Commission of the European Communities

RADIATION PROTECTION RESEARCH AND TRAINING PROGRAMME

Radiation protection programme Revision 1988-89

Post-Chernobyl actions Executive summaries

Report

EUR 13199 EN

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Directorate-General
Science, Research and Development

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Contents

Preface

The Chernobyl accident, which occurred on 26 April 1986, presented major challenges to the European Community with respect to the practical and regulatory aspects of radiation protection, public information, trade, particularly in food, and international politics. The Chernobyl accident was also a major challenge to the international scientific community which had to evaluate rapidly the radiological consequences of the accident and advise on the introduction of any countermeasures. Prior to the accident at Chernobyl, countermeasures to reduce radioactive contamination had been conceived largely in the context of relatively small accidental releases and for application over relatively small areas. Less consideration had been given to the practical implications of applying such measures over a very large area. The Radiation Protection Research and Training Programme was influential in a number of important initiatives taken within the Community immediately after the accident. Information was collected by Community scientists and, from it, an assessment made within days of the possible consequences. This showed that the health impact on the population of the European Community was not expected to be significant. About four weeks after the accident, the Programme, together with the US Department of Energy, organised a meeting in Brussels during which the data on dispersion of radioactive material were discussed and evaluated. Several other meetings followed soon after on the transfer of radionuclides in the food chain and possible health effects. These meetings were carried out in close co-operation with the DG XI (Directorate General, Environment, Consumer Protection and Nuclear Safety) within the CEC, and, externally, with international organisations such as the International Atomic Energy Agency (IAEA) and the World Health Organisation (WHO). In addition, the Commission convoked a Committee of high-level independent scientists to assess the scientific evidence from current research in view of recent nuclear incidences, to consider the possible implications for the Basic Standards and emergency reference levels and to advise the Commission on future action in radiological protection including research. (EUR 11449 EN).

Soon after the accident, additional research requirements were identified by the Programme; these were mainly better methods to assess accident consequences and the further improvement of off-site accident management. Several existing contracts were reoriented and new contracts were placed; however, the financial means then available within the Programme were insufficient to fund the additional research identified as necessary. A proposal for a revision of the Programme was, therefore, elaborated in 1986. It comprised 10 specific "post-Chernobyl" research actions. This revision, with an additional budget of 10 MEcu for a period of two years, was adopted by the Council of Ministers on 21 December 1987. With the help of the Management and Coordination Advisory Committee (CGC) "Radiation Protection" a number of institutes was identified to carry out the research in a co-operative manner, and the research began in the spring of 1988.

These post-Chernobyl activities have now been completed. Detailed reports on each of these studies will be published in separate volumes by the end of 1990 (the report on "Feasibility of studies on Health Effects due to the Reactor Accident at Chernobyl" has already been published). An executive summary of each of these studies has been prepared and these are compiled in this volume to provide an overview of the main results of the work undertaken. The help given by the members and experts of the Management and Coordination Advisory Committee (CGC) "Radiation Protection" in the preparation and monitoring of these "post-Chernobyl" actions and in the evaluation of this summary report is gratefully acknowledged.

The research undertaken within the "post-Chernobyl" actions has added considerably to the understanding of the basic underlying mechanisms of the transfer of radionuclides in the environment, of the treatment of accident victims and of how the environmental consequences of accidents may be mitigated. In addition, major progress has been made in the development of predictive and decision-aiding techniques, the implementation of which will lead to significant improvements in off-site accident management. Several new ideas and lines of theoretical and practical research have originated from the post-Chernobyl research and these have already been integrated into the ongoing Community Radiation Protection Research

Programme. A further important feature which should not be overlooked, is the close and effective collaboration of many institutes in the research; this has markedly strengthened the ties between Community institutes and scientists. The outcome of all of this work is that the Community and all other countries are now better prepared and co-ordinated should a significant release of radioactivity ever occur again

Further research is continuing within the current Radiation Protection Research and Training Programme 1990-1991 on a number of the "post-Chernobyl" topics; these also form part of the proposal of the specific Programme on "Nuclear Fission Safety" 1992-1993, e.g. real-time emergency management systems, development of countermeasures in the agricultural environment, treatment of radiation accident victims, etc. Moreover, the Community Programme is currently making a significant contribution to an international evaluation, being undertaken by IAEA at the request of the Soviet Government, on the consequences in the USSR of the Chernobyl accident and of the measures being taken to ensure safe living conditions for the affected populations.

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Synopsis of the Results of the Post-Chernobyl Actions

Introduction:

The accident that occurred in unit 4 of the Chernobyl nuclear power station discharged about 4 EBq of radioactive material into the atmosphere (excluding the radioactive noble gases krypton and xenon). It caused serious radiation exposure and thermal burns to a large number of employees and those involved in mitigating the accident.

Essentially all the radioactive noble gases, about half of the volatile elements, iodine and caesium, and only a small percentage of the more refractory elements such as strontium, cerium and plutonium present in the reactor core at the time of the accident were released to the atmosphere. Much of the radioactive material released was deposited in the vicinity of the power station, the rest was spread over most of Europe, but deposition varied widely dependent on global and local meteorological conditions. During the first weeks following the accident, the exposure to radioiodine was of predominant concern. In the long term, the long-lived caesium isotopes ^{134}Cs and ^{137}Cs present the more important problem. In the year following the Chernobyl accident, the average doses received by the population in the different regions of Community Member States varied from 0.05 mSv to 0.9 mSv. The lifetime exposure due to the accident will be less than twice the average exposure during the first year. These exposure levels can be compared to the about 2 mSv averaged annual doses from natural background radiation. Indeed, the total additional exposure from the Chernobyl accident is well within the range of the normal variability of the annual natural radiation exposure.

The Chernobyl accident re-emphasized the problems that might arise in any possible future accident: the extent and type of radioactive releases - the source term - has to be assessed rapidly, the transport of atmospheric radionuclides dependent on global and local meteorological conditions must be reliably predicted, the potential doses to man from the passage of the radioactive cloud and from deposited material (external exposure), as well as from inhalation or food and drink (internal exposure) must be assessed and strategies for the practical implementation of countermeasures be implemented. Countermeasures may include: sheltering, evacuation, treatment of persons suffering from radiation syndromes, distribution of stable iodine tablets to reduce the uptake of radioactive iodine into the human thyroid, removal of radioactivity from the top soil or from urban surfaces, procedures to interfere with the transfer of radioactivity in the food chain and removal of radioactive food from human consumption.

The CEC Radiation Protection Research Programme has taken several important initiatives to address the scientific problems created by the Chernobyl accident. It has defined additional research requirements, re-oriented some existing research contracts and strategically placed some new contracts. It also asked for a revision of the current 1985-1989 Programme to deal with some particularly urgent issues:

I. Evaluation of data on the transfer of radionuclides in the food chain,

II. Improvement of reliable long-distance atmospheric transport models,

III. Radiological aspects of nuclear accident scenarios,
A. Real-time emergency response systems,
B. The RADE-AID system,

IV. Monitoring and surveillance in accident situations,

V. Underlying data for derived emergency reference levels,

VI. Improvement of practical countermeasures against nuclear contamination in the agricultural environment,

VII. Improvement of practical countermeasures against nuclear contamination in the urban environment,

VIII. Improvement of practical countermeasures: preventive medication,

IX. Treatment and biological dosimetry of exposed persons,

X. Feasibility of studies on health effects due to the reactor accident at Chernobyl.

This synopsis aims to present, in an easily understandable way, the rationales for and the principal results of the research undertaken in this area. As a whole, this research has considerably improved Community ability to handle such emergency situations and has developed the cohesion of Community science.

I. Evaluation of Data on the Transfer of Radionuclides in the Food Chain

The behaviour of radionuclides in the environment has been studied extensively in the past using fallout from nuclear weapons tests, releases from nuclear plants or experimental setups. The data on transfer of different radionuclides under a variety of conditions have been integrated into models to predict the behaviour of releases of radioactive material under normal and accident conditions. The Chernobyl accident has provided the opportunity to verify these data under realistic conditions and to improve our predictive models. Although, in general, the new observations have not radically altered present understanding, they have shown that greater emphasis than in the past must be given to some aspects, such as the physico-chemical form of the radioactive material, behaviour in natural and semi-natural ecosystems, influence of the season of the year during which the release occurs.

Much of the radioactive material released from the accident was in the form of small particle aerosols. This material was found to be less readily transferred to plants initially. Indeed, caesium transfer to plants during the first year was less than expected, and this was confirmed in laboratory experiments. In later years, caesium, regardless of its source, becomes, in general, less available for uptake and after 5 to 10 years transfer has decreased by about a factor of ten.

The release also enabled plant uptake to be studied in soils of very different composition. It was confirmed that the soil-to-plant transfer for acid soil containing much organic matter and little clay is up to ten times higher than for other soil types. Such soil is often found in regions which, although little used for agriculture, represent semi-natural ecosystems from which radioactivity can attain man through grazing ruminants, (sheep, reindeer, deer ...) and mushrooms, berries, etc.

Information on transfer of radioactivity to man via livestock concentrated in the past on the cow with little information available on sheep, goats, pigs, chickens. It is now noted that, for sheep, transfer to milk and meat can be substantially larger than for cows. The data obtained in these studies were indispensable when intervention levels for radioactivity in animal feed had to be defined. Obviously, transfer also depends on the seasonal feeding pattern. The Chernobyl accident happened at a time when cows were already in pasture in some regions and still in the cowshed in others. The data illustrate clearly the advantages that can be obtained by keeping pasture animals indoors for some time after an accident.

Most of the radioactivity entering a river system is swept rapidly downwards causing a passing spike of activity whose transfer to man can be restricted by monitoring and, if necessary, temporarily avoiding use for drinking. Monitoring remains important for situations where contamination due to run-off and flooding of contaminated areas can occur. Substantial activity may also be bound to sediments which can accumulate at natural or artificial barriers in the rivers. Contamination in lakes can remain present for several months, particularly when such a lake is impounded.

II. Improvement of Reliable Long-Distance Atmospheric Transfer Models

Models of long-range pollutant transport have a variety of uses in the context of accidental releases of radioactive material. In the early stages after or during an incident, they can assist in providing an indication of when and where contamination might be expected to appear and what its severity would be for a postulated or known release. As measurements of environmental contamination become available, models can play a further role: if the characteristics of the release, particularly the amounts of various radionuclides, are not known, they could be used to 'work back' from measurements to properties of the release. They also provide a tool for an intelligent interpolation or extrapolation from the measurements to estimates of contamination levels in areas having no data.

The use and importance of long-range transport models in these contexts was exemplified during and after the Chernobyl accident. Most of the models used existed long before the accident and had been developed with specific uses in mind, having their assumptions and simplifications tuned to those particular applications. Wide variations exist in the complexity of the models used and in the demands they make on meteorological data and on computational resources. Few of them had been developed or optimized specifically to provide, following an accident, inputs in real time to emergency response systems.

The focus of much of the research carried out within this action has been to evaluate the merits and disadvantages of alternative modelling approaches for the above purposes, to determine the magnitude of any uncertainties or biases introduced by modelling simplifications, and to identify which approaches had the most potential for application to these types of problem. The appropriate level of model complexity and model validation were two of the key issues addressed. Significant advantages are clearly to be gained in reducing the model complexity to a minimum compatible with the intended application, in particular because of its implications for computation time.

An in-depth investigation has been carried out of the uncertainties and biases introduced into the predictions of long-range transport models consequent upon different modelling assumptions and approaches. Particular consideration was given to the extent to which the effects of major orographical features need to be explicitly modelled. The use of these models, in conjunction with measured levels of environmental contamination, was also analyzed as a means of estimating the magnitude of material released in an accident and for improving and updating the model predictions; further research is, however, required on this topic to make best use of the available information and to improve the quality of the predictions. These investigations, overall, have succeeded in providing a valuable framework for making decisions on the type and nature of modelling approaches and assumptions that can be accommodated, commensurate with the reliability demanded of the application. This information will be of considerable value in optimizing the design of off-site emergency response systems, especially for application at long distances from a release.

Long-range transport models can be validated by controlled-release experiments, but this is costly and presents formidable logistical problems; consequently, few validation studies have been undertaken. Not surprisingly, therefore, the radiological data collected from Chernobyl is viewed as a potentially valuable resource for model-evaluations. However, Chernobyl was not a controlled experiment and there will, inevitably, be limitations in its use for such purposes, not least resulting from a lack of homogeneity in how the various data were measured and reported. In order to benefit most from the use of these data, thorough collation and examination are required. A sub-set of the data have, therefore, been subjected to critical analysis and methods, which are generically applicable, developed to identify erroneous or suspicious data in the data base. Empirical descriptions have also been made of the data and can be used to make predictions of contamination levels at locations where no measurements exist. The wider application of these methods offers the potential to create an improved and more valid data base. The techniques developed could be applied readily to data collected in any future accident and thus provide some measure of quality assurance.

III. Radiological Aspects of Nuclear Accident Scenarios

Following the Chernobyl accident, it was recognized that improvements were needed in the methods used to predict, in real time, the environmental impact of an accidental release of radioactive material. These predictions are an important input to decisions on the introduction of countermeasures following an accident and, consequently, their quality has a direct bearing on that of the decisions taken. Many of the countermeasures that can be taken to avoid radiation exposure are costly, may be disruptive to life and cause anxiety, and, moreover, may themselves introduce additional risks. Decisions on the introduction of countermeasures must, therefore, be taken carefully and based on the most reliable information available at the time. The research undertaken in this action was directed, firstly, towards the development of improved and more broadly applicable methods for assessing doses in real time during an accident; and, secondly, towards the development of techniques that could be used to aid decision-makers in making difficult choices between alternative courses of action, each of which may have competing merits and disadvantages.

A) Dose assessment in real time

Prior to the Chernobyl accident, emergency planning had been concentrated on an area immediately surrounding nuclear installations where people would be most at risk should an accident occur. The extent and nature of the planning reflected judgements on the probability with which an accident may occur and its potential magnitude. The widespread dispersion of radioactive material following the Chernobyl accident drew attention to the desirability of having arrangements that would in future be capable of dealing with accidents having an impact far from the installation itself. An essential step in the formulation of such arrangements is the prediction of the impact of a release over large distances and the research undertaken was directed towards these ends.

A suite of models has been developed which forms the key elements of a system that can be used, in real time, to predict the potential consequences of an actual or threatened release of radioactive material. The suite of models comprises three main components concerned, respectively, with the prediction of the dispersion in the atmosphere of released material, the transfer of material deposited on to the ground through the terrestrial environment to man and the estimation of the magnitude of the release from measurements of radioactive material in the environment.

Three models have been developed to predict atmospheric dispersion for use over different ranges of distance from the source of the release, in particular local to the source of the release (out to a few tens of km), over mesoscale distances (out to a few hundred km) and on a continental scale (out to several thousand km). The models differ in the complexity with which they treat dispersion processes. In each case they represent a compromise between making the most reliable estimates possible within the time available. Close to the release, predictions need to be made very quickly to enable a rapid response and the modelling approach must, in general, be much simpler than at greater distances. More complex meteorological phenomena need to be modelled if reliable predictions are to be made of dispersion over large distances; in such cases, however, much more time is available for the calculations before decisions need to be made on the introduction of countermeasures. The inclusion of separate models also provides the user with the flexibility of choosing the model or models most suited to his interests. Appropriate interfaces have been developed between the models.

As an accident progresses there is a continuing need to update the predictions of the dispersion models in light of any measurements made of radioactive material in the environment. Two models have been developed for this purpose and are applicable generally in one case and limited to short distances in the other. The performance of these models has been tested for a limited range of conditions by comparison with experimental data.

Decisions on the introduction of countermeasures are strongly influenced by the potential levels of dose predicted. A further model has, therefore, been developed to calculate exposure by each of the important exposure pathways (external irradiation from and inhalation of the plume, external irradiation from material deposited on the ground, and ingestion of contaminated food) based on measured concentrations of radioactive material in the environment or on the predicted levels in the atmosphere and deposited on the ground. Account is taken of people's habits in estimating doses and of the season of the year, and a variety of other agricultural factors such as these can have a profound influence on the magnitude of the potential dose from food consumption and, consequently, on the scale and extent of any food restrictions that may need to be imposed.

The research has been successful in the development of a suite of models that can form the basis of a computer system for use in aiding decisions on off-site emergency response in the event of an accident, irrespective of the distance from the release location. The models represent the state of the art of development in their respective areas and contain a number of improvements over what was previously available. A computer software package has been prepared containing each of the models. This package is being made generally available and will be of considerable assistance to those with an interest in this area. The benefits of this research will, however, only be fully realized when the models are incorporated into operational systems for use in off-site emergency management. This is an objective of the present Radiation Protection Programme which aims to develop a comprehensive and versatile decision support system within which these models will be incorporated.

B) Decision-aiding techniques

Decisions on the introduction of countermeasures are often complex in that they generally require a balance to be made between several competing objectives. International guidance has been developed to assist in this area but it is often generic in nature and needs to be supplemented before it can be applied effectively to particular situations. This is inevitable if optimum decisions on countermeasures are to be taken; there may, for example, be wide differences in the nature of and the circumstances in which an accident may occur, and also in the available resources for and the practicability of particular countermeasures. Emergency planning is, therefore, often based on specific quantitative guidance with an allowance for flexibility of response to accommodate the situation actually encountered.

The basic principles which underlie decisions on countermeasures are that their introduction should be of net benefit to those affected (ie, their introduction should do more good than harm) and, to the extent practicable, this benefit should be maximized. In order to satisfy these principles it is necessary to evaluate all the beneficial and detrimental consequences of introducing countermeasures. The main beneficial effect will be the radiation exposures averted whereas the detrimental effects may take several forms including cost, inconvenience and disruption of lifestyle, any additional risk associated with the countermeasure itself, anxiety, etc. The balancing of these and other disparate effects is further complicated by social considerations, in particular the question of equity given that the benefits and costs are not necessarily borne by the same people. The decision problem is thus complex but is a common feature of decision-making in the social sphere and a variety of formal decision-aiding techniques are available to assist in the resolution of such problems.

The merits of different decision aids have been investigated and, for the decision problem of interest, it was concluded that the technique of multi-attribute value or utility analysis had the greatest potential. Based on this technique a decision-aiding system, RADE-AID, has been developed which enables the user to compare and rank different countermeasures strategies taking into account both quantifiable factors and those of a more qualitative nature such as social and political considerations, subject to the assignment of relative weights by the decision-maker to the various factors. The user can interact directly with the system and explore the implications of assigning different weights or importance to the various factors which may influence the decision. The system is not, however, a replacement for the decision maker but rather a decision aid which enables a broad range of alternatives to be explored quickly and, more importantly, in a consistent, structured and transparent manner.

A prototype version of the system has been completed and has been made available to other institutes actively involved in research in this area. Within the current Programme the system is being further refined and developed for possible use as a formal aid in a re-appraisal of criteria for the introduction and later withdrawal of a variety of countermeasures (eg, relocation). The system also has considerable potential for application in real time off-site emergency response systems and its use in this context is being evaluated. A further important use is in training exercises for those responsible for making decisions in an actual emergency and this will be followed up in due course. Further benefits are also expected to ensue from this work once the system is further refined, in particular its application as a decision aid to a number of more complex radiological protection problems, for example, judgements on when accident risks have been reduced to as low as reasonably achievable.

IV. Monitoring and Surveillance in Accident Situations

Off-site monitoring and surveillance during and after an accidental release of radionuclides into the environment is required for several purposes:

(1) the detection of the accident to alert the authorities;

(2) early measurement to determine the need for appropriate countermeasures;

(3) continuing radiological measurements in the environment and of foodstuffs and persons to support countermeasures and enable doses to people to be assessed;

(4) research studies to improve input data for predictive models.

Although the necessary dosimetric instrumentation is available in principle, the experience gained after the Chernobyl reactor accident in the countries of the European Community suggested that there was a need for improvement with respect to the practical aspects of measurement and collection of reliable data. Communication of the data to the decision-making authorities and the public obviously was not always appropriate. The Commission therefore supported new studies aimed at improved preparedness for the monitoring and surveillance of any future accident.

The detection of accidental releases of radionuclides is mostly based on dose-rate measuring devices such as ionization chambers, scintillation detectors and Geiger-Müller counters. The basic problem to be solved for accident detection is the discrimination between the increase in dose rate, due to man-made radionuclides, and the increase in natural background levels. Using knowledge of the correlation between rainfall and increase of dose rate from natural radiation, and employing gamma-ray spectra measured with scintillation detectors, the threshold for raising an accident alarm has been decreased considerably. The established method permits the distinction between alarm and no-alarm situations to be made if the dose-rate level increases as little as 5% in dry weather or 20% in wet weather.

Early measurements have to include air sampling and analysis for identification of the radionuclides involved, and wet and dry deposition measurements in order to enable predictions to be made, using atmospheric and environmental models, of possible doses to people. Such predictions are necessary for instigating appropriate countermeasures.

The experience after the Chernobyl accident showed that the sophisticated, time-consuming measurements available at various institutes were not suited to the large number of field and laboratory measurements required. The investigation of the applicability and improvement of simpler instruments for rapid measurement was, therefore, a central topic for the research projects. In particular, various methods of measuring the surface deposition of radionuclides were studied using commercial gamma-ray dose-rate measurements, commercial surface contamination monitors and field ("on-site") gamma-ray spectrometry. Dose-rate measurements are easy to take but difficult to interpret and can be used as guidance for areas where further investigation is required. Surface contamination measurements appear to be very difficult to take in a consistent manner. In situ gamma-ray spectrometry provides the desired information but is relatively expensive and requires experienced operators.

If the accidentally released nuclides include nuclides which are not gamma-ray emitting, such as actinides or the radioisotopes of strontium, radiochemical analysis is required. Conventional analysis procedures require times which are often unacceptable in an emergency. The development and study of rapid methods of radionuclide analysis, therefore, were important research activities, and significant progress was made. For most materials, results can now be obtained within 15 hours for the strontium nuclides and, within 20 hours, a determination of plutonium can be made. The most important recommendation derived from this study is that detection limits should be specified in advance so that decisions on sample sizes can be taken. The time required for sample preparation is dependent on the sample size.

The direct measurement of radionuclides in people has been shown to be important for independent confirmation of dose predictions and as a means of reassurance. Mobile monitoring facilities using small vans, large trucks or specially designed railway carriages are available primarily for measuring iodine isotopes in the thyroid and gamma-ray emitting radionuclides in the human body. These facilities enable measurements to be taken on a large number of people in any contaminated area.

V. Underlying Data for Derived Emergency Reference Levels

After an accidental release of radioactive material into the atmosphere leading to significant off-site contamination, radiation exposure of the population can be reduced by means of various countermeasures such as sheltering, issuing of stable iodine tablets, restrictions on agricultural production, temporary evacuation, relocation of the population. Often, restrictions in the consumption of contaminated foodstuffs can be an appropriate countermeasure and this was extensively used after the accident.

Prior to the Chernobyl accident, the Commission had suggested a high and a low Emergency Reference Level for different countermeasures which were to be applied according to the specific situation: a higher level above which the countermeasure should generally be implemented and a lower level of exposure below which the countermeasure is unlikely to be justified. In order to allow a general application, the Commission, on the advice from the Article 31 Group of Experts, took only the lower Emergency Reference Level as the basis for deriving "maximum permitted levels of radioactive contamination of foodstuffs and feedingstuffs".

The Article 31 Group of Experts derived these values by elaborating a methodology based on several assumptions which were considered conservative. Nevertheless, the need was felt to verify these assumptions by checking and developing the underlying food chain and dosimetric models and by verifying information on food consumption habits.

The assumption that only 10% of food is contaminated at maximum levels was verified by compiling a huge data set on food consumption. All Member States except Portugal and Denmark were classified into 3 groups with fairly homogeneous diets. When comparing the consumption rates of the "average EC citizen" with those adopted by the Expert Group, the data for cereals, dairy products and meat agreed rather well, whereas some discrepancies were observed for vegetables and fruits. Food consumption was also evaluated for different subgroups of the population. As expected, diet varies markedly with age from the infant, the 1-year-old up to the 18-year-old, with only minor changes at later ages. Within a Member State, regional consumption of certain classes of food may vary from 70% to 130% of the national average. People in urban areas consume less contaminated food - 70% to 100% of the national average but have a significantly higher fruit consumption - whereas people in rural areas consume from 100% to 140% of the average. Where self-sufficiency in food production is high - this is particularly true in the southern part of the EC - local contamination may cause relatively high exposures. The assessment of food distribution in and outside the EC showed that, on average, 84% of food is provided by national production, 13% is obtained from intra-Community trade; non-EC countries contribute only 3%. Obviously, these values vary widely, dependent on the type of food; highly urbanized and industrialized regions obtain, in general, more food from outside the country.

Existing dynamic models for the transfer of radioactivity through the terrestrial food chain were improved and used for verifying the assumptions made for maximum permitted contamination levels. Two models of differing complexity were compared: FARMLAND (NRPB-UK) and ECOSYS (GSF-FRG). The simpler FARMLAND model is more suited to be used with default values whereas the more complex ECOSYS model is more appropriate for evaluating more site-specific situations. Using the "default food chain model" and dividing the EC territory into four regions taking into account the different climates and farming practices as well as possible deposition pattern from an accident, the level of contamination of major agricultural products was computed. Values for the dose-per-unit intake were also recalculated for the major radionuclides and for different age groups.

On this basis and using the food consumption patterns established, it was possible to calculate different illustrative patterns of individual doses from ingestion showing the possible variation of individual doses between Member States and to identify those foods that would contribute most to the dose. It appeared, that, in general, age has only a small influence on dose and that regional agricultural practices need not be taken into account, except for the Mediterranean countries; however, the season during which the release occurs greatly affects the exposure pattern, with lower values in winter compared to spring and summer.

Based on generally accepted radiation protection concepts and the ALARA principle (As Low As Reasonably Achievable) a methodology for deriving intervention levels for foodstuffs assuming several scenarios could be developed for which the efficiency of countermeasures (doses saved) was assessed. All this information is now being made available in a readily interpretable way to decision-makers. It is hoped that this will contribute to more transparent and better harmonized emergency management.

VI. Improvement of Practical Countermeasures against Nuclear Contamination in the Agricultural Environment

Following an accidental release of radioactive material, areas near the site of the accident might be contaminated to such an extent that they require major interventions to make them safe for human use and/or agricultural production. At intermediate or far distances from the accident, situations may exist where more simple measures allow contamination of the food produced to be reduced substantially or where radioactivity levels of such food can be diminished by processing. Research dealt with the various practical implementation and decision criteria for these different countermeasures.

In the first place, the countermeasures taken in past accidents which contaminated land had to be critically reviewed and carefully analyzed, unfortunately without having access to the Soviet data on the Chernobyl accident. Several alternative procedures are available and were investigated; in several cases, additional experiments were performed.

In a highly contaminated area, it may be necessary to **remove** the entire **vegetation cover** together with the upper soil. Sometimes, it might be possible to leave some permanent vegetation in place. These procedures, although quite effective, are obviously a last resort; they cannot be used for larger areas because of the costs and the long-term detriment to the environment, particularly when the entire vegetation is removed in a very seriously contaminated environment.

The contaminated **soil** may also be **placed** partially or fully **outside the reach of the plant roots**. This can be done by special devices which place the entire uppermost soil layer deep in the ground or, less efficiently, by conventional low or deep ploughing. These procedures, as in the above case, also diminish external exposure from the ground to persons in the area. Clearly, the more soil is disturbed, the more production will suffer, at least for some time. Nevertheless, these procedures are appropriate where contamination is not extreme. On the contrary, leaching the contamination down by applying large amounts of water would only rarely be a suitable procedure.

Various techniques which **change the behaviour of the radionuclides in the soil** have also been considered, such as adding fixatives which bind the radioactivity in the soil, or using special fertilisers to reduce plant uptake. Fertilisers can be applied easily but are not very effective and, in any case, require a careful consideration of soil characteristics and aspects of plant nutrition. Fixatives are quite effective if contamination is not too high and also avoid resuspension of radioactivity, but they are expensive, render the land useless for some time and adversely affect the environment.

Changing crops to types or varieties less likely to take up caesium can be quite an efficient measure as shown by experiments, but additional research is required. **Food processing** has been investigated mainly with respect to dairy products. Investigations have shown that substantial reductions of radioactivity can be achieved in preparing butter or cheese from the milk.

Nearly all countermeasures, and in particular those in the agricultural context, have disadvantages as well as advantages. As to the disadvantages, it is not only monetary costs, which indeed can be substantial, but primarily the long-term impact on the environment and the question of what to do with the generated waste. The latter problem requires careful analysis for each individual situation.

The Radiation Protection Programme continues to give much attention to the problem of countermeasures in the agricultural environment and supports multinational contracts dealing with the rehabilitation of soils and surfaces after an accident (RESSAC) and the transfer of accidentally released radionuclides in agricultural systems (TARRAS); it also considers the problem of generated waste on a European scale.

VII. Improvement of Practical Countermeasures against Nuclear Contamination in the Urban Environment

The caesium isotopes (^{134}Cs and ^{137}Cs) represent the most important risk to the population of a contaminated urban area following an accidental release. Many urban surfaces readily intercept and retain radiocaesium fallout since caesium is expected to undergo ion exchange with other sorbed cations. Surprising, however, the absorbed caesium is retained tenaciously at these surfaces even under relatively harsh decontamination treatments with chemicals. Research carried out defined the different types of surfaces encountered in urban areas, investigated the mechanisms responsible for the "anomaly" that caesium is so strongly and specifically sorbed to roofs, pavements, walls and soils, studied by empirical test different decontamination procedures, and developed a more general strategy to the problem of urban contamination.

An **inventory of exposed materials** was needed to assess the risks of contamination in the urban environment. A case study in the United Kingdom developed a methodology to establish inventories of urban surfaces based on statistical data for manufacture and use of construction materials and on historical growth maps. This methodology can now be applied by national authorities of Member States.

When caesium is deposited on urban surfaces, it migrates, in part, into the pores of the material before being bound. This migration process is rapid especially when the surface has been dry, and the deposition occurs with rain: a porous brick or tile completely fills with rainwater in about 17 minutes. In order to determine the rate by which caesium is then bound to surfaces, rapid methods using a number of ion selective electrodes, including one specific for caesium, and a fully automatic computer controlled procedure were developed to cope with the large numbers of samples.

The vast majority of sites binding caesium hold on to it only weakly. However, about 1% of sites found on virtually all building materials and also in soil can bind caesium strongly and in an almost irreversible manner. This was demonstrated by new "masking" techniques. The chemical amounts of caesium in deposited radioactive material are very small and can all be bound to those strong sites. This explains why decontamination procedures using dilute solutions of chemical reagents such as ammonium nitrate are not very effective and do not remove more than 20-30% of deposited caesium. Indeed, penetration of the decontaminant and removal of caesium, where it occurs, is a slow process requiring more than a day for a 1 cm thick tile.

Physical methods for decontamination such as domestic cleaning equipment, street cleaning equipment, agricultural and road maintenance machinery, high pressure water jets and sand-blasting methods can prove effective as countermeasures. Real scale decontamination experiments showed that street sweeping with brooms and vacuum cleaning of a road with a dust loading of 200 g m^{-2} could remove 90% of the deposited caesium. Sweeping and vacuum cleaning following wet deposition only removed 11% from an asphaltic cover, but 50-60% from a concrete road. Decontamination of a tiled roof in Gävle (Sweden) using high pressure water jets two years after the contamination removed an unexpectedly large amount (55%) of the radiocaesium but this was due to the fact that caesium was attached to an organic layer of mosses and lichens which could be detached readily.

These laboratory and field studies indicate that chemical decontamination will be ineffective and that caesium sorption will be largely irreversible. Physical methods, through the removal of street dust, mosses and lichens, or physical abrasion techniques through the removal of a tiny top layer of material would, however, be useful. Moreover, areas likely to be contaminated such as roofs or a road might be pretreated with a dilute solution of readily available surface-active substances. This prevents, for some days, diffusion of caesium into the pores and can reduce caesium retention by about 80%.

To follow up this research, one should now move towards the further development of an integrated strategy for countermeasures in a contaminated urban environment. The scientific bases have been laid down in the present study, but the application will require that the information be incorporated into an easily manageable computer code or expert system to serve as a guide for decision makers.

VIII. Improvement of Practical Countermeasures: Preventive Medication

Radioactive iodine isotopes of short half-life, in particular ^{131}I, represent a major constituent of radioactive releases; they may be taken into the body by inhalation during the passage of the radioactive cloud or enter the food chain, particularly via the pasture-cow-milk pathway. Radioiodine taken up in the human body accumulates preferentially in the thyroid gland and can increase the risk of thyroid cancer. Because of its short half-life (about 8 days for ^{131}I), radioactive iodine is only critical during the first weeks after a release.

The risk from radioactive iodine can be reduced by impeding inhalation during the passage of the radioactive cloud (e.g. by wearing face masks), by reducing or delaying the transfer through the food chain or by inhibiting uptake into the thyroid gland by means of treatment with stable iodine. The last procedure, based on the fact that large doses of stable iodine block the uptake of the radioactive iodine, has received much attention. Indeed it is quite effective but not entirely without risk, since large iodine intakes can seriously affect thyroid metabolism, particulary in very young, old or sick persons or in people who normally receive little iodine in their diet. In a given situation and for a given population, one must therefore balance these two risks against each other in order to decide whether it is appropriate to distribute iodine tablets. The research carried out investigated both these risks, especially with respect to pregnant women and infants, and explored decision criteria and treatment protocols.

The **risks from radioactive iodine** have been investigated in the past mainly at relatively high doses and high dose rates. One study suggested, however, that the risk per unit dose of relatively small doses of ^{131}I, such as would occur after a nuclear accident, would be smaller. To verify this, an epidemiological study was initiated in which patients who had received a single or repeated administration of ^{131}I for thyroid diagnosis were compared. The study will be completed in the near future.

The **uptake of radioiodine** into the thyroid gland and therefore the risk depends on the dietary intake of iodine; where the latter is low, uptake and risks can be 3-4 times larger. Data on iodine uptake in different regions of the Community were obtained from routine thyroid diagnosis in nuclear medicine; iodine excretion which reflects dietary iodine intake was also studied. Both ^{131}I uptake and stable iodine excretion were found to vary widely even in the same region. With regard to age, a study of the uptake of radioiodine by foeti and infants of chimpanzees showed that the dose to the foetal thyroid may be substantially (as much as 30 times) larger than for adults.

The risk from treatment with stable iodine also depends on dietary intake; it is higher where this intake is low, and is also higher in the sick and the elderly. In

Germany, about half of the cases of hyperthyroidism (Basedow's disease) observed are due to a medical treatment with iodine. On the other hand, the foetal thyroid can tolerate small amounts of iodine without causing a depression of thyroid function.

From these investigations the following conclusions were drawn: normalizing dietary iodine intake by a generalized addition of small amounts of iodine to the diet would be a most efficient way for reducing the amount of radioiodine taken up by the thyroid after a nuclear accident. This procedure would also provide an efficient prophylaxis against several thyroid diseases. Unfortunately, such prophylaxis meets legal and acceptability problems.

After a nuclear accident, stable iodine as a prophylaxis should be administered to pregnant women, neonates, infants and children up to 16 years of age. However, care must be taken to ensure that iodine doses to pregnant women are kept low so that no hypothyroidism is induced in the foetus. Unless expected doses are very large, i.e. in the near field of an accident, administration of stable iodine to people older than 16 years will be of no benefit and will be useless when more than 6 hours have passed since the intake of radioiodine. No prophylaxis should usually be given to people older than 45 years because this medication may present a larger risk, particularly in persons with cardiac or thyroid diseases. It must be admitted, however, that, in an emergency, public anxiety and practical considerations may make it difficult to insist on these criteria.

IX. Diagnosis and Care of Radiation Accident Victims

During the first hours and/or days following the Chernobyl accident, several hundreds of persons, particularly those involved in salvage operations, were exposed to radiation from the burning reactor and its radioactive releases. Many of the victims also suffered thermal burns and/or inhaled radioactive material. In most of these cases, the radiation dose received by these individuals and its distribution over the body is unknown.

When large parts of the body are exposed, failure of the bone marrow to replace the different functional cells in the blood and deficiency of the immune system cause the principal symptoms of radiation disease which, when severe, can result in death. The choice among the various treatment possibilities is governed by the degree of damage and, if based on poor diagnosis, can do more harm than good, for example an inappropriate transplantation of bone marrow. In such a situation, an assessment of the biological damage is the most urgent task, and, as many of these accidental exposures are inhomogeneous and some bone marrow is spared, physical dose measurements are rarely reliable. Indeed, the haemopoietic functions may recover if only about 1 from 100,000 bone marrow cells survive.

