contributions of the exposure pathways do not show a significant distance-dependence except the slight decline of external radiation from the passing plume, which expands during dispersion. For the same reason, internal irradiation following inhalation decreases continuously outside the evacuation area, and the external radiation from ground surface becomes dominant at large distances. The logarithmic distance scale emphasizes this behaviour.

The consumption of food and the interdiction of food distribution is an important issue after a large release of activity. The model implemented in UFOMOD allows analysis of ingestion doses from the relevant foodstuffs and radionuclides for releases at different times of the year (see Sec. 6.9). Fig. 10.8 shows the contribution of foodstuffs and radionuclides to the effective 70a-doses estimated for a release in winter and summer.

In addition to individual doses, doses to a population group are of interest especially with respect to countermeasures and their effectiveness. Conventionally, such doses are quantified by the assessment of the so called "collective dose". It is calculated by multiplying the number of people by the expected doses. To facilitate the interpretation of collective dose distributions, several graphical



<u>Fig. 10.8:</u> Illustration of the contribution of foodstuffs and radionuclides to the effective 70a-dose for a release in winter and summer

presentations are possible demonstrating the distance dependence of characteristic quantities, like mean value and percentiles; in addition, the correlation with the individual dose values may be of interest to see the dose ranges where collective doses accumulate. An example is given in Fig. 10.9, which clearly demonstrates, that the main contributions to the total collective dose come from individual doses in the range of 10^{-2} Sv to $5 \cdot 10^{-2}$ Sv.

The quantity "collective dose" is not suitable for all applications of ACAs, because the interdependency between certain dose levels and the number of persons affected is lost. However, this interdependency is of great value to people who have to decide on medical and administrative countermeasures. Consequently, forms of presentation have been developed to show how organ doses and the number of people are linked probabilistically. The starting point is in principle a 3-dimensional probability (frequency) distribution of the number of people with organ doses in certain dose intervals. These distributions are calculated for each radial distance band assuming a release has occurred. These 3-dimensional distributions are not easy to review, interpret and present completely. A reasonable reduction of information adapted to the special application is necessary. In some applications, for instance, the mean and the maximum number of persons within a given dose range or a given distance could suffice.

Typical results are given in Fig. 10.10, which shows the mean and maximum number of persons with acute bone marrow doses above the dose level 0.5 Gy with respect to the distance from the site after the accidental release. The curves show, that such doses occur at distances up to about 10 km. A total mean number of 440 persons with doses above 0.5 Sv was calculated from the distribution; 15 of these persons receive doses greater than the LD_{50} value of 4.5 Sv. These numbers along with the corresponding distributions allow the analysis of the collective early fatality risk and also allow conclusions

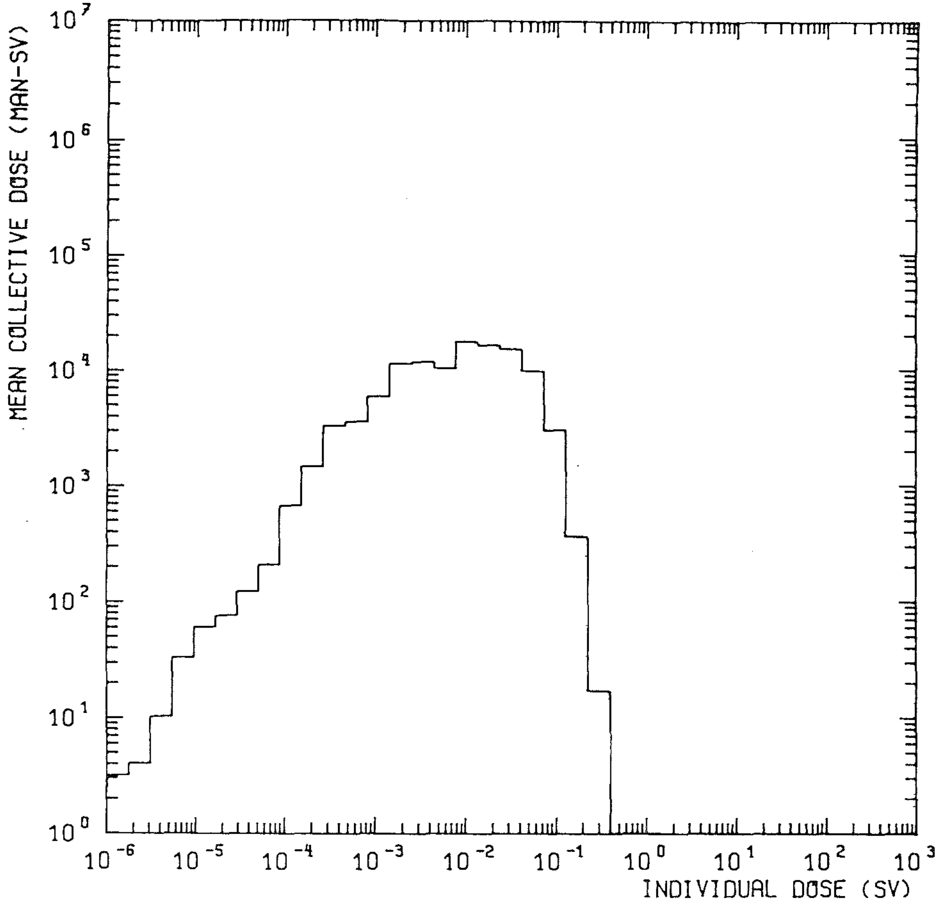


FIG. 10.9: ILLUSTRATION OF THE CORRELATION BETWEEN MEAN COLLECTIVE DOSE AND INDIVIDUAL 70 A-DOSE (BONE MARROW)

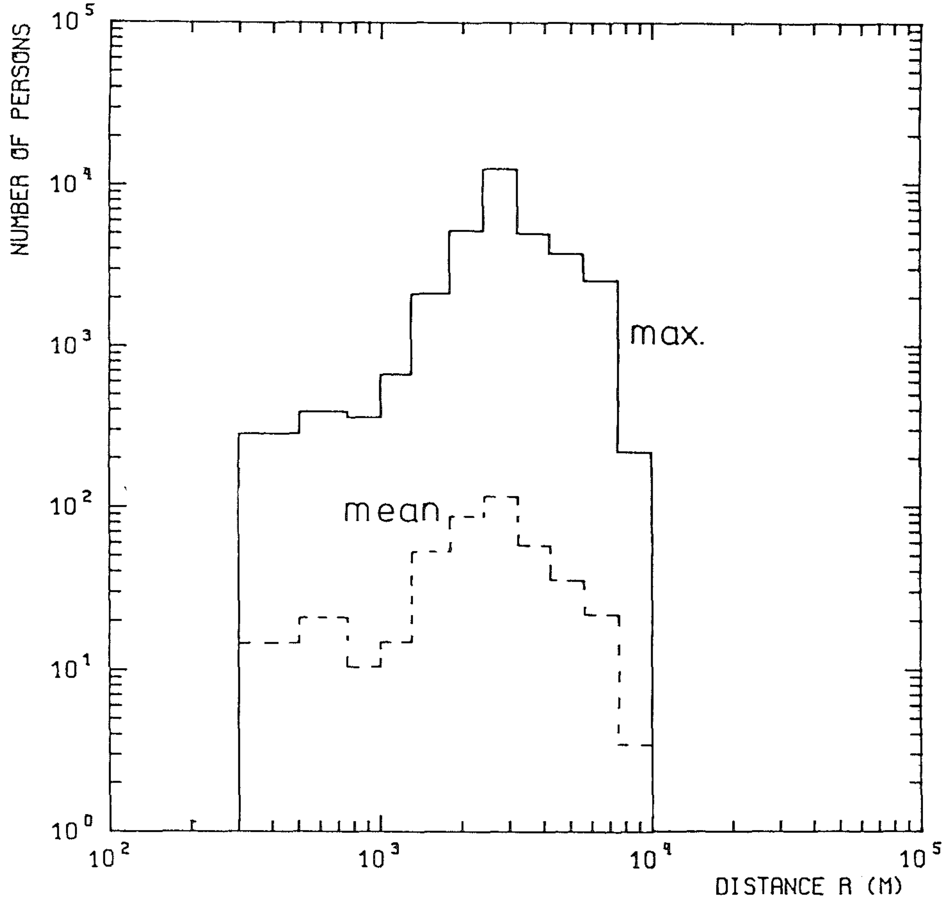


FIG. 10.10: EXAMPLE OF THE MEAN AND MAXIMUM NUMBER OF PERSONS WITH ACUTE BONE MARROW DOSES EXCEEDING 0.5 SV

to be drawn on the effectiveness and the necessity of countermeasures. Similar distributions calculated for different sites may be helpful in assessing their characteristics with regard to risk minimization.

10.4 Health effects

The most widely used and best known presentation of the final results of an ACA is the CCFD of health effects. The Figs. 10.11 and 10.12 show examples of CCFDs of early and late fatalities estimated with the UFOMOD subsystems NE87/1 and FL87/1 for the release described in Sec. 10.1. From each CCFD curve the expected conditional frequency of a number of fatalities being equalled or exceeded can be read.

In each of the figures, the overall CCFD curve is broken down by the contributions from each health effect. This enables the different types of health detriments to be ranked in terms of number of persons affected and frequency.

By comparing Fig. 10.11 and 10.12, it can be observed that the distributions of early and late fatalities show quite different-behaviours: early fatalities are calculated in the whole range from the smallest consequence value (= 1 early death) up to some maximum value, which shows up in the CCFD by a non-zero gradient over the whole curve. In contrast to this, late fatalities are estimated in a restricted consequence band. This is reflected in the CCFD by a zero gradient up to some minimum consequence value, from which the curves decline to lower frequencies with increasing numbers of fatalities.

These characteristic differences in the consequence estimations result from the fact that early fatalities are calculated on the basis of sigmoidal dose-risk relationships with thresholds (see Fig. 7.1 in Sec. 7.1). Only in accident situations doses above these thresholds are to be expected,

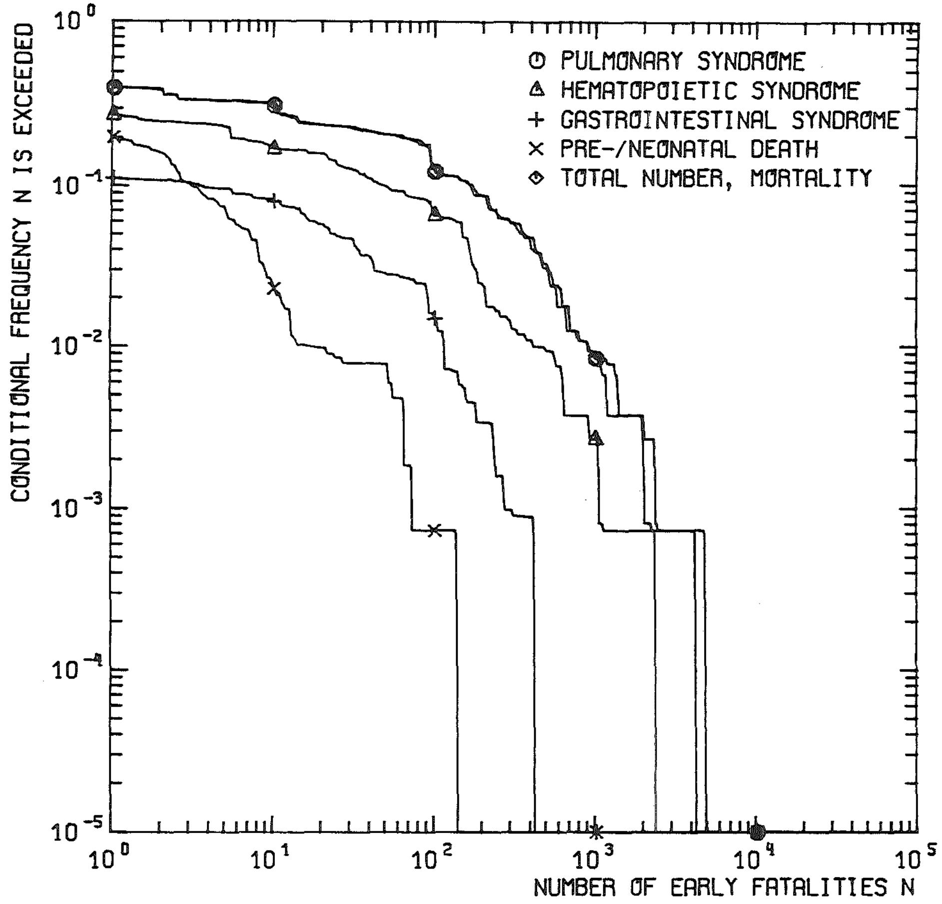


FIG. 10.11: ILLUSTRATIVE CCFDS OF EARLY FATALITIES (RELEASE ASSUMED)

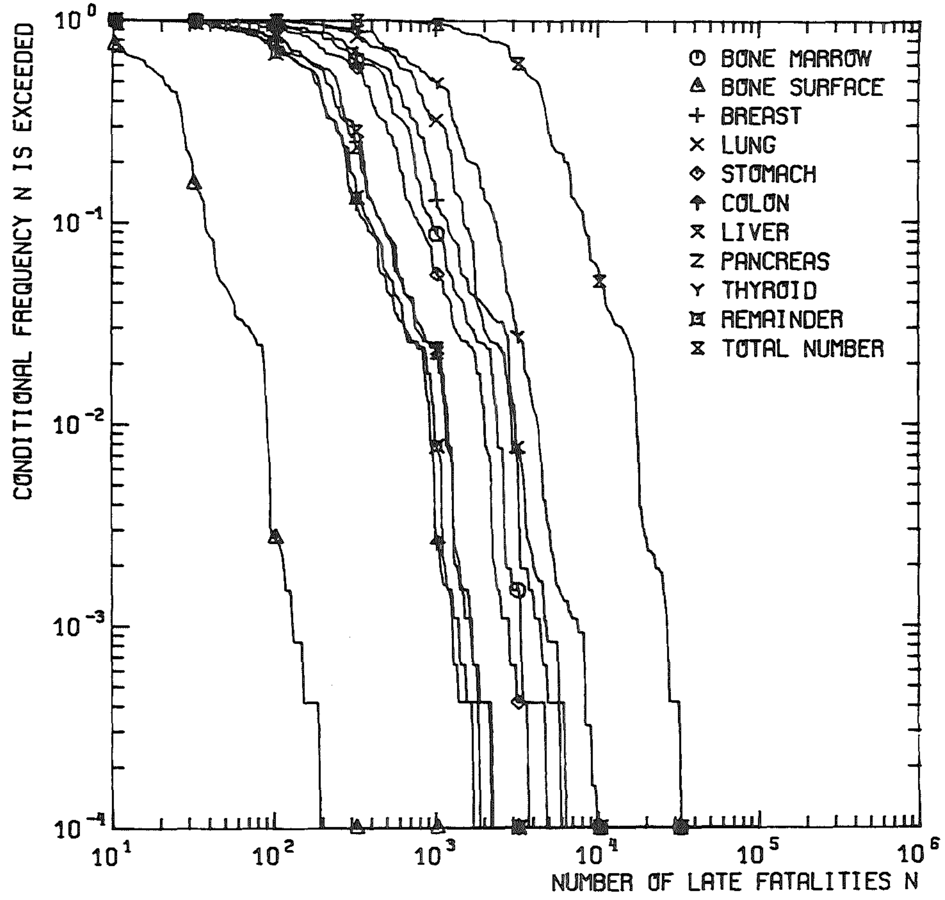


FIG. 10.12: ILLUSTRATIVE CCFDS OF LATE FATALITIES (RELEASE ASSUMED)

so that early fatalities are predicted, whereas in all other cases no early deaths occur. Since in the most of the post-release conditons, the expected values of acute doses do not exceed this level of incidence, the conditional frequency of occurrence for early fatalities is very small and below the corresponding numbers for late fatalities.