Therefore, research has aimed to improve the methods to establish the risk of the individual patient to develop a fatal radiation syndrome. A careful analysis of 300 cases from past radiation accidents enables a decision-aiding system to be developed based on the behaviour of peripheral blood cell counts, the severity and rate of development of clinical sickness and genetic markers for radiation damage. Methods based on genetic damage in circulating cells can help to evaluate biological damage after an accident; these have been improved by introducing more efficient and rapid tests and by providing procedures to assess the degree of inhomogeneity of an exposure. An original approach to determine the number of surviving haemopoietic stem cells was based on studying the response to the new haemopoietic growth factors in cell cultures and in vivo. Progress was made in all these areas, but the problems involved have not yet all been resolved.

New approaches for treatment have also made use of the haemopoietic growth factors which are now becoming available due to modern biotechnological methods. Studies in vitro and on monkeys demonstrated that such a treatment has no adverse effects and stimulates progenitor cells from all the different cell lines in the bone marrow. Treatment with haemopoietic growth factors GM-CSF and Interleukin-3 soon after an exposure might now be recommended in all patients who are expected to develop pancytopenia and should shorten the pancytopenic period and reduce the associated risks in patients who will eventually recover spontaneously. On the other hand, it would now seem that only very few patients could profit from bone marrow transplantation under such circumstances because in many accident cases some marrow is often spared because of the inhomogeneous distribution of the dose over the body.

The diagnosis and treatment of radiation accident victims requires special facilities and experience which is only available in a few hospitals and institutes in the Community. They must co-operate closely to create a network of "stand-by" medical and laboratory facilities to be used in cases of accidents which will constitute an expert system available to all. Moreover, training is needed to provide authorities, medical doctors and nurses with the special knowledge needed to handle such situations. This is now being implemented in the Community Radiation Protection Research Programme.

X. Studies on Health Effects due to the Reactor Accident at Chernobyl

Many people have worried about possible consequences of the accident to the health of the population and particularly of children in the European Community. The Commission has, therefore, asked a group of three independent laboratories to investigate whether any consequences might be expected, and, if they occurred, whether they might be detectable by an epidemiological investigation. The conclusions of this feasibility study were then considered, and were appropriately modified, by a Panel of high level epidemiologists from the Community, the United States and Japan, and the resulting joint report has been published in document EUR 12551.

The Panel evaluated the available data on the exposure pattern and the dose levels in the Community due to the radioactive releases from the Chernobyl reactor accident. It then considered the different health effects that might be induced by such doses based on the most recent assessment of radiation risks and, finally, it estimated whether epidemiological studies in the Community could provide sound information.

Doses to populations of Member States due to the Chernobyl accident varied from 0.05 mSv to 0.9 mSv in the first year after the accident, with an additional total exposure in all following years not exceeding that in the first year. Averaged over the population, such exposure levels are less than the normal background radiation levels that result in annual doses of the order of 2 mSv.

Possible consequences of radiation exposure could be short-term effects, including developmental effects induced in the foetus or embryo, occurring within a few weeks and long-term effects, i.e. cancer and possibly heritable genetic effects that become demonstrable years after exposure, or in future generations.

Recent information on radiation risks has been reliably obtained from the survivors of the atomic bomb explosions and a variety of other exposed populations. Most short-term effects require substantially elevated doses of radiation, i.e. of the order of grays, and are therefore not expected in the situation discussed here. Some developmental effects, expressed as congenital malformations, could conceivably be induced by doses less than 1 gray, but the low probability of such effects being induced, given the post-Chernobyl exposure situation, and their high spontaneous rate of occurrence precludes their being detected in any of the exposed populations in the European Community. Although it is thought that cancer might be caused with a small probability even by low doses of radiation, the high spontaneous incidence of cancer and its considerable variability will make it impossible to detect increases which, in adults, would be well below 1‰ of the normal cancer incidence. The same arguments also apply to the occurrence of heritable genetic effects in the offspring of those exposed.

The most sensitive radiation effect is probably the induction of childhood cancer and, as this is a rare disease which appears within a few years after birth, it would be most amenable to study. Good childhood cancer registries exist in many countries, and it was suggested that a study could try to correlate the cancer incidence with the time of the accident and the place of residence of the mother during pregnancy.

Nevertheless, the estimated foetal doses resulting from the Chernobyl accident are so low that, on the basis of present risk estimates for childhood cancer, it is unlikely that any attributable increase in risk could be demonstrated. Moreover, the complexities introduced by the need to allow for the higher doses experienced from natural background radiation or medical X-rays would conceivably mask any possible effect or produce spurious results. However, there is clear public concern about childhood cancer from radiation, and it might be possible to detect an effect in a carefully controlled study if our risk estimates were too low by a factor of about five. Therefore, the Panel recommends that a small epidemiological survey of childhood cancer be conducted within areas where selected cancer registration was in existence at the time of the Chernobyl accident. Such a study, supported by the Radiation Protection Programme, is currently being carried out by the International Agency for Research on Cancer (part of the World Health Organization).

I. Evaluation of Data on the Transfer of Radionuclides in the Food Chain

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2. Introduction

The radiological consequences of radionuclides discharged from nuclear installations are usually evaluated using dose assessment models. In these models the passage from one compartment into another, e.g. the transfer from soil into plants, from plants into milk or meat is defined by transfer factors which are influenced by various parameters. From the long-term viewpoint only the long-lived nuclides like $^{134/137}Cs$ are important for long-term radiation risk assessment after the Chernobyl accident. With respect to assessment of the radiation risk due to soil-to-plant transfer of radionuclides originating from the Chernobyl accident into the food chain, it turned out that several transfer parameters were insufficiently or not considered in the calculation models used leading to uncertainties in prediction. Before the Chernobyl accident occurred, research was mainly concentrated on agricultural food production, but there was still a lack of knowledge of local, specific conditions. Transfer factors for the pathway soil-fodder-animal products are poorly defined, especially for the different ruminants given various types of feed and submitted to various feeding practices. Little attention was given to semi-natural and natural ecosystems, which were used extensively. But there was a number of pathways leading directly to man primarily via food products derived from forests, meat, dairy products and possibly water supplies. These areas mainly have poor soil quality which results in a higher soil-to-plant transfer. Even for the aquatic pathways of radionuclides it is necessary to have predictive models in the case of an event like the Chernobyl accident. To improve radiation dose prediction the CEC has initiated the Post-Chernobyl Radiation Protection Programme "Evaluation of Data on the Transfer of Radionuclides in the Food chain" including four main items to be studied by different laboratories:

- Impact of chemical speciation on the radionuclide transfer in terrestrial ecosystems after a core disruptive accident, especially in soils and plants (CEA),
- Soil-to-plant transfer factors in semi-natural (ITE, ENEA/DISP) and agricultural ecosystems (RIVM, KFA, ENEA/DISP)
- Plant-to-animal transfer factors in semi-natural and agricultural ecosystems (CEN, ITE, MacAuly, NRPB, ENEA),
- Transfer in aquatic systems and their importance for the contamination of the food chain (IFE, LNETI, MAFF, ENEA).

3. Impact of Chemical Speciation on Radionuclide Transfer

Following the Chernobyl accident and the fallout observed in Europe, a pertinent question was whether the radioactive substances released under very special conditions were present in the physicochemical forms in which they are generally observed. If the forms were different, to what extent did this affect their migration in the soil and in the food chains? Would existing transfer models have to be revised? The work carried out included three phases:

- a bibliographical review of the current state of the art in this area,
- experimental investigations to determine the form of the fallout detected in soil and sediment samples taken from southern France, in order to assess any modifications in the transfer factors,
- laboratory simulations of a reactor core meltdown accident to reproduce a "source term" that can later be used in experimental contamination tests under controlled laboratory conditions.

Fallout in south-eastern France was abundant enough after the Chernobyl accident to perform laboratory analyses. Rainwater runoff in mountainous regions and accumulation in the lower parts of lakes or granular snowfields (névés) resulted in significant radioactivity levels in some soil samples.

Soil and sediment samples were taken in a small (2.6 km^2) valley in the "département administratif des Alpes Maritimes" at altitudes ranging from 1500 to 2600m.

When the samples were taken in the autumn of 1987, only ^{137}Cs, ^{134}Cs, and occasionally ^{106}Ru, were detectable. The behaviour of caesium in fallout from Chernobyl was compared with caesium introduced in known chemical form as CsCl. Water samples were taken for in situ speciation of chemical forms.

Caesium in the fallout from atmospheric weapons tests or the nuclear industry is always found with the cation resins (i.e. in cation form). Part of the caesium collected in these samples was associated with the anion resins, however. Despite the verifications performed, this result must be considered with caution, although it is consistent with the hypothesis that part of the caesium released from Chernobyl was associated with colloids that generally carry a negative charge. Ruthenium was systematically found in the anion resins, as expected.

a) Characterisation by Successive Extractions

The procedure consists of subjecting a soil or sediment to increasingly powerful reagents in order to separate out the following fractions:

- water-soluble compounds in the soil solution (water),
- cation forms from the adsorbent complexing agent, fixed on clay or organic matter (ammonium acetate),
- chelated cations fixed on clay or organic matter (copper acetate),
- forms bound to humic and fulvic acids (sodium pyrophosphate and sodium hydroxide mixture),

- the non-extracted forms corresponding to humine.

All of these operations did not reveal any difference in caesium behaviour between the fallout and the CsCl additive. In each case, caesium was strongly bound to the soil or sediment particles: the non-extracted fractions represented 95% of the soil and 78-79% of the sediment samples.

b) Investigation of Transfer Factors

Radishes were grown in soil pans, half of which contained unmodified soil samples, and the other half soil to which ^{137}Cs was added as CsCl. The transfer factors were found to be roughly three times lower for caesium from Chernobyl fallout (0.017) than for the caesium additive (0.047). This confirms the findings for filtered rainwater after the accident.

Investigations using natural samples were limited by the small quantities of radionuclides present in the environment, and by radioactive decay of most of these nuclides. Attention was therefore given to reproducing an accident source term in the laboratory. Two types of device were used:

- The POLYR mock-up at the Cadarache Nuclear Research Centre an induction furnace capable of reaching temperatures of the order of 2800°C,
- A modified atomic absorption atomizer at the Catholic University of Leuven: the maximum temperatures are similar to those obtained in POLYR, but the aerosols are released directly into a room-temperature contamination vessel.

Both experimental facilities were charged with representative core mixtures, comprising 16 elements including fuel, control rod materials, stainless steel components and fission products. Two different mixtures were tested, one containing 60% UO_2 and the other only 6%. Similar results were obtained in both facilities.

- Granulometry gave a the median diameters ranging from 0.7 to 1.6 μm depending on the test conditions and corresponded to the calculated values.
- Particle morphology was fully comparable to the results obtained with fallout from the Chernobyl accident. The aerosols were very heterogeneous, and the surface was covered with roughly spherical nodules generally smoother than the nucleus. No structural information on the small particles was obtained even under high magnification, except that they resembled the protuberances.
- Overall chemical composition: the particles generally showed a silver-indium facies, with deficiencies for certain elements including uranium, zirconium and ruthenium. Iodine was not

found in the particles in appreciable quantities: this highly volatile element was probably released in the early stages of the heating cycle, primarily in the form of gaseous iodine. The compositions generally agreed with the predicted results.

- Some crystallised chemical forms were identified:
  - caesium was found as caesium iodide and caesium hydroxide, both of which are soluble,
  - ruthenium was observed in pure metallic (insoluble) form, as after the Chernobyl accident,
  - strontium was also found in metallic form. Other forms were also found, but are of lesser interest,
- Particle water solubility was also investigated. This factor determines the biological availability and plant uptake capacity of the radioactive pollutants. Among the principal fission products in this study, caesium solubility varied from 69 to 99% depending on the initial composition; strontium solubility ranged from 0 to 45%, and ruthenium was totally insoluble. These findings are consistent with the chemical forms identified.

c) Conclusions

A bibliographical review indicated that nuclides were probably released in the form of aerosols with a median aerodynamic diameter of about 1 μm. The principal chemical forms of the radionuclides of interest to radioecology had been defined, but considerable uncertainties remained.

An investigation of fall out from Chernobyl still present in some natural samples confirmed the particle nature of the contamination. Although theoretical studies had predicted that caesium would be found in soluble form, a fraction of the caesium was probably associated with colloids: this should diminish soil-plant transfers by a factor of nearly three, as confirmed by experimental findings.

Laboratory aerosol generation experiments provided a satisfactory simulation of the accident source term. The mean grain size was found to be about 1 μm. Most often, the particles showed a compact nucleus surrounded by smaller protuberances easily eliminated by rinsing in water.

The solubility of fission products with radioecological impact appeared similar to the solubility generally observed for the elements involved, and depended on their chemical properties. When caesium is generated from uranium-rich mixtures it is moderately soluble, as observed in fallout from the Chernobyl accident; when the initial mixture contains little uranium, however, caesium is almost totally soluble.

Short-term transfer factors to plants following an accident were found to be lower than those based on standard commercial sources because of the lower solubility values.

4. Soil-Plant Transfer

a) Semi-natural and natural ecosystems

A wide range of natural ecosystems has been contaminated by fall out from the Chernobyl accident. The association of caesium deposition with high rainfall means that the areas affected by the fall out are often those in countries which experience Arctic, Boreal and Atlantic climates. This high correlation between rainfall and deposition also means that much of the material has been deposited in upland areas where agriculture is of a marginal nature or natural plant communities dominate. Pathways back to man from the natural and semi-natural systems vary both in type and importance. The main pathway is by way of animals via meat and dairy products. Direct use of the ecosystem only occurs when native fruits are collected. Important pathways in some countries can be by way of wild fungi which are collected in large quantities for food and flavouring.

Two approaches have been used to investigate the behaviour of radionuclides in natural and semi-natural ecosystems. The first has been to use three study areas within Europe where heavy contamination has occurred and the second to intensively study the individual species from a number of sites within one contaminated study area. The three European areas used for studies were in north-eastern Italy (Friuli-Venezia Giulia region), Norway (Jotunheim reserve) and Scotland (Loch Laggan, Highland region). The detailed contaminated study was carried out in Cumbria, England, where within a few tens of kilometres of each other eleven sites were sampled intensively for individual plant species. The approach at the European sites has been to sample both the soils and vegetation from at least three ecosystems and at the Cumbrian sites to concentrate on the variation within individual species. The results showed that soil-plant transfer factors are highest for the bryophytes and lichens. This is to be expected in view of their mode of nutrition, although these values are not truly comparable with those of the higher plants. Nevertheless, these species can be a significant component of many of the vegetation types studied and the part they play in holding radionuclides in the upper parts of the system is important. Transfers to both bulk vegetation samples and individual species are larger for ^{134}Cs than ^{137}Cs. This indicates a greater availability of the Chernobyl derived caesium and the existence within the soil caesium pool of a less plant-available pre-Chernobyl component. With a few exceptions the ericaceous shrubs such as Vaccinium myrtillus and Calluna vulgaris gave the highest transfer factors. In the northern European and the more intensive Cumbrian sampling, the higher plant activities have been found in association with the damp, organic soils with lower activities associated with the drier mineral soils. The calcareous soils at the Italian sites are very different in character to the mineral soils in the northern European sites, and caesium remains highly mobile in them. Caesium behaviour in the Italian podsols, even though they have developed over calcareous rock, is similar to that in the northern European ones.

The natural and semi-natural ecosystems studied there are important pathways back to man. Radiocaesium uptake by vegetation is variable and, within a site, depends on the individual species concerned. In some of the soil profiles, notably the podzol, Chernobyl-derived material is held much further up the profile than that from weapons fallout and is thus more likely to be found in the rooting zone. Activity of ^{137}Cs tends to be more enhanced in the clay-sized fractions and this may well reflect the ageing of weapons fall out. There appears to be no one dominant physico-chemical process in these natural and semi-natural ecosystems but it is possible that the soil biology has a strong influence on caesium mobility.

b) Agricultural Ecosystems

The main aim of this study was to examine whether soil-to-plant transfer of caesium originating from Chernobyl is indeed higher than the transfer of caesium from other contamination sources in agricultural ecosystems. A comparison of transfer of caesium originating from Chernobyl with transfer of caesium from other contamination sources should be based on many measurements because the variability in soil-to-plant transfer factors (TFSP) is usually large. Furthermore, in such a comparison differences in environmental conditions between the locations where uptake of caesium was measured should be taken into consideration because these conditions influence the transfer. Therefore, a second aim of the study is to quantify influences of environmental parameters on TFSP of caesium. Apart from statistical studies, post-Chernobyl TFSP in agricultural ecosystems were estimated in Germany and Italy.

The choice of the method to evaluate a large amount of TFSP depends on the aim of the study, the nature of the data and the way they have been sampled. The aim of this study is to compare Chernobyl and non-Chernobyl transfer data and to quantify environmental influences relevant for this comparison. For the evaluation of environmental influences on TFSP by use of the IUR data file a special procedure, called the "relative comparison method", has been developed. The relative comparison method may be used to analyse data files in which (1) data are clustered according to groups of parameters and (2) interactions between parameters are expected and insufficient information is available to determine the effects of these interactions. Results of the statistical studies show that the soil-to-plant transfer factor of Cs originating from Chernobyl was about a factor of 2 lower than the transfer factor for Cs from other contamination sources under comparable conditions. Three main factors (time lag, soil organic matter and translocation from older plant parts) may explain the difference between the observed and expected transfer of Cs:

- Cs becomes less available in the course of time. After 5 to 10 years the availability has decreased by about a factor of 10. Direct comparison, without correction for time lag, of Chernobyl data values with measurements on transfer of nuclear weapons fallout may thus overestimate the transfer by up to about a factor of 10.
- Part of the Chernobyl data refers to upland soils in north and north-western Europe. The greater part of these soils is characterized by a high soil organic matter content, extremely low pH values, a low clay mineral content and a poor nutrient status, usually under a humid, cool climate. Transfer on soils with high organic matter contents was shown to be about ten times larger than on soils with less than 10% organic matter. In fact, processes related to a high organic matter content of the soil may cause an increased transfer of Cs. Under the prevailing climatological conditions microbial decomposition of soil organic matter can lead to the formation of NH^4 ions which prevent Cs ions from adsorption on the solid phase.
- High transfer factor values measured in spring and summer after the Chernobyl accident may partly refer to direct uptake by above ground plant parts instead of uptake by the roots from the soil, even when the harvested plant parts grew after the deposition. Translocation from

plant parts (roots, stolons, etc) present during deposition to parts which developed after deposition may be the cause of unexpectedly high Cs contents in the harvest. Effects of region and season can be traced back to differences in soil type, variation in crops, differences in agricultural practices and above all varying weather conditions (temperature, rain fall). Dutch observations collected over a period of 4 to 7 years show that climatological factors cause fluctuations in transfer dependent on season of a maximal factor of 10, depending on the type of crop. Increases in transfer seem to correspond with decreases in rain fall or temperature. The transfer factor of Cs isotopes on sandy soils appears 3 to 5 times higher than on loam and clay respectively. Furthermore, transfer increases with increasing soil organic matter content. The impact of pH in the range pH 4.5 to 7.5 on soil-plant transfer is negligible. Experimental factors were also found to have an impact on the transfer of Cs. In lysimeters, transfer appeared to be roughly 3 to 4 times lower than in the field, which might be caused by differences in soil and crop management as well as in the way soil was contaminated.

The impact of the above-mentioned factors suggests that these factors must have caused regional and seasonal differences in the transfer of Cs originating from Chernobyl.

The investigations were carried out in a high contaminated region in south-west Germany (Upper Swabia). Three soil types could be distinguished. On the bottom land of the river Iller alluvial soils were found (Allochthone Kalkvega, calcaric Fluvisol). On the lower terrace soils were described as brown soils (Braunerde, Cambisol). The third soil type developed on a terminal moraine and was called degraded brown soil with a perched water table (Parabraunerde-Pseudogley, Luvisol-Planosol). The variations of TFSP within the group of Cambisols and Fluvisols were very small. Only in the group of soils with a perched water table (Pseudogley) were variations higher. This might be explained by local differences in the water regime of that soil type. In contrast to brown soils and alluvial soils, soils with a perched water table have many more differences in topography in that region. Therefore, water regime is changing drastically in small distances as well as other soil parameters. The medium TFSP of Cambisol (0.0014) and Fluvisol (0.00069) can be distinguished from the medium TFSP of the soil with a perched water table (0.0067), which is significantly higher. Differences in TFSP of Cambisol and Fluvisol are not significant.

Field Studies in the Northeast of Italy to determine TFSP in the agricultural environment of the highly contaminated area of the Friuli-Venezia Giulia plain started in May 1986 and required a preliminary stage to determine:

- the ^{137}Cs soil deposition in the Friuli-Venezia Giulia region;

- the principal parameters necessary to characterize the complex agricultural environment (physical and chemical parameters of soils, agricultural practices, etc).

Transfer factors for ^{137}Cs from soil to forage crops have been evaluated from data collected in 1986 and 1987. Sampling stations have been selected on the basis of a regional soil study and ^{137}Cs Chernobyl depositions. ^{137}Cs transfer factors from 1987 data have been evaluated in soils collected up to 10 cm of depth because all sampling stations were unploughed after Chernobyl and therefore most of the ^{137}Cs contamination has remained in the superficial layers. Soil to forage crops transfer factors from 1986 data are generally higher than those from 1987 data. This behaviour could be due to translocation from roots, stolons, etc to leaves, and of ^{137}Cs previously translocated during the deposition period, from leaves to other parts of plants. The 1987 data show that the lowest ^{137}Cs transfer factors from soil to forage crops have been found in soils with a content >40% of particles with size greater than 2 mm. In medium clayey, clayey and medium silty soils the transfer factor values are similar. This behaviour could be due to the highest mean values of extractable phosphorus and potassium in the CML class and to the deeper root system of forage crops in the presence of coarse soils and gravel.

h) Conclusions

Statistical evaluations show that soil-to-plant transfer factors of Cs originating from Chernobyl were about two times lower than the transfer factors for Cs from other contamination sources due to the three main effects "time lag", "soil organic matter" and "translocation". Effects of region and season could be traced back to differences in soil type, variation in crops, differences in agricultural practices and varying weather conditions. Field studies in south Germany were carried out to determine post-Chernobyl TFSP for radiocaesium on three different soil types. The mean TFSP for cereals on Cambisol were found to be 0.0014, on Fluvisol 0.00069 and on Planosol 0.0067. Determination of TFSP in north-east Italy showed that lowest TFSP were found on soils with a content of more than 40% of particles with a size greater than 2 mm, which could be due to the highest mean values of extractable potassium in these soils and to the deeper root system of forage crops in the presence of coarse soils and gravel.

5. Plant-Animal Transfer

a) Semi-natural ecosystems

The Chernobyl accident occurred at a time of the year when few animal-based food products were being taken from semi-natural ecosystems in western Europe. These semi-natural ecosystems often occur in upland regions. Consequently the high correlation between rainfall and the deposition of Chernobyl fallout over Europe meant that they received high levels of radioactivity. Animals grazing on semi-natural ecosystems are the most common, direct route by which radioactive contamination in these areas reaches the human food chain. Although there is some cropping of species such as wildfowl, hare and rabbit, and products such as honey, ruminants form the most important pathway to man. Some ruminants, such as moose and deer are hunted. Other species which are more actively managed (e.g. hill sheep and cattle or reindeer) are allowed to graze freely for some part of the year and are collected at intervals for culling, etc. Some mountainous areas are only commercially grazed in the summer months, for instance by dairy cattle, goats and sheep in Alpine areas, Greece and Scandinavia. Semi-natural ecosystems provide a wide variety of habitats for ruminants. Different ruminants may occupy different ecological niches in the same ecosystem. This natural diversity makes comparative studies of the transfer of radiocaesium more complex than in agriculturally managed systems. Since the Chernobyl accident there have been many studies of the transfer of radiocaesium to ruminants in semi-natural ecosystems. Some conclusions drawn from the work in the 1960s and 70s in Scandinavia, the USA and the USSR could be applied to semi-natural ecosystems after the Chernobyl accident. However, the data were ultimately of limited use in continental Europe, particularly with respect to the dominant vegetation species, climate, soil types, animals and management practices. Since semi-natural ecosystems often receive higher than average precipitation they are more likely to receive high levels of deposition following a nuclear incident. Hence comparatively high activities of radiocaesium will be deposited into systems with ecological characteristics which promote high radiocaesium levels in grazing animals. Therefore animals in a semi-natural ecosystem will often be a potentially important source of radiocaesium following a nuclear incident. The deposition of fall out from weapons testing has occurred over many years and plant uptake of radiocaesium was thought to be relatively unimportant. In contrast, fallout from the Chernobyl accident was deposited over a few days, largely as a consequence of the coincidence of rainfall with the contaminated cloud. The importance of the link between soils which allow high radiocaesium uptake by vegetation and high radiocaesium concentrations in ruminants from semi-natural ecosystems has therefore been more evident since the Chernobyl accident. It is evident that there was sufficient knowledge before the Chernobyl accident to enable us to predict that semi-natural ecosystems would experience problems of high radiocaesium activities in grazing animals following deposition from a nuclear accident. However, the existing data were probably not adequate to predict the magnitude of the resulting problem or its longevity. There has been an improvement in transfer data describing the uptake of radiocaesium into ruminants since the Chernobyl accident. It is now generally accepted that the transfer coefficient for sheep is higher than the previously accepted value. Although there are further indications that comparatively high transfer occurs in other, generally small, ruminants, including the smaller species of deer, the data are limited and further studies are needed in controlled laboratory conditions. Given the lack of good transfer data for ruminants in semi-natural ecosystems prior to and since the Chernobyl accident, it is difficult to compare the transfer of pre-Chernobyl radiocaesium with that from the Chernobyl accident in these ecosystems. However, it seems that the availability of Chernobyl radiocaesium increased from soon after deposition, when some of it would have been present as a surface deposit, compared with when it was incorporated into plant tissue. Once this had occurred there is no evidence to suggest that it was absorbed to any greater or lesser extent than pre-Chernobyl radiocaesium,mainly because data prior to 1986 is too sparse to allow an adequate comparison. There are obvious difficulties in determining a parameter such as the transfer coefficient for animals in semi-natural ecosystems. Even for studies of domesticated animals a great deal of time, effort and money has to be devoted to overcome the difficulties listed above. For some wild ruminants such studies are impossible. Indeed it is questionable whether transfer coefficients are of much value in these situations. It is suggested that for comparative studies of these sorts of ecosystems it may be more useful to determine aggregated transfer parameters where the activity concentration in an animal tissue (Bq kg^{-1} fresh weight) is compared to that in the soil (either Bq m^{-2} or Bq kg^{-1} dry weight). This would overcome many of the uncertainties of estimating radionuclide intake. However, it must be recognised that these would be highly ecosystem-specific and that their applicability in predictive models may be limited. In agricultural systems it has long been recognized that the time of deposition will have a profound influence on the contamination levels of foodstuffs. This would also be true of semi-natural ecosystems. If deposition occurs in winter, immediate doses may be reduced if domesticated ruminants have already been removed to winter grazing. The presence of snow may also influence the distribution of fallout causing amplified levels in areas in which it accumulates and decreased deposition in sites exposed to the wind. In the summer, semi-natural ecosystems may be used for dairy animals, particularly in Alpine areas, hence potential doses from milk products would be enhanced. There is an obvious influence of the time of deposition with regard to the hunting season. There are considerable financial implications for governments in trying to limit radiocaesium dose to populations via this route. For instance, since the Chernobyl accident many million ECUs have been spent in compensating farmers and on countermeasures. However, countermeasures for animals in semi-natural ecosystems have been much improved and could be implemented in any future accident. There are secondary ecological implications which may result from either governmental or individual responses to the high contamination levels in animals. Browsing damage to trees in forest ecosystems may occur if less hunting took place. One of the potential measures to reduce radiocaesium levels in vegetation is to fertilize more accessible areas; however, this may cause changes in the vegetation species structure of the ecosystem. The Chernobyl accident has reinvigorated research into the radioecology of natural and semi-natural ecosystems and it is apparent that these areas will have problems for many years to come. We still need more information to quantify the importance of these environments, relative to the agricultural system, to predict eventual transfers to man.

In the advent of deposition from a nuclear incident ruminants in semi-natural ecosystems are likely to have comparatively high radiocaesium activity concentrations in their meat and milk, compared with ruminants from agricultural areas. Ecological characteristics in these environments which make them vulnerable to this form of pollution include the presence of:

- soils lacking the specific clay minerals which immobilize radiocaesium and which therefore allow its uptake into vegetation,
- vegetation species with high uptake rates and/or retention of radiocaesium,
- ruminant species with a high transfer of radiocaesium from gut to tissues,
- climatic factors such as high precipitation rates.

b) Agricultural Ecosystems

Among the various types of radiation exposure due to the release of radionuclides from nuclear installations, the transfer soil-plant-animal products-diet is one important route leading to internal radiation of man from food uptake. Therefore, after the Chernobyl accident, especially due to the characteristics of the source term and regarding the speciation of the deposited radionuclides, numerous and varied samples of agricultural products were collected and analysed, both for food contamination control and scientific studies. Also for animal products, calculations carried out in the months after the accident brought to light large discrepancies between model predictions and field observations. On the other hand, one of the conclusions reported by the CEC Article 31 Expert Group (Radionuclide transfer factors for animal feeding stuffs and animal products) was that some transfer routes were poorly documented (transfer to milk other than cow's milk, transfer to growing animals, transfer to poultry). These findings and conclusions reactivated the interest of the scientific community for radioelements like iodine and caesium which were, before Chernobyl, generally considered as sufficiently documented.

The aim of this research, in the framework of this action of the CEC post-Chernobyl programme, was to investigate the transfer from plants to animals and their products for the main radionuclides deposited by the Chernobyl fall out. It also aimed at comparing the transfer data for the Chernobyl radionuclides with data obtained for other source terms, and at generating new data in less documented fields. Three animal species of major importance for human nutrition have been considered: cattle, sheep and chicken. The investigations were performed with cattle, grazing on contaminated pasture over a longer time period and receiving dietary supplements. The retention of radionuclides in fodder and the transfer into cow's milk was studied under field and controlled conditions. Similar studies were conducted with sheep. In addition, the transfer into sheep organs and pregnant sheep was investigated. Also, the transfer of radiocaesium into eggs of hen and chicken meat was studied feeding a standard hen or chicken food artificially contaminated with $^{134}CsCl$. The results of these investigations led to the following conclusions:

initial interception of fall out radionuclides by pasture grass was a function of the herbage density at the time of the deposit. The greater the herbage density, the greater the fraction of the deposit that is intercepted by the green cover. However, the increase of interception efficiency is less than proportional to the increase in herbage density. Thus, due to a higher dilution in a larger vegetation mass, the specific radioactivity on herbage may be significantly lower in pasture with high vegetation density than in that with a low grass yield at the time of the deposit. As a consequence, animals grazing on high vegetation density meadows will ingest less radioactivity than those grazing on low vegetation density meadows. Short-term retention of deposited radionuclides is governed by physical decay, weathering processes, dilution by plant growth and removal of contaminated parts by harvesting and grazing. Agricultural practices such as grazing pressure (number of animals per unit area) or grazing pattern (continuous or block grazing pattern), profoundly affect the retention of radioactivity on pastures and, in fine, the evolution of contamination levels in animal products, especially in milk. The short-term effective half-times for the Chernobyl radiocaesium on pasture grass calculated at the different sampling sites considered in this study ranged from 2.6 to 23 d; those estimated for radioiodine were more comparable (4 to 5.2 d). Long-term contamination of forage plants is mainly dependant on the soil properties which influence the availability of radionuclides deposited on or leached into the ground for uptake by roots. In this regard, the quality of the pasture plays an important role on the long-term availability and transfer of the deposited radiocaesium. In lowland pastures, generally characterised by a rather high clay content in soil, caesium is adsorbed on to the exchange complex and its availability for plant uptake is reduced. In the soils of uplands pastures, poor in clay minerals and potassium, caesium remains available for a much longer time period (see chapters on natural ecosystems). All these parameters affecting the retention in forage should be kept in mind when assessing the changes in the contamination of farm produce with general models that were not necessarily designed for the particular set of conditions, characteristic of the region or ecosystem considered. It is recommended that site specific data should be compared with model predictions in order to check the validity of the model assumptions. There was some evidence that the availability of Chernobyl radiocaesium was less than that of the ionic forms. The grass-to-milk transfer coefficients were lower in sheep fed contaminated grass collected in Scotland three days after the deposit than in those grazing on upland fells during summer 1987, when caesium was incorporated into the plant material from soil by root uptake. However, comparing under controlled conditions the transfer to cow's milk of radiocaesium associated with hay collected in mid-June 1986 and that of ionic forms, only a slight reduction, if any, in availability was observed for the Chernobyl caesium. The rainfalls during the six weeks between the time of deposit and the harvesting of hay are suspected to have leached the contaminated particles in which caesium was poorly available from the grass. Despite the difficulty in measuring or estimating herbage intake, and the subsequent intake of radionuclides, transfer coefficients were calculated from the field data collected after the Chernobyl accident. Estimates of the transfer coefficients to milk and meat vary widely but some trends are evident:

- transfer coefficients for milk and meat vary as a function of the animal species (higher transfer in sheep compared to cows),

- the age of the animal is another parameter that influences the transfer of radionuclides (higher transfer in young than in adults, although concentration in the foetus is lower than the concentration measured in the muscles from its dam),

- transfer coefficients also vary depending on the physico-chemical form of the radioactive element considered and with the source term (higher transfer for the Chernobyl Cs than for the Cs - associated with silt - on a salt marsh near Sellafield) and with the time after the deposit (higher transfer for the Chernobyl Cs one year after the accident than in the months following the deposit). These aspects have been extensively discussed for sheep. A better description of the gastro-intestinal absorption depending on animal species, age and physiological status (pregnancy, lactation) as well as on feed characteristics and chemical form administered is needed to explain the wide variation observed under different conditions. Such studies will allow more reliable predictive models to be made.

6. Transfer in Aquatic Systems

Considerable quantities of data were collected from lakes and rivers in the immediate aftermath of the Chernobyl accident. Often it was obtained with no thought as to its subsequent scientific use and had little supporting data. Hence, interpretation of unusual results was often very difficult if not impossible. The present report will concentrate on limitations in our understanding which have been exposed in the wake of Chernobyl and will make recommendations on both the collection of data in the future and the most important directions for future work. Much of the work relates to Cs, as this was the most abundant and easily measured element in the Chernobyl fall out, but the general principles are common to all nuclides, although they may differ in subtle details. Work focused on elucidating specific subsections of a conceptual model of radioactive transfer from catchments to the aquatic system and from there into aquatic fauna. The main aim was to use the opportunities offered by accidental releases, particularly from Chernobyl, to identify areas where understanding was poor and further, more detailed, research was required. The conclusions from the results of these investigations on the fate of radiocaesium in aquatic ecosystems can be summarised as follows:

Using the increased understanding obtained from models and from measurements made in the aftermath of the Chernobyl accident it is now possible to make some informed comments about the treatment of aquatic systems to aid their recovery after a pulse input of radionuclides from the atmosphere, such as occurred after Chernobyl. A pulse of radioactivity will pass through a river system relatively quickly, although the original pulse will spread over a longer length of river in the extra time it takes to pass down a long river, compared to a short river. Hence the first line of defence is simply to monitor and shut water treatment inputs appropriately to avoid contaminating water supplies. Assuming the pulse is short, that only relatively little runoff occurs from the contaminated catchment and that flows in the river are reasonably high, then the river water will clear itself fairly rapidly. If the initial contamination was high then the sediments may have been contaminated, in which case one of two options is open. In a regulated river it may be possible to open control gates to create surges of water of sufficient turbulence to keep contaminated solids in suspension until the system has flushed itself. Alternatively, the riverbed can be mud pumped in the worst affected areas to remove polluted mud. This approach should be attempted as soon as possible after the clearance of the water column so that the minimum of diffusion into the sediments and the minimum of dilution by uncontaminated fresh sediment occurrs so that the minimum of sediment has to be transported and disposed of. In lakes and reservoirs, these events proceed over a much longer time. The events after Chernobyl confirmed that the mixing in lakes extends the time for which a lake is contaminated, compared to a point on a river system and it is rare that problems last less than a few months. From the models which have been developed it would appear that there are two options: if considerable quantities of uncontaminated water are available, then it may be possible to increase the flow rate through the system, increasing the hydraulic washout losses from the lake. This option is seldom likely to be viable unless the pulse input is very localised. The second option is to treat the lake with a relatively fine (a few tens of microns diameter) solid material which has a high, and preferably irreversible, affinity for the radionuclide(s) in question. For Cs, illite would be ideal. The radionuclide would absorb to the solid and settle to the lake bed within a few days. This approach would be less applicable to shallow lakes where re-suspension regularly occurs. If chemical changes in the sediment could bring about a re-mobilisation of the contaminant then the introduced material would need to be mud pumped from the surface of the sediment within a short time of the treatment. If the radioactive input were long lasting then there is little that can be done directly for the aquatic environment until the input ceases, apart from issuing warnings about the dangers of eating fish caught in the water and making extra provision for treatment at water supply treatment works. In order to make the best use of radioecological data which are collected in the future (for whatever purpose), every effort should be made to measure the following parameters with every sample taken for radioactivity measurements and these data should always be reported with the activity data:

- a major ion balance (Ca, Mg, Na, K, Cl, SO_4, NO_3, alkalinity/carbonate, pH and conductivity). These parameters define the water. They are generally present in mgl^{-1} quantities and hence usually compete with low concentration radionuclides in absorption and ingestion processes,

- suspended solids concentrations. Both the total and organic component should be reported. These measurements are a controlling variable in defining the solid liquid distribution of radionuclides (Kd-values),

- total phosphorus is a major parameter defining the productivity of lakes, and larger, slow flowing rivers,

- ammonia concentrations (for Cs). Concentrations of ammonia of the order of a few hundred $\mu g\ l^{-1}$ are sufficient to compete effectively for Cs specific adsorption sites and release radioactivity into solution,

- weight and length of fish (as well as species identification) and, ideally, age. These data can be used to assess the growth rate of the fish. Larger fish will contain higher concentrations compared to smaller fish of the same species,

- concentrations of major algal species suspended in the water. In productive lakes algal cells can provide an enormous surface for adsorption,

- concentration of radioactivity in the top few cm of sediment with % organic matter, a major cation analysis and, ideally, an XRD analysis of the major mineral content,

- for rooted aquatic plants the same data as above should be reported, but for a homogenised sample covering the whole of the root zone depth,

- physical information on the lake or river should always be given such as: river cross section or lake properties, instantaneous flow rate and annual mean flow rate for rivers, mean and summer retention time for lakes,

- whenever possible, concentrations of as many radionuclides as possible should be measured.

7. General Conclusions and Recommendations

Within the framework of this action, four research priorities have been defined to be studied by different laboratories from various member countries. The main conclusions drawn from the results of these extensive investigations are reported below. The concentration of 16 elements was determined in the aerosols. Iodine was quickly released, and was thus found only in very small quantities in the aerosols. The chemical forms of radionuclides predicted by theoretical studies (CsI, CsOH, metallic Ru and Ag) were found together with some unexpected compounds such as a cadmium-caesium nitrite. The solubility of fission products with radioecological impact appeared similar to that generally observed for the elements involved, and depended on their chemical properties. Strontium shows low or moderate solubility, Cs is moderately soluble too, if it is generated from uranium-rich mixtures, as observed in the Chernobyl fall out. In natural and semi-natural ecosystems soil-plant transfer factors are consistently larger for radiocaesium of

Chernobyl-derived material as compared to that from weapons fallout reflecting a greater plant availability. In some of the soil profiles, notably the podzol, Chernobyl derived caesium is held much further up the profile and is thus more likely to be found in the rooting zone. In agricultural ecosystems the influence of the soil type on the soil-to-plant transfer of radiocaesium was confirmed from the results of field studies. In cereals grown on a soil with a perched water table, significantly higher transfer factors were determined than in cereals from Cambisol and Fluvisol. The use of lightly contaminated sewage sludge did not lead to a serious increase of radiocaesium in plants. On soils with high content of coarse sand and gravel the transfer factors seem to be lower, supposedly due to higher values of extractable potassium in these soils and to deeper penetration of the roots. Statistical evaluations show that soil-to-plant transfer factors of Cs originating from Chernobyl were about two times lower than the transfer factors for Cs from other contamination sources due to the three main effects "time lag", "soil organic matter" and "translocation". Effects of region and season could be traced back to differences in soil type, variation in crops, differences in agricultural practices and varying weather conditions. In the advent of deposition from a nuclear incident ruminants in semi-natural ecosystems are likely to have comparatively high radiocaesium activity concentrations in their meat and milk, compared with ruminants from agricultural areas. Ecological characteristics in these environments which make them vulnerable to this form of pollution include the presence of:

- soils lacking the specific clay minerals which immobilize radiocaesium and which therefore allow its uptake into vegetation,
- vegetation species with high uptake rates and/or retention of radiocaesium,
- ruminant species with a high transfer of radiocaesium from gut to tissues and-climatic factors such as high precipitation rates. Estimates of the transfer coefficients to milk and meat vary widely but some trends are evident:
  - transfer coefficients for milk and meat vary as a function of the animal species (higher transfer in sheep compared to cows),
  - the age of the animal is another parameter that influences the transfer of radionuclides (higher transfer in young than in adults, although concentration in the foetus is lower than the concentration measured in the muscles from its dam).

Transfer coefficients also vary depending on the physico-chemical form of the radioactive element considered and, obviously, are related to the source term.

Scientifically speaking, the Chernobyl accident provided a very useful test of our understanding of the transfer of radionuclides through aquatic environments. It highlighted several flaws in our knowledge of the dynamics of transfer, particularly the contribution made by certain types of catchment to elevated water concentrations and the importance of using correct food chain pathways for predicting fish flesh concentrations. An initial outline of the ideal requirements for information which should be collected during any repeat of the Chernobyl incident has been made, along with recommendations for the reinstatement of polluted water. Future work should concentrate on areas which limit the portability of predictive models, particularly sources of variability in Kd values and CF values, but also including the effect of catchment type, transfer processes from water to sediment and sediment release mechanisms.

Recommendations

After the Chernobyl accident the concentrations of radiocaesium in plants and animals were found to be higher than expected. It is evident that the mechanisms controlling the mobility of radiocaesium in many systems, particulary the natural and semi-natural were poorly understood. The cause of the high concentrations was attributed to a higher bio-availability of the Chernobyl derived material. Whilst this was partially the reason the higher transfers have been shown to be due to a complex of factors, including climate and soil conditions, which are discussed in the report. At the time of writing there are indications that the originally deposited Chernobyl material has undergone changes and the transfer factors from plant to soil are becoming similar to those of radiocaesium originating from other sources.

One of the most important factors which was recognized to influence transfer of caesium from soils to plants is the effect of climatological conditions. As until now hardly any relevant studies have been carried out on climatological effects on the transfer of radionuclides, more research on this phenomenon is necessary.

Studies after the original deposition focused on contamination of agricultural systems and their food products. These studies were poorly structured due to the need for quick assessments of the doses to the population. Well designed studies using standardised methodology would enable the implications of any future event to be assessed quickly and remedial measures applied.

Initially research was devoted to an examination of agricultural systems despite the fact that larger areas of natural and semi-natural vegetation had been contaminated. The importance of these systems in the movement of material back to man was underestimated and models derived from agricultural systems are totally inadequate to deal with the situation.

Recommendations for the future are, therefore, that all contaminated ecosystems should be investigated and that sample collection, treatment and analysis is coordinated internationally. Research needs to be started as soon as possible after an accident and a scientific programme should be prepared so that in the event of a future incident delays are avoided. Systems to be studied extend from the tundra systems of northern Europe to the still poorly understood systems of the Mediterranean regions. In view of the events after Chernobyl particular emphasis should be given to high rainfall areas throughout Europe. Important areas for future research in the natural and semi-natural ecosystems of Europe could include:

- the effects of climatic factors on radiocaesium movement,
- further monitoring of the Chernobyl material to investigate any long term changes in behaviour,
- the development of models concerned with natural and semi-natural systems,
- a study into the role of soil composition on the behaviour of radiocaesium with particular reference to upland organic systems,
- investigations into the reasons for differential uptake of radiocaesium by species in the same habitat, studies of other radionuclides which might be involved in accidents, in particular the actinide elements. In the future much more detailed supporting data should be collected along with radiochemical data, and suggestions of minimum requirements should be made. Future work should concentrate on areas which limit the portability of predictive models, particulary sources of variability in Kd values and CF values, but should also include studies of the effect of catchment type, transfer processes from water to sediment and sediment release mechanisms.

II. Atmospheric Transfer Models

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2. Introduction

The Chernobyl accident, although a tragedy in human terms, provided a valuable opportunity to examine our ability to model the dispersion and deposition of pollutants released to atmosphere as they are transported over long distances by the wind.

Models of long-range pollutant transport have a variety of uses in the context of accidental releases of radioactivity: in the early stages after or during an incident, they would assist in providing an indication of when and where contamination might be expected to appear in subsequent days and what its severity would be for a postulated (or known) release magnitude. As measurements of contamination become available, models can play a further role in emergency response: if the characteristics of the release, particularly the amounts of various radionuclides, are not known, they could be used to "work back" from measurements to properties of the release. They also provide a tool for an intelligent interpolation or extrapolation from the measurements to estimates of contamination levels in areas having no data. On a longer time scale after an accident, they could assist in forming a total view of the situation and in assessing how important were various phenomena in determining the final contamination patterns.

As in all situations where models play a key role, the question of validation arises. Controlled-release experiments on this scale are costly and present formidable problems of logistics, which explains why there have been relatively few to date. Not surprisingly, therefore, the radiological data base from Chernobyl, besides its many dosimetric uses, is viewed as a potentially valuable resource for model-evaluation purposes. However, it has to be borne in mind that Chernobyl was not a controlled experiment and there are likely to be limitations on its utility from this standpoint. In particular, data collection in various countries was not motivated primarily by a desire to generate a coherent set of measurements on a European or global scale and the data base is correspondingly inhomogeneous: there were no agreed procedures nor uniformity of standards. Hence there is a need for a thorough collation and examination of the Chernobyl data before their maximum potential can be realised.

In all modelling contexts mentioned earlier, the question of model complexity arises. Many long-range models of various types have been applied to the Chernobyl accident. Most of these existed long before Chernobyl happened; they were usually developed with specific uses in mind, having their assumptions and simplifications tuned to those particular applications. They vary widely in the level of detail they require from the meteorological data and in the demands they make on computational resources. It is an open question, however, as to what are appropriate levels of complexity for the various modelling tasks listed earlier. There will be significant advantages in an operational context in keeping the complexity to a minimum compatible with the goals in mind, but deciding what is this optimum level requires a great deal of investigation and inter-comparison.

A particular issue concerns the extent to which the effects of major orographical features need to be treated explicitly in operational models of long-range dispersion.

During and after the Chernobyl accident a number of ad hoc analyses were applied with a view to working back to information on the source term from the radiological measurements. There is a need for a more rigorous examination of the limitations and overall reliability of these techniques where uncertainties exist in both the environmental data and model predictions.

Linked via the themes introduced above, four research tasks were undertaken with the overall aim of enhancing the usefulness of long-range atmospheric dispersion models in accident situations; these are described separately below in four parts.

3. The Analysis of Radiological Measurements in the REM Data Base

a) Objectives

The project deals mainly with the rationalization of the Italian radiological data provided by the REM (Radiation Environmental Monitoring) data bank, together with a brief examination of the French data to verify the validity of the method applied.

Attention is focused on analysis of the measurements of air concentration but similar methods can be applied to deposition data. The purpose is twofold: on the one hand, to devise a procedure for checking the data and locating "suspicious" measurements, i.e., those which are scarcely explainable on any rational basis; on the other hand, to construct an empirical parameterization of the distribution of air concentration as a function of time.

The experience gained in the analysis of the Seveso chemical accident (July 10th, 1976) indicates that the raw experimental data from such events are likely to contain much more information than initially apparent.

The Joint Research Centre (JRC) of the European Community (EC) at Ispra started in 1987 to collect the results of measurements performed by numerous laboratories within the EC following the Chernobyl accident (26 April 1986), and subsequently constructed the REM (Radiological Environmental Monitoring) data bank. REM is a comprehensive European data bank containing not only data obtained from official documents provided by the EC Member States, but also many other measurements extracted from unofficial documents and via private communications from research institutes and universities. Correspondingly, the format of the entries in the bank is capable of distinguishing measurements made on different sample types or using different apparatus, sample preparation or analysis techniques.

In general, the data in a single category vary in quality and accuracy due to the differences in measuring techniques, level of documentation and professional experience of the measuring team. A further problem in the first version of the REM data bank used here concerns the resolution of the geographical information provided: the longitude and latitude associated with each measurement generally refer to the administrative centre of the Province within which the measurement was taken. This forces a subdivision of the whole data sample into sets of measurements each associated with a given Province, which constitutes a relatively extended geographical area. The problem then arises of how the measured values are distributed within a given Province and its nearby regions.

b) Results

The analysis was limited to the radionuclides ^{137}Cs, ^{134}Cs, ^{131}I and ^{132}I. Complete sets of data for all the four nuclides were made available from the REM bank for eight Italian Provinces (Alessandria, Latina, Milano, Matera, Piacenza, Pavia, Roma and Vercelli) comprising a total of 1850 data items. To check its validity for a wider area, the analysis was extended to 4101 measurements covering sixteen Provinces and including ten nuclides, although the detailed results are not reported here.

The REM data provided do not quote an error on the data values. This deficiency cannot be rectified by simply assuming that uncertainties are due to random counting errors alone: there will also be systematic uncertainties inherent in the techniques employed. The lack of information on uncertainties is potentially a major hurdle to the application of the fitting procedures used. Therefore, a method was devised for estimating an effective standard deviation for each data item based on the variability observed in the data.

The analysis of the data within a given Province makes it possible to identify obvious outliers and to select a set of consistent values for comparison with models. Data with suspiciously anomalous values were reported to the JRC Ispra group for inspection and critical reconsideration. Over forty instances have been reported so far and, where necessary, the REM data bank entries have been modified.

A mathematical interpolating function was devised to represent the temporal trend of the measured airborne concentration for an individual radionuclide, from the first arrival of the plume until the concentration decayed to a background level. A single function was found to be generally applicable to each Province and each radionuclide separately, as well as to the set of measurements taken as a whole.

The function depends upon four parameters: the first (called the "slope" parameter below) is the decay coefficient in the exponential decay of the air concentration to a background level, expressed as a modification to the radioactive decay constant for the radionuclide concerned; the second is related to the peak air concentration and is thus representative of the "strength" of the radioactive cloud; the third is related to the arrival time of the radioactive cloud at the given location; the fourth represents the background level to which the air concentration decays after long times (in principle not necessarily identical to the background concentration before the accident).

In the literature, reference can be found to total background levels, such as gross beta activity, but nuclide-specific background data for the radionuclides of interest were not readily available for the required locations. Thus, the fourth parameter extracted from the fit is a source of new information on background after Chernobyl.

The above formula has been fitted to the time distribution of the radionuclide concentration in air separately for all the sixteen Provinces for which data were available.

The fitted values of the slope parameter for the eight Provinces where the nuclides ^{137}Cs, ^{134}Cs, ^{131}I, and ^{132}I were contemporaneously detected strongly suggest that this parameter might be characteristic of a given radionuclide but not dependent on location. This empirical observation is important in that it opens up the possibility of extrapolating to areas not having comprehensive data.

Therefore, an optimum value of the slope parameter was extracted from a fit to the data for all eight Provinces taken together, thereby reducing the number of free parameters by seven; this exercise also had the effect of reducing the variability from Province to Province in the remaining parameters.

The analysis of the French data contained in the REM data bank shows that, contrary to the case for Italian Provinces, the air concentration data set for an individual French "Département" is sparse (on average only fifteen measurements per "Département") and the values span a wider range. Nonetheless, the same statistical method used in handling the Italian data (i.e., fitting with the same mathematical function, etc.) was applied to the French data. The results show that the same mathematical function is able to reproduce the time evolution of the air concentration in France without changing either the basic principles of data handling or the physical assumptions adopted. This analysis included four "Départements" where all four major nuclides (^{137}Cs, ^{134}Cs, ^{131}I and ^{132}I) were measured. Both the individual and global fits are consistent with those obtained for the Italian data.

Application of the statistical method described above to the air concentration in both Italy and France has thus led to some significant results. The validity of the proposed theoretical function for interpolating the data has been adequately demonstrated. It has also been shown that the global fit to find the slope parameter leads to a more homogeneous set of values for the other parameters.

In addition, an indication has been given of how to adapt the mathematical function to account for the double peaks in the air concentration observed at some locations.

As a subsidiary to the above analysis, the application of fractal techniques to the data has also been examined. Fractal concepts provide a natural language for dealing with apparently anomalous fluctuations; they have been shown to be applicable to diverse meteorological variables such as the shapes of clouds and the spatio-temporal fluctuations in rainfall intensity. Thus, the fractal approach can be expected to provide powerful tools for describing the spatial variability of the air concentration of radionuclides from Chernobyl.

The fractal approach was applied in the present work by adapting an appropriately modified version of a model for the simulation of rain fields. By this means, the known fractal character of the dispersion process was exploited in determining values for the air concentration in locations for which measured values were not available. Contrary to traditional interpolation procedures, which amount to a "smoothing" of the distribution, the fractal approach takes seriously the potential for large fluctuations in the radionuclide concentrations, and incorporates these at a level governed by the information contained in the measured distribution of air concentrations in surrounding regions.

The mathematical functions discussed earlier are used to generate a set of air concentration values distributed in space and time which act as the starting point for the fractal algorithm. An example of the technique is given for a small region within Pianura Padana (Italy).

c) Conclusions and Recommendations

A significant finding of this work has been that the time evolution of the air concentration, as experimentally observed for the four principal radionuclides in eight Italian Provinces, can be described using a single empirical function which contains parameters with definite physical meaning. The function is flexible enough to describe well the data in all cases considered; the goodness-of-fit is striking given the wide scope of the analysis.

One of the parameters introduced provides a self-consistent definition of the time of arrival of the radioactive cloud at a given point, independent of the meteorological information.

The method used to describe the data in Italy is also found to apply to the French data.

The method could be profitably extended to the other measurements contained in the REM data bank, thereby making available an homogeneous set of data on arrival times and on the time evolution of the concentration throughout Europe.

The potential for utilising fractal concepts has been demonstrated. In regions where data are scarce, the fractal approach has the advantage of automatically introducing into interpolation or extrapolation procedures supplementary information on the spatial distribution which relates to the known fractal nature of the pertinent physical phenomena.

It appears that there would be significant benefit in developing and calibrating an empirical model of fractal type, capable of taking advantage of the experimental information available from field measurements performed by various laboratories immediately after an accident and continued over varying periods of time. Such a model would provide a means of rapid extrapolation to regions where comprehensive data were not available; it could also form the basis for incorporating fractal insights into other atmospheric transport models.

4. The Estimation of Source Terms from Radiological Measurements

a) Objectives

Many basic nuclear installations (power reactors, nuclear fuel reprocessing plants) may, in the case of an accident or incident, release radioactive gases and aerosols into the atmosphere.

Past experience has shown that it is difficult to specify accurately the "source term" either during or immediately after an accident. Here, the source term comprises:

- the chemical nature of the radionuclides released;
- the amount and time distribution for each radionuclide released;
- the physical state of the various radionuclides released - whether gaseous, aerosol, organic or inorganic vapour.

Radiological protection experts therefore have to make do with ranges that are reduced over time by adjusting to activity measurements made in the environment.

In certain cases, some components of the release will be monitored. For example, radiation counters in outlet ventilation stacks may measure total beta radioactivity and this data could be used to gauge the magnitude of the source term. However, such information would only be available in an accident if the radionuclides were discharged from the stack and the counters were still in correct working order. In general, on-site measurements will at best give incomplete information on the source term and there is also a need to make the best use of off-site data.

Determination of the source term is usually a means to an end: a key objective is to predict the air concentration and ground-contamination fields in those regions where measurements have not yet been made. Conventionally, this is carried out by first collecting the best available information on the conditions of the discharge, such as its height, prevailing weather conditions, the composition of the discharge and its activity level, along with the magnitude of parameters governing the deposition process (deposition velocity, washout coefficient). Atmospheric transport models of varying degrees of complexity are then used to predict from this information the air concentration and ground deposit fields.

The purpose of this study, however, is to put forward a method for using the results of off-site air-concentration and deposition measurements made in a given zone in order to obtain the best estimate of the source term and of the overall air concentration and deposit fields, at the same time optimising the parameters required in the atmospheric transport model.

This method is fundamentally different from those approaches that assign fixed values to the environmental transfer parameters and then use these either with a hypothetical source term to work out concentration fields or in conjunction with radiological measurements to work back to an estimate of the source term. In the proposed approach, in contrast, all or part of the set of environmental-transfer parameters, as well as the source term, become unknowns within the problem, in addition to the values of air concentration and deposition required. Only the radiological measurements and perhaps some of the environment parameters enter as fixed parameters.

Since the measurements are used as a basis for determining the values of the source term and of the environmental transfer parameters, they yield the best air-concentration and deposit fields that are supported by the information available.

The objectives set out above are typical of optimum control problems. It is known how to construct various types of models of atmospheric transfer which are sufficiently accurate when the model parameters are well enough known. However, the parameters used in the model fluctuate a great deal or are not known exactly and it is often only possible to specify a range of values.

The problem can therefore be summed up as follows:

- the atmospheric transfer parameters of the problem may vary within specified ranges.
- it is required to obtain the distributions of air concentration and ground deposit using parameter values that lie within a prescribed variation interval and which provide the best possible fit to measurements made in the field.

The method proposed is independent of the type of atmospheric transfer model adopted and of the way in which the equations used to construct the model are solved. The method consists of solving the atmospheric transfer equation, subject to a number of constraints. Firstly, the atmospheric transfer parameters are defined to lie within certain ranges and, secondly, a function is devised such that its control will yield the best possible fit to the measurements made in the field.

In order to provide an operational solution to the problem, the method proceeds by linearizing the solution of the atmospheric transfer equation with respect to the various parameters. Then a mathematical programme is defined, made up of constraints on the variation of atmospheric-transfer parameters and constraints which ensure that the values given by the solution of the atmospheric transfer equation lie within a range determined by the radiological measurements. The solution of the mathematical programme is a set of parameters satisfying the constraints and optimizing the so-called "economic function". If the constraints and economic function are linearly related to the parameters, this mathematical programme is termed a "linear programme".

The so-called "simplex" method was chosen to solve this mathematical programme, now reduced to a linear programme. This method has the advantage of not being limited just to the process of fitting: it enables the performance of sensitivity analyses and the implementation of processes which aid decision-making. It also makes it possible to pick out the most incongruous activity readings or the most inadequate parameter values.

b) Results

To accomplish the task outlined above, a computer code, STAR, has been written. This enables the calculation of optimum values for the quantities of the various radionuclides released in an accident and, in addition, the calculation of optimum values of parameters such as windspeed, wind direction, deposition velocity entering into a plume model of atmospheric transfer.

This code constructs a linear programme from the following data entered by the user:

- the relative coordinates of the measurement points with respect to the release point;
- the type of measurements;
- the name of the radionuclide to be considered;
- the results of measurement;
- the date and hour of the beginning of the measurement;
- the date and hour of the end of the measurement.

The current version of the code is based around the straight-line Gaussian model of atmospheric dispersion, although is flexible enough to utilize more complex models if the user can supply the pertinent information.

The user chooses which parameters are to be controlled from a standard list (vertical and lateral dispersion coefficients, radioactivity released, washout coefficient, deposition velocity, windspeed, wind direction, release height and height of the mixing layer). When the user chooses to control a parameter, the lower and upper values of the interval of variation of the parameter must be provided.

This numerical method has been tested in a number of different situations. A first simulation focused on determination of the source term, using five air radioactivity readings, for a radioactive aerosol composed of only one radionuclide. A second simulation focused on determining both the source term and the windspeed, using twenty air activity readings, again for a radioactive aerosol composed of only one radionuclide.

The last test focused on determining the source term, the windspeed and the wind direction appropriate to a field experiment performed at Bruyères-le-Châtel in 1985 involving a release of tritium to atmosphere. The objective of the experiment was to observe the behaviour of tritium in the geosphere, particularly following an atmospheric release. To this end, thirty-two points of measurements were located within an area determined from the forecast wind direction. In this last test, both wind speed and wind direction, in addition to the source term, were treated as unknowns to be determined from the measurements of air concentration.

This last test demonstrated the validity of the method. The derived value of the wind direction agrees well with the actual value and the values of the windspeed and amount of radioactivity released are in reasonable agreement (the error on the assessed source term is 38%). It has to be stressed that this method will be efficient only if the model used is realistic: it can be deduced, therefore, that the atmospheric transfer of tritium during this experiment can be realistically represented by a straight-line Gaussian model.

c) Conclusions and Recommendations

The first version of a computer code, named STAR, has been completed; this version can only deal with air-concentration measurements. The code only requires modest computing resources: a few hundred kilobytes of memory and twenty seconds run time on a standard workstation are needed for a typical run.

Future work could include the introduction of a pre-processor enabling the management of all radiological measurements performed around the release point (such as deposition on soil, external dose-rate, atmospheric activity) and the creation of a corresponding mathematical programme to determine the set of parameters essential to the estimation of a radiological situation such as windspeed, wind direction, source term and deposition velocity.

Also, the mathematical programme could be modified to take into account other types of radiological data such as ß-activity measurements performed on gaseous effluents passing through a stack, or external dose-rate measurements performed inside the nuclear power plant. Such measurements complement to some extent those performed away from the site: the external irradiation inside the plant and the gross ß measurements from the stack are typically dominated by noble gases and iodine. Consequently, this would allow a better estimate to be made for these components of the release.

Another possibility is the construction of mathematical programmes for determining the kinetics of the radioactive release, if the time development of the radiological measurements is sufficiently consistent. In practice, if the measurements give the integrated activity from time t_1 to time t_2, it will be impossible to resolve the behaviour in time of the release between t_1 and t_2. The source term between these two times has to be considered constant. But if the mathematical programme is given a set of measurements of radioactivity performed at a series of times t_1, t_2,..., t_n, it would be possible to calculate the radioactivity released within the intervals t_1 to t_2, t_2 to t_3, etc.

In this extension to include a wider range of measurements, the method presented here has a number of strengths:

- the possibility of setting constraints on parameter values;
- the ready identification of inconsistent measurements;
- the facility to set bounds on the difference between measurement and calculation.

Finally, this study has demonstrated the advantages of the linear-programming method: computation is rapid and the technique is efficient for both linear and non-linear parameters.

Overall, the method has potential for application in real-time systems but needs further development in practical implementation.

5. Long-Range Atmospheric Transport Models for Emergency Response

a) Objectives

This project has its origins in the efforts made during and after the Chernobyl accident to predict and analyze the pattern of radioactive contamination on a European scale, utilising routinely available meteorological information coupled to long-range dispersion modelling. As the Chernobyl experience was digested by agencies concerned with radiological protection, additional attention was naturally given to the potential of this type of modelling for operational use in an emergency-response context. If long-range atmospheric dispersion models are to play a role in decision-making, it is essential that an informed awareness is developed of the uncertainties in their predictions: this project aims to contribute to an appreciation of the uncertainties accompanying the use of trajectory models for emergency-response purposes.

A vast array of long-range atmospheric dispersion models exists, often developed with a specific task in mind and, accordingly, based on differing assumptions and approximations: model complexity and the associated demands on computing resources vary widely. What type of model and what degree of model sophistication is appropriate to the emergency-response context are key questions, not easily answered. Insights into these issues will emerge, however, as models of different type are exercised individually in test situations and compared. A major aim of the studies was to contribute to this process by assessing the relative merits of a number of alternatives in the formulation of a long-range trajectory model.

Understandably, the radiological data base collected after Chernobyl is viewed as a valuable resource for evaluating dose-assessment models, including the "dispersion" component of such models. From the viewpoint of emergency response, comparisons with Chernobyl data might be expected to provide, for example, information on how accurately models can estimate the angular position, spatial extent and time of arrival of contamination resulting from a burst of radioactivity after it has travelled about 1000 km from its point of origin. However, a number of uncertainties surround the specification of the Chernobyl release and hinder the process of model evaluation. Part of the work was, therefore, aimed at shedding light on the extent to which comparisons of model predictions against Chernobyl radiological data can assist in the evaluation of long-range dispersion models.

The key initial step was the development of a long-range atmospheric transport model which makes use of routinely available wind-field data on a European scale: this then formed a framework for investigating the issues introduced above.

b) Results

Chernobyl comparisons

A comparison was made of predicted versus measured air concentrations at a variety of locations in Europe for a single radionuclide, ^{137}Cs. Most of the data used in these comparisons were taken from the Ispra-based REM data bank. In this scoping study, only a small sub-set of 10 locations were used, chosen as those having a set of measured ^{137}Cs air- concentrations that were comprehensive for the period of the accident; the locations were spread widely across Europe, with some of them close to regions of major orography.

Separate calculations were performed using the wind fields on three different pressure surfaces - 950 mb, 850 mb and 700 mb (corresponding, typically, to approximately 500 m, 1500 m and 3000 m height, respectively) - considered to span the pertinent range appropriate to the Chernobyl incident.

The discussion of the comparisons focused on (a) peak concentration magnitudes, (b) time-of-arrival and (c) the shape of the time profile of concentration. On the basis of this limited set of comparisons it was concluded that the model is capable of predicting the dilution factors at long range (i.e., of the order of 1000 km), arising from spatial and temporal fluctuations in the wind, usually to within a factor of a few (3, say) using winds on an appropriate pressure surface; advection of pollutant in the boundary layer using the 850 mb wind field will usually predict to within about a day the time for material in the mixed layer to arrive at a radial distance of the order of 1000 km from the source. The detailed shape of the air concentration versus time was not well predicted.

Supporting investigations

The first study concerns the "height" at which winds are extracted from meteorological data in order to construct trajectories. This is an issue for Chernobyl since there was considerable uncertainty in the distribution of effective height of release; it is also a general issue in dispersion modelling from the viewpoint of how to model the advection of material spread vertically throughout the boundary layer and how to account for the contribution of wind shear to lateral and along-wind dispersion.

The values found for the separation of trajectories tracked on different surfaces as they cross a given set of radii indicated that height uncertainties extending up to the 700 mb level could lead on average to several tens of degrees of uncertainty in angular location of the ground-level region of influence of an individual (3-hour) plume element after travel of the order of 1000 km.

Considering the set of separation values obtained by stepping the start time for the trajectories through the Chernobyl weather sequence, a noteworthy feature is the width of the distribution: even in this 10-day sequence, values are found spanning virtually the whole of the possible range from 0-π radians, indicating the large uncertainties that would follow from using wind information at only a single height to assess advection.

The "height" study also examined the difference in time taken by trajectories tracked on different pressure surfaces to reach various radial distances from the release point. The 950 mb-700 mb differences are typically of about a day for a few days of travel. This will tend to be an overestimate of the uncertainty in arrival time of increased air concentrations at ground level (arising from differential advection of material spread up to the 700 mb level); in rainy conditions, however, it will be a reasonable measure of the uncertainty in the time at which ground contamination may first be experienced.

The second study concerns the modelling of lateral and along-wind dispersion, examining how important it is to include various potential contributions and whether it is necessary to model them explicitly in a given situation or simply to use a formula representing their average of typical effect. This modelling has an impact on the predicted lateral extent of contamination from a burst of pollutants on predicted concentration magnitudes and on the predicted time of first arrival of significant contamination at a given distance.

The comparison of contributions to lateral dispersion indicated that the contribution due to the spatial gradients in the wind field at any one level was roughly comparable to the shear contribution on average in the Chernobyl case.

The results relating to the change in the mean wind direction from one release time to the next (swinging) imply that, typically, large "gaps" do not appear in the concentration field if plumes are released every three hours and only one trajectory per three hours is constructed. Nevertheless, there are some occasions when the swinging over 3-hours (and even over 1 hour) is much larger than the relative dispersion. On the other hand, in a fraction of cases the 3-hour swinging (and occasionally even the 24-hour swinging) is much less than relative dispersion.

The distributions of values of lateral-dispersion estimates on a given pressure surface, obtained by stepping plume release times 3-hourly through a 10-day weather sequence, are notably wide: fluctuations by a factor of 3 around an average value can readily arise even in quite a short weather sequence and values up to ten times the mean are not uncommon.

The modelling of lateral and along-wind dispersion due to spatial gradients in the wind field also influences time-of-arrival. The results show that the extent to which dispersion via spatial gradients can cause material to arrive at radii of the order of 1000 km earlier than the mid-point trajectory is certainly very variable but in absolute terms is not usually of practical importance. On the other hand, material released at some time during a 3-hour period can arrive at a radius of 1000 km up to several days ahead of other material released in the same 3 hour period.

A third study was aimed at examining how typical the Chernobyl experience was, for example from the viewpoint of the dispersive capability of its synoptic patterns or its wind shear. The analyses reported above concerning separation of trajectories on different pressure surfaces and the ratio of 3-hour swinging to relative dispersion were repeated for 3 other source locations. It was found that the distributions for different locations overlap to a large extent, the Chernobyl distributions being neither universally narrower nor wider than those for the other locations.

c) Conclusions and Recommendations

Chernobyl comparisons

Evaluation of model performance with regard to advection (i.e., both time-of-arrival and plume angular position) is hindered by uncertainties in the height of the Chernobyl release and by its prolonged nature. These set major limitations on the extent to which comparisons against Chernobyl data can be used to assess the performance of long-range models in an emergency-response context.

Information on the accuracy of the model's prediction of the angular location and lateral extent of a plume element at a given radial distance from the source is difficult to extract from a set of comparisons at individual locations; a more sophisticated analysis - using indicators of the mismatch of the spatial pattern as a whole - might be capable of revealing some information on this point, although data uncertainties are likely to prevent firm conclusions.

Supporting investigations

In making predictions of time-of-arrival and angular location of plume elements at long range, the wind field at a number of heights should be considered, where the range of heights is chosen to reflect information on, or uncertainties in, the temperature structure of the boundary layer and the elevation of the release. This would contribute to an awareness of the uncertainties that might arise from wind-direction shear, which is often large and for which it may not be adequate to use a notional representation.

In modelling the lateral extent of plume elements at long range, there is a need generally to include both the effect of relative dispersion (the effect of gradients in the wind field on material released at a given time) and "swinging" (change in the mean trajectory over the duration of the plume element) for release time steps of the order of an hour or more. Situations commonly arise in which either one or other or both of these contributions have a significant impact on the spreading of material released over a few hours.

In view of the highly variable nature of relative dispersion generated by the complex synoptic wind patterns common over Europe, it will not generally be sufficient to model relative dispersion via a simple formula representing the average spread taken over an ensemble of weather patterns: some form of explicit recognition of the specific effect of the prevailing synoptic pattern is required.

The values found for relative-dispersion and synoptic swinging in the Chernobyl analysis, together with the full set of results obtained for other source locations, indicate that there was nothing exceptional about the Chernobyl case. Nevertheless, considering the large variability in the synoptic weather patterns experienced in Europe, there will no doubt be situations which make significantly more (or less) stringent demands on the modelling than did Chernobyl. Repeating the analysis for other weather sequences would shed further light on the extent to which the Chernobyl experience can be considered representative in the demands it makes on long-range modelling.

6. Atmospheric Dispersion in Complex Terrain

a) Objectives

The Chernobyl accident has demonstrated that long-range atmospheric transport and diffusion models are useful in evaluating the consequences of such events. Various models have been used to reproduce the air concentration and deposition patterns from the Chernobyl accident over Europe and the entire northern hemisphere.

In these calculations, complex-terrain effects, especially those arising from large topographical irregularities, were not included. The difficulties in introducing these effects arise from the fact that such disturbances have a considerable and complex effect on wind flow and deposition patterns.

In the long-range (as well as the short-range) transport of radioactive (or other) pollutants, any gross topographical disturbance (e.g., a mountain range) with a height comparable to the depth of the upstream boundary layer is expected to alter significantly that depth. Also, the topographical feature will have an appreciable influence on the transport and deposition of the pollutant due to changes in the wind-flow pattern and turbulence intensity. The post-Chernobyl experience has indicated that such complexities could have an influence in some circumstances.

Thus, a major aim is to clarify through a series of computer calculations the influence of large topographical disturbances on long range transport of pollutant material. This influence is expressed in terms of major parameters such as wind flow patterns, boundary layer heights, concentration profiles and deposition velocities.