Late fatalities have been calculated using a linear dose-risk relationship. Since in all post-release conditions for an inland site, the dispersing radioactivity reaches to distances far from the sites contaminating large areas where many people live. Although small doses result from this low-level contamination a large number of people are affected, which leads to a non-zero collective damage in all cases. The reduction factor between the highest conditional frequencies for early and late fatalities gives the probability that after an accidental release numbers of early fatalities are estimated to be < 1. The probabilities are included in Tab. 10.1.

Characteristic quantities can be derived from the CCFD of consequences. Assuming that a release has occurred, expectation and percentile values of fatalities can be calculated. Characteristic quantities derived from the CCFDs of early and late fatalities (Fig. 10.11 and 10.12) are listed in Tab. 10.1. The median value (50th percentile) of early fatalities is zero, again reflecting the fact that early fatalities are only calculated in some small percent of the accident consequence situations. Due to the asymmetry of the frequency distribution of early fatalities (with a large peak at zero-events), the expectation value has no real significance because it cannot be assigned to any point of the distribution. In contrast to this, the expectation and median values of the CCFDs of late fatalities are approximately of the same magnitude which corresponds to a nearly symmetric frequency distribution.

characteristic quantities		total number of early fatalities	late fatalities
expectation value		64	4479
value	p = 50	0	4169
at the	p = 90	174	8128
pth	p = 95	393	10230
percentile	p = 99	912	16980
probability of zero fatalities		60.1	0.0

Tab. 10.1: Illustrative characteristic quantities of the CCFD's for early and late fatalities

cancer types	exposure pathways: cloud-shine	ground-shine	inhalation	ingestion	partial sum
leukemia	0.06	5.41	0.98	5.50	11.95
bone surface	0.00	0.16	0.12	0.22	0.50
breast	0.12	10.47	0.32	3.22	14.13
lung	0.08	7.25	8.70	2.75	18.78
stomach	0.06	6.11	0.37	2.85	9.41
colon	0.02	2.42	0.57	1.50	4.51
liver	0.04	3.51	0.67	1.56	5.78
pancreas	0.04	3.64	0.18	1.57	5.43
thyroid	0.02	2.14	13.19	9.55	24.90
others	0.03	3.05	0.19	1.36	4.61
partial sum	0.47	44.16	25.31	30.08	100.0

Tab. 10.2: Examples of the percentage contribution of cancer types and exposure pathways to late fatalities

Similar to collective dose distributions, CCFDs of health effects show integral results; causal connections to dose levels or distance ranges, in which they occur, are lost. Therefore, forms of presentations illustrating such correlations were developed. An example is given in Fig. 10.13, which links the mean number of leukemia cases with the individual 70a-bone marrow doses. It is obvious, that more than 90% of the fatalities are calculated from doses below 0.05 Sv. This result illustrates very clearly, that late somatic health effects occur in a very large population group with low individual radiation dose levels.

People living around a nuclear facility may be more interested in estimates of the individual risk. This individual risk is in general evaluated in terms of the frequency of the incidence of early and late health effects. Fig. 10.14 shows the 99,9% fractiles of the individual risk to suffer lethal and non-lethal early health effects as a function of distance from the point of release. It is obvious, that in the case of the release assumed, the individual risk of early fatality is limited to the distance of 5 km in nearly all accident situations.

To analyse the collective damage of early and late fatalities the contribution of the different sources of risk must be quantified. A first step in this direction is to break down the fatality risks by cancer types and exposure pathways. The percentages listed in Tab. 10.2 give the corresponding contributions to the late fatality risk estimated for the release considered. The percentages are averaged over all accident situations considered in the ACA (mean values).

The exposure pathway "external radiation from the passing plume" is of less importance due to the short period of irradiation of persons at low dose rates. All other exposure pathways cause a protracted irradiation of organs and with this a higher probability of cancer fatality.

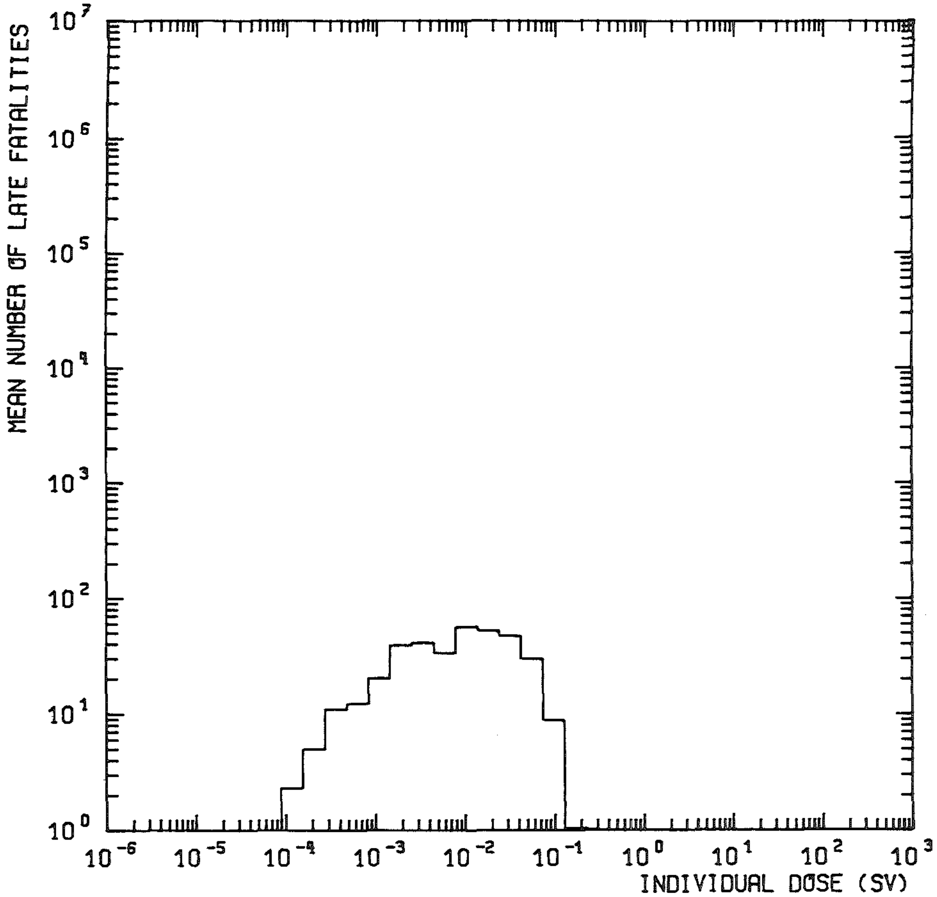


FIG. 10.13: ILLUSTRATION OF THE CORRELATION BETWEEN THE MEAN NUMBER OF LEUKEMIA DEATHS AND THE INDIVIDUAL 70 A-BONE MARROW DOSES

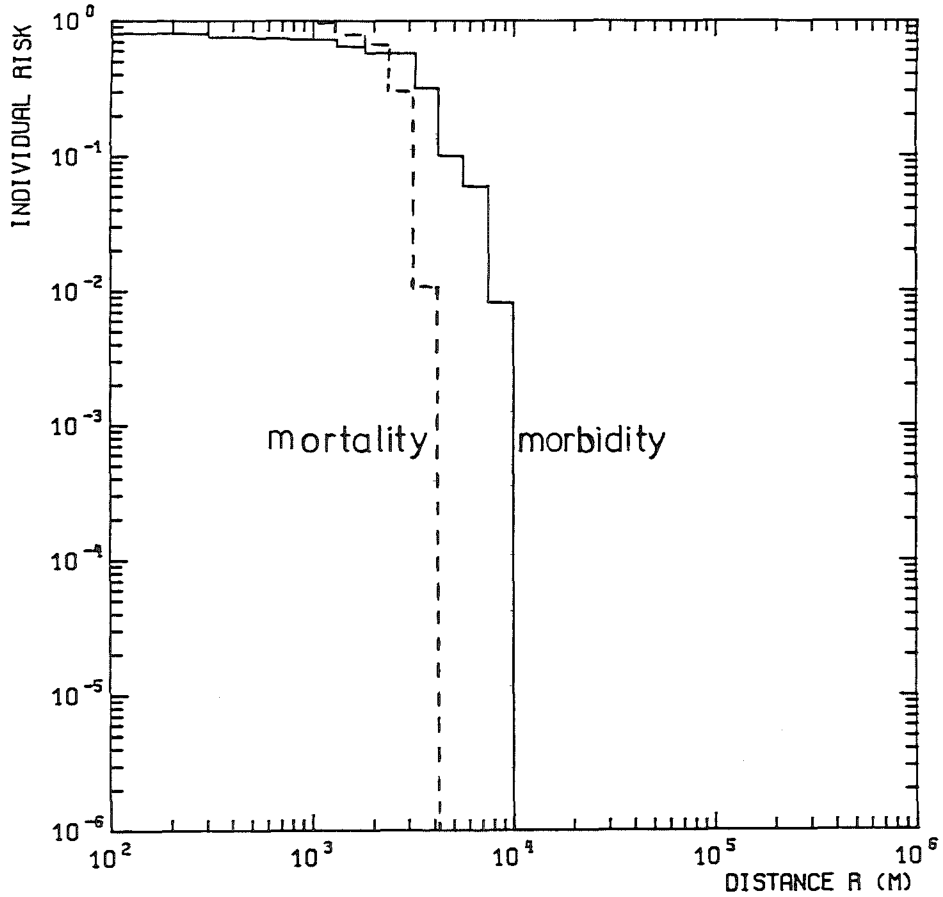


FIG. 10.14: EXAMPLE OF THE 99.9TH PERCENTILES OF INDIVIDUAL RISK OF EARLY HEALTH EFFECTS (RELEASE ASSUMED)

A breakdown of collective damage by causes of death may help to give an understanding of the sources of risk and allow judgement, for example, on the effectiveness or adequacy of emergency and countermeasures actions.

The presentations of health effects assessments discussed till now refer to the overall individual risk and the overall collective detriment of early and late injuries or fatalities. As described in Chap. 7, early health effects (esp. fatalities) occur within several weeks or months after exposure; in contrast, late fatalities (leukemia and cancer) are evidenced years or decades later. Moreover, long half-life radionuclides released at nuclear accidents cause a chronic exposure which also influences the time dependent incidence of late fatalities.

In this connection the following two questions arise: first, how is the incidence of late fatalities distributed within time after the accident, and second, how far lie the incidence rates originating from the nuclear accident above the natural incidence rate ? These questions cannot be answered completely by the ACA results obtainable with the ACA computer codes used till now.

As described in Chap. 7, the new program system UFOMOD offers the possibility to calculate the occurrence of late fatalities as a function of time after the accident. Consequently, all the presentations described above are available in time dependent forms. As an illustrative example, Fig. 10.15 shows the time dependent yearly percentage contribution to individual risk of leukemia and lung cancer mortality by ingestion at 500 km distance from the site (for the individuals of the generations living at the time of accident). To investigate the influence of seasonal effects, the results are given separately for assumed releases at 1st of January and 1st of July.

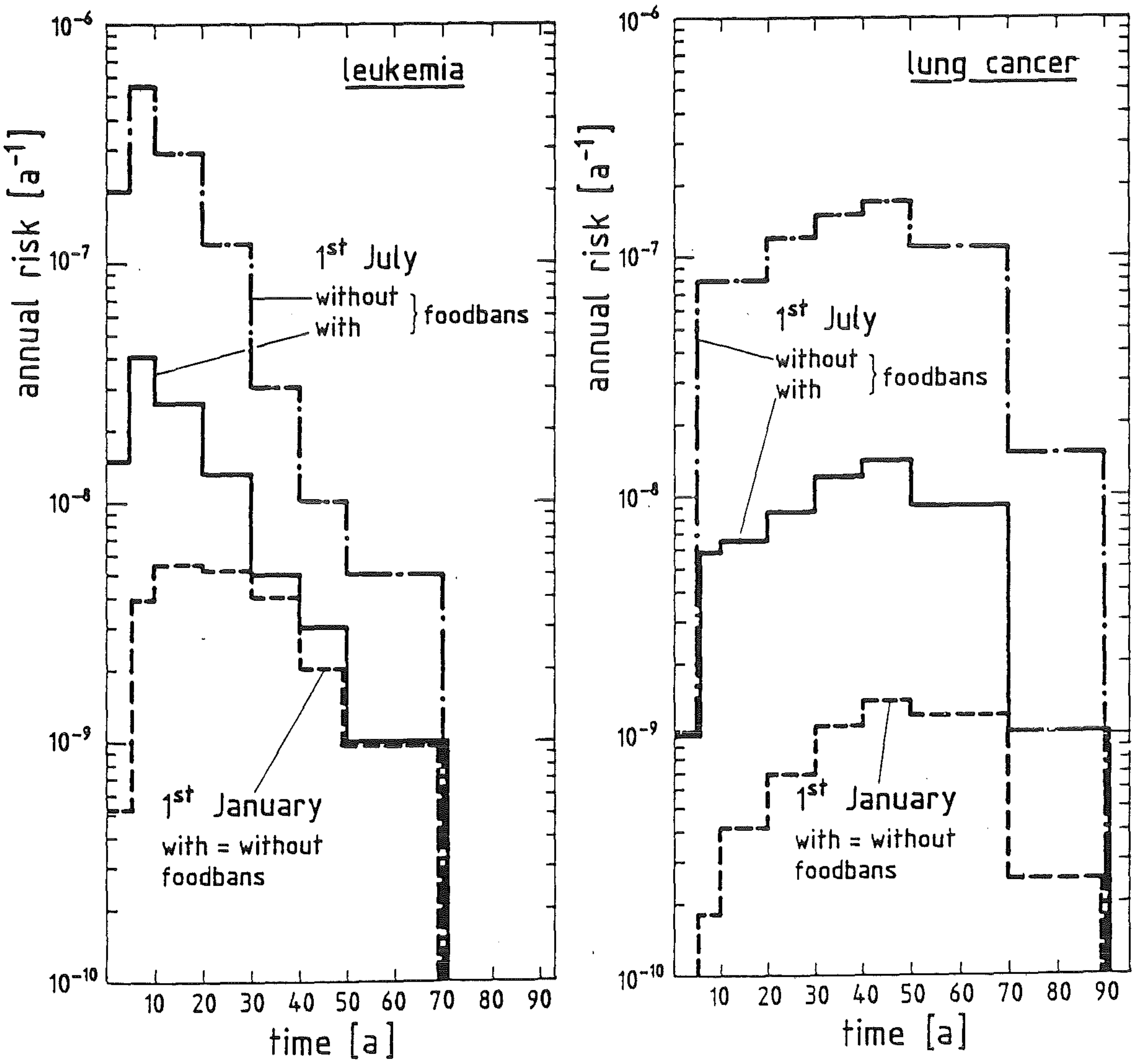


Fig. 10.15: Time dependence of individual leukemia and lung cancer risk by ingestion at 500 km distance (living generations)

Due to the different latency and manifestation periods of the two types of health effects, their time patterns in the population are rather different: the risk of leukemia is highest relatively short after the accident (between 5 and 10 years) and declines afterwards, whereas the risk of lung cancer increases up to 40-50 years, when it reaches its maximum.