Calculations were performed with the ADREA-I code, under development at the National Centre for Scientific Research "DEMOKRITOS" in Athens. This code is specifically designed for cases where the terrain is characterised by a high degree of complexity and the ambient conditions are not simple (e.g., stable/unstable conditions, stagnant conditions, etc). Treatment of complex domains is achieved by allowing a boundary surface of arbitrary irregularity to cross a calculation cell in such a way that an increase in the terrain complexity does not translate into an increase of problem complexity.

The fluid dynamics and thermodynamics are described by the conservation equations of mass, momentum and energy whereas the mass conservation of the pollutant is fulfilled through a separate concentration transport equation. The turbulence-closure modelling is based on the eddy viscosity/diffusivity concept; anisotropic effects are also included. The conservation equations include compressibility effects, giving the potential to extend the calculation domain to high altitudes, thereby enabling an analysis of mountainous regions of arbitrary height.

Prediction of long-range transport over complex terrain can in principle be made by using advanced codes such as ADREA-I. It is important, however, to investigate if simple models, which require relatively low computer storage and run times, can handle adequately the presence of complex terrain.

b) Results

The calculations were performed for typical values or ranges of values for main parameters such as the geostrophic wind velocity, degree of atmospheric stability, vertical profile and vertical extent (HC) of the upstream concentration distribution, height and width of mountain range, etc.

More specifically, a 1000 m high, two-dimensional mountain range of Gaussian shape is used as a basis for the present studies. This height, not uncommon in the European territory, has been selected on the grounds that it is comparable with typical boundary-layer depths. Several values of the ratio of mountain height to width at half height were considered.

The wind direction was assumed perpendicular to the mountain range to maximize its effects.

Calculations were carried out for neutral, stable and unstable atmospheric conditions. In neutral conditions, a number of wind speeds were considered. The parameters chosen for stable conditions were representative of Pasquill category F.

To simulate unstable stability conditions, steady state stable conditions were assumed in the morning hours. An unstable boundary layer was generated during the day due to solar heating of the ground, represented by a prescribed (sinusoidal) temperature variation with time. Representative unstable conditions arose during the early afternoon hours, and quasi steady-state concentration calculations were performed during the latter period.

For the upwind concentration profile, both uniform and non-uniform distributions were considered.

The calculation parameters are the three velocity components, the turbulent kinetic energy and the concentration integrated over the lateral direction. The results are given in terms of flow field distribution, boundary layer height, concentration profiles upstream and downstream of the mountain, ground concentrations and "flat terrain" concentration comparisons.

c) Conclusions and Recommendations

The present calculations have shown that topographical disturbances comparable to the boundary layer height can cause appreciable disturbances in the wind and concentration pattern in the mixing region around mountains; they can also significantly affect the boundary layer height. The following detailed conclusions can be drawn from the studies:

- for 2-D mountains, the influence of the mountain in the vertical direction appears to cease roughly above 2.5 times the mountain height. It should be noted that this is an upper limit for 3-D cases, considering the additional degree of freedom of the wind to bypass the mountain horizontally,
- the ground concentration and deposition behaviour in the mountain region is strongly dependent on deposition velocity. The distribution of the deposit across the mountain region seems to be influenced by the degree of stability, flow reversal, and the concavity-convexity of the ground. The phenomena are complex and difficult to quantify at this stage. Experimental support is needed for this purpose,
- the mountain presence causes an increase in the boundary layer height as expected. In ideal neutral conditions, this disturbance persists to a downwind distance of up to several times the mountain half-height width, contributing considerably to the concentration mixing downstream of the mountain,
- mountain narrowness and atmospheric stability enhance the flow reversal behind the mountains. Such reversals are responsible for creating secondary concentration peaks behind the mountain.

The question "Is it possible to convert complex terrain calculations to equivalent simple flat terrain ones? " may be answered as follows:

- In the mountain region itself this does not seem possible unless one assigns substantial uncertainty factors which are difficult to quantify without theoretical and experimental evidence. The use of advanced 3-D models is probably inevitable for realistic predictions.
- In the region far from the mountain:

  i For an upwind concentration height (HC) greater than the depth of the mountain influence zone and a uniform distribution below HC, the question can be answered in the affirmative.

  ii For large HC but non-uniform distribution below, the calculations show that equivalent flat-terrain calculations are made possible by the introduction of the concept of the "effective mountain mixing height", H^*. The reference value of H^* is given by:

  $$H^* = \text{mountain height} + \text{flat-terrain boundary layer height}$$

  The calculations have shown that for narrow mountains this reference value has to be decreased somewhat. The calculations also indicate that stability influences H^*.

  iii If such flat-terrain calculations are applied when the pollutant upstream of the mountain does not extend well above the mountain top, predicted values of ground concentration far downstream of the mountain are likely to be valid. The particular calculations performed show an underestimation of concentrations by up to 20%.

With respect to future strategy concerning the availability of models that can treat satisfactorily complex terrain, the following recommendations can be made:

- features of complex-terrain effects should be included in the simple "flat-terrain" models. The suggestions and the ideas expressed in the present work might be useful for this purpose.
- the need for reliable predictions of wind and concentration fields in the regions near mountains, at reduced computational cost, may be fulfilled by "coupling" simple models and advanced models. By such means, the advanced models can be utilized only in specific regions of interest such as complex-terrain regions.

IV Radiological Aspects of Nuclear Accident Scenarios

A) Real-Time Emergency Response Systems

1. Participating Institutes

- Comitato Nazionale per la ricerca e per lo sviluppo dell'Energia Nucleare e delle Energie Alternative, Direzione Sicurezza Nucleare e Protezione Sanitaria (ENEA-DISP), 1044 Rome, Italy, R. Caracciolo, F. Desiato, M. Masone,
- Commissariat à l'Energie Atomique, Institut de Protection et Sûreté Nucléaire, Centre d'Etudes Nucléaires de Fontenay-aux-Roses (CEA-IPSN), 92265 Fontenay-aux-Roses, France, N. Parmentier, D. Robeau,
- Imperial College of Science, Technology and Medicine, Mechanical Engineering Department (ICSTM), SW7 2BX London, United Kingdom, H.M. ApSimon, B.M. Barker, J.N. Wilson,
- Gesellschaft fur Strahlen- und Umweltforschung, Institut fur Strahlenschutz (GSF), 8042 Neuherberg, Federal Republic of Germany, H. Müller, G.Pröhl, H.G. Paretzke.

2. Introduction

As part of the post-Chernobyl programme, the need was recognised for improved capabilities for the real-time assessment of accident consequences and emergency response procedures. Whereas such emergency response capabilities had hitherto concentrated on smaller accidental releases characteristic of design basis accidents, it was recognised as important to cater for a wider spectrum of accident scenarios, including those with potential consequences on a European scale. In particular, those responsible for decision making and the introduction of countermeasures would require computer-based support systems. This project has therefore worked towards the provision of key components of real-time computerised support systems, embodied in software packages to be made generally available for use in European Community countries.

These software packages include numerical models suitable for the simulation of the atmospheric transport, dispersal and deposition of a release over local (out to a few tens of kilometres at most), mesoscale (out to 100 to 200 kilometres), and long distances (over the whole of Europe). To aid in accidents where there are large uncertainties about the source term, packages have been developed addressing the deduction of estimates of the quantities of radionuclides released, by combining measurements and model simulations and optimising the agreement between them. Finally, as a tool to aid in the assessment of doses and the efficacy of possible countermeasures, a special package has been produced for dose assessment taking into account different exposure pathways.

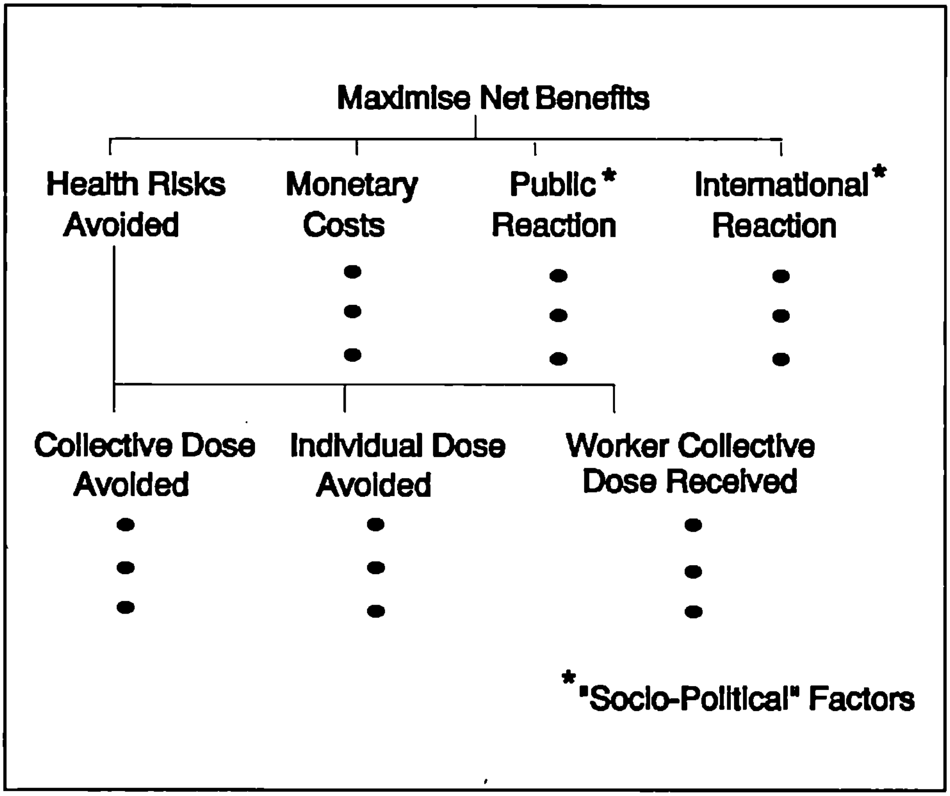

Figure 1 Generalised scheme for the structure of real-time emergency response systems.

The context in which these various components of a real-time support system may be used will vary in different European Community countries according to the particular arrangements for nuclear accidents and emergencies, and the division of responsibility at local, regional and national levels. A generalised scheme is illustrated in Figure 1, showing how the components may be linked to each other and to the relevant control centres.

In order to be able to fulfill their assessment and decision-making roles, these centres will also require access to information about the source and available radiological measurements, together with agricultural production, demographic and other relevant data prepared for such eventualities. This information is also required by the computer codes developed in this project, plus additional data, such as meteorological windfields for the atmospheric dispersion models.

From the outset, the software packages have been developed to be compatible with each other and to take account of the information flows required between them, as well as the needs of the assessment teams and decision makers. However, each package can also be used as a stand-alone module if required; for example the short-range model might be used at a local emergency centre close to a site. To make optimum use of the modules within an overall computerised real-time support system, high quality graphics packages to produce appropriate displays and maps will also be required. However, such packages will inevitably need to be individually tailored to the different requirements of different users.

4. Short-Range Atmospheric Dispersion

The objective of the short-range dispersion model in the real-time emergency response system is to provide a rapid evaluation for areas close to the site of the accident in relatively simple meteorological and terrain conditions. The model thus needs to be fast, and therefore relatively straightforward, and it also needs to be able to derive the necessary model parameters from few, simple input data, while at the same time maintaining flexibility with respect to the type of input data which could be available. Furthermore, the model should be suitable for use on a relatively small computer.

In order to satisfy the above criteria, a Gaussian puff model, SPADE (Sequential Puff for Atmospheric Dispersion Evaluation) has been developed. SPADE has been designed to estimate ground level air concentrations, deposition and cloud γ dose rate in flat or gently rolling terrain resulting from the dispersion of either stable or first-order decaying (e.g., radioactive) atmospheric pollutants. It is best suited for evaluation of plume behaviour out to about 20 km from the source. Model results beyond 20 km should be used with caution to 50 km, and as a screening tool for distances beyond 50 km.

The dispersing plume is simulated by a sequence of Gaussian puffs whose trajectories are determined from a single wind profile. Meteorological and source data are allowed to vary with time and the time interval between successive sets of data is flexible. The other major features of SPADE are:

- atmospheric stability and dispersion parameters may be derived by different methods based on the available measurements and the site characteristics,
- plume rise and buoyancy-induced dispersion are simulated,
- total or partial reflection from the top of the mixing layer is considered,
- puff number is controlled by merging adjacent puffs and deleting those away from the calculation domain,
- the point source can be located anywhere inside the domain to optimize the extent of the useful calculation area in the case of a prevailing wind direction,
- dry and wet deposition as well as puff depletion are modelled,
- an optional cloud γ dose model is incorporated in SPADE.

SPADE requires a set of time-independent data, like geographical data (domain size and coordinates), source characteristics (time of release start, pollutant species, deposition velocities), code parameters (duration of time step, times of required output analysis) and several sets of time-varying meteorological and release rate data. The required meteorological data are principally wind speed and direction, mixing layer height, rain intensity, and additional data for the estimation of atmospheric turbulence (cloud cover, wind direction fluctuation, or solar radiation).

SPADE calculates instantaneous and time-integrated air concentration, total deposition and wet deposition values on a 20 x 20 grid and at a maximum of 100 receptors located anywhere inside the calculation domain. The size of the grid interval is given as an input. The ground is assumed to be level, so no topographical data are required. The output analyses can be generated any time after the beginning of the release. The absorbed dose rate in air from a γ-emitting plume can be calculated by SPADE, as an option. However, it should be done only for a limited number of receptor points due to the much longer time the code takes to calculate the γ doses compared to the dispersion calculations.

As far as the limitations of SPADE are concerned, it must be emphasised that the current version uses only one set of meteorological data at a time and so does not allow atmospheric parameters and wind field to vary spatially. Thus, it should not be applied to complex terrain or meteorological situations. Additionally, gravitational settling is not treated by the model.

4. Mesoscale Atmospheric Dispersion

The mesoscale atmospheric dispersion code, MC31, has been developed to calculate atmospheric dispersion and deposition out to 100 to 200 kilometres from the source. Over such distances, it is necessary to allow for such complicating factors as complex terrain, urban areas, coastal regions and spatially and temporally varying meteorological conditions. To allow for such factors in simulating atmospheric dispersion, a Lagrangian approach has been adopted as the basis for the code, MC31, which, like the Monte Carlo methods used by Imperial College for the long-range model, treats the release as an assembly of particles tracked forwards in space and time, but is more in the nature of a stochastic model. The methods are based on work performed in the Soviet Union (Khintchine, Guikman, Skorokhod, Kolmogorov et al) and Japan (Ito). The model gives the spatial distribution of a radionuclide at specified times and accumulated deposition.

To apply the model, it is necessary to specify windfields and turbulence over a regular rectangular three-dimensional grid of cells, updated at regular intervals. Within this fixed grid, each particle is followed in a series of time steps. In each time step, the particle is moved in such a way as to represent advection with the wind plus a turbulent displacement, which is prescribed statistically. By considering a large number of particles, the distributions of radionuclide air concentrations over space and time corresponding to a release in the specified windfield and turbulence conditions are well represented.

The novel aspect of the model lies in the way in which the displacement of the particles is treated. Thus the forward motion of a particle is considered in the context of a moving box aligned along the mean wind direction local to the particle. The size of the box depends upon the windspeed and turbulence and the length of the time step: the larger the time step the larger the box, subject to the constraint that the box must be entirely within a single rectangular windfield grid cell, inside which the windfield and turbulence are constant. Additional constraints may further reduce the time step, for example, to ensure that it does not extend beyond the specified times at which the meteorological conditions are updated, or at which results giving air concentrations corresponding to the instantaneous spatial distributions of particles are required.

The maximum length of the time step and the dimensions of the box having been established, the next step is to consider the probabilities of the particle taking the various exit routes from the box during the time interval. More specifically, the particle may either be displaced to one of the corners of the box or it may remain at the centre, equivalent to it being advected by the mean wind velocity alone. The probabilities of these different results/destinations are calculated as functions of the box dimensions, time interval and turbulence components. The particle is then randomly assigned to one of these positions, according to their relative probabilities.

A similar statistical approach is taken in the representation of dry and wet deposition processes in the model. During each time interval, the probability of a particle being deposited by dry deposition is determined, according to the specified dry deposition velocity. Similarly, the probability of a particle being deposited in precipitation is deduced according to the prescribed washout parameter, and the occurrence and intensity of the precipitation. The flexibility of this approach allows a variable scavenging efficiency to be attributed to the precipitation according to the height of the particle. According to the probabilities of deposition, either the particle is removed to the ground and is no longer considered in the simulation, or it continues airborne into the next time interval. Radioactive decay is treated in a similar fashion.

The method is thus an economical and computationally efficient approach to simulating the atmospheric dispersion of a radionuclide in non-homogeneous conditions over complex terrain. However, it does require considerable additional computing resources in comparison with the short-range model SPADE. MC31 requires as input the source as a function of time, together with the relevant nuclide characteristics. Also, as is the case with the long-range model, 3-DRAW, MC31 requires externally generated three-dimensional windfields and precipitation fields to be specified over the model domain and it also requires turbulence fields to be similarly specified. These data can be obtained from a mesoscale forecasting model such as that operated by the French Meteorological Service.

The accuracy of the model depends on the numerical techniques used and the representativeness of the data supplied. The accuracy of the numerical technique is readily controlled by the number of particles considered (varying as Vn). Thus, the limiting factor is likely to be the accuracy of the meteorological data. In contrast to 3-DRAW, the simulation is restricted to consideration of nuclides characterised by a single decay constant in any one computer run.

5. Long-Range Atmospheric Dispersion

The programme, 3-DRAW, has been developed to model long range atmospheric transport and dispersion in real-time and predictive modes, using output from a meteorological forecasting model. In the design of 3-DRAW, several objectives were identified. The model should be capable of identifying those regions which are likely to be contaminated following an accidental release, and also give an indication of the scale of any such contamination. In identifying the likely scale and extent of contamination following an accident, the model should only utilise standard output from a meteorological forecasting model. The model was also to be compatible with the short-range and mesoscale models also under development. In addition, the model was required to calculate quantities which correspond to those observed in the field, and also the inputs to a dose response module, that is, atmospheric concentrations integrated over sequential periods and accumulated wet deposition. Lastly, the model should be capable of considering those nuclides which could give rise to significant consequences over long distances from an accident site.

The 3-DRAW model is a 3-dimensional random walk or Monte Carlo model, which differs substantially from the mesoscale model MC31. It is capable of simulating atmospheric dispersion and transport on a continental, or hemispherical scale, according to the meteorological forecasting model output used. A release is represented by a sequence of particles, which are advected through a windfield specified by the forecasting model, with random turbulent displacements from the mean flow. 3-DRAW can treat a number of different radionuclides simultaneously. Each particle represents a given activity of each nuclide under consideration, according to the magnitude of the release. Depletion processes (radioactive decay, and dry and wet deposition, according to the radionuclide) can then be modelled by depleting these activities, while still tracking all the particles released.

This method involves the release of fewer particles than are required when particle numbers themselves are depleted. The direct calculation of atmospheric concentrations, as described below, on a grid of cells at ground level according to the length of time taken by the particle in traversing the grid cell and the nuclide activities represented by the particle, further reduces the number of particles, and thus the computing resources needed. The Monte Carlo technique also has the advantage that the results can be interpreted as an indication of the probability of a particular area being exposed as well as giving an indication of the probable magnitude of exposures. In addition, it is comparatively straightforward to distinguish the contributions to exposures from different sections of an extended release, numerical diffusion is not a problem, and the technique is also ideally suited to parallel processing.

Horizontal winds are linearly interpolated in time and space, in the upper layers of the atmosphere, while a logarithmic wind profile is fitted between the ground and the lowest forecast wind level. Vertical winds are interpolated in time and height only, as they are normally specified as mean values over the forecast model grid elements. Super-imposed on the windfield is a dynamic boundary mixing layer which varies diurnally in height according to the underlying surface and whether or not it is raining. As a default option, the diurnal mixing layer profile is currently specified externally according to latitude and time of year. Within the mixing layer, horizontal turbulent displacements are derived as a function of wind shear across the mixing layer, while vertical turbulent displacements are represented by the random re-assignment of the particle height after each time step. Above the mixing layer, wind flow is assumed to be laminar; vertical turbulent displacement is ignored and horizontal turbulent displacement is assumed equivalent to that in stable air.

Exposures are accumulated on a grid which is specified independently of the forecasting model, as a function of the time spent by individual particles over each grid cell. Thus, time-integrated air concentrations and total dry and wet deposition are determined rather than instantaneous air concentrations and deposition rates. Particles only contribute to the mean time-integrated air concentration for an exposure grid cell when they are within the mixing layer above the cell. Particles above the mixing layer do not contribute to the surface air concentration, neither are they depleted by dry deposition, which is also restricted to particles in the mixing layer. Dry deposition is modelled by applying a nuclide-specific deposition velocity over the depth of the mixing layer.

The distinction between dynamic (or frontal) precipitation and convective precipitation which is normally made in forecasting models is usefully preserved in the modelling of wet deposition. Dynamic precipitation can reasonably be assumed to be uniform over the forecasting model grid and to deplete particles at all heights, with the removal of activity modelled by a washout coefficient. Convective precipitation on the other hand is non-uniform over the model grid cells, and is treated statistically in recognition of this, with particles either missing a convective cell, or entering either a low or a high rainfall area within the cell. Also, only particles within the mixing layer are assumed to be depleted by convective rainfall. The extent of the areas of low and high rainfall and the rainfall rates within them are derived from the mean convective precipitation rate in the model cell. The depletion of the activity associated with particles in such systems is modelled by a washout coefficient.

3-DRAW produces mean time-integrated air concentrations, dry and wet deposition, and rainfall encountered by the release, on an exposure grid, for successive 6-hour and 24-hour periods, as well as over the entire period of the simulation. It is thus able to generate output files which may then be used as input by the dose response module. The time-integrated air concentrations may also be represented as mean air concentrations over successive 6 hour periods. In addition, particle positions every 6 and 24 hours may also be produced as output.

The most significant requirement of the 3-DRAW model is the forecast wind fields and dynamic and convective precipitation fields from a forecasting model. The model is capable of operating when only horizontal wind fields are supplied, as these can be pre-processed to generate mass-consistent vertical velocities. The model may be initiated either from interactive dialogue with the user, from a file of source term data which may be supplied by a source term evaluation module, or by taking a file of particle activities and positions and advecting these forwards.

A first version of 3-DRAW has been designed, developed and subjected to preliminary testing within this contract. This model inevitably has several limitations which will require further development. The absence of a routine for the specification of the mixing layer height over the model domain is a significant limitation to the general applicability of the model. There are also several special situations which the model does not currently consider. The most important of these is the transport of a release in frontal regions, where the fixed time step used in the model can easily result in the advection of particles through the frontal surface. The whole question of the integration of the model results with field radiological data, in order to obtain a best estimate of the pattern of exposure, has still to be addressed in any detail.

It is hoped to address these topics in future work. For example, the proposed investigations into particle transport in the vicinity of fronts will involve considering the identification of such regions from the forecasting model wind fields, rainfall and available synoptic output. Then, in the light of this investigation, alternatives to the current method of linear interpolation of the wind field and advection with fixed time steps, which are more appropriate to known patterns of atmospheric motion in frontal regions, need to be identified and developed. In addition, the applicability of the 3-DRAW model to parallel processing on a transputer-based system, which would yield a substantial saving in computer time and resources required, also warrants further study.

6. Source Term Estimation

In the early phase of an accident the assessment of the radiological scenario is almost completely based on the modelling capabilities. The effectiveness of this kind of evaluation, however, depends on the availability of important data, like meteorological conditions and source term, that can usually be received earlier than field measurements. As the situation evolves, this last type of data becomes available and it is very important to integrate radiometric observations and model predictions with the aim of reducing uncertainties and optimizing the assessment of the accident consequences. The complexity and effectiveness of the "feed-back" processes depend on the quantity and quality of measured data and on the model capability. The approach can be simplified if attention is focused on the optimization of a subset of parameters.

Modules for the estimation of the source term can be considered a specific category of feedback models and their availability becomes very important where there is a lack or breakdown of release monitoring instruments.

In the present research programme two such modules were developed: STEP and STAR. STEP is based on a few simple considerations about the uncertainty of the concentration field produced by a dispersion model and its comparison with monitoring data available in emergency situations. Thus, after running a dispersion code with unit source rate, STEP rotates the computed concentration pattern until the best correlation between observed and calculated patterns is reached. The average ratio between observed and computed values at sample points is then the estimated source term.

STEP does not depend on the particular dispersion model adopted: it can be applied in conjunction with any model, provided its output is in the form of a matrix of concentration values on a fixed Eulerian grid.

The application of STEP is limited to all the cases for which the assumption that the computed concentration pattern is similar to the measured one is reasonable, i.e., it should not be applied in very complex terrain situations or wherever some crucial input parameters of the dispersion model, like the effective source height, are very uncertain, or in rapidly varying meteorological or source term conditions.

STEP has been tested in two different ways. Firstly, it has been evaluated against a set of data collected during two meteo-diffusive campaigns (1983 and 1984). The results showed that in about 90% of the episodes the emission rates have been predicted within a factor 2 and in all within a factor 3. Secondly, a study was performed, simulating a release of radioactive material and varying some meteorological input data, to investigate the STEP sensitivity with respect to the uncertainty of atmospheric stability, horizontal wind fluctuation and wind direction.

The results showed that STEP's performance is not very sensitive to the inaccuracy in the horizontal dispersion and the average wind direction evaluations. It is sensitive to the atmospheric stability, but the results are generally still acceptable if the correct stability category is missed by one and sometimes two categories. The only critical case is that of an elevated release in stable conditions. These preliminary results of the STEP test are encouraging. The model needs to be validated against further experimental data to be applied with sufficient confidence in real emergency situations within the limitations specified above.

The STAR code adopts a more global approach to the problem than the STEP code. STAR uses air concentration and deposition measurements made in a given zone to obtain best estimates of the source term, the dispersion model transfer parameters, and the overall air concentration and deposition fields.

This kind of method is fundamentally different from those approaches that assign standard values to the environmental transfer parameters and then use them with a hypothetical source, either to work out concentration fields, or in conjunction with radiological measurements to work back to an estimate of the source term. In STAR, on the other hand, all or part of the set of environmental transfer parameters, as well as the source term, become unknowns within the problem, as do the values of air concentration and deposition required. Only the radiological measurements and perhaps some of the environmental transfer parameters are fixed parameters.

Thus, the measurements are used as a basis for determining the values of the source term and the environmental transfer parameters, thereby yielding the best air concentration and deposition fields that are supported by the measurements made. The above objectives are typical of optimum control problems. It is known how to construct various types of models of atmospheric transfers which are sufficiently accurate when the model parameters are well enough known. However, the parameters used in the model fluctuate a great deal or are not known exactly, and it is often only possible to specify a range of values.

In order to provide an operational solution to the problem, the method proceeds by linearizing the solution of the atmospheric transfer equation with respect to the various parameters. Then a mathematical programme is defined, made up of constraints on the variation of atmospheric transfer parameters and constraints which ensure that the values given by the solution of the atmospheric transfer equation lie within a range determined by the radiological measurements. The solution of the mathematical programme is a set of parameters satisfying the constraints and optimising the so-called "economic function". If the constraints and economic function are linearly related to the parameters, this mathematical programme is termed a "linear programme".

The so-called "simplex" method was chosen by CEA to solve this mathematical programme, now reduced to a linear programme. This method has the advantage of not being limited to a simple stage of adjustment: it enables the performance of sensitivity analyses and the implementation of processes which aid decision making.

It also makes it possible to pick out the most incongruous radioactivity readings or the most inadequate parameter values. But other methods of optimisation can be used to solve this kind of optimum control problem.

The linearisation of the solution of the atmospheric transfer equation is a problem that can be approached more or less easily, according to the method used to resolve the equation. For example, at one extreme an exact calculation of the derivative could be replaced with a finite increments calculation. In a particular study, the calculations of the derivatives of the analytical solutions to the diffusion-convection equation obtained using the Gaussian plume resolution method can be used. In this case, derivatives of atmospheric concentration are expressed with respect to the following parameters: horizontal dispersion, vertical dispersion, discharge height, height of the mixing layer, deposition rate, washout rate, windspeed, and the source term of a given radionuclide.

The wind direction can be considered as a parameter only if a plume model is used. In this case, the best fit is calculated for a given direction. The goodness of the fit is qualified by the value of the optimised economic function. A gradient method based on the decrease of the economic function in the space of parameters identifies the best fit: the minimum of parameters including the parameter "wind direction".

7. Dose Assessment

The management of the situation after large-scale radioactive contamination of the environment requires a fast and reliable tool for the prognosis of the radiological consequences for the population concerned. For this purpose, the dose assessment program system, EURALERT, has been developed.

Starting from the radioactive contamination of the near-ground air and of precipitation at up to 1,000 locations, the radiation exposure at these locations is calculated. All relevant exposure pathways are considered:

- the external exposure from radionuclides in the air,
- the external exposure from radionuclides deposited on the ground,

- the internal exposure due to inhalation,
- the internal exposure due to the ingestion of contaminated foodstuffs.

EURALERT consists of two different programme modules, one which allows a fast assessment of the most important doses and contamination of foodstuffs for all locations, and one which allows a more detailed calculation of these quantities at individual locations. Together, these results give an overview about the expected doses for different age groups and the importance of the pathways considered, and give a first indication about the necessity and effectiveness of countermeasures. The spatial distribution of predicted doses identifies the areas of greatest concern. Additional programmes are available for considering quantitatively the potential reduction of doses by implementing different countermeasures, for example:

- the introduction of intervention levels for activity in foodstuffs,
- temporary changes in human consumption rates and feeding management for domestic animals,
- recommendations to the public to stay indoors.

EURALERT has been developed to take into account the experience obtained from the post-Chernobyl application of the radio-ecological model ECOSYS. The external exposure is estimated taking into account the shielding efficiency of houses and the time spent indoors and outdoors in urban and rural areas. For the inhalation dose estimation, the filtering effect of houses can also be considered.

The food chain module in EURALERT considers seventeen plant foodstuffs and sixteen animal foodstuffs. For the calculation of the initial contamination of the plant, dry and wet deposition are modelled separately taking into account the seasonally dependent development of the plant canopies. The activity concentration in plant products at the time of harvest is estimated from the loss of activity due to weathering and physical decay, the growth dilution and the transport of radionuclides within the plant from the foliage to the edible parts.

From the activity concentration in feedstuffs, those in animal products (milk, beef, pork, eggs, etc) are calculated taking into account the kinetics of the radionuclides in the animals. The loss or enrichment of activity in plant and animal products during processing and culinary preparation is considered as well as the decay of activity during storage. The ingestion dose results from the time-dependent activity concentrations in the foodstuffs and the human consumption rates; besides mean consumption habits, those of critical groups can be applied. The dose assessment is done under the assumption that food is produced locally; it is also possible to consider it being partly imported from uncontaminated areas.

For every location at which the activity in air and precipitation is given in the input file, the respective dose to an individual at this location is calculated. If a location is representative of a certain area (i.e., if the activities in air and precipitation are mean values for this area) the resulting dose is to be regarded as a mean dose of this area and, when multiplied by the number of inhabitants of this area, yields a rough estimate of the collective dose within the area. Variations in the individual doses within an area which are due to variations in individual consumption habits or agricultural practices, etc, can be estimated by re-running the programme with different values of these parameters.

The model results are written to data files which can be printed or used for graphical output (e.g., maps of contamination or doses, graphs of time dependency of activity concentrations or doses). The software to prepare the graphics has to be provided by the user.

For every location for which the dose assessment is to be performed, EURALERT requires those quantities which control the contamination of the different plant types and the soil during the deposition event:

- the time-integrated radionuclide concentration in the near-ground air,
- the nuclide-specific activity deposited by precipitation per unit area,
- the amount of precipitation.

These input quantities can be predicted by the atmospheric dispersion codes developed in collaboration with this module, and their output can be directly used for the dose assessment. On the other hand, if the above quantities have been measured at certain locations it is possible to base the dose predictions on these measured values.

The external γ exposure from the radioactive cloud is dependent upon the extent of the dispersion of the cloud. At small distances from the release point, assessment of the external γ exposure from the cloud requires knowledge of the cloud geometry. Consequently the absorbed γ dose in air has to be provided by the dispersion model. An adequate model is included in the SPADE code for the short range. This is not necessary at greater distances, and EURALERT calculates absorbed γ dose in air as well as organ doses and effective dose by assuming a semi-infinite homogeneous cloud.

The simulation of the transfer of radionuclides through food chains requires many parameters describing the different processes. In addition, data such as the habits of people staying indoors and outdoors and the shielding of γ radiation by houses are needed for the assessment of external and inhalation exposure. Many of these parameters vary to a high degree within the different countries of the European Community. The programmes have, therefore, been designed to be easily adaptable to the different conditions. The programme system is delivered with a data base that is representative for German conditions. All model parameters are in data files which can be edited. The selection of adequate values of all model parameters has to be done by the user who applies the model to regions with different conditions. For the future it is planned to provide default values of all model parameters for all regions of the European Community.

Further future development of the EURALERT code will address the consideration of additional foodstuffs which are of importance for some regions of the European Community, and the extension of the data base for additional radionuclides.

8. Summary and Future Requirements

Software packages have been developed under a collaborative project, as five major components of a computer-based support system for use in emergency response systems in European Community countries in the event of a nuclear accident. These packages incorporate numerical models to simulate atmospheric dispersion locally, near the source (SPADE), over mesoscale distances, out to a few hundred kilometres

(MC31) and on a continental scale (3-DRAW). The models reflect the particular requirements and complexities over these different distances, within the context of a nuclear accident emergency.

In addition, attention has been given to combined interpretation of radiological measurements and model estimates, particularly in those situations where there are large uncertainties in the source term and the relative quantities of different nuclides released. The STEP and STAR modules provide alternative approaches to using available measurements and model estimates to make deductions about the source term; STAR also optimises model parameter values and the agreement between the observed and estimated data.

The introduction of countermeasures and their effectiveness will depend on both the levels of the exposures and the reductions in doses that the countermeasures can achieve. A flexible module for dose assessment (EURALERT) has therefore been provided. This estimates doses from different exposure pathways based on levels of contamination in near-ground air and deposited on the ground in precipitation, which may be supplied either by the dispersion models or directly from measurements.

These packages have been developed in the overall context of a computerized real-time emergency response system, and attention has been given to making them compatible with each other. However, each package may also be used individually where appropriate; for example, the short-range model could be applied alone at a local emergency centre at the accident site. All the codes have been written in FORTRAN 77 and implemented on the same system (VAX). Detailed technical descriptions of the models, the concepts on which they are based and the computational techniques used are given in the combined project report, together with an indication of the data and computational resources required. User manuals are already available for some of the packages, although additional work would be required to make them more user friendly, a highly desirable attribute of any computer-based support system, especially those designed to provide assistance in emergencies.

Future requirements

The main limitations and uncertainties have been discussed at joint meetings during the the project and have led to the identification of areas where useful improvements can be made. In addition, the need for more work on model validation and testing has been recognised.

The accuracy and uncertainties in the various types of model estimates produced depend only partly on the models themselves. They are largely limited by the representativeness of the data available, which is likely to vary greatly according to the particular accident situation. How these uncertainties can be effectively communicated to the decision-makers in an emergency is also a difficult problem.

Certain contributory factors can be identified where more detailed consideration and evaluation are desirable. These include, for example, topographical effects, demographic and geographical aspects and agricultural practices; also, complex meteorological situations such as frontal systems, or stagnant anticyclones where wind directions are highly variable. The probable significance of such factors will vary throughout Europe. There are also several processes which have not yet been allowed for, such as deposition in mist and fog, or gravitational settling and the complicating effects of buildings on the dispersion of the release close to the source.

Further attention is also required as to how model components may be integrated into overall emergency response and assessment procedures. Although the interfaces between the software packages developed under this project have been defined in relation to the data transferred between them, there are further considerations. For example, there may be a step between supplying an average wet deposition value based on rainfall averaged over a grid cell in a dispersion model mesh, and the identification of potential "hot spots" within that area which may be critical for dose impact and countermeasures' assessment. Similar problems apply to the interfaces between dispersion model output and measured data.