The risks of both cancer types - without foodbans - for a release in July quantitatively exceed those for a release in January by about two orders of magnitude, but the slopes of the curves are also significantly different. These observations reflect the fact, that for an assumed release in the summer season the effects of direct deposition lead to a much higher contamination of the foodstuffs in the first year after the accident than in the subsequent years, when the more inefficient processes of root uptake and resuspension are the only ways of activity transfer to the foodstuffs; this is also the case for an accident in the winter reason.

The differences in the slopes are less expressed when foodbans are taken into account. In the case of the summer release, they strongly reduce the influence of the higher contaminated foodstuffs in the first year. Releases in winter lead to much lower contamination levels and foodbans are imposed in much smaller areas. Therefore, with the given source term, the foodbans do not affect the risk at a distance of 500 km for the release assumed in January. Fig. 10.16 shows the expectation values of the estimated annual numbers of fatalities from all late health effects considered in UFOMOD and exemplarily from leukemia and lung cancer. The difference in the time behaviour of leukemia and lung cancer can again be observed. The overall incidence rate has a maximum at about 40 to 70 years after the accident; after 100 years, the rates become comparatively small.

The percentage contributions of the living generation to the cumulative number of cancer fatalities is given in Tab. 10.3. About 70% of the health effects estimated to occur over 200

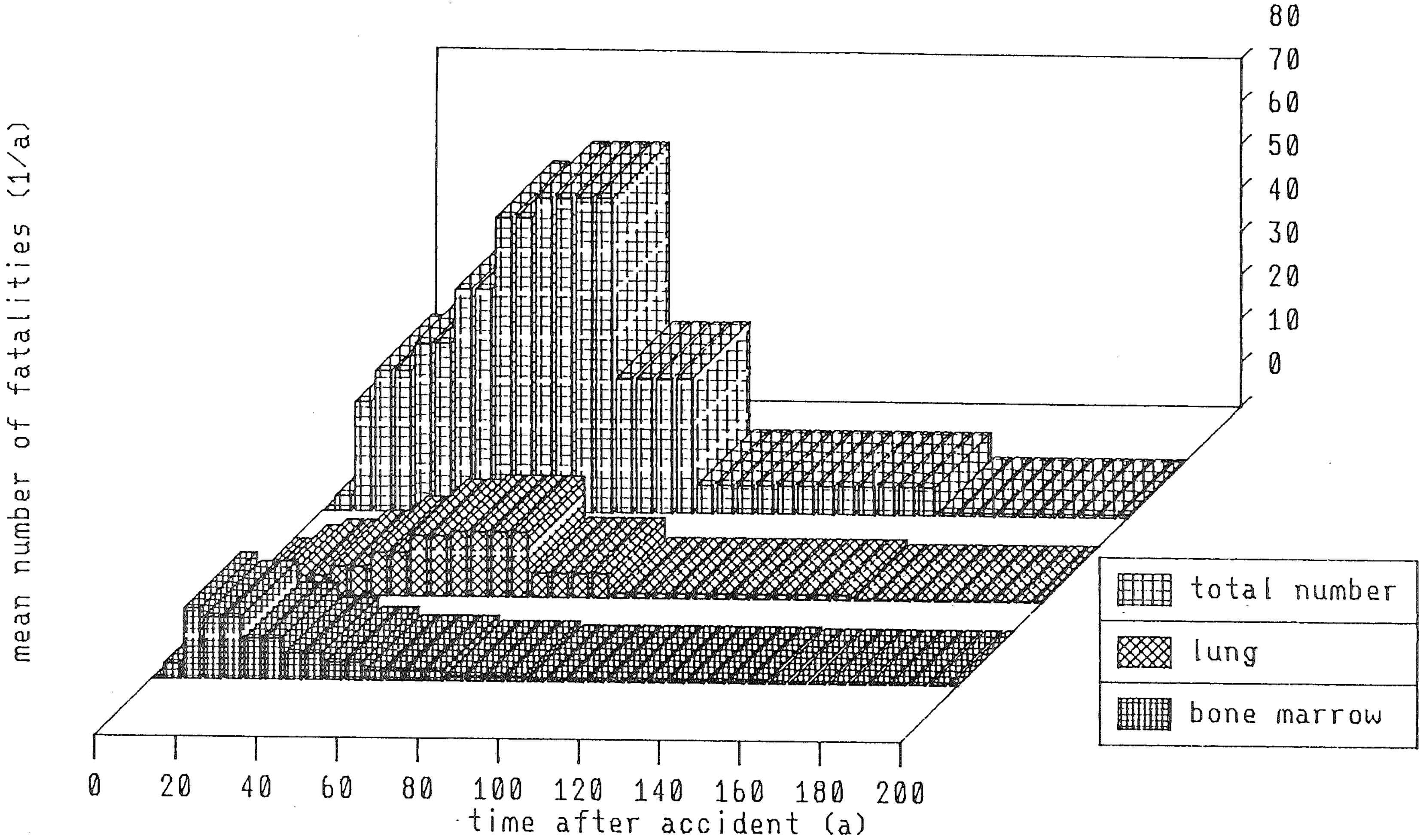


Fig. 10.16: Examples of the time dependent mean number of late fatalities for different cancer types

years after the postulated accident manifest in the generation alive at the time of the accident.

Integration time /a/									
5	10	20	30	40	50	70	90	150	200
94%	93%	92%	92%	92%	91%	86%	79%	72%	72%

Tab. 10.3 Contributions of the living generation to the cumulative numbers of cancer fatalities

10.5 Areas and persons affected by countermeasures

Countermeasures are imposed to reduce the individual risk and the number of health effects in the population. The areas and number of people affected by these countermeasures reflect their economic impact. They are an important information to judge the effectiveness and feasibility of measures.

Therefore, all comprehensive risk studies contain CCFDs and tables with derived quantities of the areas where countermeasures are expected to be imposed and the number of people living there. The time-dependent modelling in UFOMOD of long-term countermeasures (relocation, decontamination, food-bans) allows the corresponding figures and tables to be presented as a function of time after the accident. Fig. 10.17 shows illustrative CCFDs of the relocated areas. It is easily to be seen, that after the accident presumed (see Sec. 10.1), areas with relocation in the first year cannot be resettled within the next 20-30 years. In 99% of all cases, areas with relocation for more than 30 years are about a factor of 3 smaller than the initial area, and after 70 years about one tenth remains unsettled. Similar results are obtained for the

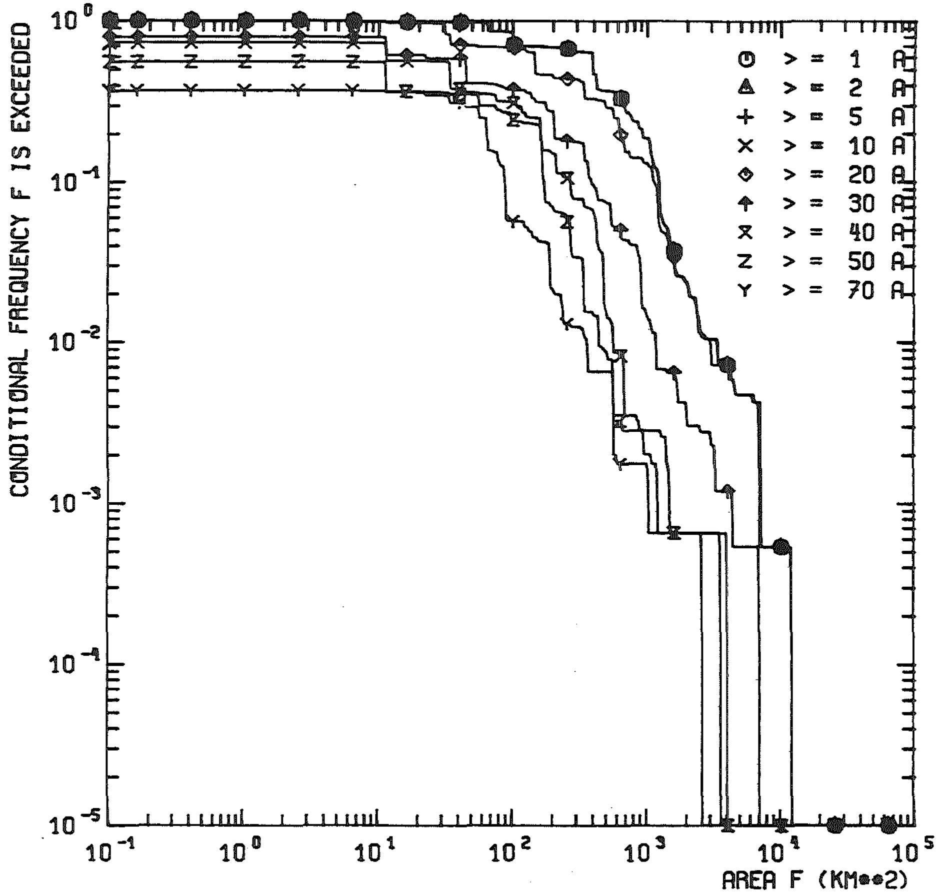


FIG. 10.17: ILLUSTRATIVE CCFDS OF THE AREAS AFFECTED BY RELOCATION FOR DIFFERENT TIME PERIODS (RELEASE ASSUMED)

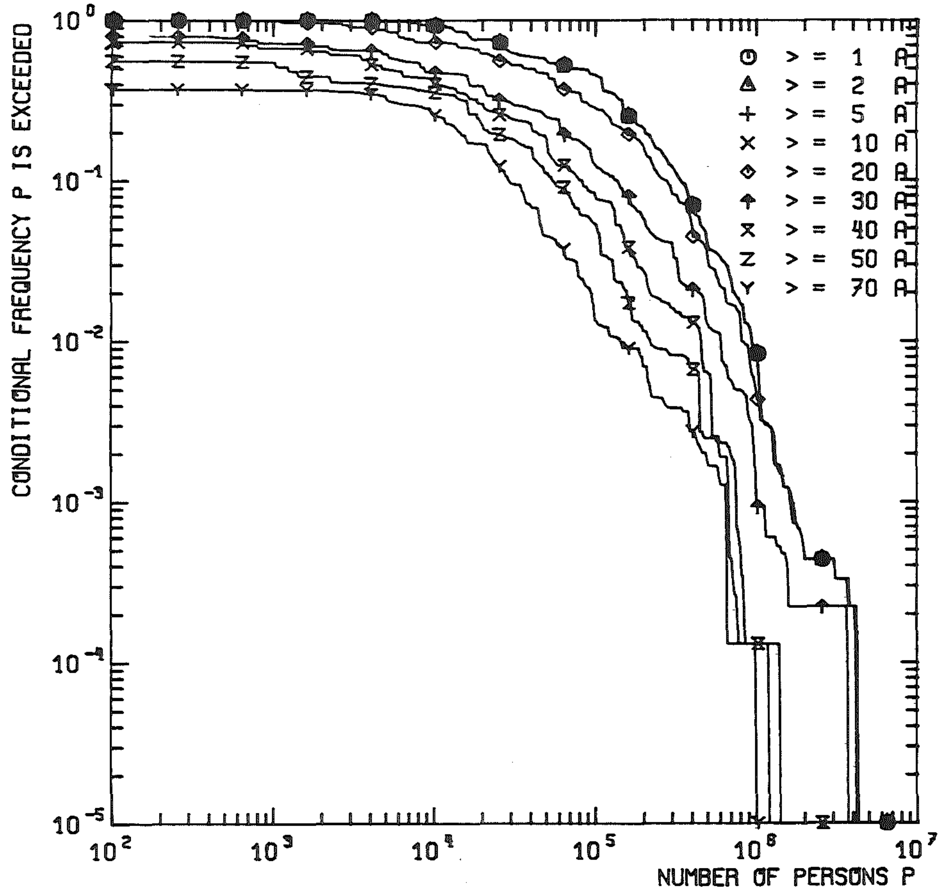


FIG. 10.18: ILLUSTRATIVE CCFDS OF THE NUMBER OF PERSONS RELOCATED FOR DIFFERENT TIME PERIODS (RELEASE ASSUMED)

number of persons relocated for different time periods (see Fig. 10.18).

11. Summary and future improvements

The development of the new program system UFOMOD was governed by two main aims, namely

- to assess the consequences of accidental releases of radionuclides from nuclear facilities as comprehensively and realistically as possible, and

- to cope with the various requirements emerging from the broad field of applications of ACAs, especially as help in decision-making in emergency planning, siting, research priority setting and parallel to regulatory and licensing procedures.

Special demands on the modelling of atmospheric dispersion emerged from the broad spectrum of possible source terms. The incorporation of different trajectory models with ranges of validity near to the site and at far distances, respectively, is a significant step foreward to an appropriate treatment of site-specific problems and questions arising in connection with the transportation of radioactive material over large land areas up to thousands of kilometres. The new structure of UFOMOD clearly reflects this problem-oriented modelling by the division into three subsystems each built to assess accident consequences resulting from acute or chronic exposure.

Completely new data sets of age-, sex- and time-dependent dose-conversion factors for external and internal radiation from up to 141 radionuclides are available. The ingestion pathway is modelled to consider seasonal dependencies in the agricultural use of farmland and its influence on the contamination level of the 8 foodstuffs specified in the program. The emergency actions and long-term countermeasures are supposed to succeed according to the widely accepted recommendations of international commissions. The detailed parameterization of the geometry of evacuation areas, the intervention criteria for fast relocation, relocation, decontamination and food-bans, and the behaviour of the population in the case of an emergency allows parameter studies to be performed with respect to the optimization of strategies and plans. In this context, the implementation of new dose-risk-relationships and new time- and age-dependent dose-risk-factors for a variety of lethal and non-lethal non-stochastic and stochastic health effects, respectivelly, is an important improvement: the effectiveness of measures can be discussed on the basis of the individual risk reduction and the collective health detriments saved. A special algorithm developed for ACA codes allows individual and collective leukemia and cancer risks to be calculated as a function of time after the accident.

According to the modular structure of the new UFOMOD program system, an easy access to the results of the various submodels exists. This facilitates not only the detailed presentation of intermediate and final results of an ACA and the illustration of correlations between them, but also sensitivity and uncertainty analyses showing the ranked influence of the submodel parameter variations on the results of interest.