More work is also required on the combined interpretation of radiological measurements and modelling results and the "feed-back" between the two, for example the updating and revision of modelling estimates of dispersion and contamination, as measurements become available. There are also major tasks involved in the provision of high quality graphics and the clear presentation of assessments according to user needs. Bearing in mind the rapid advance in computer technology it is also worthwhile considering the potential for improvements to the models that these advances will permit. Thus, parallel processing techniques could introduce significant improvements in the costs and operating speed of the Monte Carlo dispersion models.

In conclusion, in developing and expanding these software packages, it is important to lay sound foundations for the development of emergency response procedures, not just for the present but also for future decades.

B) The RADE-AID System

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2. Introduction

If an accidental release of radionuclides occurs, it may lead to an increase in the exposure of individuals to radiation and, hence, to an additional health risk in the exposed population. The significance of this additional health risk will very much depend on the magnitude and characteristics of the release and the subsequent environmental contamination. Depending upon the assessed significance of the resulting health risk, countermeasures may be implemented to reduce the exposure of the affected population.

In order to provide guidance for decisions on countermeasures, international recommendations have been developed. These are necessarily generic in nature and need to be developed in more detail in emergency plans for specific sites and situations. Such site specific emergency plans take account of local factors, such as the population distribution, the type of potential accidents and the available resources for implementing countermeasures. However, site specific emergency plans cannot provide detailed guidance for all postulated accident scenarios and variations in local conditions. Instead, the plans combine specific and quantitative advice with an allowance for flexibility of response, recognising the importance of informed judgement concerning the actual situation as an input to decisions on countermeasures.

The aim of the RADE-AID project is to develop a computer system which can be used to support the formulation of decisions on countermeasures following an accidental release of radionuclides. The system is intended to be an aid following an actual accident and a tool for assistance in planning and training. Possible uses include: aiding the determination of planned intervention levels and withdrawal criteria, the development and exercising of emergency plans, the training of those responsible for making decisions following an accident and analysis of the decision-making process itself.

This summary describes the problems inherent in formulating decisions on countermeasures and the manner in which RADE-AID can assist in addressing these problems. The final section presents some stylised applications of the RADE-AID system, which illustrate its use and the form of support which it can provide in the decision-making process.

3. The Problem

The purpose of introducing countermeasures after an accidental release of radionuclides is to reduce the exposure of (and hence, the health risk to) individuals. However, the consequences of taking countermeasures are not limited to the reduction of exposures. There will be other consequences, some beneficial, some harmful, and it is necessary to take account of all these consequences when formulating decisions on countermeasures.

Principles have been developed for the introduction of countermeasures which recognise this need to take account of all the beneficial and harmful consequences. The first principle states that no countermeasure should be introduced unless it produces more good than harm, i.e., the introduction of the countermeasure should be justified. The second principle states that the countermeasure should be introduced in a manner which maximises the net benefit. This is known as optimisation, and is complementary to the principle of justification.

In order to determine whether the introduction of a countermeasure is both justified and optimised, it is necessary to evaluate all the beneficial and harmful consequences of introducing that countermeasure. Apart from reducing the radiation health risk to the potentially exposed population, the major beneficial consequence of introducing countermeasures is likely to be the re-assurance provided to individuals because action has been taken. However, there may be a wide range of harmful consequences, depending on the countermeasure involved. Some countermeasures may involve physical risk to individuals, for example, evacuation undertaken in adverse weather conditions such as fog or ice. Most countermeasures will involve a monetary cost, although the level of expenditure will range from relatively small amounts for short-term, small-scale countermeasures (e.g., sheltering within a small area) to very large amounts for such countermeasures as widespread decontamination or food interdiction. Moreover, the nature of all the monetary costs will not be same. For example, intervention measures will require the expenditure of money, whilst the interdiction of economically productive land will result in the loss of potential income. Other possible harmful consequences are disruption to the normal or anticipated lifestyles of individuals and population groups, exposures to workers involved in implementing the countermeasures (particularly intensive decontamination), anxiety in the affected population resulting from the knowledge that countermeasures are required, and repercussions on international relations and trade.

The first problem is quantifying all these very different types of consequences. Whilst some are, at least in theory, straightforward to assess (e.g., monetary cost) others, particularly social consequences such as disruption, re-assurance and anxiety, are much more difficult to quantify.

The second problem is that the beneficial and harmful consequences of taking countermeasures are unlikely to be shared equitably. In terms of the health risks, the risks resulting both from exposure to radiation and from implementation of the countermeasure vary between individuals, and particularly with age. For example, elderly people may be at greater physical risk from the introduction of countermeasures (particularly evacuation) than younger people, whilst their risk of incurring cancer, as a result of radiation exposure, is substantially lower. Another way in which the health risks may be shared unequally concerns workers, since workers deployed in the contaminated area (e.g., for informing the public on the countermeasures to be introduced, for facilitating evacuation or for carrying out decontamination) may receive enhanced exposures compared with those of the people they are protecting. Monetary costs are also unlikely to be shared equitably. For example, where there is disruption to trade the costs may be borne by individuals and firms located well away from the area in which the countermeasure is implemented. Finally, there is likely to be an inequitable sharing of the social costs of countermeasures. For example, whilst the decision to take action may provide re-assurance to one group of individuals, the knowledge that such action is necessary may result in increased anxiety for others. Again, if an area of land is interdicted, individuals' leisure and work activities may be significantly disrupted, or, if individuals are moved out of an area, the receiving communities may experience serious social upheaval. It is clear, therefore, that decisions on countermeasures raise questions of social equity; social value judgements must be made in order to determine how widely the harmful consequences of countermeasures should be shared.

A third problem concerns the possible over-reaction of the public to a countermeasure. For example, if a particular food is interdicted for concentrations exceeding a given level, then the public may avoid purchasing that type of food entirely. Again if people are relocated from an area, other individuals, outside, but relatively close to, that area, may perceive themselves to be at risk and so move away, causing consequent social problems for both the area they leave and the place they move to. Finally, there may be pressure on the decision-maker to take countermeasures in order to demonstrate to the population that caring action is being taken. However, if action is taken then this may reinforce a belief that the situation is life-threatening.

It is therefore clear that any decision to introduce countermeasures must take account of a number of different factors. These factors may often compete, in the sense that ensuring the best outcome for one may result in a less favourable outcome for another. It is therefore necessary to balance all the factors, weighing one against another, in order to determine what are the best courses of action in a particular set of circumstances.

It is recognised that the conclusions of this balancing process may be dependent upon the exact circumstances at the time of the accident. The radiological, economic and, particularly, the political and social circumstances will determine both the magnitude of the beneficial and harmful consequences of introducing given countermeasures, and the degree to which they influence the final decision. For example, it is entirely possible and reasonable that, given an accident which affects different places, possibly at different times, the decisions taken on countermeasures for each of these places may differ. What is important for the decision process is that all the important factors can be shown to have been assessed, so that the best actions may be taken in each particular situation.

4. The RADE-AID System

a) General Decision-Aiding Techniques

It has been shown in the previous section that the problem facing decision-makers following an accidental release of radionuclides is one of balancing many complex and competing factors (hereafter called "criteria"). Decision-aiding techniques have been developed for, and applied in, a wide range of situations involving competing criteria. Their usefulness is firstly based on the way in which they help the problem to be structured and broken down into its component parts and, secondly, on the way in which they support the decision maker in working with the formal selection process to find an optimal solution to the problem. In this way, specific aspects of the problem can be addressed explicitly and insights gained into their significance for the final decision.

A review was carried out of the different techniques which are available in order to determine the best approach for the RADE-AID decision logic. Of these, three techniques were short-listed for more detailed consideration: cost benefit analysis

(CBA), analytical hierarchy process (AHP) and multi-attribute value/utility technique (MAVT).

Some applications of CBA provide very similar features to those of MAVT, and it was recognised that, in certain situations, CBA techniques may be appropriate for aiding decisions on countermeasures. However, it is difficult, within the CBA framework, to take into account explicitly the preferences of decision-makers for competing criteria. Furthermore, it may be difficult (or impossible) to express certain criteria in monetary terms. Finally, it is also difficult to extend the CBA methods to take account of the valuation of uncertainty. This last disadvantage of CBA must not be confused with sensitivity analysis. Sensitivity analysis is always possible, but it merely explores uncertainty in the magnitude of consequences, not uncertainty in the nature of these consequences. Since these are all aspects of the problem RADE-AID is designed to address, it was decided not to use CBA for the system.

AHP supplies an explicit structuring and analysis of the problem, but it is not ideal for enabling trade-offs to be explored and expressed. Also, if the set of criteria is revised, it is necessary to re-evaluate all the trade-offs and preferences for every criterion, regardless of whether they were considered in the original analysis. One of the advantages of AHP is that it enables internal consistency checks on these trade-offs and preferences to be made. This aspect of the method has been used in the RADE-AID system as an optional technique.

MAVT is a well-developed and proven method for evaluating options in decision situations involving multiple criteria. The technique combines relatively straightforward mathematics and clear logic structure, with flexibility and ease of interaction with the user. Explicit trade-offs can be made between the criteria, and the relative importance attributed to the outcomes of different options, evaluated against a single criterion, can be specified directly. Finally, the technique can be extended to address uncertainties about the predicted outcomes of decisions to value the risk involved and to balance it against other criteria. For these reasons MAVT was selected to form the basis of the decision logic for the RADE-AID system.

b) Description of the RADE-AID Decision Logic

The most important feature of the RADE-AID decision logic is the emphasis on careful structuring of the problem, so that it can be broken down into a number of discrete steps. It is intended that information from each of these steps (i.e., not just the final step) may be used by the decision-maker as input to the decision. The steps can be summarised as follows:

- the identification of decision criteria,
- the identification of decision options,
- the calculation of the consequences of each decision option in terms of the criteria,
- the valuation of the consequences and the determination of the relative importance of the criteria,
- the overall valuation and ranking of the decision options in terms of the stated criteria,
- the exploration of the sensitivity of the ranking to changes in the valuation of the consequences and to trade-offs between the criteria.

The first step is to define the problem in terms of the desired objectives. Following any accident, the objective must be to act in a way which is both justified and optimised (as discussed in Section 3). In other words, the objective must be to maximise the net benefits, taking into consideration the possibility of introducing no countermeasures. This overriding objective can be described in terms of subsidiary criteria, and these can be sub-divided further into a number of even more detailed criteria. This sub-division can continue until a set of criteria has been defined which is helpful in terms of evaluating the consequences of different countermeasures' options.

In order to facilitate this structuring of the criteria, RADE-AID enables the user to construct a visual representation of the problem in the form of a criteria hierarchy. An example is helpful in this context. Following an accident which results in the contamination of milk by iodine-131, the maximisation of the net benefits may be split into four criteria which are considered to be important for the implementation of milk bans: the health risk avoided, the monetary cost and the adverse response of the population and the international community. Depending upon the available information and the nature of the situation, a useful further sub-division of the "health" arm might be: "collective dose avoided", "individual dose avoided" and "collective dose received by workers implementing the countermeasure". The criteria hierarchy for this example is shown in Figure 2. In RADE-AID, this hierarchy may be constructed interactively by the user, with each "arm" of criteria being split down to the level of detail most helpful for the problem. Moreover, if, following investigation of the problem using RADE-AID, the initial structure is found not to be ideal, it may be readily altered as necessary.

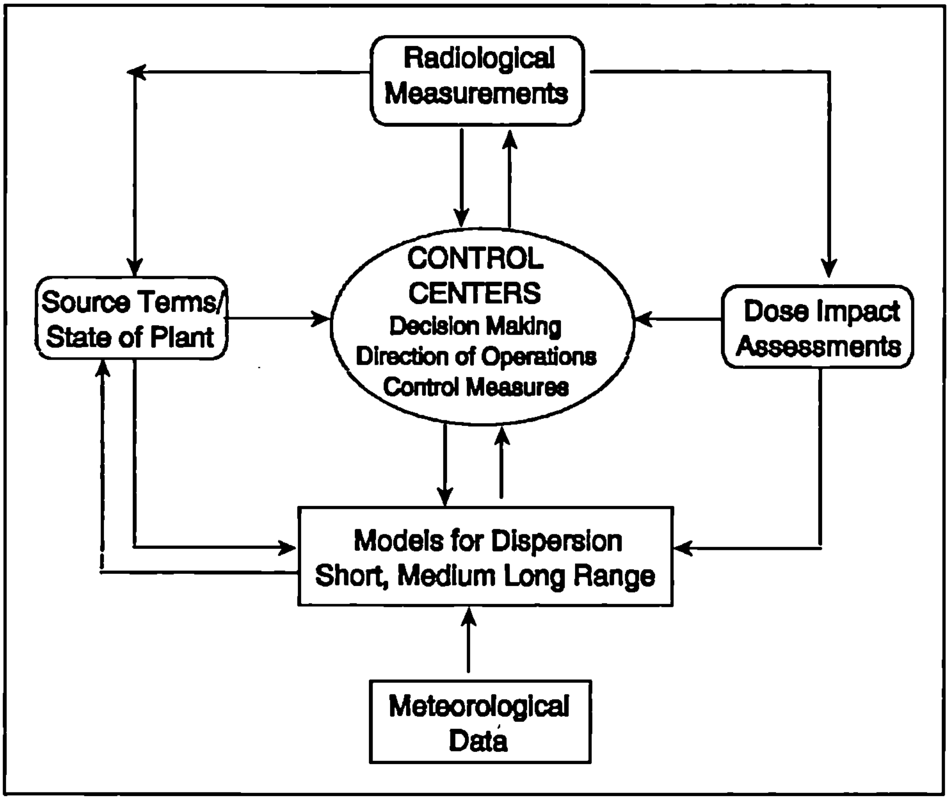

Figure 2 Illustrative Criteria Hierarchy.

Once the criteria have been clearly set out, the user must specify the decision options available. In theory, there may be a very wide range of options, but in reality, practical and political constraints may limit this range significantly. Taking the above example, the range of decision options might be to set a milk ban for intervention levels of concentration ranging between 10^2 Bq l^{-1} and 10^4 Bq l^{-1}. As with the decision criteria, it may be helpful to describe these options in finer detail, for example, by specifying the disposal options which may be possible for the contaminated milk, in conjunction with each intervention level option. Generally, it is helpful to limit the number of countermeasures' options considered; often it is most profitable to specify a few options which bound the possible range, and then, by using RADE-AID iteratively, to refine the options which appear most promising.

The consequences of taking each countermeasure option are then evaluated against the decision criteria. The evaluation is typically performed by the use of models or expert judgement.

After the determination of the consequences (either qualitatively or quantitatively) a relationship between consequences and the degree of appreciation of these consequences has to be established (for each criterion). In RADE-AID this valuation is measured on a scale between 0 and 1, where 0 indicates that the consequence of the countermeasure option is appreciated least, and 1 indicates that it is appreciated most. It is also possible not to assess the consequences of countermeasures and the valuation explicitly. In this case, a valuation of the countermeasures is performed by directly assigning values to specific options.

Having defined the problem and evaluated the consequences of different options in terms of the criteria, the decision-maker then specifies the overall importance of each criterion for his decision (i.e., he assigns weights to each criterion). These weights may reflect both the range of the consequences evaluated for each criterion and the general importance of the criterion itself. The effect of the range of consequences on the weighting of a criterion may be illustrated as follows: if the monetary costs of the milk bans varied between £10^4 and £10^8, whilst the collective doses saved only varied between 100 man Sv and 1000 man Sv, the scale on which monetary costs are valued will need to be longer than that for dose saved, and the relative weight assigned to the criterion will need to be correspondingly greater.

The weights should clearly also reflect the importance of that criterion. In particular, the weighting of the criterion of adverse public response would be expected to reflect very strongly the attitude of the decision-maker; some decision-makers might assign a relatively high weight to this criterion, almost regardless of the range of actual scores evaluated against it. This may be demonstrated by comparing particular points on different criteria scales. RADE-AID provides several procedures for eliciting these weights and enables the user to select the procedure most suited both to his way of thinking and to the problem.

At this point, each option has been assigned a set of values which reflect how well each criterion is met by that option, and each criterion has been assigned a weight which indicates its relative importance to the decision. RADE-AID combines the values with the weights to evaluate the overall ranking of the countermeasures' options in terms of how well they achieve the stated criteria. This process gives each option a score between 0 and 1, 1 indicating the most preferred option. All the options are presented to the user, together with their scores, so that the ranking can be examined. Graphical displays enable the user to investigate the effect on the overall ranking of options of varying the relative weights of the criteria.

c) Use of RADE-AID

RADE-AID has been designed to allow it to be used iteratively for planning and training purposes, although it is unlikely that this facility will be of value in its use following an accident. In the preliminary stages of planning, the problem may be poorly understood and the significant factors only very poorly quantified. However, by using RADE-AID to gain insight into the problem, and also into the stability and robustness of the ranking of countermeasure options, the decision-maker can be helped to structure his thinking and identify more clearly the reasons for and implications of his decision.

One of the important features of the RADE-AID system is that it enables trade-offs between the benefits and the harmful consequences of taking different courses of action to be explicitly addressed and explored. These trade-offs are based on the judgement of the decision-maker. They depend on the decision-maker's assessment of the relative desirability of taking each action, with respect to their consequences, and on the relative importance he attaches to each type of consequence. Trade-offs are personal; there can be no objective or universal rules for making them.

It is important to recognise that whilst the use of decision-aiding techniques can help to make the reasons for decisions clearer and to target the expenditure of resources into appropriate areas, they can also be indiscriminately rigorous, in that all aspects of problems which might have been overlooked or assessed intuitively may be explicitly addressed and evaluated. It is therefore important that the level of resource applied to the decision should match the importance and complexity of the problem to be solved. The RADE-AID system is being specifically developed to enable the appropriate level of resources to be utilised in different applications. Default data and supporting guidance are being collected to assist users in applications where detailed research is not warranted. Where better information is available or desirable, or where the decision is intended solely to reflect the judgement of the user, the system will accept alternative input generated by the user.

In the preceding paragraphs, the general operation of the RADE-AID system has been described. RADE-AID is an evolving system, and the prototype version which has been developed under the present contract does not include every feature which would be desirable in such a system. For the prototype system emphasis has been placed on development of the decision logic and user-friendly interaction with the decision-maker, for both the elicitation of criteria, values and weights, and the performance of sensitivity analyses. Less emphasis has been placed on the calculation and display of relevant information concerning the radiological situation and other factors. In the prototype, the data necessary for the decision process have to be provided from outside the system. This prototype system has been designed to run on IBM-compatible Personal Computers.

It should be emphasised that RADE-AID is not intended to replace the role and judgement of the decision-maker. It is intended as a decision-aiding tool, not a decision-making machine. Given a decision problem with competing criteria, a decision-maker must necessarily assess the consequences of various alternatives and value them according to these criteria. This process may be achieved intuitively or explicitly. The advantage of performing the analysis explicitly, using formal techniques, is that the process is clearly structured and it is less likely that important factors are overlooked. Moreover, by indicating which aspects of the problem are crucial to the decision, and which are not, resources can be channelled to obtain the information necessary for formulating the decision.

5. Illustrative Applications

In order to explore the appropriateness of the decision logic for the management of radiological emergencies, two illustrative applications were considered. These explored the use of the decision logic for decisions on countermeasures against external exposure and on food interdiction. The applications were deliberately stylised both for simplicity and to illustrate the possibilities of the system. The purpose of these illustrative applications was solely to demonstrate whether the prototype system forms the basis of an appropriate and flexible decision-aiding tool. However, the structures developed for the problems and the associated data are considered to be appropriate for providing assistance with planning.

The two applications were chosen to explore the introduction of very different types of countermeasure, the first involving the potential relocation of people and the potentially resource-intensive operation of decontamination, and the second involving the combinations of actions which could be taken to reduce the exposure of the population from contaminated foods. In addition, different procedures were used for valuing the consequences of countermeasure options in terms of the criteria, and for eliciting the relative weights assigned to the criteria. In this way, the use of the system was explored as fully as possible. For the purposes of these illustrations it was assumed that the countermeasures for external exposure and food interdiction are completely independent.

The two types of problem (control of external exposure and control of foods) have been structured using the same fundamental criteria. These are the health risks avoided, the monetary costs, and the adverse public and international reaction. These criteria are those illustrated in Figure 2. Depending on the application and valuation approach (i.e., direct or indirect) adopted, these criteria hierarchies were further split so that the more general criteria were more precisely defined.

a) Control of External Exposure

One possible long-term exposure pathway, following an accidental release of radioactive material, is external exposure from radionuclides deposited on the ground. If this occurs, there are two types of countermeasure which can provide protection for individuals in the contaminated area; the individuals may be moved out of the area until the levels of radioactivity have reduced, or the area may be decontaminated. If both types of countermeasure are carried out, then the decontamination of land and property will reduce the time for which individuals must be kept out of the area.

The criterion for introducing relocation is generally specified in terms of a dose rate; for decontamination, a target level of decontamination is commonly defined. The problem for the decision-maker is therefore to determine which countermeasures, if any, should be carried out, and to specify the appropriate criteria for them. (In practice, the problem is more complex, because other aspects of the decision, such as how quickly people from different areas should be moved out, the appropriate dose rate to allow return from relocation and whether some areas should be preferentially decontaminated, also need to be addressed. However, these aspects were omitted from the illustrative applications.)

For the purposes of exploring the use of the RADE-AID decision logic, two highly stylised accident situations have been postulated. They are each identical in magnitude and release characteristics, but one is assumed to occur in an area of relatively low population density (site A), whilst the other is assumed to occur in a more densely populated area (site B). The assumed releases are very large, representing the rapid release of about 1% of the volatile core inventory of a large (gigawatt) reactor.

The criteria defined in the hierarchy in Figure 2 were represented by ten proxy attributes which it was considered might be more easily quantifiable than the primary criteria. These included such factors as the numbers of people initially relocated and the perceived acceptability of the intervention level used. These attributes were used as performance indicators for the various options, with regard to the criteria concerned. The choice of these attributes reflected the judgements and preferences of the authors; it was recognised that they would not necessarily encompass all the factors of concern to decision-makers. However, it was judged that they formed a sufficiently comprehensive set for the purposes of illustrating the application of the system.

The possible countermeasures options at each site were defined to be a set of five different intervention levels for relocation, ranging from 5 mSv y^{-1} to 100 mSv y^{-1}. Since much of the land around site A was assumed to be agricultural or parkland, it was assumed, for simplicity, that decontamination of the land would not be carried out (or at least, only in relatively small areas). However, for site B, which was assumed to be mainly urban or industrial the option of decontamination was considered.

Use of RADE-AID to explore these scenarios proved very useful in providing insights into the problems posed and also in indicating where more research was required. Two specific illustrations of these benefits are discussed below. However, it should be remembered that any conclusions drawn result from the personal preferences of the authors and are not intended to reflect necessarily the conclusions which others would draw.

It became apparent that although the consequences of taking the same countermeasures at the two sites were often very different (e.g., fewer people were affected for site A), this would not necessarily result in the adoption of different intervention levels at the two sites. Clearly, the choice of intervention level depends upon the preferences and weights expressed for the various consequences, but since a reduction in detrimental consequence (e.g., number of people relocated) was usually accompanied by a reduction in a beneficial consequence (e.g., collective dose saved), consistent assumptions regarding the criteria often yielded similar conclusions regarding the best intervention level for the two sites.

RADE-AID showed that unless very significant weight was attached to the criterion of monetary costs, then the uncertainty on the calculated costs did not influence the overall decision, and so significant refinement of these calculations would probably not be warranted.

b) Control of Food

Internal radiation exposure to members of the public through ingestion of contaminated foods may be limited by the imposition of food bans. In the present context, food bans include all methods by which consumption of contaminated food may be prevented; whether by disposing of contaminated food or by reducing its contamination using processing or storage before it is available for consumption. Following Chernobyl, food was banned if the concentration of radionuclides in it exceeded given intervention levels. This approach was used in the stylised applications of RADE-AID for food bans.

If a decision is taken to ban food with activity concentrations greater than a specified intervention level, then it is necessary to determine how food exceeding these levels should be dealt with, and also, how future contamination of foods above the intervention levels can best be avoided (e.g., natural or forced decontamination of land, or feeding alternative feeds to livestock). Such decisions may be quite complex. For example there may be several radionuclides to control (each with different physical and chemical properties), and the ease with which control measures may be applied may vary with soil type, weather conditions and the agricultural practices of the area. Moreover, there will exist external constraints in terms of the resources (e.g., equipment and storage facilities) which can be utilised. Some possible courses of action may result in additional doses to workers or even to the general population.

For the illustrative application of RADE-AID it was decided to consider only the imposition of grain bans. The harvesting of grain occurs discretely (and has been assumed here to occur only once a year) and this makes it easier to model the consequences of taking different countermeasures. However, it is judged that the consideration of grain bans provides a sufficient demonstration of the potential of RADE-AID as a decision-aiding system for the control of other foods.

For the example applications four releases were considered which cover a broad range of characteristics with respect to the temporal and spatial extent of food bans. Three releases of different magnitudes were assumed to occur in summer, whilst the fourth was assumed to take place in winter. The winter release and two of the summer releases consisted of a mixture of iodine-131, caesium-134 and caesium-137. The remaining summer release contained only iodine-131.

For the countermeasures' options, three intervention levels of activity concentration for each radionuclide were chosen, spanning two orders of magnitude. In addition, a set of options for dealing with the banned grain, and the land that produced it were specified. These included storage, processing and disposal of the banned grain and various types of decontamination measures applied to the land.

The criteria hierarchy shown in Figure 2 was extended for the monetary arm, but not for the socio-political arm. This was to enable the use of the direct valuation of options against the two socio-political criteria to be explored. Supporting information concerning the extent of bans, the amount requiring disposal, etc, was calculated and presented to the user to assist in the direct valuation.

These applications demonstrated a number of features of the system. The ability to screen out, from the decision logic, countermeasures which could never achieve the stated criteria (e.g., situations where it would not be practical to store the milk until contamination levels had reduced below the intervention level) was useful for reducing the number of options which were presented to the user, and hence the perceived complexity of the problem. Exploration of the ranking using the sensitivity analysis facilities was useful in providing deeper insights into the problem and for identifying those options which warranted more detailed investigation. A comparison of the winter and summer accidents clearly showed that the optimum countermeasures vary with the time of year at which the accident occurs.

c) Discussion

The illustrative applications demonstrated that RADE-AID can form a useful tool in the determination of decisions on countermeasures. A number of aspects of its usefulness were highlighted, and these are discussed below.

The structuring of the problems in terms of the criteria hierarchies and the identification of factors relevant to the decision helped in the thorough exploration of the problem and an explicit consideration of which were the key criteria. This meant that when the consequences of taking various actions were presented, their significance was more readily appreciated and quantified.

The explicit consideration of all types of consequences and the presentation of information relating to them provided useful insights into the decision problem. For example, consequences which might generally be considered important might be shown to have no influence for a particular accident scenario, or consequences could be identified as being a potentially very significant factor in the decision.

The explicit assigning of weights and values also deepened understanding of the decision problem. It encouraged the thorough consideration of each of the criteria and their relative importance. It also required the user to assimilate properly the information provided by the consequence predictions, so that meaningful values and weights could be assigned. Thus, this step, again, encouraged deeper insights into the decision problem and, therefore, into the best solutions.

The overall ranking of the countermeasures options, by the system, in terms of the expressed preferences of the user, was helpful in two respects. Firstly, it often clearly indicated countermeasures options which could be excluded from further consideration (i.e., those at the bottom of the ranking order). Secondly, it triggered re-evaluation of those options which were ranked towards the top of the ordering. This was particularly important in cases where the initial ranking appeared to be counter-intuitive. In this case, re-examination of the problem and the weights and values assigned would reveal the reasons for this ordering. It was then possible to decide whether the inputs required changing, or whether, in fact, the overall ranking did, indeed, reflect the relative merits of the options.

The facilities for exploring the sensitivity of the ranking to the assigned weights were found to be particularly helpful. Using these displays, it could be seen clearly which inputs were dominating the ranking, and those to which the overall ranking was most sensitive. Where the ranking was sensitive to a particular value, the accuracy of the prediction leading to the assignment of that value could be assessed and conclusions reached concerning the robustness of the evaluation. Similarly, where the ranking was sensitive to the magnitude of a particular weight, the degree of belief in that weight could be assessed and conclusions drawn. Equally, the sensitivity analyses could be used to show the range of possible rankings which might reasonably be achieved by varying the values and weights within what were judged to be reasonable bounds. In this way, options could be identified which would never be optimum, and also the range of options which could be justified reasonably well could be seen.

6) Conclusions

The choice of the appropriate type and level of intervention to mitigate the radiation exposure of the population after radioactive contamination of the environment requires a balance to be achieved between a variety of competing criteria. The magnitude of these criteria may vary with the accident characteristics, and their relative importance may be sensitive to political and social value judgements. The radiological decision-aiding system, RADE-AID, uses decision analysis techniques to compare and rank different intervention strategies by considering both directly quantifiable factors and factors of a socio-political nature. The user can interact directly with the system, so RADE-AID can help the decision-maker to explore the consequences of and reasons for his decisions.

A prototype version of RADE-AID has been developed. This computer programme comprises the full decision logic, together with facilities for assigning weights, constructing criteria hierarchies and value functions, and performing sensitivity analyses on the influence of changing the weights. It can be made available to interested institutions on a research basis. It is hoped that, through this interaction with other researchers, enhanced progress on this project can be achieved. In this phase of the project, emphasis has been placed on the development of an appropriate decision logic and procedures for eliciting value judgements and weights from the user. Subsequent development will include enhanced facilities for presentation of supporting information.

In order to explore the usefulness of the RADE-AID decision logic, some stylised applications have been considered. These involve decisions on the implementation of countermeasures to reduce external exposure and the imposition of food bans to reduce internal exposure. The results demonstrated that use of RADE-AID can provide insights into the decision problem, and so assist the user in determining the appropriate course of action. They also highlighted areas where improvements in the system would be beneficial. These were generally aspects of the system which had been previously identified for development in the next phase of the project.

Future work will concentrate on the presentation of supporting data and extensions to the decision logic and sensitivity analysis functions. However, the most important aspect of future work will be to discuss the application of RADE-AID with decision-makers. If RADE-AID is to be of assistance to decision-makers then it is important that its further development be carried out in conjunction with them. In this way, guidance can be developed on the appropriate structuring of countermeasures problems, and the valuation of consequences and relative weights to criteria, so that the system can be tailored to the requirements of those with responsibility for deciding on countermeasures after an accident.

IV Monitoring and Surveillance in Accident Situations

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2. Introduction

Monitoring and surveillance after an accidental release of radionuclides to the environment can be considered in four categories:

- detection of the accident,
- early measurements to determine the need for countermeasures,
- continuing surveillance of radionuclides in the environment, in foods and in people; until the situation returns to normal, to assess doses, to demonstrate that countermeasures have provided adequate protection and to provide public reassurance,
- research studies, to follow the behaviour of radionuclides in the environment, in foods and in people so as to improve predictive models.

Experience gained as a result of the Chernobyl reactor accident suggested that there was scope for improvement with respect to the practical aspects of the measurement and collection of reliable data and their communication in suitable forms to the decision-making authorities and the public. Studies were required to define how the multitude of measurements required can be made rapidly and reliably by various organisations, and how their standardisation and harmonisation can be achieved.

The Commission therefore re-directed its programme to accommodate additional research programmes concerned with preparedness for monitoring and surveillance of any future accident. Seven research contracts were initiated as a result. Progress achieved in the course of these one-year contracts is summarised below. Conclusions are drawn and recommendations made for future work.

In the context of the post-Chernobyl action, attention should also be drawn to the programme "Radioactivity Environmental Monitoring" (REM) initiated by the CEC and carried out at the Joint Research Centre at Ispra. Several of the aspects mentioned below are also dealt with in the REM programme.

3. Accident Detection Networks

There were two contracts concerned with the detection of unusual levels of dose rate and the interpretation of readings from simple dose-rate instruments and alarm monitors.

One, by Walmod-Larsen et al of Risø National Laboratory, Denmark, was concerned with development of a nation-wide on-line early warning monitoring network with high sensitivity to accidental discharges and good discrimination against variations in natural radiation levels. The objective given to the Laboratory was that the system should be able to detect an increase due to man-made radionuclides corresponding to a 10% increase in the natural background level.

A test station was constructed consisting of:

- a wide-range ionisation chamber, with a range of 0.01 $\mu Sv\ h^{-1}$ to 100 $mSv\ h^{-1}$;
- a NaI (Tl) detector with a multi-channel analyser;
- a rain intensity gauge.

The instrumentation is controlled by a micro-computer, which stores the data and transmits data to a central computer via the public telecommunications network. The hut housing the equipment is temperature controlled.

Data from the ionisation chamber have been collected for more than two years. Careful analysis of the rate of variation of dose rate and rainfall rate have led to the formulation of an algorithm that permits an alarm to be raised if the dose-rate level increases by 5% in dry weather or 20% in wet weather.

Detailed analysis of the results from the NaI(Tl) spectrometer has led to the following procedure: The spectra obtained are analyzed by fitting spectra from the naturally occurring isotopes ^{40}K and Rn daughters. the remaining counts beyond a preset level, taking counting statistics into account, is then expected to be caused by man-made radionuclides.

The objective of being able to detect an increase in the natural dose rate level due to man-made radionuclides corresponding to a 10% increase seems to be achievable by the system.

A nation-wide network of eleven stations has been set up to act as an early warning system for deposition of man-made radionuclides on Danish territory.

The second contract in this category was by Ortega et al of the Universidad Politecnica de Catalunya. The contract consisted of: a survey of monitoring networks in members states of the European Community; analysis of results obtained over a two-year period from networks around two nuclear power stations sited in Spain, calculations of detector response to natural and man-made radionuclides in the environment; development of calibration techniques for environmental dose-rate monitoring; development of a new electrometer for use in measuring environmental dose rates.

The survey addressed the existence of monitoring networks at the time of the Chernobyl reactor accident as well as networks planned or implemented since that time. The environmental surveillance systems in existence at the time of the accident were mainly in research centres or at nuclear power stations sites. All systems proved sufficiently sensitive to detect the Chernobyl radioactivity. As a result of the accident, most countries developed plans for national monitoring networks, but little consideration has been given to linking networks between countries. The networks are largely based on Geiger-Muller counters, although ionisation chambers are used in some. Provision has also been made in some plans for measurement of radionuclides in airborne particles and radio-iodine in both particulate and vapour forms.

The existing networks in Catalonia consist of four measuring stations around each of two nuclear power station sites. Each station has a monitor for measuring environmental dose rates in the range 0.01 $\mu Sv\ h^{-1}$ to 100 $mSv\ h^{-1}$. This wide range is achieved by the use of two Geiger-Muller probes. Each station is connected to a computer on the power station site which then transmits data to a control computer at regional government headquarters. A detailed analysis has been made of data from these monitoring stations collected over a two-year period. The availability of the stations has been between 75% and 90%. Most failures were probably due to breakdowns in the data transmission telegraphic lines. During the two-year period studied, there were eight occasions when abnormal values were observed i.e. values higher than three standard deviations above the mean of all measurements obtained in the previous six days. Correlations have been observed between rainfall and increase in dose rate, with a time delay of between one and two hours.

A mathematical model has been developed to predict dose rates due to natural and man-made radionuclides in the environment. To provide validation of the model, dose rates on beaches along the Catalan coastline were measured with an ionisation chamber and samples were collected for laboratory analysis of radionuclide content. Good correlation was found between the measured and calculated dose rates.

4. Dose-rate measuring instruments

Burgess et al, National Radiological Protection Board, UK, have evaluated five instruments suitable for measuring environmental background dose rates and assessed their suitability for use in emergency situations. Four of the instruments tested were those commonly used within the European Community, but one relatively new instrument was included. The instruments were: three scintillation detectors; one energy-compensated Geiger-Muller detector; and one high pressure ionisation chamber.

A comprehensive evaluation programme was followed. Laboratory measurements included: linearity tests, to determine the variation in response with indicated dose and dose rate; energy response, to check the variation in response with changes in photon energy; polar response, to investigate the variation in response with changes of direction of incident radiation, tests of sensitivity to changes in temperature and humidity; determination of battery life under normal conditions. In addition, each instrument was evaluated in the field to assess ease of use in realistic operating conditions.

High-pressure ionisation chambers show the quickest response to changes in gamma radiation levels, but all the instruments tested are capable of giving a reliable indication of significant changes in environmental dose rates. The instruments which use scintillation detectors operating in the current mode show the greatest variations in response when subject to significant temperature changes. This is a disadvantage for field measurements. In contrast, instruments based on high-pressure ionisation chambers and energy-compensated Geiger-Muller detectors are much less sensitive to temperature changes.

All instruments were also evaluated by making measurements at a number of sites including areas of normal and elevated natural radionuclides, an area of high deposition of Chernobyl radiocaesium and an area contaminated with industrial discharges. The evaluation considered matters such as ease of use, portability, weather proofness and time taken to make a measurement. Details are given in the full report.

5. Measurement of surface contamination with ß-emitting radionuclides

Lauterbach et al, Physikalisch-Technische Bundesanstalt (PTB), FRG, have evaluated commercially available surface contamination monitors. The evaluation was carried out in collaboration with 18 institutes which measured surface activity sources calibrated at PTB. The radionuclides were chlorine-36, cobalt-60, strontium-90/yttrium-90 and promethium-147, and the instruments involved in this programme were mainly Geiger-Muller counters, scintillation detectors and proportional counters with methane, butane, xenon or a mixture of butane and propane as filling gases.

Measurements were taken under carefully controlled conditions by trained operators who knew the identity of the radionuclide. Even so, the activities reported by the participants varied over almost an order of magnitude, even for instruments of the same type. In the case of accidental contamination, the composition of the radionuclide mixture could be quite complex and not known. It is recommended that measurements with portable contamination meters should be used to distinguish between more and less contaminated areas and as a guide to where samples should be taken for laboratory measurements; the reading of the instruments should not be used as an indication of the true surface deposit, without careful evaluation of the measurements.

6. In situ gamma-ray spectrometry

Bramati et al (ENEL, Italy) have evaluated the technique of in situ gamma-ray spectrometry for measurement of surface concentration of radionuclides and radiation exposure rate in accidental contamination situations. The instrumentation was selected on the basis of compact size and light weight, together with a high level of efficiency and resolution. The detector was a hyper-pure germanium detector with 1.76 keV resolution and 20% efficiency at 1.3 MeV. The cryostat of 7 litres capacity permitted operations for 3 to 4 days before refilling with liquid nitrogen was required. The rest of the equipment included: a portable analyzer, a personal computer with hard disk and printer; a telescopic tripod for mounting the detector. This complete set of equipment was contained in two cases with a total weight of 60 kg. Ancillary equipment included: a generator to provide the power supply of the printer; 25 l dewar for liquid nitrogen storage. A surface concentration of 10^4 Bq m^{-2} can be measured in a few minutes, at 3% confidence level.

The performance of the in situ gamma-ray spectrometry technique was evaluated in two measurement campaigns; one in an area of low natural activity but high Chernobyl deposition; the other in an area of high natural radiation and low Chernobyl deposition. In addition to in situ gamma-ray spectrometry, dose rates were measured with two different instruments and soil samples were collected for laboratory analysis. All measurement results agreed well. However, it was noted that gamma-ray spectra acquired in the field with simple processing equipment require careful analysis by trained operators.

7. Rapid methods of radionuclide analysis

In the immediate aftermath of an accidental release of radionuclides into the environment, measurement of activity concentrations in environmental materials are required rapidly to aid decisions on the need for countermeasures. In the case of accidental releases from nuclear power reactors, most of the radionuclides of potential radiological importance are gamma-ray emitters and so their activity concentration can be determined directly by measurement with high-resolution germanium detectors and the minimum of sample processing. However, other potential types of accidents releasing other radionuclides should not be neglected and Green and Wilkins (National Radiological Protection Board, UK) have evaluated rapid methods of radiochemical analysis for actinides and for radioisotopes of strontium.

Published procedures for the radiochemical isolation of actinides were reviewed and it was found that none offers particular advantages in terms of speed. All procedures are quite complex and it was therefore recommended that, in an emergency, laboratories should make use of their established and validated methods. For many environmental materials, the plutonium content can be determined by alpha spectrometry following radiochemical isolation within 20 hours, with results for higher actinides being available the following day. Unfortunately, results for air filters, a medium of urgent interest, can only be achieved on a longer timescale because of the greater time required for ashing.

The capability of direct measurement of the low-energy photons with hyper-pure germanium detectors was also investigated. This technique is of practical use only when used for measurement of the photon emissions from the decay of ^{241}Am. Inference of the content of plutonium isotopes then requires knowledge of the radionuclide composition of the release.

The normal procedure for determination of strontium-90 in routine analyses requires measurement of the beta emissions of its decay product, yttrium-90, following a delay of about 3 weeks for ingrowth. Such a protracted procedure is clearly unacceptable in an emergency. Furthermore, strontium-89 may also be present. A method based on the determination of strontium-89 by Cherenkov counting and subsequent measurement of strontium-90 by liquid scintillation counting has been tested and validated. Full details are given in the report.

One of the most important recommendations is that the required detection limits should be specified in advance so that sample sizes can be decided. This is of fundamental importance because the time required for sample preparation is dependent upon sample size.

8. In vivo measurements

Where possible, direct measurements of radionuclides in the human body provide independent confirmation of doses estimated from limited environmental measurement and predictions of human intake by inhalation and ingestion following transfer of radionuclides to foodstuffs. Experience following the Chernobyl reactor accident has shown that they are also more directly reassuring to members of the public than are such calculations.

Pellerin et al (SCPRI, France) have continued development of mobile monitoring facilities, designed primarily for measurement of iodine isotopes in thyroid and gamma-ray emitting radionuclides in the human body. The equipment used for whole body measurement can also be used for measuring radionuclides in environmental samples. The philosophy was to choose standardised units that could be deployed in small vans, in large trucks or in a specially-designed railway carriage. The intention is to be able to perform measurements on a large number of people anywhere within France within 24 to 48 hours after an accidental release of radioactive materials. The equipment could also be made available for use elsewhere in Europe.

9. Conclusions and Recommendations

1. Perhaps inevitably, most contracts focused on monitoring and surveillance following accidents at nuclear installations which would involve the release of gamma-ray emitting radionuclides. One (Green and Wilkins) considered the measurement requirements for accidents involving a substantial release of actinides and radioisotopes of strontium and one (Lauterbach et al) considered surface contamination with beta-emitting radionuclides. Emergency response planning, at the national level, must consider accidents that may not release gamma-ray emitting radionuclides. Specific consideration should be given to accidents involving nuclear weapons or satellites powered by plutonium sources.

2. Since the Chernobyl reactor accident, many countries have developed national monitoring systems to detect accidental releases of radionuclides. These are mostly based on dose-rate measuring devices. Consideration should be given to:
   - linking data from national networks into a Community-wide network,
   - improved methods of distinguishing increases in dose rate due to accidental releases from natural variations in background levels,
   - automatic air-sampling and analysis, so as to provide immediate identification of the radionuclides involved in an accidental release. An independent evaluation of currently-available equipment would be useful.

3. None of the contractors in this programme considered sampling from aircraft to determine the extent and composition of the plume of radioactive material. Techniques for isokinetic sampling of particle- and gas-phase radionuclides from aircraft exist. Some consideration should be given to the availability of suitable equipment and aircraft within the Community and to how such data can be used in predictive modelling of the trajectory of the plume and estimating the radiological consequences for the areas affected.

4. Several contracts within this programme considered various methods of measuring surface deposition of radionuclides: gamma-ray dose-rate measurement (Burgess et al); surface contamination measurement (Lauterbach et al); in situ gamma-ray spectrometry (Bramati et al). Dose-rate measurements are easy to do, but difficult to interpret; they should be used as a guide to areas

where further investigation is required. Surface contamination measurements appear to be difficult to undertake in a consistent manner. In situ gamma-ray spectrometry provides the necessary information, but requires expensive instrumentation and experienced operators.

5. None of the contractors considered aerial surveillance of deposited activity. This can be achieved by deploying dose-rate measuring instruments (but the same limitation applies as above) or high-resolution germanium detectors in aircraft. Measurement techniques and mapping techniques exist. Consideration needs to be given to the administrative arrangements needed so that adequate monitoring of affected areas of the Community can be achieved rapidly in order to demonstrate to the public and to decision makers that all affected areas have been identified.

6. There is a need for simple screening of contaminated goods, animals and people, in order to distinguish between those uncontaminated and those requiring further investigation. The interpretation of such measurements will depend upon the radionuclide composition, and appropriate advice needs to be given for each particular circumstance.

7. Experience following the Chernobyl reactor accident suggests that there is a need for measurements of radionuclides in people, as a means of reassurance.

8. In the event of an accident, many organisations will undertake measurements of dose rates and of radionuclides. There is a need to provide guidance in advance of any future accident on sampling, measurement and reporting procedures, so as to ensure the quality and comparability of the data.

9. There is a need for central collation of data, both at national and at Community level. More consideration needs to be given to methods of data handling, display and interpretation both for public information and for decision making.

10 Emergency response plans must be prepared in advance of any accident, they should be regularly reviewed and updated, staff must be trained and procedures must be followed.

V. Underlying Data for Derived Emergency Reference Levels

1. Participating Institutes

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2. Introduction

After accidental releases of radioactive material to the atmosphere leading to significant off-site contamination, various countermeasures will need to be introduced to reduce the radiation exposure of the population. These countermeasures may include: sheltering, evacuation and issuing of stable iodine, together with imposition of restrictions on agricultural production and relocation of the affected population. In many cases the banning of foods would be an important countermeasure. This report is concerned with the underlying information that is required for calculating derived intervention levels (DILs) for foodstuffs.

The introduction of countermeasures affects the normal lives of the people concerned, and therefore undesirable social or economic consequences may follow. It is the task of the competent authorities to make decisions, taking into account the positive as well as the negative effects of planned countermeasures.

The International Commission on Radiological Protection (ICRP) has specified the most important criteria to be considered when planning an intervention as follows:

- serious non-stochastic effects should be avoided,

- the risk of stochastic effects should be limited by introducing countermeasures which achieve a positive net benefit to the individuals involved,
- the overall incidence of stochastic effects should be limited by reducing the collective dose equivalent until the consequences of further reducing the health detriment in the affected population are balanced against the cost of further countermeasures.

The ICRP approach has been accepted, in general, by national and international authorities as the basis for emergency management and this has led to Derived Intervention Levels generally expressed in terms of projected individual effective dose equivalents. However, positive as well as negative consequences of countermeasures may change with local, seasonal and other conditions. Thus, the result of a cost-benefit analysis will depend on the specific situation. This inhibits the setting of one dose level at which a specific countermeasure has to be introduced. Therefore, ICRP and CEC have proposed a set of two dose levels for intervention, the Emergency Reference Levels. The lower value is the dose below which the countermeasure is not likely to be justifiable. Derived intervention levels should be given as well, expressed in terms that are applicable to the results of the measurements that form part of a special monitoring programme (IAEA, 1982). In the case of contaminated food this might be radionuclide concentrations in food products. For practical reasons the CEC and other international organizations, such as FAO or WHO, have taken the lower level as the basis for deriving levels for foodstuffs.

Prior to the Chernobyl accident, several international organizations defined emergency reference levels of dose (ERLs). However, no general guidance is available for setting derived intervention levels (DILs) for food. The problem was addressed by the CEC, through the Article 31 Group of Experts which proposed a methodology for determining derived intervention levels for different classes of foods.

The concept is described by the equation:

$$A = \frac{E}{V*D*f}$$

A Derived intervention level in Bq kg^{-1} (Bq l^{-1});
E Intervention level of dose in Sv y^{-1};
D Effective dose per unit ingested activity in Sv Bq^{-1};
V Consumption rate of foodstuffs of concern in kg y^{-1} (1/y);
f Relative contamination factor, definition according to the Group of Experts: fractional contamination of a foodstuff in relation to the considered intervention level; $0<f<=1$.

The need was recognised for a compilation of data that would allow more detailed calculations and an examination of the adequacy of the proposals of the Article 31 Group of Experts.

In 1987, the CEC set up a programme of work to consider underlying data for derived intervention levels. This report represents the results of this programme of work. The areas considered are data on radioecological models, distribution and consumption of foods, internal dosimetry, critical group considerations, emergency management, and the effects of countermeasures on doses.

3. Food Chain Modelling

A number of dynamic models for the transfer of radioactivity through the terrestrial food chain exists in the European Community (EC). One of the aims of this programme of work was to make recommendations on a general model suitable for use in the EC. This model could then be used to calculate derived intervention levels in the absence of site specific information. Two dynamic food chain models, ECOSYS and FARMLAND formed the basis of this work. ECOSYS was developed at the Gesellschaft für Strahlen- und Umweltforschung (GSF) in the Federal Republic of Germany, and FARMLAND was developed at the National Radiological Protection Board (NRPB) in the United Kingdom.

a) Model Validation

Predictions of both ECOSYS and FARMLAND were compared with sets of environmental measurements to test the validity of the models in a variety of situations as a first step in recommending a general model.

Data sets for model validations were readily available for the Federal Republic of Germany and the United Kingdom, but no suitable data are available for the Mediterranean countries where the climate and agricultural practices are different. The majority of data available for the model validation studies were for the pasture-cow-milk pathway.

The model predictions of ECOSYS were compared with measured data in four areas: the interception of wet deposited activity; the pasture-cow-milk pathway; and the transfer of activity to meat and grain.

The measured and predicted interception factors agreed with many measured results within 10 percent, with the largest differences being about a factor of two. The predictions of the transfer of caesium and iodine to milk were generally in good agreement, usually within a factor of two of the measurements and often closer. Good agreement was also obtained comparing ECOSYS predictions against results from feeding experiments concerning the transfer of caesium from feed to beef. Concentrations of caesium-137 in the various types of grain were measured in the Munich area following the Chernobyl accident. Assuming an average deposition for the area, concentration in grain was predicted by ECOSYS. Given the large local variations in deposition, the predictions agreed well with the measured concentrations.

For validating the FARMLAND model, data sets were used for the pasture-cow- milk pathway, the activity in beef, the activity in sheep meat and the activity in grain. In comparing the FARMLAND predictions with measurements for the pasture-cow-milk pathway, the overall transfer was broken down into components.

In general, the predicted concentrations of ^{131}I, ^{90}Sr, and ^{137}Cs in grass agreed well with the measured concentrations, but in cases where the deposition occurred during heavy rainfall, large differences between measurements and predictions could be observed. In comparing the data on activity in sheep and beef the overall agreement was reasonable, taking into account the boundary conditions of the measurements. For grain, the predicted concentration fell within the range of measured concentrations for the various cereal types.

In summary, both ECOSYS and FARMLAND were in reasonable agreement with measurement data in a variety of situations. FARMLAND has been developed as a general model and default model parameters were used in the comparisons. This tended to lead to greater differences than found using ECOSYS, a more detailed model that takes into account more site specific factors, notably relating to deposition.

b) Comparison of Model Predictions of ECOSYS and FARMLAND

Following the validation exercise, the two models ECOSYS and FARMLAND were compared in a number of situations.

The sub-models for the prediction of the deposition of radionuclides to plant and soil are rather different. FARMLAND does not differentiate between dry and wet deposition, and seasonal variation due to the development of the plant canopies is not taken into account. For both wet and dry deposition, a constant interception factor is applied. In contrast, in ECOSYS dry deposition is modelled taking into account the stage of development of plants which is characterized by the actual leaf area index at the time of deposition. For the estimation of interception of activity deposited in rainfall, an approach is used considering the stage of crop development, the water storage capacity of plant leaves, and a parameter describing the ability of the radionuclide to be fixed on the plant. These different approaches in modelling dry and wet deposition are an important reason for the differences found in the comparison of the two models.

The translocation of radionuclides from the foliage to the edible parts is modelled in a similar way in ECOSYS and FARMLAND. In this comparison only winter and spring wheat is considered, and for winter wheat, especially at the beginning of the growing period, translocation rates are assumed in FARMLAND which are much higher than those assumed in ECOSYS.

The approach for estimating the contamination of plants due to root uptake is similar in both models. There are some differences in the soil-plant transfer factors but they do not lead to substantial differences in predicted concentrations. The assumptions made about the soil mass and the leaching of radionuclides out of the root zone cause differences in the predicted activity concentrations which are of minor importance. There are some differences in the parameters modelling the transfer of radionuclides to animal food products. For strontium the differences are of little importance, and for caesium the transfer factors for beef and cow's milk are more than a factor of two different.

c) Choice of a Default Model for the Transfer of Radionuclides in the Food Chain

Based on the results of the model validation and the model comparison, a version of the model was proposed which had default parameters for translocation, root uptake, transfer to animals, and agricultural practice and which can be applied to all regions of Europe when no country-specific parameters are available. Different fields of applications are suggested due to the varying complexities of modelling of deposition and interception. FARMLAND uses a generic approach, and is therefore suitable for use in accident assessment codes and for situations where only limited information about the deposition and the contribution of dry and wet deposition is available. ECOSYS uses a complex approach that is more appropriate for application in real-time dose assessment systems, for specific sites in emergency situations when different weather conditions have to be considered, and when information about the deposition characteristics is available from monitoring networks.

Using the default model and parameters, activity concentrations as well as time-integrated activity concentrations are calculated for spring and winter grain, potatoes, leafy vegetables, root vegetables, milk, beef, lamb and pork after deposition on 1 January, 1 May and 1 July.

After deposition during the growing period, the biggest part of the integrated activity concentrations results from the contamination in the first year which is due to the effectiveness of the foliar uptake. Exceptions are the activities of Sr-90 in potatoes and root vegetables. In most cases the integrals are significantly higher (up to more than an order of magnitude) after depositions in May or July compared to deposition in January.

There are significant variations in farming practice and crop growing periods within the countries of the EC. To evaluate these effects on the concentrations in foodstuffs, Europe has been divided into four regions according to climatic conditions and farming practices. Concentrations in food were calculated for each region using the "default" food chain model with the appropriate farming practice for each region. Results were obtained for winter wheat, spring wheat, potatoes, leafy vegetables, milk, beef and sheep meat.

4. Food Consumption Habits

Food consumption in the different countries of the European Community and consumption of different subgroups of the population were investigated and compared with the assumption made by the Article 31 Group of Experts.

Firstly, information on average annual consumption of ten classes of food and drink was collected for the entire population of each EC country. All quantities were expressed as consumption of the raw, unprepared product. In general, collected data refer to 1986.

Subsequently, variations in food consumption between subgroups of the population were studied due to influence of age, sex, social class, season, level of urbanization, regional habits and level of self-support.

Three sources of data on food consumption were used. Food supply balance sheets were available for all countries and were used for the evaluation of national food consumption. These food balance sheets use statistical data on production, imports, exports and stock variations to establish amounts available for consumption of individual inhabitants of the country, averaged by age, sex, etc. The calculated individual amounts usually overestimate real consumption, because losses in the retail shop and the home (due to decay, damage, waste and use of food for pets) are not taken into account.

Household budget surveys and food consumption research data, which are often thought to give a more reliable estimate of real consumption, were available in some cases and used to study food consumption of subgroups in the population.

a) Food Consumption in Various Countries

The estimates of the average annual food consumption rates for individuals in all EC countries for 1986 are based on food balance sheets. For application of the data in calculations, the national diets were generalised by grouping countries with a fairly homogeneous diet and three groups of countries were defined.

Group 1 consists of the United Kingdom and Ireland (19% of the total population of the EC). The diet is characterized by a low consumption of fruit and a high consumption of potatoes and fresh dairy products.

Group 2 consists of Italy and Greece (21% of the EC population). Consumption of cereals, vegetables and fruit is high, and consumption of fresh dairy products is low.

Group 3 consists of France, Belgium and Luxembourg (BLEU), the Federal Republic of Germany, the Netherlands and Spain, and accounts for 56% of the total population of the EC. The group is less homogeneous than the first two groups and represents intermediate consumption of most foodstuffs.

Two countries (Portugal and Denmark) could not be classified with any of the three groups. Portugal has the lowest individual total consumption per year (80% of the average of the entire EC). Consumption of cereals, potatoes, vegetables and fish is high, consumption of fruit, milk plus milk products and meat is low. The Danes favour milk products, pork and fish, and consume few cereals, potatoes, vegetables and fruit. For the three groups of countries and for the entire EC ("average EC citizen") mean diets were calculated.

When comparing the consumption rates of the "average EC citizen" with the assumed mean adult food consumption adopted by the Article 31 Expert Group for deriving intervention levels, the data for cereals, dairy products and meat agree rather well.

For cereals, an average consumption rate of 100 kg y^{-1} is assumed by the Article 31 Expert Group, the estimated mean value is 84 kg y^{-1} with a range between 58 kg y^{-1} in the Netherlands and 115 kg y^{-1} for Italy. A similar range has been found for meat: 55 kg y^{-1} in Portugal and 106 kg y^{-1} in France. In this case the mean assumed and estimated mean values are identical: 80 kg y^{-1}.

A wider range has been estimated for milk products. The Portuguese have a very low consumption rate of 55 kg y^{-1}; whereas the Irish consume 206 kg y^{-1}. For the derivation of ERLs a mean EC value of 120 kg y^{-1} has been assumed by the Article 31 Expert Group compared with 124 kg y^{-1} which has been estimated for the average EC-citizen.

Discrepancies can be observed for vegetables and fruit. The Article 31 Expert Group assumes a total consumption of vegetables and fruit of 100 kg y^{-1}. This might be a suitable value for one of the food groups but not for both. The consumption of vegetables ranges between 71 kg y^{-1} in Denmark and 156 kg y^{-1} in Greece and Italy (mean in EC: 110 kg y^{-1}), and that of fruit between 52 kg y^{-1} in the UK and 172 kg y^{-1} in Greece (mean in EC: 106 kg y^{-1}). The mean consumption rate of potatoes is 81 kg y^{-1} for the whole EC with a range from 35 kg y^{-1} (Italy) to 126 kg y^{-1} (Ireland). As the Article 31 Expert Group did not consider potatoes in their derivation and their assumptions for fruits and vegetables are low, their figure for the total diet of 550 kg y^{-1} is 20% lower than actual values for the average EC citizen.

b) Food Consumption of Subgroups of the Population

Regional differences and differences in age and the level of urbanisation appear to have the largest influence on food consumption. Total consumption increases regularly with age from 1 year-old infants to 18 year-olds, with only few changes in later years. Infants of 1 year-old consume about 50% of the total adult diet; for 5 and 10 year-old children this figure is 60 and 80% respectively. The percentages apply to the total diet as well as to separate classes of food, except for consumption of milk and milk products which remain fairly constant with age.

Within a country, regional consumption of a certain class of food may vary from 70 to 130% of the average national consumption. Consumption of potatoes and fruit may even be twice as high in a given region.

Consumption in rural and urban areas was compared with the entire country. In urban areas consumption varies from 70 to 100%, with a high consumption of fruit (up to 130%). In rural areas the values range from 100 to 140%, with fruit consumption being lower (80 to 110%). The effects of factors of sex, social class and season are rather small.

The influence of sex on total food consumption and on consumption of separate foodstuffs increases with age, from no difference at the age of one, up to a difference of around 20% at the age of 10 and older. Females always consume less, except for fruit and vegetables.

The only differences in consumption during the four seasons were observed for vegetables and fruit. Consumption was smallest in those months when supply was low, which is often at the end of spring.

People with a low income have, for some foodstuffs, a relative consumption which can be 10 to 50% lower or higher than the consumption of people with a higher income. However, for most foodstuffs the differences are small. Self-sufficiency and consequent possible increased consumption may cause relatively high exposure to radioactivity in the event of a local contamination.

Self-sufficiency in vegetables and drinking milk from local farms is considerable for the BLEU, the Federal Republic of Germany, France, Italy and Ireland. Greece has a significant level of self-sufficiency in wheat, and consumption of milk and cheese from local farms. Self-sufficiency seems to be more important in the south of the EC.

Consumption by critical groups will not be dependent on separate factors but on combinations of factors. The uncertainty involved in quantifying effects of combinations of factors is large because the different factors are often correlated. Therefore, only the most important factors are considered, except for age, which should not be correlated with the other factors studied. When the influence of region and level of urbanisation are combined, the average amount of food consumed by a specific group may vary between 50% and 200% of the average amount consumed by the total population.

Investigations of consumption habits in critical groups in Southern Bavaria indicate a relatively small deviation from the EC-assumption.

5. Distribution of Food

The Article 31 Expert Group introduced the relative contamination factor in establishing Derived Intervention Levels (DILs) for activity in foodstuffs (see eq. 1). The factor was assumed to be 0.1 and should be applied to the full value of the DIL. Scenarios for which the value of 0.1 is satisfactory are for instance: the annual intake of food is uncontaminated for 90% and for 10% only contaminated up to the DIL; or, the activity concentration does not surpass 10% of the DIL when averaged over the whole year. So the factor is partly determined by the radioactive decay of the nuclides present, and partly by the dilution of contamination due to the distribution of foodstuffs. Dilution can occur in two ways: exportation of contaminated food, and a decrease of local contamination by importation of uncontaminated food from other regions or countries.

When calculating doses due to ingestion, it is generally assumed that consumed amounts are all produced locally. This hypothesis is valid for a limited number of people living in rural areas with a low population density and a large production of foodstuffs. It is less valid for most of the people living in areas with a high population density, where local production is insufficient and foodstuffs must be imported from other regions of the same country, from other EC countries, or even from non-EC countries. Therefore, distribution and local production need to be studied, areas of production and consumption have to be determined, and the dilution factors have to be estimated. Another reason for studying the transportation of foodstuffs is that the level of exchanges within the Community and other countries needs to be known when authorities have to decide on a countermeasure which might temporarily limit or ban trade in certain foods.

The European Community has achieved a high level of self-sufficiency for the main foodstuffs with its policy for agriculture. In general, most countries overproduce many different products and are self-supporting. A low percentage of imports comes from countries outside the EC.

Self-sufficiency is higher than 80% for all animal products (milk and milk products, butter and cheese, meat and eggs) in almost all countries. As a result, imports are low compared with production, in general less than 25%. More than 80% of imports by Community countries come from within the EC. There are a few countries which show large deficits for a given product: Italy for all dairy products, the United Kingdom for butter and cheese, Greece and Italy for meat, and the Federal Republic of Germany for eggs.

Self-sufficiency varies much more for the different plant food products. It rises to 90% for potatoes in all countries with the exception of Ireland (80% only). Moreover, 90% of the potatoes imported in each country come from within the EC. Viewing the EC as a whole, imports represent no more than 10% of production and more than 90% come from within the EC. But there are large discrepancies between countries: overproduction in the southern countries and the Netherlands with large deficiencies in Denmark, Ireland, the United Kingdom, and the Federal Republic of Germany (more than 50% of the usable amount of fresh vegetables is imported into the latter Member State). For fruit there is a general deficit in the EC: imports represent one-third of the production and are supplied equally by non-EC countries and EC countries (Greece, Italy and Spain). Regarding wheat, importation rises to 20% of production. BLEU, Ireland, Italy, the Netherlands, and Portugal show severe deficiencies; 80% of these requirements are provided for with wheat from EC countries, principally France and the United Kingdom.

The Netherlands has a very efficient agricultural system which makes it the largest exporter of potatoes, vegetables, all dairy products, and all kinds of meat and eggs. The other countries show a more complex situation: they are exporters for certain products and importers for others. For instance, all southern countries export vegetables and fruit but they lack meat or certain dairy products; France is the major exporter of wheat but lacks pork.

A general deficit of foodstuffs exists in all regions that are highly urbanized and industrialised. These regions also correspond to small areas without agriculture but with intense trade and distribution networks. For their imports, the preference that is commonly shown at the country level for EC products is generally less notable.

The analysis of regional exchange estimated from French data leads to some conclusions of general values about loading practices. Fresh vegetables and fruit are transported twice on average, first from the production region to the region with market installations, and then from the market to the region of consumption. The ratio of transported to produced amounts is 3/2 for raw milk. For other dairy products numerous loadings must be expected and the same holds true for meat. In contrast, grain is transported once from the grain elevator to the region of milling and transportation distances are short.

In summary, on average 84% of resources are provided for by national production, 13% by production from other EC countries, and only 3% from the non-EC-countries. On the basis of these average figures, imports of uncontaminated food from foreign countries are unlikely to decrease the contamination level of food by more than 20% when national production is contaminated, but, contamination will probably not be homogenous for large countries. The regional exchanges that always take place will have considerably more importance. Thus, high dilution factors can be reasonably expected for foodstuffs produced and consumed regionally; they will depend on regional self-sufficiency and can be estimated by national authorities on a case-by-case basis. Such considerations for large regions do not hold for small areas that can be severely affected as they are in the near field of an installation where a large accident has occurred.

6. Internal Dosimetry of Ingested Radionuclides

ICRP recommended biokinetic parameters and dosimetric models for calculating radiation doses for occupationally exposed adults following intakes of radionuclides by inhalation and ingestion. These parameters are, however, not necessarily appropriate for calculating radiation doses to members of the public following the release of radionuclides into the environment. For the calculation of doses to members of the general public, it is necessary to take account of the effect of age on the biokinetics of radionuclides, as well as on anatomical and physiological parameters. Incorporation of radionuclides into foodstuffs may also result in changes in their absorption within the gastrointestinal tract. Information is needed on the transfer of radionuclides to the developing embryo and foetus following intake of radionuclides by the mother.

The radionuclides for which values of dose-per-unit intake are given are: isotopes of strontium, ruthenium, iodine, caesium, plutonium and americium. In each case, the age groups included in the main calculations are 3 month-old infants, 1, 5, 10 and 15 year-old children and adults. Doses to the foetus are considered separately. Variability and uncertainty in the calculation of dose-per-unit intake are estimated for $^{134/137}Cs$, ^{131}I and ^{239}Pu. A summary of the general approach is given below followed by a brief discussion of biokinetic parameters and values of dose- per-unit intake for the individual radionuclides.

a) General Approach

The calculations of doses for adults are generally consistent with the approach taken by the ICRP on internal dosimetry. For children, doses are affected by the smaller body size and organ masses. In addition, for all but non-penetrating radiation, it is likely that the proportion of decay energy delivered to different tissues will change. These physical differences are taken into account using calculations based on a series of anthropomorphic phantoms.

Doses to the gastrointestinal tract from ingested radionuclides are calculated using the ICRP model for adults. There is insufficient information available to allow the use of age-specific residence times; it is considered that the use of adult values will tend to overestimate doses to children.

The values of gut absorption (f) recommended by the ICRP for the calculation of doses to workers apply in general to inorganic forms of the elements. The possibility that different values may be appropriate for absorption from food has, therefore, been considered. The absorption of radionuclides tends to be greater in the newborn, although the results of animal experiments suggest that the enhancement of gut transfer decreases progressively with increasing age, reaching adult values by about the time of weaning in most cases. Adult f values are taken to apply to children of one year of age and older. For infants in the first year of life, a Nuclear Energy Agency (NEA) Expert Group has recently recommended a general approach which is consistent with the available animal and human data and is adopted in this report. For f values between 0.01 and 0.5 in the adult, an increase by a factor of two is assumed, but for the elements with f values of 0.001 or less, a value 10 times the adult value is assumed.

After absorption from the gastrointestinal tract to body fluids, the distribution and retention of radionuclides depends on the element concerned. The turnover of radionuclides in children may be more rapid than in adults and this needs to be taken into account. In the case of bone-seeking elements, plutonium and americium, which deposit on bone surfaces, age-dependent models have been developed. These take into account bone recycling which leads to the gradual burial of surface deposits, the release of radionuclides from bone, and some transfer to bone marrow. Similarly, bone turnover has been taken into account in a biokinetic model for strontium which deposits throughout the bone volume. These models are used in this report in place of the ICRP model which assumes that the initial deposition pattern remains unchanged.

The possibility of radionuclide intake by pregnant women requires estimates to be made of doses to the developing foetus. This is complicated by the rapid growth and differentiation of the foetus such that the consequences of an intake are likely to depend on the period of gestation during which the intake occurs. Although it is necessary for many radionuclides to rely on animal data concerning placental transfer, differences in placental structure indicate that care is needed in extrapolating results to man. Preliminary dose estimates are given in this report for chronic maternal intake throughout the year including pregnancy.

b) Strontium

The ICRP f value of 0.3 has recently been endorsed by an expert group for use in calculating doses to members of the public including children from one year of age. An f value of 0.6, twice the adult value, was also recommended for children in the first year of life, following the approach explained above. These values are adopted in this report. For strontium absorbed in body fluids, the age-dependent model for skeletal uptake and retention development by Leggett has been adopted. The committed effective dose equivalent (CEDE) is dominated by the contributions from the dose equivalents to bone surfaces and red bone marrow. Dose-per-unit intake is greatest for 3-month-old infants and 1-year-old children because of their lower skeletal mass and high strontium-90 uptake during rapid bone growth. Dose per unit intake is lower in older children and adults but a peak value at 15 years of age corresponds to a renewal of rapid bone growth during adolescence.

Estimates of doses to the foetus from strontium-90 have been made by assuming that strontium uptake by the foetus will be related to that of calcium, but that a placental discrimination factor will apply. For chronic ingestion of strontium-90 by the mother for the year including pregnancy, and taking into account the activity present in the child at birth, the total committed effective dose equivalent is similar to that of the mother. The in utero dose contributes half of the total CEDE.

c) Ruthenium

An f value of 0.05, as recommended by ICRP (1979) and NEA (1988), is considered appropriate for ruthenium incorporated in food and drinking water by adults and children from one year of age. For infants in the first year of life, the NEA (1988) value of 0.1 has been adopted. For ruthenium absorbed into body fluids, animal data have shown that the subsequent tissue distribution is fairly uniform. Biological half-times have been derived from these data for adult animals; no information is available on the retention of ruthenium as a function of age. In the absence of information on the effect of age on tissue distribution and retention, the greater values of dose-per-unit intake for younger children are due solely to their lower body mass. The values of dose-per-unit intake for 3 month-old infants also takes into account the increased gut transfer. However, the increase in f from 0.05 to 0.1 results in only a small increase in dose-per-unit intake because 70-80% of the CEDE, in each case, is due to doses from unabsorbed ^{103}Ru and ^{106}Ru in the large intestine.

Doses to the foetus have been calculated for chronic maternal intake of ^{103}Ru and ^{106}Ru during the year including pregnancy. For ^{106}Ru, the CEDE to the child is about 70 times less than the maternal CEDE. This estimate includes both in utero irradiation, based on a placental discrimination factor of 0.1, applying throughout gestation, and the dose from activity present at birth. For ^{103}Ru, because of its penetrating photon emissions, foetal irradiation is very largely from activity in the maternal tissues, and the discrimination factor does not apply. On this basis, the estimated dose to the child is similar to the maternal dose.

d) Iodine

Iodine absorption from the gastrointestinal tract is rapid and virtually complete. An f value of 1.0 is applied to intakes of the iodine in food and water at all ages. The biokinetic model for the uptake of iodine by the thyroid and its subsequent distribution and retention, is that adopted by the ICRP (1979). Information on age-related changes in the retention of radioiodine in the thyroid is taken into account. Although the data are available, they indicate that the turnover of iodine decreases with age. Shorter biological half-times have therefore been adopted for children and infants. The dose is mostly delivered to the thyroid with much lower doses to other tissues. For the long-lived isotope, iodine-129 (half-life of $1.6.10^{7}$ years), the reduction in dose at younger ages due to shorter biological half-times counteracts the effect of smaller thyroid mass which leads to similar values of dose-per-unit intake for 3 month-old infants and 1, 5 and 10 year-old children, with slightly lower values for 15 year-old children and adults. For iodine-131, because of its shorter half-life (8 days), the effect of changes in retention times is reduced and the dominant factor determining the age-dependence of dose-per-unit intake is thyroid mass. Values of dose-per-unit intake therefore show a progressive increase with decreasing age, with about an order of magnitude difference between adults and 3 month-old infants. Similarly, for iodine-132 (half-life of 2.4 hours) the effect of thyroid mass results in one order of magnitude greater values of dose-per-unit intake in infants than in adults.

Estimates have been made of foetal doses after chronic maternal intake of iodine isotopes throughout the year including pregnancy. The assumption that the concentration of radioiodine in the foetal thyroid will be twice that of the maternal thyroid from the 11th to 38th week of gestation, results in foetal doses very similar to annual maternal doses.

e) Caesium

Soluble forms of caesium are virtually completely absorbed from the gastrointestinal tract. There is some evidence from human studies that absorption from food may not always be complete, but an f value of 1 is applied here to all ages. Caesium is distributed uniformly throughout body tissues. The biological half-times recommended by the ICRP (1979) for adults have been adopted. There is strong evidence that the rates of loss of caesium from the body are greater in children than adults, and shorter biological half-times have therefore been used for children (Leggett, 1986) and infants. In general, the shorter biological half-times at younger ages counteract the effect of lower body mass, resulting in values of dose per unit intake that are largely independent of age, the maximum difference is a factor of about two.