Not all modelling aspects planned for the new program system UFOMOD could be realized in the versions described in this report. At present, investigations are under way or projected aiming at the development of three completing submodels to enable the assessment of

- economic consequences in the form of monetary costs,
- genetic effects,
- radiological consequences of tritium releases.

The decontamination of rural, urban and agricultural areas, presently modelled by one single decontamination factor, will be treated in more detail as far as the economic module is available. By the inclusion of cost- (effort-) benefit analyses, more reliable results of the extent and duration of long-term countermeasures can be expected.

A further improvement is planned by the implementation of a special simplified atmospheric dispersion model to estimate the spatial concentration distribution for low-level long-duration (weeks or months) releases of radioactive material. To that purpose, the computer code ISOLA /56/ has been modified for use in UFOMOD.

The radiation exposure by the contamination of the skin and of clothes may become an important pathway in the case of nearground releases or rainfall conditions. Corresponding dose-conversion factors for the skin and other organs have been made available /57/ for the future modelling in UFOMOD.

The assessment of individual and collective leukemia and cancer risks provides an incomplete picture of the fatal consequences. On a societal level, the presentation in form of the loss of life expectancy may be more relevant. In addition, this loss of life expectancy differs significantly between early and late fatalities. The basic loss of lifetime data have been calculated by GSF /49, 50/ together with the dose-risk-factors for stochastic somatic health effects. Future versions of UFOMOD will be extended to allow loss of life expectancy assessments and their adequate presentation.

Together with an increased application of the new program system UFOMOD, data gaps may become obvious, like missing radionuclides in the list of dose-conversion factors, the partial dependency of dose-conversion factors from particle size distributions and the chemical form of radionuclides. Further requirements may emerge from the economic module, like land-use data and grids with information on the economic structure.

References

/1/ Ehrhardt, J., Hasemann, I.
UFOMOD: Structure, output and illustrative applications
Report KfK-4331, in preparation

/2/ Panitz, H.-J., Päsler-Sauer, J., Matzerath, C.
UFOMOD: Atomospheric dispersion and deposition
Report KfK-4332, in preparation

/3/ Matzerath, C., Steinhauer, C., Ehrhardt, J.
UFOMOD: Exposure pathways and dose assessment
Report KfK-4333, in preparation

/4/ Burkart, K., Steinhauer, C.
UFOMOD: Countermeasures and intervention levels
Report KfK-4334, in preparation

/5/ Steinhauer, C., Matzerath, C., Ehrhardt, J.
UFOMOD: Health effects models
Report KfK-4335, in preparation

/6/ Hasemann, I., Ehrhardt, J.
UFOMOD: Program description and user's guide
Report KfK-4336, in preparation

/7/ Steinhauer, C.
UFOING: Program for assessing the off-site consequences from ingestion of accidentally released radionuclides
Report KfK-4475 (1988)

/8/ Panitz, H.-J.
Accident consequence assessments with different atmospheric dispersion models - a Benchmark study
Report KfK-4445 (1988)

/9/ Ritchie, L.T., Johnson, J.D., Blond, R.M.
Calculation of Reactor Accident Consequences, Version 2
NUREG/CR-2324 (SAND-1994) (1981)

/10/ Clarke, R.H., Kelly, G.N.
MARC - The NRPB Methodology for Assessing Radiological Consequences of Accidental Releases of Activity
NRPB-R127 (1981)

/11/ Bayer, A., Burkart, K., Ehrhardt, J., Hübschmann, W., Schückler, M., Vogt, S., Jacobi, W., Trott, K.R.
The German Risk Study: Accident Consequence Model and Results of the Study
Nuclear Technology, Vol. 59, p.20-50 (1982)

/12/ Proceedings of the "Workshop on Methods for Assessing the off-site Radiological Consequences of Nuclear Accidents", Luxembourg, April 15-19, 1985
Commission of the European Communities,
Report EUR-10397, ISBN 92-825-5991-2

/13/ Methods for assessing the off-site radiological consequences of nuclear accidents
Joint report by the Kernforschungszentrum Karlsruhe, FRG, and the National Radiological Protection Board, Chilton, Didcot, UK, May 1985
Commission of the European Communities,
Report EUR-10243 (1986), ISBN 92-825-5951-3

/14/ Päsler-Sauer, J.
Comparative calculations and validation studies with atmospheric dispersion models
Karlsruhe, Report KfK-4164 (November 1986)

/15/ ApSimon, H.M., et.al.
Long range atmospheric dispersion of radioisotopes. Part 1 - The MESOS model, Part II - Application of the MESOS model. Atmospheric Environment, 19, 99-125 (1985).

/16/ Straka, J., Geiß, H., Vogt, K.J.
Diffusion of Wate Air Puffs and Plumes under Changing Weather Conditions
Contr. Atmosph. Physics, 54, 207-221, 1981

/17/ Mikkelsen, T., Larsen, S.E., Thykier-Nielsen, S.
Description of the RISO-Puff-Model
Nuclear Technology, Vol. 76, Oct. 1984, pp.56-65

/18/ Panitz, H.-J.
Accident Consequence Assessments with Different Atmospheric Dispersion Models
Paper presented at the International SNS/ENS/ANS Topical Meeting on Probabilistic Safety Assessment and Risk Management, Aug. 30-Sept. 4, 1987, Zürich
Conference Transactions, Vol. III, 933-938, Verlag TÜV Rheinland, Köln, 1987

/19/ Steinhauer, C., Matzerath, C., Ehrhardt, J.
Method for calculating time dependent individual and collectice cancer risks in the accident consequence assessment code UFOMOD
Proceedings of the joint OECD (NEA)/CEC Workshop on "Recent Advances in Reactor Accident Consequence Assessment"
Rome, Italy, Januar 25-29, 1988
Report EUR-11408, p.278-288 (1988)

/20/ Hanna, S.R., Briggs, G.A. and Hosker, R.P.
Handbook on Atmospheric Diffusion. Technical Information Center, U.S. Departement of Energy, pp. 102, 1982

/21/ Bultynck, H. and Malet, L.M.
Evaluation of Atmospheric Dilution Factors for Effluents Diffused from an Elevated Continuous Point Source. Tellux, XXIV, 455-472, 1972

/22/ Geiss, H.
Ausbreitung von Schadstoffen in der Atmosphäre: theoretische Grundlagen und praktische Anwendungen.
Kerntechnische Gesellschaft e.V., Bonn,
KTG-Seminar, Band 1, Verlag TÜV Rheinland, Köln, pp. 50, 1983 (ISBN 3-88585-127-X)

/23/ Doury, A.
Pratiques francaises en matière de prévision quantitative de la pollution atmosphérique potentielle liée aux activités nucléaires.
Proc. CEC Seminar on Radioactive releases and their dispersion in the atmosphere following a hypothetical reactor accident, April 1980, Riso, Denmark, p.403-448

/24/ Smith, F.B.
A scheme for estimating the vertical dispersion of a plume from a source near ground level.
3rd meeting of an expert panel on air pollution modelling, Paris, October 1972.
Brussels NATO-CCMS report 14 (1973)

/25/ Schwarz, G.
Deposition and Post-Deposition Radionuclide Behaviour in Urban Environments
in: Workshop on Methods for Assessing the Off-Site Radiological Consequences for Nuclear Accidents, 15-19 April 1985, Luxembourg, Report EUR 10 397EN, pp. 33-57, Commission of the European Communities, 1986

/26/ Vogt, S., Hübschmann, W. und Wittek, P.
Niederschlag und Washout im Unfallfolgenmodell der Deutschen Risikostudie - Kernkraftwerke
Report KfK 3548 (1983)

/27/ Brenk, H.D. und Vogt, K.J.
The Calculation of wet Deposition from Radioactive Plumes
Nuclear Safety, 22, 362-371, 1981