Doses to the foetus have been calculated for chronic maternal intakes of ^{134}Cs and ^{137}Cs throughout the year, including pregnancy. In utero doses are taken to be the same as the greatest doses to maternal tissues during the 38 weeks of pregnancy. The overall dose estimates for the child are very similar to maternal doses from the year's intake.

f) Plutonium and Americium

ICRP recently revised its biokinetic models for plutonium and related elements (ICRP, 1986). On the basis of an extensive review of animal data on gut transfer, together with limited human data, an f of 0.001 was recommended as a cautious value to apply to intakes of food. For infants in the first year of life, a value of 0.01 was recommended. These values have been used in this report. For plutonium and americium absorbed in body fluids, the main sites of deposition are the liver and skeleton. The ICRP biokinetic model, which specifies the initial distribution between organs and biological half-times, takes no account of bone remodelling as discussed above. Leggett and his colleagues have developed models which take into account bone turnover (Leggett and Eckerman, 1984, Leggett and Warren, 1987). The models also apply to children, taking into account greater initial deposition on bone surfaces and greater bone turnover. These have been used in this report and compared with ICRP assumptions. In each case, the CEDE is due largely to doses received by bone surfaces, red bone marrow, liver and gonads. The use of the Leggett models, in comparison with ICRP parameters, has little effect on dose-per-unit intake for adults; the greatest effect is for infants with a maximum reduction in a dose of about a factor of two for ^{241}Am. The dose-per-unit intake values for infants take account of a greater gut transfer of 0.01 compared with 0.001 for children of one year of age and older. This results in a proportional increase in the doses to the skeleton, liver and gonads.

Doses to the foetus have been calculated for chronic maternal intakes of ^{241}Am and isotopes of plutonium. Estimating foetal doses on the basis of a placental discrimination factor of 0.1 between the 8th and 38th week of gestation, and taking into account activity in the child at birth, the CEDE to the child is about two orders of magnitude less than the maternal CEDE.

7. Estimates of Individual Doses in EC Countries due to Ingestion of Contaminated Food

The default food chain model was used to calculate concentrations in leafy vegetables, grain, potatoes, other root vegetables, fruit, milk, beef and sheep meat. The default parameter values and agricultural practices were used in these calculations.

A number of different sets of individual doses have been calculated. For most of these the "default" food chain model and agricultural practice were used to estimate the concentrations in food. However, the effect of using food concentrations estimated assuming appropriate agricultural practices of each country is also considered. Adult average individual doses were calculated for a number of sets of the dietary intakes. The diets considered are those appropriate for each country individually, then those for groups of countries in the EC, and finally for an "EC" diet, weighted according to the population in each country. The variation of individual doses with age is estimated by calculating average individual doses for 5- to 10-year-old children based on the "EC" weighted dietary intake. For these calculations the dose-per-unit intake data for children and adults discussed above were used.

In these calculations account was taken of the loss of activity due to waste, as well as losses during processing and culinary preparation, but no account was taken of delays between production and consumption.

From the estimates of individual doses presented it is possible to make a number of general points. The differences in doses following deposition at different times of the year are quite marked. These seasonal differences are seen both for the total ingestion doses and also in those foods which contribute most to the total dose.

The foods that contribute most to individual doses for deposition at a particular time of the year depend, to some extent, on the mix of radionuclides considered. For deposition of strontium-90, iodine-131 and caesium-137 in January, the intake of fruit and green vegetables dominated the resulting ingestion doses. For deposition in May the important foods are different for the three radionuclides considered. For strontium-90 potatoes, green vegetables, milk and cheese are important, for caesium-137 it is cereals, milk and meat that are important, while for iodine-131 the important foods tend to be potatoes, vegetables, fruit and milk. For deposition on 1 July the important foods are again different. Cereals but not potatoes are now important for strontium-90, while potatoes are no longer important for iodine-131. Contribution to the dose of various foods in different Member States depends on the consumption pattern. For countries with a higher consumption of sheep and/or goat meat (Greece, Ireland and the UK) this food becomes important, contributing 10 to 15% of the dose for a deposition in May. In many cases consumption of pork has been found to be an important contributor to dose, notably for deposition in July. However, this finding should be treated with caution as it has been assumed that the diet of pigs comprises 100% contaminated winter grain. Pigs are often given a variety of different feedstuffs, some of which are imported from some distance, and so would not necessarily be contaminated following an accident. The doses from ingestion of pork may therefore have been overestimated. The relative importance of the intake of fruit should also be treated with caution. The intake of fruit includes a large component due to the consumption of fruit juices, and in many countries these are imported from outside the EC. The intake of offall was not included in the dose assessment but additional calculations have shown that its inclusion would increase the doses by only a few percent.

Calculations are also made of the ingestion doses for 5 to 10 year-old children and the results compared with those of adults. The differences with age were found to be small. For deposition of iodine-131 alone the doses calculated for 5-year-old children were about a factor of three higher than for adults. However, for deposition of strontium-90 or caesium-137, doses to adults were calculated to be higher than those for children.

The effect of using an appropriate regional agricultural practice in calculating ingestion doses, compared with a "default" European practice, has also been investigated. The effects are generally small and indicate that for many situations assuming a default agricultural practice is adequate. However, for the Mediterranean countries or countries with similar climate (southern France, Italy, Greece, southern Spain and South Portugal), differences up to a factor of four are estimated for deposition in July. In this case regional agricultural practices should be taken into account. The same food chain model parameters have been used for all regions; using more site specific parameter values could have an effect on the result presented here.

8. Characterisation of Critical Population Groups

The model parameters that characterise the pattern of food supply assume consumption habits which are representative for the whole Community and do not consider special situations, such as individual consumption patterns or a regionally bound high level of self-sufficiency in an above-average contaminated area. As it is not known to what degree the range of consumption habits is covered by the model data, a survey has been carried out to investigate the food consumption of critical groups.

The study was conducted in a region bordering the Alps in south-east Bavaria, where the highest deposition of radiocaesium (>42000 Bq m^{-2} ^{137}Cs) from the Chernobyl accident occurred within the Federal Republic of Germany. There, the origin, type and amount of dose-relevant and season-dependent food items were determined in self-sufficient groups, including hunters and mushroom-pickers, and compared with those who were not self-sufficient and chosen as a reference group. To examine the influence of consumption habits on the internal dose by ingestion, simultaneous whole-body counting measurements were conducted in time intervals of 1.5-2 months and the contamination of critical foodstuffs with radiocaesium was measured by random critera.

a) Consumption Habits

Depending on the season and the population group, the milk consumption deviates from German consumption statistics by a factor of 0.5-2.2. In agreement with observations during recent years, including 1989, the highest milk consumption was observed among those who were self-sufficient. Among the dose-relevant products, raw milk was the most critical food during the first 1-2 years after the nuclear accident of Chernobyl, because raw milk is consumed regularly in large amounts without a radiological control.

For all groups, more fresh vegetables were consumed than could be expected according to national statistical data. The daily consumption rates exceeded the average German and EC value by a factor of 1.8 and 1.2, respectively. The hunters consumed twice the amount of fresh meat indicated by German statistical budget surveys, due to a larger supply of locally produced pork, sheep, and locally killed game. The average German consumption rate of only 1 kg y^{-1} for game is a small dietary component, but for hunters it ranks as a major foodstuff because its consumption of 15-22 kg y^{-1} is comparable with the statistical values for the consumption of beef and pork and other meat. For mushroom-pickers the consumption rate of mushrooms comes into the category of major foodstuffs: the consumption rate in autumn and spring is about 60% of that in summer and is in total equivalent to about 15 kg y^{-1}. During the one-year period of analysis and according to the type of population, the following food classes are underestimated by the European Statistical EC data: vegetables and fruit in each examined population group, milk products in the group of self-supporters, as well as fresh meat in the group of hunters. With the exception of vegetables, the population-specific differences are balanced out when the group-specific consumption rates are averaged over the total population groups and the whole period of investigations. Additionally, the regional data on food items are in the same range as the values for the analogue food classes consumed in the three main groups of the EC countries.

b) Origin of Food

For self-sufficient groups the fraction of raw milk and milk products produced regionally is 100% and 75%, respectively. The local production of vegetables contributes in spring and summer as much as 60% to the needs of the population groups. Also 20-40% of meat (pork, lamb, mutton, beef, veal) is obtained from the region. Data on maximum amounts of regional foodstuffs consumed are computed for milk and milk products for self-sufficient groups, followed to a lesser extent by game for the group of hunters. This means that the dilution of activity by distribution of the foodstuffs is relatively small for a part of the population in rural areas, as consumption of local products, especially milk, is preferred.

According to the present study, self-supporting groups obtain about 75% of the relevant foodstuffs from the region, while non-self-supporting groups obtain only about 35%.

c) Dose to Man

In the first year after Chernobyl the mean internal dose was 570 mSv to non-self-supporting groups in south-east Bavaria. The main contribution to the dose results from the consumption of locally produced milk. During the following years the individual doses declined in parallel with the decrease in the contamination of the major foodstuffs, to 10 mSv for self-supporting groups and 6 mSv for non-self-supporting groups in 1989. Due to the reduction of radiocaesium activity in major foodstuffs, the relative importance for the dose to man from activity in wild mushrooms and game increased from 1986 to 1989.

In 1988 the dose to game-hunters, mushroom-eaters and self-supporters was about the same, but in 1989 game-hunters were the most critical group followed by mushroom-eaters. This is due to reduced consumption of contaminated mushrooms. The mushroom-eaters reacted to the results from the first whole-body measurements with special caution by selecting less contaminated wild mushrooms for meals and by avoiding highly contaminated species, such as Boletus badius. Dietary duplicates of mixed mushrooms (Boletus edulis, chanterelle, russula, model) were contaminated up to the same level as game in the range of 200-500 Bq kg^{-1}.

The results indicate that in any emergency situation, as a first approximation self-supporters should be classified as the most critical population group. The self-supporters were selected in the vicinity of conveniently-situated medium-sized towns and often had their place of work in the urban environment. In view of this it is unlikely that these persons represent a minority in at least some countries. Rather, they constitute an important section of the population that should be quantified and considered in the introduction of protective measures to avoid supply problems.

9. Emergency Management

After radioactive contamination of the environment a considerable reduction in the exposure of the public may be achieved by temporary countermeasures introduced by national public health authorities.

Besides dose reduction, countermeasures always lead to intervention in the normal daily practice and, therefore, undesirable social or economical consequences are involved. It is the task of the competent authorities to make decisions taking into account the positive as well as the negative effects of planned countermeasures. An outcome of the research is a methodology to derive intervention levels for food and a set of realistic countermeasures to be considered when intervention is needed.

a) Methodology Aspects

ICRP and IAEA have based their Derived Intervention Levels for food on the basis of two intervention levels of dose and on the ALARA (As Low As Reasonably Achievable) principle. Above the upper dose level, a countermeasure aiming at a reduction of dose in nearly all cases is necessary, whereas below the lower dose level, the countermeasure is not justified. Between both levels, advantages and disadvantages of a countermeasure have to be balanced in order to justify its implementation. The methodology was elaborated on the basis of dosimetric considerations as described above, and an economic approach based on the ALARA principle.

b) Possible Countermeasures

In order to make decisions on countermeasures, a detailed survey has to be made available on costs, effectiveness and feasibility aspects related to implementation of the various countermeasures.

The Chernobyl accident showed that such a detailed survey was lacking. During the subsequent years, information has become available that should be added to present knowledge. In this report an overview is presented of effects related to the implementation of the most important countermeasures.

Countermeasures may be classified as preventive or curative. Preventive countermeasures in food production will be implemented primarily in the agricultural environment. Examples are fertilisation, deep ploughing and liming of the soil. Curative countermeasures may be taken during food processing, storage or food trade.

c) Preventive Countermeasures

It is generally agreed that preventive countermeasures on radioactive contamination of food should be preferred because they cause less disturbance in the chain of production, preparation, distribution and consumption of food. However, food contamination interventions associated with actions such as liming, ploughing or fertilisation are often not effective or reliable. Other possible curative countermeasures such as removal of the topsoil layer or stabilisation by a foam may be more efficient, but these countermeasures are impractical for large contaminated areas due to the amounts of waste and costs involved. In certain cases one might change to crops with a lower or no transfer of radionuclides to the human diet, such as grain, oils, sugar or cotton. One also has to consider that implementation of preventive countermeasures will change food contamination, not immediately, but after a period of several weeks or months.

A very effective and simple countermeasure to reduce the contamination of animals is the feeding of uncontaminated feeding stuff. Contamination of animal products can often be reduced by about 2 orders of magnitude. Nowadays, a change towards qualitative better fodder just before slaughtering is indeed common practice in intensive cattle breeding. A change towards less contaminated feeding stuff has been implemented after the Chernobyl accident, but even such a simple measure could severely disturb farming planning and economy. Furthermore, availability of uncontaminated feeding stuff could be limited.

Quite a number of additives have been examined to determine their capacity to reduce uptake or to increase excretion of radionuclides. The use of prussian blue could reduce the caesium contamination of animals by about a of factor 10. Alginates may reduce the uptake of strontium by about a factor of 4 without negative side effects.

d) Curative Countermeasures

The experience after the Chernobyl accident revealed a need for curative countermeasures other than destruction alone.

In the case of contamination with short-lived radionuclides, storage may be a simple, cheap and very effective measure. After transformation into products with better storage possibilities, such as canning or the production of cheese, the maximum storage time which will not negatively affect food quality will be about two years. By this countermeasure, contamination by all radionuclides with half-lives of 50 days or less will be decreased by three orders of magnitude or more. One has, however, to consider the capacities for storage and processing in the period after the accident.

Doses due to ingestion of radionuclides may be reduced by changes in food processing, by optimised decontamination procedures, or by differentiation in the processing and final destination of foods according to their contamination level.

During the production of cheese about 80% of the radionuclides are concentrated in whey. Stimulation of the production of cheese could be accompanied by a higher production of butter and cream, which are also less contaminated. Decontamination of milk could, in certain accident situations, decrease levels of radioactivity by one or even two orders of magnitude. Techniques based on the use of ion-exchange resins were well developed in the sixties and a new technique based on complexation by hexacyanoferrate was used after Chernobyl. However, the possibilities for the implementation of such a technique are limited due to the large quantities of fresh milk produced daily which have to be processed within a short time, and the large amount of capital necessary for the construction and maintenance of the decontamination facilities.

For meat, certain ways of pickling or marinating may result in contamination levels of Caesium which are about an order of magnitude lower while the taste remains good. For other types of food normal processing often leads to a removal of 20 to 60% of the radionuclides present in it, but attempts to decontaminate food further brought, in general, only poor decontamination results combined with negative effects on taste, appearance, and nutritional value of the food.

Distribution and mixing of food, although cheap and feasible, does not affect collective doses and are, therefore, not considered in this report. However, social and economic consequences of non-intervention might, in certain cases, favour mixing of food with different contamination levels.

Use of contaminated food as feed for animals may be an alternative to destruction. Compared to destruction the economic loss will be smaller. However, use of contaminated feed for livestock will result in contaminated animal products like meat and milk which may cause a considerable distrust amongst farmers and the population, and may even affect food trade. The contamination of animal products can, as discussed above, be reduced by a period of feeding with uncontaminated fodder before slaughtering, and the contamination of animal products will be considerably lower than the corresponding contamination of the feed.

Contaminated food may be used as raw material for industrial processes, such as production of distilled beverages, starch, gluten, glucose or cardboard. If the final product is not food, a nearly complete dose reduction will be accomplished. Possibilities for using contaminated food for non-food products are, however, limited.

In general, dose reductions obtained by the destruction of food will be nearly complete. Destruction as radioactive waste is by far the most expensive solution, at least 0.47 ECU l^{-1}. Normal refuse destruction only costs about 0.026 ECU kg^{-1}. Also, the destruction capacity for radioactive waste is limited. Nevertheless, if a small area is extremely contaminated, destruction of its production as radioactive waste might be the best countermeasure. In general, destruction in the field could be easier to implement than destruction of large food stocks. However, ecological effects and consequences for future crops must be well known before food can be destructed in the field. Contamination of future crops will be orders of magnitude lower than contamination of the first crop as soil uptake is a less effective contamination pathway when compared to direct deposition on the foliage.

e) Selection of Countermeasures

For most countermeasures, cost, effectiveness and feasibility will vary with the type of food and the accident situation. A selection of relevant countermeasures thus has to be made for each type of food separately and it must be done for each following emergency situation.

However, several situations are valid for a wide variety of accident situations and food products, and may facilitate an eventual selection of countermeasures in the future.

Important factors influencing a decision are the half-life of the radionuclides involved, the contamination level of the food product and the proportion of the food production involved.

The first criterion for a countermeasure to be selected is, of course, its capacity to reduce food contamination below the reference level. In general, destruction of overproduction may be a common "cheap" countermeasure. For short-lived radionuclides storage is a good alternative for destruction, whereas for long-lived radionuclides, food processing or decontamination may be important to save food when the contamination level is no more than about 5 times the intervention level. If the contamination level is higher, withdrawal from normal food trade is practically the only way to intervene. In this case, destruction and use as animal fodder are the most relevant intervention modes.

Often it will not be possible to select just one countermeasure for a large amount of contaminated food. The contamination level will not be constant over the entire amount of food, and capacities for storage, destruction, processing, etc. have to be taken into account. Intervention aiming at a minimum of disruption and costs may take into account a number of countermeasures, specific for the typical situation in the affected areas.

10. Effects of Countermeasures on Ingestion Dose

The food chain model ECOSYS has been used to estimate the effectiveness of some selected countermeasures, especially of food bans, the application of Derived Intervention Levels (DIL), and measures concerning feed management.

After a nuclear accident during the vegetation period, food bans can reduce ingestion doses significantly. The activity concentrations in many foodstuffs have a pronounced peak in the harvest following the accident due to the effective uptake of radionuclides via the foliage. Food bans can reduce the potential intake of short-lived radionuclides more effectively than long-lived radionuclides. For short-lived radionuclides, the intake with milk and leafy vegetables pre-dominates, therefore temporary bans of these foodstuffs affect the total intake significantly. For long-lived radionuclides a greater part of the intake is due to the contamination of cereals, fruit, meat, etc. which can be influenced by temporary food bans only to a relatively small extent.

Bans on milk and leafy vegetables are more effective the earlier the bans are introduced after deposition, due to the short delay between production and consumption. A fast response after a nuclear accident requires well equipped facilities for the detection of increased levels of artificial radioactivity in air and rain.

The reducing effect of the application of derived intervention levels on dose reduction is dependent on the total activity, as well as on the deposition pattern (contribution of dry and wet deposition), and on the season. In so far as the spatial distribution of the deposition is not homogeneous over very large areas, and the population does not eat exclusively locally produced food, the application of derived intervention levels can probably ensure that an ingestion dose of 5 mSv in the first year is not exceeded. In reality foodstuffs above the intervention level would not come on to the market, and for the food consumed the intervention level would be the upper limit of the activity concentration in foodstuffs.

Countermeasures concerning feed management such as the application of additives and change of diet are appropriate to reduce the activity concentration in foodstuffs considerably, or to reduce the potential dose due to highly contaminated foodstuffs. On the other hand, all these countermeasures presuppose the collaboration of farmers and the acceptance of the former by farmers and consumers (e.g. application of prussian blue compounds). Another important presumption is the existence of a well-organised feed management which is able to carry out the recommendations of the authorities on the farms.

In real accident situations, a situation-specific combination of countermeasures should be the most effective way for a minimisation of the ingestion dose.

11. Conclusions

When comparing the diet of the "average EC citizen" with the values on food consumption adopted by the Article 31 Expert Group for the derivation of intervention levels, there is agreement on dairy products and meat. The value of the Article 31 Expert Group adopted for fruit and surface vegetables is about one-third lower than the value of the "average EC citizen", whereas the value for cereals is about 25% higher.

The influence of several factors on food consumption has been considered. Differences in age, region, and the level of urbanisation seem to have the greatest effects. Effects of sex, social class and season are rather small.

Within one country, regional consumption of certain foods may vary by 30% from the average national consumption. Consumption of potatoes and fruit may even be twice as high in a given region. Consumption in rural and urban areas, when compared with that of the entire country, varies from 20 to 50%, and is higher in rural areas for most products. Self-sufficiency influences the amounts consumed by individuals which are increased in general for population groups. Self-sufficiency seems to be more important in the south of the EC than in the north; it may play a very important role in the event of local contamination in rural areas.

Distribution of foodstuffs is recognised as of major importance for two reasons. Firstly, exporting contaminated food and importing uncontaminated food from other regions or countries will decrease local contamination. Secondly, authorities need to know the importance of exchange within the Community and with other countries when deciding countermeasures which might temporarily limit or ban the trade of foodstuffs. However, the importance of exchanges between EC countries should not be overestimated. Indeed, in each EC country a high level of food products has been achieved for the main foodstuffs, and in general most countries face overproduction. However, a general deficit of foodstuffs exists in all regions that are highly urbanised and industrialised. This also applies to small areas with no agricultural vocation but with intense trade and distribution networks; for their imports, the preference that is commonly given to EC products is generally less pronounced. A case study was initiated after the Chernobyl accident which concerns critical groups such as self-supporters, game-hunters and mushroom-eaters. According to the study, 75% of the food consumed by the self-supporting groups comes from the region, whereas only 35% of the food for the non-self-supporters was produced locally. Models to predict the transfer of radionuclides through terrestrial food chains have a number of uses in the context of Derived Intervention Levels (DIL). These are both in deriving the levels and in applying them in the event of an actual accident. For example, results of food chain models can be used to investigate the extent to which food countermeasures would be required in particular circumstances. They can also be used in the period following an accident before measurements are available, and to determine how long any countermeasure might be retained. A default model has been suggested for use in the EC in the absence of site specific information. It is based on the models FARMLAND and ECOSYS. In any applications of the default model the variability in the results should be borne in mind. Variations in the predicted concentrations in food in different meteorological conditions are particularly important. The variations due to release at different times of the year and different agricultural practices are also significant. In addition, the uncertainty in the food chain model results, due to lack of knowledge of the parameter values, should be recognised. For most accident analyses, when full details of the meteorological conditions and other site specific data are available, a more detailed food chain model such as ECOSYS is more appropriate. A model such as ECOSYS is also better if knowledge of the likely range of possible food concentrations following a given accidental release is required, for example for emergency planning. Illustrative calculations of individual doses from ingestion were intended to show the possible variation of individual doses between EC countries and which foods contribute to the doses following an accidental release at different times of the year. The most significant difference in doses seen is that due to accidental releases occurring at different times of the year. These seasonal differences are observed both for the total dose and also in which foods contribute most to the total dose. Significant differences were found in foods that contribute most to doses in the different countries of the EC depending on the consumption pattern. Calculations were also made of the ingestion doses for 5- to 10-year-old children and the results compared with those for adults. The differences with age were found to be small. Furthermore, it can be concluded that in most circumstances it is adequate to use dietary intakes that are representative of the EC as a whole in estimating doses. Also, in general it is not necessary to take into account regional agricultural practices in estimating doses. An important exception appears to be the Mediterranean countries and additional work is required to better characterise the food intakes, agricultural practices and food chain transfers in that region. In estimating doses from the ingestion of radionuclides by the general population, values of dose-per-unit intake have been calculated for 3 month-old infants, for 1-, 5-, 10- and 15-year-old children and for adults. The radionuclides considered were isotopes of strontium, ruthenium, iodine, caesium, plutonium and americium and, for each element, using approaches that are consistent with those of an ICRP Task Group on age-dependent dosimetry. The corresponding dose per unit intake was calculated. Intakes of radionuclides by pregnant women and doses to the foetus have also been evaluated. Although single values have been given for dose per unit intake for a particular radionuclide and age group, it is also necessary to consider the variation between individuals and uncertainties in these estimates. These parameters have been quantified in this report for the examples of caesium isotopes, iodine-131, and plutonium-239. Finally, a possible methodology to derive intervention levels for foodstuffs was developed. The methodology is based on general radiation protection concepts and on the ALARA (As Low As Reasonably Achievable) principle. Information was provided on the effectiveness, costs and feasibility of a wide variety of countermeasures which may be considered when the contamination of food exceeds intervention levels. The dosimetric effectiveness of a food ban, which is the most common decision, has been estimated by using the dynamic radioecological model ECOSYS. After accidental releases during the vegetation period, food bans can reduce ingestion doses significantly. They are more effective for short-lived than for long-lived radionuclides, and the shorter the time between the deposition and the start of the ban, the better the effectiveness is of the ban. This requires well equipped facilities for the detection of increased levels of artificial radionuclides in air and rain. Using ECOSYS, the reduction of dose following the application of the DILs was assessed. The reduction is dependent on the total activity deposition as well as on the deposition pattern (contribution of dry and wet deposition) and on the season. In so far as the spatial distribution of the deposition is concerned, it is not homogeneous over large areas and people do not eat exclusively food that is produced locally. The application of DILs can probably ensure that an ingestion dose of 5 mSv in the first year is not exceeded. In the event of of contamination with short-lived radionuclides, storage is very effective. In the event of contamination with long-lived radionuclides which is more than a factor 10 higher than intervention levels, destruction of food is the most effective intervention, although in certain cases (milk) decontamination procedures may be used. At lower contamination levels, a good alternative might be to use contaminated food as fodder for animals. Indeed countermeasures concerning the feed management, such as application of additives, delay in slaughtering, and changes of diet, are appropriate for the reduction of the activity concentrations in foodstuffs or of the potential dose due to highly contaminated foodstuffs. Also, when the contamination level is below 3 to 5 times the intervention level, food processing may result in a sufficient reduction of the radioactivity. In real accident situations, one may expect that a situation-specific combination of countermeasures would be the most effective way to minimise the ingestion dose. Apart from technical or economic considerations, experience shows that the feasibility of intervention depends on other aspects. Reactions of the public may have a large impact on food economy. Important trade disruptions may already occur in situations where intervention is still far from being considered. Public discussions about ethical questions may also arise in accident situations. To conclude, the transfer of radionuclides in several parts of the human food chain is very dependent upon the conditions of food production. Knowledge of the effects of possible countermeasures with regard to doses, and their economic and social consequences, should be available for decision-makers in an integrated, updated and readily interpretable way. This requires continuous monitoring by the authorities and scientists responsible.

VI. Improvement of Practical Countermeasures against Nuclear Contamination in the Agricultural Environment

1. Participating Institutes

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2. Introduction

It is quite clear that reclamation of rural areas after accidents, with some special exceptions, had not been given much attention in the pre-Chernobyl period. Nevertheless, contamination of some rural areas in or near the site of a nuclear accident, nuclear tests or high radioactivity releases have created needs for reclamation of agricultural areas, and some limited research on this subject has been carried out in the past, and some practical experience with countermeasures has been obtained. Moreover, research in some related fields, such as soil-plant transfer factors and radionuclide transfer in food processing, could enable recommendations for decisions to be made, some action models to be designed and priorities of research needed to be established. This information could be used for selecting, in the near future, a scale of techniques for countermeasures in order to deal with different kinds and levels of radioactive contamination derived from an accident at a nuclear installation.

With this aim, the task of the collaborating laboratories in the development of this project has been:

- to collect and elaborate the information available on:
  - deposition of contamination on vegetation and soils (direct contamination),
  - behaviour of contaminants in the soil and transfer into the plants (indirect contamination),

- to investigate the means for reduction of the contamination levels in the rural environment by:
  - removal of contaminated vegetation and agricultural products,
  - implementation of agro-technical countermeasures to soils,.
  - reduction of the radiological consequences for people by food processing and selection of crops and soil uses.
- to assess the effectiveness of the countermeasures undertaken in rural areas.
- to initiate supplementary investigations on:
  - the acquisition of data related to the deposition of radionuclides and evaluate their interception rate by the vegetation cover of several crops at different stages of growth,
  - the feasibility to reduce the soil-plant transfer of radionuclides by soil amendments,
  - the transfer factors for different species of crops growing in several types of soil,
  - the study of the transfer of radiocaesium from raw whole milk to a wide range of milk products produced by the dairy industry.

The main conclusions to be drawn from this action are discussed below, according to the following natural sequence of activities that would have to be considered in order to establish action to be taken in the case of an accident.

- Historical analysis of land recovery operations
- Characteristics of contamination:
  - deposition study of the contaminants on the vegetation,
  - behaviour of radionuclides in the soil and their transfer to vegetation and crops.
- Countermeasures applicable:
  - treatment of vegetation,
  - treatment of contaminated soils (mechanical and chemical),
  - alternatives to these treatments (crop selection and food processing).
- Evaluation of the countermeasures to be undertaken.
- Further needs for Community action.

3. Lessons from the Past for Remedial Actions

As part of an extensive analysis of the scenarios where an accident took place, a nuclear test was carried out or where a high radioactive contamination occurred with the consequent impact on the agricultural environment, was made. The scenarios reviewed were:

- Accidents: Windscale (UK, 1957), Palomares (Spain, 1966), Thule (Denmark, 1968), Rocky Flats Plant (USA, 1958) and Chernobyl (USSR, 1986).
- Nuclear tests: Bikini Atoll (1946-1958), Enewetak Atoll (1948-1958) and Nevada Test Site (1951-1975) (USA)
- Others: Hiroshima and Nagasaki (Japan, 1945) and Los Alamos (USA, 1942-1965).

Information about the type and use of soil, kind and level of contamination, cleanup criteria and countermeasures applied per scenario, is shown in table 1.

Scenarios	Use	Type	Containment	Level of Contamination	Clean-up Criterium	Countermeasure
Los Alamos	Residence Recreation activities	Desert and soft volcanic rock	U, Pu and fission products	^{239}Pu 8.2 Bq/kg ^{137}Cs 4.6 Bq/kg	ALARA	Soil removal
Bikini	Residence and agriculture	Coral rock and coralline sands with minimum organic content	Transuranics Cs,Sb,Co,Rh	<120 μR/hr	<5.92 kBq/kg averaged over 1/16 ha (for soil removal)	Decay Debris removal De-vegetation Soil removal
Enewetak	as for Bikini	as for Bikini	Transuranics Cs, Sr, Co	^{239}Pu <20 Bq/kg ^{137}Cs <6.7 kBq/kg ^{90}Sr <25 Bq/kg ^{241}Am <1.2 Bq/kg	as for Bikini	De-vegation Ploughing Soil removal
Nevada	Desert	Sandy Calcareus alluvium	Reactor fission and activation products	300 acres greater than 0.37 MBq/m², few acres greater than 2.6 MBq/m²	<5.92 kBq/kg averaged over 1/16 ha (for soil removal) and ALARA	Ploughing Soil removal Vacuum Scraping Oiling Leaching
Windscale	Urban and agricultural		^{131}I ^{137}Cs ^{90}Sr ^{89}Sr	$7.4x10^{14}$Bq total $2.2x10^{13}$Bq total $3.0x10^{12}$Bq total $3.3x10^{11}$Bq total <4mR/hr	Milk samples <0.1 μCi/l, Decrease activity with half life < 8 days	Milk consumption restriction
Rocky Flats Plant		Very rocky 20% clay & organic matter	Pu	200-3000 kBq/m² in drum storage area; in Lip area 20.7 GBq	Soil removed if >1000 Bq/g and returned if < 30 Bq/g	Soil removal Stabilisers
Palomares	Urban and agricultural	Silt and sandy	Pu	>1200 kBq/m² 2.2 ha 120-1200 17 ha 12-120 87 ha <12 120 ha	> 562 μg/m² 5.4-562 μg/m² <5.4 μg/m² <77 μg/m²	Scraped+removed water+plough water permissible where other measures could not be applied
Thule		Ice	Pu	≤14.8 gBq/km²		Ice removal
Chernobyl	Urban and agricultural	Sandy and argyllo-arenaceus svard-podzolic acid	^{137}Cs and fission products $2x10^{18}$ Bq released	50% of released material in 30 km zone	To recover the area (levels?)	De-vegetation Soil removal Ploughing Stabilisers Fertilisers

Table 1: Description of scenarios, clean-up criteria and countermeasures

Information about laboratory and other field research on countermeasures for land recovery was also compiled. The analysis of this information shows important details about the application of countermeasures per scenario and facilitates the final evaluation of the recovery operations.

A review of the literature (Risø) was made to collect information on root uptake of caesium, strontium and plutonium in order to estimate the applicability of different treatments in land reclamation in distant areas after the release of these radionuclides.

4. Characterisation of the Contamination

The radionuclides released into the environment as a result of an accident may spread over large areas and cause a tremendous impact on agricultural ecosystems. The dry or wet deposit of radioactive aerosols upon the surface of the earth may be partly intercepted by the vegetation, depending on its thickness and characteristics, the magnitude of the primary radioactive deposit between the soil and the covering layer of vegetation.

Quantifying the distribution between soil and vegetation is one of the important factors to bear in mind when deciding which countermeasures ought to be applied in order to recover the soil. One possible countermeasure is the partial or total elimination of the vegetation, and this may be either the only or the first step in the a sequence of different decontamination measures.

Few data are currently available regarding the soil vegetation distribution percentages occurring as a result of accidents in nuclear installations. Therefore, the experiments carried out in Cadarache (France) in order to obtain the specific values of these distribution coefficients for various types of crops are extremely interesting. The experimental studies, carried out with an aerosol marked with uranine in order to stimulate deposition, made it possible to discover the great importance of the kind of vegetation and its vegetative and growth stage at the time of deposition, as well as the prevailing meteorological conditions.

The studies were carried out on crops of significant agricultural and economic interest. They included tall growing plants (cereals, maize, sunflowers), market garden plants (lettuce, peas, French beans) and broad-leaf plants (beet and cabbage).

The curves of the interception coefficient according to the aerial part of the vegetative productivity (g dry m^{-2}) drawn up for potato, wheat, maize and sunflowers display a significant variability where plants with an important vertical growth show by far the highest interception coefficient which, moreover, depends on the growth stage. These results indicate the need to correct our present knowledge of deposition velocity depending on the kind of vegetation. It seems that the consideration of a single deposition velocity related to a concentration in volume of air and a deposition on the soil surface is not enough for the general description of the deposition of the pollutant.

5. Countermeasures and their Applicability

When radioactive contamination has occurred, and depending on the specific properties of the contaminated agricultural zone, a distribution of the radionuclides in the different compartments of the environment takes place. In the event of a contamination leading to exposures exceeding the established intervention levels, a decision must be taken as regards remedial action which, by applying countermeasures, may eventually make it possible to recover the agricultural zone for normal use.

The various countermeasures that are eventually provided for may be classified in the following four groups:

- treatment of the vegetative cover present at the time of the accident;
- chemical treatment of soil;
    - mechanical treatment of soil
    - alternatives to "in situ" soil treatments.

The main characteristics of each of these countermeasures are set out below, with an appraisal of their efficiency and giving their advantages and their disadvantages.

The evaluation of the main countermeasures that are applicable was carried out by analysing the historic context in which they have been applied in various cases of contamination, and on the basis of certain planned experiments undertaken in laboratories and in the field.

For each of the countermeasures, the available information on methodology, practicability and cost has been evaluated.

a) Removal of Vegetation

The removal of vegetation by harvesting crops has been clearly referred to in the cases of the accidents at Palomares and Chernobyl only. Interesting information about de-vegetation has also been obtained from decontamination operations on Bikini and Enewetak where nuclear experiments were carried out in the context of atomic weapons tests.

Experiments were carried out in order to determine decontamination efficiency and the effort required when using various agricultural harvesting machines to remove contaminated crops or mulch from the land. The results show that the decontamination achieved for all the experimental harvests was lower than 75%.

The main advantages, disadvantages and research required with respect to the **removal of vegetation and crops** are:

Advantages:
- reduce the area contamination level by about 50%,
- no disturbance of soil layer and productivity.

Disadvantages:
- dependent on:
  - type and densitity of vegetation,
  - state of crop growth,
  - dry or wet deposition,
  - season for natural perennial woods,
  - period of time between contamination, cutting and removal,
- must start as soon as possible,
- requires considerable time,
- involves problems of waste treatment and disposal,
- environmental impact,
- decades required for re-vegetation in natural ecosystems.

Further knowledge needed:
- efficiency, practicability and time required for each method of vegetation removal, ecosystem involved, type of crops, contamination level,
- norms and methods for protection of personnel during the execution of each method,
- treatment and disposal for removed vegetation,

- establishment of reference levels for application of this countermeasure in different ecosystems.