/28/ Briggs, G.A.
Plume Rise and Buoyancy Effects
in: Randerson, D. (Ed.): Atmospheric Science and Power Production, pp. 327-366. Technical Information Center, Office of Science and Technical Information, U.S. Departement of Energy, 1984

/29/ Erste allgemeine Verwaltungsvorschrift zum Bundesimmissionsschutzgesetz (Technische Anleitung zur Reinhaltung der Luft) vom 27.2.1986,
GMBI, Ausgabe A, Bonn, 28.2.1986, S. 93

/30/ Hosker, R.P.
Flow and Diffusion near Obstacles
in: Randerson, D. (Ed.): Atmospheric Science and Power Production, pp. 241-326. Technical Information Center, Office of Science and Technical Information, U.S. Department of Energy, 1984

/31/ Briggs, G.A.
Lift-Off of Buoyant Gas Initially of the Ground.
ADTL Contribution File No. 87. Air Resources Atmospheric Turbulence and Diffusion Laboratory NOAA, Oak Ridge, TN, USA, 1973

/32/ Hall, D.J. and Waters, R.A.
Further Experiments on a Buoyant Emission from a Building
Warren Spring Laboratory, Departement of Trade and Industry, Gunnels Wood Road, STEVENAGE, Hertfordshire, SG1 2 BX, U.K., 1986, pp. 44

/33/ Müller, H.M. and Jacob, P.
Gamma exposures from Gaussian clouds
Gesellschaft für Strahlen- und Umweltforschung (GSF) mbH, in preparation

/34/ Manier, G.
Vergleich zwischen Ausbreitungsklassen und Temperaturgradienten
Meteorologische Rundschau, 28, 6-11, 1975

/35/ Projekt Sicherheitsstudien Entsorgung (PSE)
Berechnung der Ausbreitung von Radionukliden über den Luft- und Nahrungspfad und der potentiellen Strahlenexposition bei Störfallereignissen in oberirdischen Anlagen der Entsorgung;
Abschlußbericht, Fachband 9, HMI, Berlin, Januar 1985

/36/ Jacob, P., Paretzke, H.G., Rosenbaum, H., Zankl, M.
Effective Dose Equivalents for Photon Exposures from Plane Sources on the Ground
Radiation Protection Dosimetry 14, 299-310 (1986)

/37/ Jacob, P. and Paretzke, H.G.
Dose-rate conversion factors for external gamma exposure
Nucl. Instr. Meth. Phys. Res. A255, 156-159 (1987)

/38/ Meckbach, R., Jacob, P., Paretzke, H.G.
Shielding of gamma radiation by typical European houses
Nucl. Instr. Meth. Phys. Res. A255, 160-164 (1987)

/39/ Jacob, P., Paretzke, H.G., Rosenbaum H., Zankl, M.
Organ doses from radionuclides on the ground
Part I: Simple time dependencies
Health Physics 54, 617-634 (1988)
Part II: Non-trivial time dependencies
Health Physics 55, 37-49 (1988)

/40/ Jacob, P., Meckbach, R.
Shielding factors and external dose evaluation
Proc. Workshop on consequences of accidental contamination of the urban environment June 9-12, 1987, Roskilde, DK
Rad. Prot. Dos. 21, No.1-3, 79-85 (1987)

/41/ Meckbach, R., Jacob, P., Paretzke, H.G.
Gamma exposures due to radionuclides deposited in urban environments
Part I: Kerma-rates from contaminated urban surfaces
Submitted to Rad. Prot. Dos.

/42/ Matthies, M., Eisfeld, K., Müller, H., Paretzke, H.G., Pröhl, G., Wirth, E.
Simulation des Transfers von Radionukliden in landwirtschaftlichen Nahrungsketten
GSF-Bericht S-861, 1982

/43/ Dosisfaktoren für Inhalation oder Ingestion von Radionukliden (Erwachsene, Altersklasse 1 Jahr, Altersklasse 5 Jahre, Altersklasse 10 Jahre, Altersklasse 15 Jahre)
Bundesgesundheitsamt
ISH-Berichte 63, 78, 79, 80, 81 (1985)

/44/ International Commission on Radiological Protection
Protection of the Public in the Event of Major Radiation Accidents: Principles for Planning
ICRP Publication 40, Pergamon Press, Oxford and New York (1984)

/45/ Evans, J.S., Moeller, D.W., Cooper, D.W.
Health Effects Model for Nuclear Power Plant Accident Consequence Analysis
Report NUREG/CR-4214, July 1985

/46/ Alpert, D.J., Chanin, D.I., Helton, J.C., Ostmeyer, R.-M., Ritchie, L.T.
The MELCOR Accident Consequence Code System (MACCS)
SAND 85-0884C (1985)

/47/ Sprung, J.L., Aldrich, D.C., Alpert, D.J., Weigand, G.G.
Overview of the MELCOR Risk Code Development Programme
SAND-83-0894C (1983)

/48/ Scott, B.R., Hahn, F.F.
Early occurring and continuing effects
Chap. 1 of the revised version /45/, draft of August 19, 1988, unpublished

/49/ Schindel, F., Henrichs, K., Paretzke, H.G.
Einfluß von Zeit-Projektionsmodellen auf Schätzungen von Krebsrisiken durch Radionuklide
Proc. IVth European Congress of IRPA, Salzburg, 1986

/50/ Henrichs, K., Paretzke, H.G., Chmelevsky, D., Gerken, M.
New Estimates of Risk Surfaces for Somatic Late Effects of Low Doses of Ionizing Radiation
Proceedings of the joint OECD (NEA)/CEC Workshop on "Recent Advances in Reactor Accident Consequence Assessment"
Rome, Italy, January 25-29, 1988
Report EUR-11408, p.271-277 (1988)

/51/ BEIR-III Report
The Effects on Populations of Exposure to Low Levels of Ionizing Radiation. Report of the Advisory Committee on the Biological Effects of Ionizing Radiation, Division of Medical Sciences, National Academy of Sciences. National Research Council, Washington, D.C. (1980)

/52/ Pfeffer, W., Schnadt, H., Burkart, K.
Investigation of the parameter "driving time" in evacuations in the accident consequence assessment code UFOMOD of the German Risk Study Phase B
Radiation Protection Dosimetry 21, 159-164 (1987)

/53/ Pfeffer, W., Hofer, E., Nowak, E., Schnadt, H.
Parameterization of the driving time in the evcuation or fast relocation model of an accident consequence code
Proceedings of the joint OECD (NEA)/CEC Workshop on "Recent Advances in Reactor Accident Consequence Assessment"
Rome, Italy, January 25-29, 1988
Report EUR-11408, p.312-322 (1988)

/54/ Kreymborg, A., Raitz von Frentz, R., Rödder, P.
GUW - Gesellschaft für Umweltüberwachung mbH
Computerprogram zur Umrechnung von Bevölkerungs- und anderen Daten aus der Rasterdarstellung mit geographischen Koordinaten in die Polarkoordinatendarstellung
GUW-Bericht 85.0685.01, Aldenhoven/Jülich, (Oktober 1985)

/55/ Commission of the European Communities
Methodology for Evaluating the Radiological Consequences of Radioactive Effluents Released in Normal Operations
Doc. No. V/3865/79-ENFR (1979)

/56/ Hübschmann, W., Honcu, S.
ISOLA IV - Ein FORTRAN 77-Programm zur Berechnung der langfristigen Dosisverteilung in der Umgebung kerntechnischer Anlagen
Report KfK-4146 (1987)

/57/ Henrichs, K., Eiberweiser, C., Paretzke, H.G.
Dosisfaktoren für die Kontamination der Haut und der Kleidung
GSF-Bericht 7/85 (1985)

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