An important problem, yet to be solved, is the treatment and disposal of the large volume of radioactive vegetative waste that would result from such a countermeasure.

b) Chemical Treatment of Soil

The chemical treatment of soils to reduce crop contamination is one of the countermeasures that has attracted the most research. This would be less traumatic than other methods such as the removal of a fertile layer of soil.

The results obtained and the possibilities of their being used as countermeasures are described below.

Soil Amendments

Countermeasures based on the application of mineral fertilisers can make use of the competition for plant uptake of related elements such as potassium ànd caesium, or add zeolite-type clays which have a high cation exchange capacity. Zeolites were used at Chernobyl for treating light textured sward-podzolic soils.

Experiments have recently been carried out in order to study the influence of fertilisers like potassium, phosphorus and nitrogen on the transfer factors of caesium and strontium in terms of the type of soil and plant. Potassium is the only element that can reduce the transfer factor of Cs and to a lesser degree of Sr in soils with a high cationic exchange capacity. In soils with a low cationic exchange capacity an excess addition of potassium produces an increase in the transfer factor. Ammonium fertilisers should be applied for contaminated agricultural land if compatible with the type of crop.

The main advantages, disadvantages and research required with respect to the use **soil amendments** are:

Advantages:
- more easily applied than other countermeasures,
- selective reduction in uptake of radionuclides,
- corrects also problems of soil fertility and acidity.

Disadvantages:
- none of the soil amendments is very effective,
- application depends on:
  - type of soil,
  - chemical state of the radionuclide,
  - availability at required site.

Further knowledge needed:
- effects of soil amendments on reduction in uptake of certain radionuclides and reduction in soil productivity for different types of soil.

Fixatives and Stabilizers

The term "fixative" refers here to any material used to bind radioactive particles to a surface. In general, the use of fixatives would be the first countermeasure to be taken before other decontamination operations. Their application prevents the dispersion and re-suspension of contaminating particles present on the soil surface.

Fixatives have been experimented with and used to prevent the dissemination of contaminating radioactive particles on the surface of apparatus, laboratories and nuclear installations. The experiments applying foam have recently been extended to cases of agricultural soil contamination and this is also currently used at sites contaminated from the Chernobyl accident. Its effectiveness is related both to the possibility of forming impermeable, membraneous surfaces and to the binding with the particles.

The field experiments were mainly carried out with petroleum-based products (road, oil, emulsified asphalt, diesel oil, etc) and with polyurethane foams. Both were used to determine cleaning capacity, removability and durability, the influences of climatic and environmental conditions on different types of soil, costs and criteria for their application.

The main advantages, disadvantages and research required with respect to the **application of fixatives to soil** are:

Advantages:
- is a good temporary countermeasure to:
  - reach maximum reduction of radionuclides, avoid resuspension by wind or any physical disturbance,
  - gain time until decisions can be made on:
    - plant removal,
    - surface soil removal,
    - treatment of vegetation and soil,
    - waste disposal (vegetation and soil).

Disadvantages:
- land is almost useless during the period,
- very restrictive for animal life,
- requires constant monitoring of contaminants under cover,
- drainage needed since water does not penetrate,
- most fixatives have serious environmental consequences,
- mostly applicable only to small areas.

Further knowledge needed:
- estimation of short- and long-term ecological impact,
- relation between application of fixatives and loss of soil productivity for different crops.

Leaching

The leaching of soils, by irrigating them with large quantities of water in order to wash down the radionuclides contaminating the surface and fertile layer to deep levels, has been investigated with regard to the ^{90}Sr uptake by plants. Some results were obtained with this procedure.

Laboratory experiments were carried out in order to study the effect of leaching the Nevada Test soils with solutions of nitric and citric acids to remove plutonium from the upper soil layers, but the results were not very promising. This countermeasure presents more drawbacks than advantages, as can be seen from the following list of advantages and disadvantages, and its application does not really eliminate a large amount of the radionuclides from the plant rooting zone.

Advantages:
- cheap,
- no resuspended material from wind or mechanical disturbances.

Disadvantages:
- mobility to depth only moderate dependent on soil profile,

- decreases soil productivity since essential nutrients move with the contaminants,
- addition of fertiliser is necessary,
- risk of contamination of surface and sub-surface water,
- large amounts of water needed.

c) Mechanical Treatment of Soil

As a result of the need to apply remedial action to agricultural zones which have suffered radioactive contamination, mechanical procedures were used for soil treatment. Consequently, there is adequate experience available, particulary with regard to the total or partial removal of the upper layer of contaminated soil, and normal and deep ploughing. At present, attempts are being made to develop a procedure whereby the top layer of the soil can be placed below the root zone.

Removal of Soil

The total elimination of the surface layer of soil is practically the only countermeasure which, in conjunction with the prior elimination of vegetation, is able to provide almost 100% decontamination. It can be done in a relatively short period of time and is not very expensive. However, applying this method results in a large volume of radioactive waste.

On the Nevada Test Site experiments were carried out to appraise the different methodologies and compare their results and, on the basis of their positive and negative aspects, choose the most appropriate ones. Three types of terrainhave been cleaned , i.e., nuclear flat compact soil, a gravel-like soil and a rocky area. The methods tested were mainly the use of front-lade, a vacuum system or, simply, the use of a shovel. The type of terrain imposes constraints on applicable in given situations.

The main advantages, disadvantages and research required with respect to the **complete removal of soil surface** are:

Advantages:

- decontamination could be almost complete,
- cheaper than leaving some shrubs,
- can be carried out rapidly.

Disadvantages:

- ground cover will be reduced and primary productivity decreased to some extent,
- re-vegetation is extremely difficult unless microcatchement depressions to collect and concentrate run-off are made for artificial replanting on sites where shrubs were standing,
- fertiliser, organic matter or fresh soil may be required,
- native animals would be initially lost but would later be replaced from adjoining areas,
- "dust bowl" conditions would exist unless soil is stabilised until vegetation regrows,
- large amounts of waste are produced,
- type of terrain can impose conditions on the mechanical equipment used.

Further knowledge needed:

- development of equipment and techniques for construction of microcatchment depressions,
- development of seeding and transplanting techniques for re-vegetation in the catchment basins,
- elaboration of a list of plants and crops which would grow in the disturbed soil area,
- evaluation of reduction of soil productivity and recovery for different plants and crops,
- improvement of techniques for waste reduction and disposal.

The main advantages, disadvantages and research required with respect to a **removal of soil surface that leaves some vegetation** are:

Advantages:

- re-vegetation of natural environments will occur more rapidly than after complete removal,
- remaining vegetation provides seeds for re-vegetation, and fertile shrub sites are preserved for man-made replanting,
- costs of re-vegetation are small or non-existent,
- dust resuspension is reduced, especially when soil stabilisers are used,
- the area is reasonably acceptable from an environmental and an esthetic point of view.

Disadvantages:

- decontamination not 100% effective,
- ground cover diminished with some reduction of primary productivity,
- erosion from rainfall could increase unless soil is stabilised,
- problems of waste removal and disposal exist,
- clean-up process is more expensive than complete surface soil removal,
- large problems of dust resuspension during removal and transport,
- type of terrain can impose conditions on the mechanical equipment,
- inexperienced operators could recontaminate "clean" areas.

Further knowledge needed:

- development of equipment for removing soil around shrubs without destroying them,
- identification of plants around which it is difficult to clean,
- methods to reduce or solve more quickly problems removing the fertile layer of soil,
- improved vacuum equipment for application to large areas,
- improved treatments for waste reduction and disposal.

Normal and Deep Ploughing

Ploughing land having suffered from radioactive contamination is not in itself a decontamination process. The contaminating radionuclides will remain in the soil whatever the depth of ploughing. Nevertheless, it is a process whereby the contamination of the soil surface can be reduced. It allows it to be mixed and diluted in the earth in such a way that the availability of radionuclides for plants and animals will be modified in proportion to the dilution achieved and the depth reached by the roots of the crops.

Normal ploughing can be carried out with conventional farm machinery. It has no negative impact on the agricultural soil and is one of the cheapest and most effective ways of treating the soil. Deep ploughing, however, can have greater drawbacks depending on the depth of the fertile layer and the characteristics of the underlying layers.

The main advantages, disadvantages and research required with respect to **normal and deep ploughing** are:

Advantages:

- reduces radiation exposure from the surface,
- reduces resuspension of radioactivity,
- modifies the availability of radionuclides to plants dependent on the depth of the root zone,
- can be performed by conventional farm machinery and procedures,
- is one of the cheapest and most effective methods for soil treatment,
- disking following ploughing decreases the heterogeneous distribution of radionuclides.

Disadvantages:

- radionuclides remain available to plants although they are greatly diluted,
- is not useful for high levels of radioactive contamination,
- poor crop production in many soils after deep-ploughing,
- addition of fertiliser and lime to the topsoil needed after deep ploughing,
- impervious caliche layers and rocks could present obstacles.

Further knowledge needed:

- elaboration of a list of the root depth of different plants for optimal plough depth,
- addivities to correct for loss of soil fertility by deep ploughing in different types of soil.

Deep Placement of Contamination

Soil contamination due to the deposition of aerosols released after an accident occurs on the upper few mm of the soil surface especially in the case of dry deposition. This leads to separating the contaminated surface layers, turning them upside down or placing them between two different layers. Whether this can be done or not, obviously depends on the characteristics of the surface layer and on its vegetation. Turning over a whole fertile zone will prevent loss of soil fertility.

In Risø (Denmark), a project is currently being developed to construct machinery that could skim off the top 5 cm of the soil layer and bury it under some 50 cm without inverting the layer between 5-50 cm, in order to avoid a loss of fertility. The successful development of this project would have a fundamental impact on countermeasures as a whole.

The main advantages, disadvantages and research required with respect to **deep placement of contaminated surface soil** are:

Advantages:
- nearly 100% decontamination of surface soil,
- radionuclides made unavailable to crops,
- important reduction in radiation exposure from the surface.

Disadvantages:
- disturbance of soil layers and fertility,
- re-vegetation necessary in natural ecosystems; wil be sparse for a long period of time,
- composition of lower soil layers could hinder this countermeasure.

Further knowledge required:
- development of suitable equipment for application in large ares,
- elaboration of a list of root depth of plants to determine optimal depth for soil placement,
- list of additives to correct the loss of soil fertility due to the procedure in different types of soil.

d) Alternatives to Soil Treatments

Regardless of the dose of external radiation from surface contamination of agricultural areas, the most significant risk over a period of time will come from radionuclides getting into the human diet as a result of crop contamination in those zones. Because of the large financial costs and the effort required to achieve an effective decontamination with the above-mentioned countermeasures, certain alternatives have been suggested for the treatment of soils.

The main alternatives foreseen at the moment are:

- to grow varieties of crops with smaller rates of uptake of radionuclides;
- to grow crops which will add only little radioactivity to the human diet;
- to use processes which yield products with lowest radionuclide concentrations from the contaminated crops;
- to grow crops for feeding animals and not for direct human consumption;
- to use contaminated pastures for beef or mutton production instead of dairy products;
- to remove radionuclides from milk and other products by special treatments during processing;
- to grow crops for industrial uses.

In the past, attention was given to the substitution of typical crops in favour of others with a smaller human radiological impact. In Risø (Denmark), research has been carried out in recent years to determine the differences in the absorption of Cs by roots of different varieties of the same species in order to substitute them for the usual, more absorbing crop. Four varieties of barley and three of rye grass were tested for their sensitivity to the Cs uptake from clay loams and organic soils, and significant differences were revealed for varieties of the same species.

The main advantages, disadvantages and research required with respect to the choice of crop species are:

Advantages:
- significant reduction in contamination of crops achievable,
- requires only the selection of varieties from a species,
- no change in farming procedures,
- no increased costs,
- no adverse environmental effects.

Disadvantages:
- straw cannot be used for fodder,
- cash return from crop can be diminished.

Further knowledge required:
- behaviour of the different varieties in other types of soil.

6. Food Processing mainly of Dairy Products

Milk and milk products constitute a substantial part of the human diet and are a very important way by which food-borne radionuclides are ingested.

A project to study the transfer of radiocaesium from whole milk to a wide range of milk products manufactured by the Irish Dairy Industry was set up. The Irish experimental work shows evidence that more than 80% of the whole milk caesium can be distributed in each of the following products (see also Figure 1):

- skimmed milk
- casein whey
- cheese whey
- cottage cheese whey.

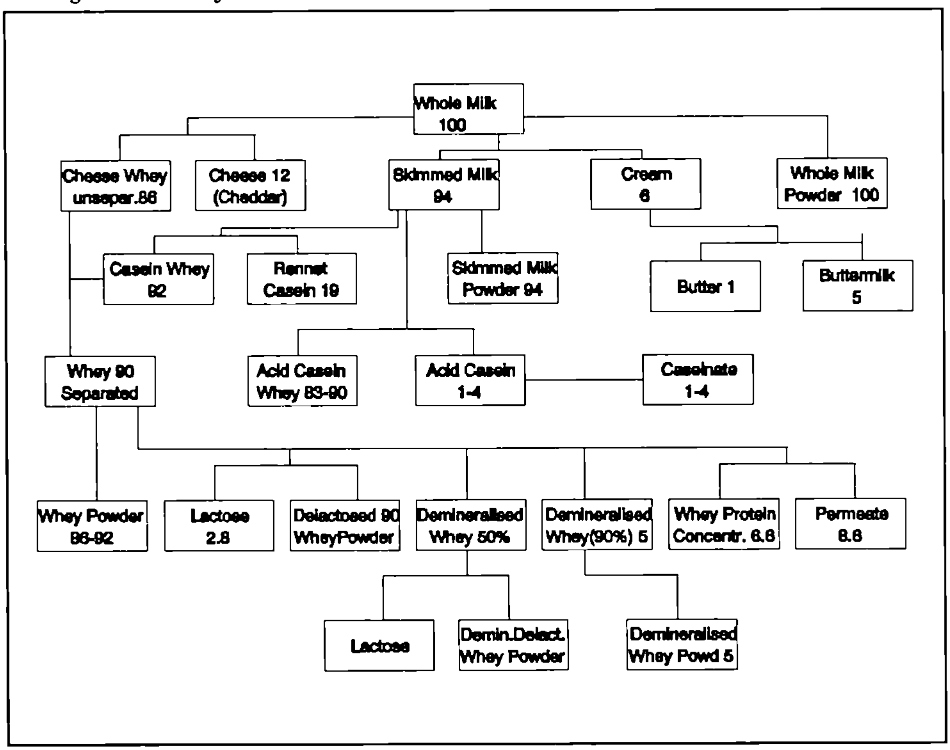

Figure 1 Principal milk processing pathways. The percentage distribution of radiocaesium to most of the products is indicated. (The analysis of the remaining products is presently being completed).

7. Further Research Needs

With reference to the CEC Post-Chernobyl Action "Countermeasures in the Agricultural Environment" and from information contained in the participants' contributions, it appears clearly that further research is required with respect to:

- the behaviour of soil and plant radionuclide uptake as a function of their physico-chemical state as released during accidents in pressure and boiling water reactors,
- the development of guides and tables on:
  - soil-crop transfer factors for the most important radionuclides, types of soil and climatological conditions. Chemical amendments to reduce the concentration of contaminants and uptake by different crops,
  - the impact of the removal of fertile soil layers on the productivity of different crops and procedures to recover the soil fertility for the usual or alternative crops.
  - the type of plants and crops which could grow in disturbed soil areas.
  - the root depth of crops and its influence when deep ploughing and deep placement of contaminants are carried out,
  - the migration of surface contaminants in different types of soil and its influence on the contamination of underground water and water stores,
- the study of resuspension of contaminated soil particles and their indirect quantitative impact on crops.
- the development of techniques and machinery for deep placement of contaminants.
- the improvement of vacuum equipment for surface soil removal over large areas.
- the development of techniques and machinery for the laying on of microcatchment depression soils and for the vegetation in the catchment basins,
- the treatment for waste reduction and disposal of radioactive vegetation and soil removed,
- the alternatives to land recovery:
  - crop management
  - processing of food products (vegetable, fruits, etc)
- the models and specific parameters to determine the impact of agriculturnal countermeasures over a period of time in the most typical environments of Europe.

VII Improvement of Practical Countermeasures against Nuclear Contamination in the Urban Environment

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2. Introduction

The work described in this report was sponsored by the Commission of the European Communities in 1987 as the seventh of ten post-Chernobyl actions under its Radiation Protection Programme

In the aftermath of any nuclear accident the primary concern is the well-being of the local population who would need to be evacuated and rehoused if radiation levels were unacceptably high. Any countermeasures which reduced or avoided the need for evacuation or minimised the time that people had to spend away from their homes, must rank highly in nuclear accident contingency planning.

The potential for widespread contamination was tragically realised by the accident at Chernobyl in 1986, when some 135000 people had to be evacuated from a zone within 30 km of the plant and significant amounts of radioactive debris were deposited in many parts of Europe remote from the accident site, especially in areas where the deposition was enhanced by heavy rainfall. Levels of ^{137}Cs in excess of 30 kBq m^{-2} were found even at sites more than 2000 km from Chernobyl, and in this research a survey in Gävle (Sweden) revealed levels in excess of 100 kBq m^{-2}

Of the radioactive fission and activation products which might be released in the event of a severe accident, ^{134}Cs and ^{137}Cs would pose the greatest threat to the population of a contaminated urban complex in the medium and long term. This has been confirmed following the Chernobyl release when it was found that the single most important isotope in terms of its contribution to the total radiation dose of the population of the Soviet Union and to the whole body doses of individuals was ^{137}Cs.

In recognition of the importance of radiocaesium in contributing to the hazards in terms of dose contribution, this study has focused almost exclusively on countermeasures against contamination of urban surfaces by this isotope.

The earliest studies on Chernobyl depositions demonstrated that many urban surfaces, such as roof tiles and concrete, have a considerable potential for intercepting and retaining radiocaesium fallout by both dry and wet deposition. Interception by such surfaces is not in itself surprising since caesium (cation) would be expected to ion exchange with sodium, potassium, calcium (also cations) which are known to occupy anionic adsorption sites on the surfaces of almost all urban minerals, natural and synthetic. What was surprising was that the adsorbed caesium was retained tenaciously on these surfaces even under relatively stringent decontamination treatments. Caesium ion, after all has a purely ionic chemistry quite akin to that of sodium or potassium and the other members of the alkali metal group and forms no covalent complexes. Resolution of this "anomaly" was a major objective in this research programme and an essential step in assessing surface decontamination (or prevention) strategies.

Research Strategy

The first major task of this research was to identify those surfaces which selectively adsorb caesium fallout by direct on-site or field measurements particularly those made in Gävle (Sweden). This was followed by a statistical evaluation of the prevalence and distribution of such surfaces in urban environments of the Community. Inventories of this type have not been made previously and in this study there was a serious attempt to develop and test a methodology which although applied in the first case to the United Kingdom, could, with little modification, be applied elsewhere in the Community and used in the assessment of risk and the feasibility and cost of specific countermeasures.

Based upon an appraisal of the chemical constitution, mineralogy and morphology of these urban surfaces a series of laboratory experiments was performed to identify the sites of caesium adsorption and further to identify and measure the numbers of sites available to caesium and their affinity for that ion. It is from this work that a true assessment of the potential of particular surfaces to intercept caesium can be obtained and from this work also that the chemistry of decontamination might be assessed.

In addition to the site specific or chemical aspects of sorption there are certain physical aspects of materials which determine interception and the rates of sorption and desorption of caesium (or other nuclides) on urban surfaces. These include the physical properties of roughness, porosity, surface areas, capillarity, and wettability. Taken with ionic diffusion these factors will determine the density of sites available for sorption of caesium and determine the rate, at least under wet conditions, at which this nuclide may find these sites. Above all it will determine the degree to which externally applied decontaminant will penetrate and release adsorbed nuclides.

In parallel with the investigation of detailed chemistry, the available techniques for decontamination and their efficacy have been critically reviewed and decontamination tests made in situ. In conclusion strategies for decontamination and reclamation of the urban environment were assessed.

3. Urban Contamination

Dispersed pollution is deposited by two major processes, by precipitation as wet deposition, and in the absence of precipitation, by dry deposition. In between, we have the specific foggy deposition. All three forms are of particular interest when assessing the risks of reactor accidents in the context of risk assessment. The reason for this is that external gamma doses delivered by the deposited material are often major contributors to acute effects, and doses from long-lived contaminants are usually long-term hazards. In risk assessment it is extremely important to deal with depositions in the urban areas where most people of the European Community live and work.

It is not sufficient to know the total deposition of nuclides, since to make a realistic risk assessment, the spatial distribution of the deposition in the urban area must be known as well.

It is therefore important to know the deposition on the most prevalent surfaces in the urban area, such as roofs, walls, streets, parks and squares and on green surfaces, such as trees, lawns and gardens. These may vary from city to city or even district to district within a city: In a United Kingdom case study, the methodology for the preparation of an inventory of urban surfaces has been made, giving the prevalence, distribution and classification of such surfaces.

In dry deposition, small particles, especially in the size range 0.1-5 μm, are important to risk assessment.

For surface cover consisting of individual elements, as in the urban case, the spatial distribution of the deposit within the "canopy" created by these elements is important. In the urban case, the spatial distribution of the deposit on external vertical and horizontal surfaces has dosimetric significance even to people indoors. The shielding effect of buildings is only partial.

Very few experiments on real urban surfaces have been performed for dry and wet deposition. The Chernobyl accident however gave an opportunity to obtain more precise information and assessment.

a) Dry Deposition

Earlier measurements, made during the passage of the first cloud from Chernobyl over the Roskilde area of Denmark, provided some insight into how the various isotopes are distributed on different surfaces. Dry deposition was measured for various nuclide components. Measured in terms of dry deposition velocity, v_d, particle-bound caesium had the smallest values, around 1.10^{-4} ms^{-1} on street surfaces. At the next level, ruthenium, lanthanum and elementary iodine had deposition velocities of about 5.10^{-1} ms^{-1}. The highest deposition velocity was found for particulate cerium and zirconium.

For caesium which was the main topic of this programme of research, the dry deposition velocities on house walls were five times less than on street surfaces and on rough surfaces such as corrugated roofs and grass, it was a factor of three to five times higher than for roads.

b) Wet Deposition

In wet deposition, it was found that the concentration of radioactive material in the run-off water (defined as the water that goes into the sewer system during an episode with contaminated rain), can be very different from its concentration in the rain water itself. This is due to retention of nuclides on the urban surfaces. Initially a rather large proportion of nuclide deposited can be retained in this way.

The ratios of concentration of nuclides in run-off compared with that in rain water gives an estimate of the interception potentials of these surfaces, which in general varies for particular isotopes. On cement and roof tiles about half was intercepted for caesium, ruthenium and barium. "Eternite" a common roofing material of asbestos cement, however, showed a much higher affinity, absorbing 80%. The pretreatment of this surface with silicone oil reduced this uptake to only 25%. The concept of a pretreatment strategy was investigated further.

In Gävle (Sweden) a series of measurements were made to identify the relative wet contamination on different urban surfaces. It was found that just after deposition 40-80% of the caesium initially deposited remained on paved areas, 30-90% on roofs and 1-3% on walls. After two years 5-20% was left on paved areas, the percentages depending strongly on traffic and 20-70% remained on roofs. All the deposited caesium was found still present on the walls. (These percentage figures have been corrected for decay.)

In order to improve the reliability of predictions of the distribution of radioactive material, field studies of dry deposition in the urban area are needed and a more reliable model for determining the distribution has to be developed. In the case of wet deposition it is clear that the major retention of caesium is primarily on grassed areas, followed closely by roofs and paved areas. Walls are of relatively little importance, with an interception of about 1% of that measured for grassed areas. It is clear that the low interception by walls is due to their minimal rain exposure, compared with roofs or pavements, which are directly exposed. There remain major differences within the categories of roofs and pavements which are obviously related to their chemical structure, roughness and porosity. It is reported in subsequent sections how these factors were examined systematically, with the dual objectives of improved understanding of the underlying processes and to seek countermeasures.

From the risk assessment point of view there is a great need for a reliable model which can predict the concentration in rainwater of radioactive material under given weather conditions and the distribution of materials to urban surfaces including run off.

4. Inventory of Urban Surfaces

It was evident at the outset that any formulation of realistic countermeasures against nuclear contamination of urban environments would require a detailed inventory of the urban environment with a classification of the types, prevalence and distribution of urban surfaces which would be exposed to fallout in the event of a nuclear accident. Field studies in the town of Gävle have indicated the relative importance of certain surfaces, (roof tiles, pavements, grass, trees etc.). It was clearly essential to classify and assess the prevalence and distribution of such surfaces in cities across the Community. Ultimately this information is required to assess the degree to which specific surfaces will intercept and retain fallout and to determine the salient factors in their morphology, chemistry and mineralogy to assess risk and prioritise countermeasures.

The required information on the fabric of urban areas must include details of the types, prevalence and distribution of materials present. This information is essential to coordinate field and laboratory studies for the assessment of the binding potentials of radionuclides, and formulate and assess possible countermeasures such as decontamination or protective pretreatment.

The surfaces which are exposed in cities may vary dramatically, according to climatic, cultural and historic factors, not only across Europe, but also within individual countries. From the outset of this study, it was apparent that details of the fabric of cities within the European Community were not catalogued nor were there, on record, any clear cut methods by which this task might be implemented. A case study of the United Kingdom in which methods for quantifying and recording an inventory of the (sorptive) urban surfaces was tested. The United Kingdom was chosen because it contained a number of distinct cultural and regional divisions which find expression in variations and preferences in architecture, materials and even the legal specification of building standards (as for example between England and Scotland) dictated by historical and climatic differences. Modern building methods and even architectural preferences differ little for modern public buildings and office blocks throughout Europe. There are larger variations in style and materials for private dwellings, but it is in older (pre-1920) buildings that major differences may occur, especially if local stone was preferred.

To prepare an inventory of urban surfaces within the United Kingdom, three broad strategies were used.

The first step was the selection of cities spread across the country taking into account variations in historical, geographical and climatic conditions, which might influence local building preferences and choice of construction materials.

Secondly , on-site observations based on photographs, Ordnance Survey Maps and (historical) growth maps of the chosen urban environments were carried out. This proved effective for classifying regions where a significant proportion of buildings were constructed with traditional, local, man-made or natural materials such as stone, brick, slate or clay tiles.

Finally, a quantitative assessment was made using production and distribution figures for construction materials in the United Kingdom over the last forty years.

Once materials were identified it was then possible to use both manufacturers' technical specifications and a literature assessment to identify the role of specific construction materials as potential sorbents for radionuclides. These materials could then be studied both in the laboratory and in field studies to assess the degree to which the radionuclides penetrate and are adsorbed.

This survey provides comparisons which show that exposed urban surfaces do differ substantially from city to city. Differences occur both in the types and in the preponderance of the materials which make up the fabric of urban centres of population which would significantly influence both the potential radiation risk and influence the strategy of countermeasures.

These marked variations both in types and distribution of construction materials within the United Kingdom make it reasonable to assume that such wide variations will also be observed throughout the rest of the Community.

It is evident, that to have a logical and defensible evaluation of the probable efficiencies of proposed countermeasures against nuclear contamination of the urban environment, this survey of exposed surfaces must be extended to all other member states of the European Community.

5. The Mineralogy and Chemistry of Urban Surfaces

a) Mineralogy

Urban surfaces are extremely varied in mineralogy and chemical composition. In general terms, a distribution can be made between two broad classes of materials. The first class includes the various types of rock, including sedimentary, metamorphic and igneous rock, which may be used, as such, as building materials or as crushed aggregates in mortar and concrete. The second class includes man-made materials both inorganic and organic and mostly silica-based and include bricks, clay tiles, cement, mortar and concrete, and those organic in nature which include paints, and bituminous or asphaltic materials.

The mineralogy of rocks is extremely varied. It includes materials which are relatively inert such as quartz and feldspars, a broad range of mica, clay minerals and zeolite, chemical minerals (carbonates, sulphates, sulphides) and some oxides (of iron, titanium, aluminium). The mineralogy of fired clay products is quite varied depending upon the composition of the raw materials and the duration and temperatures of firing. It consists mainly of a broad range of aluminosilicates, including feldspars, quartz and suites of oxides of aluminium, iron, magnesium, calcium and titanium. The main mineral component of set cement is tricalcium disilicate hydrate, known as tobermorite. In addition, rock aggregates represent an important element in mortar and concrete.

Examination of the overall composition of these various materials reveals that most are characterised by the presence in them of components which are known to exhibit ion exchange properties. Accordingly, it might be expected that many of these materials will be selective towards caesium ion. Of particular importance in the present context is the, near ubiquitous, presence of micaceous materials, well-known for their fixation of caesium.

b) Ion Exchange and Caesium Binding Capacities

For a realistic assessment of countermeasures against radiocaesium sorption, it is necessary to determine both the total caesium ion binding capacity and its ease of displacement on a representative range of exposed urban surfaces. It is also necessary to determine the mechanism of sorption and should it be ion exchange (as indeed was proved in this work) identify the sites and to determine which ions previously occupied them. During the course of this research, a caesium ion selective electrode was developed and tested. With this electrode and a range of commercially available ion selective electrodes (including those for sodium, potassium, calcium and hydrogen ions) a titration methodology was created by which the uptake of caesium and the corresponding release of displaced counter-ion, was measured rapidly and precisely.

The whole titrimetric system was automated. Multi-ionic titrations were performed using a computer-controlled system which allowed for additions of varying amounts of electrolytes, stirring times and graphic displays as the titrations progressed. Data on ion sorption, ion release, pH and other vital experimental data were collected, calculated and displayed. Uptake and release of ions from the materials under investigation were calculated by mass balance.

From the data collected, Cs^+ uptake, Cation Exchange Capacities, Cs^+ distribution coefficients, Cs^+/Na^+ selectivities and K^+/Na^+ selectivities were readily obtained. These last were then processed to obtain Cs^+/K^+ selectivity coefficients.

These multi-ionic titrations were fully computerised and automated so that samples could be tested in a much shorter time than by conventional batch equilibration procedures using radioactive isotopes or other analytical methods. The urban materials, bricks, tiles, clays etc., were ground to a fine powder (2 μm) and titrated in dispersion in aqueous solutions. The release of potassium ions on dispersion of the untreated material in water or acid, proved a good indication that high caesium binding potentials were to be expected. This titrimetric survey provided a measure of the total cationic exchange capacity for a wide range of urban materials and associated minerals. More than one hundred urban samples and related minerals were collected from sites across Europe. In particular, experiments were conducted with red clay roof tiles from the town of Gävle in Sweden, which were found to be contaminated by radiocaesium due to Chernobyl fallout.

The cation exchange capacities of the construction materials tested were considerably lower than those of clay minerals such as illite and montmorillonite. They range from 0.008 mmole g^{-1} for a clay roof tile to 0.075 mmole g^{-1} for road surfacing aggregate.

The cation exchange capacities of these dispersions were found to be proportional to the surface areas of the particles of the samples, determined independently by nitrogen sorption, using the BET method. Ion exchange capacities per unit area of BET surface were constant. From BET surface area measurements on the whole tile or brick the Cs^+ binding capacities per square metre of superficial surface of these construction materials in the urban environment were obtained. The total exchange capacity for a 1cm deep section of a Gävle rooftile has been calculated at

47 mmol per square meter of superficial surface. This is a very large ion exchange capacity, equivalent to the capacity of almost 30 ml of commercial cation exchange resin.

Selectivities were generally in the order $Cs^+ > K^+ > Na^+$ with the magnitudes varying according to the nature of the material. The maximum selectivity of Cs^+ over K^+ was 5 for a concrete tile from Bavaria. It is clear that these relatively abundant "macrosites" have low selectivities for caesium and are not those responsible for the tenacity with which fallout radiocaesium is bound. As further confirmation it was shown that the caesium bound to these sites can be easily and reversibly exchanged for potassium or sodium (or ammonium) ions. This was shown using sophisticated new radiochemical techniques, these highly selective sites have been discovered and their selectivities and other binding properties quantified.

Although they are not the ultimate destination of caesium fallout, it is most likely that these macrosites play an important role in the mechanism by which radiocaesium in rainwater is intercepted on these surfaces. In this mechanism, these poorly-selective but abundant ion exchange sites will serve as intermediate binding sites, facilitating the removal of radiocaesium present at hyper-dilute concentration in the fallout rain. The caesium thus sorbed can then find its way (slowly) by surface diffusion to the one percent or less of highly active sites where they become irreversibly bound and remain thereafter. This mechanism would explain the otherwise improbable fact that radiocaesium at extreme dilution is efficiently scavenged by the very small number of active sites which are present on each square meter of exposed surface. If these macrosites were to be blocked or rendered inactive, then, it might be hypothesised that radiocaesium sorption might be significantly reduced. This concept of a preventive strategy (based on pretreatment with surfactants) has been developed further.

c) Identification of the Specific Sorption Sites for Radiocaesium

At this point it is useful to recapitulate the observed facts on the interception and retention of radiocaesium. Subsequent to the Chernobyl accident, a number of reports, (confirmed in this research), have demonstrated that radiocaesium is (a) very efficiently intercepted by a variety of urban surfaces such as roofs and pavements and (b), subsequent to adsorption, radiocaesium is very tenaciously retained and very resistant towards desorption treatments. It may be added that field trials have shown that, of the common ions, ammonium is superior to potassium as a displacement agent although neither could be considered as useful in any practical sense. The relatively large numbers of reversible ion exchange sites (macrosites) found universally on urban surfaces determined by titration, and responsible for the bulk of their ion exchange properties have none of these properties and are not responsible for caesium retention. The search for selective sites was pursued further. A comprehensive study of the quantitative aspects of radiocaesium sorption and desorption on some key substrates present in the urban environment was made.

On the basis of the classical and empirical distribution coefficient (K_D) approach, evidence is given for the presence of a small number of sites which are extremely sorption-selective towards radiocaesium which represent less than one percent of the total ion exchange capacity determined in this study and in agreement with the results of this study and of the titrimetric methods. However such an approach is entirely inadequate for quantifying the details of the sorption process on these highly specific caesium binding sites. For this reason entirely new procedures have been developed for characterising the number and sorption properties of these specific sites. These procedures are based upon the use of masking techniques, which eliminate the disturbing influence of the vast majority of regular and non-specific ion exchange sites and allow direct measurement of both the numbers of ion selective sites present and their ion selectivity pattern.

In the first instance these methods were applied to micaceous clay minerals, known to show the specific sorption of caesium and which are also known to be present ubiquitously in sedimentary metamorphic and igneous rocks and, possibly also, in fired clay products, as residues. The procedure is based upon the use of the silver thiourea complex (AgTU) as a masking agent for the much larger numbers of reversible macrosites. This cationic complex exhibits a very high selectivity for these sites and in its presence caesium is sorbed only by the very much smaller number of highly selective "Frayed Edge" sites (FES) which correspond to no more than 1% of the overall ion exchange capacity. It is shown that these sites are characterised by an exceedingly high preference for caesium over potassium ions which occupy them in the natural state. This selectivity is of the order of 10000 and so these sites are some 2000 times more selective for caesium than the macrosites for which the equivalent selectivity coefficient is only 5. On these sites also, potassium is invariably less competitive than ammonium, generally by a factor of 5.

With these methods it was demonstrated quantitatively that the extreme caesium selectivity of sandstone and roofing slate was due to the role of these highly caesium selective sites on the micaceous clay mineral content.

Similar highly selective sites have been identified by this method on fired clay products. As in micaceous clays, these sites have an exceptionally high selectivity for caesium and they too prefer ammonium over potassium but to a lesser degree. Street dust samples (which play an important role in the resuspension process) originating from various cities within the community also show these high selectivities and these masking procedures demonstrated that the caesium sorption behaviour was entirely similar to clay minerals and fired clay products.

The sorption of caesium ion in cement products was quite different and proceeded by a reversible ion exchange mechanism. The very selective sorption of radiocaesium on such materials is most likely to be ascribed to the rocky (micaceous) aggregates exposed in such surfaces. The same conclusion is drawn for specific caesium sorption on bituminous and asphaltic surfaces. The organic component binds caesium weakly, if at all. The results can be briefly summarised in the following terms:

a) most urban surfaces are characterised by the presence of a small number of sites - generally of the order of 1% of the overall exchange capacity - which show very pronounced selectivity towards poorly hydrated cations such as caesium, ammonium and potassium;

b) these sites show an exceedingly high selectivity for caesium as compared to potassium, with a selectivity factor of the order of 10000;

c) the sorption of radiocaesium in the specific sites is essentially controlled by the levels of potassium and ammonium in the contacting liquid phase (rainwater);

d) the ammonium ion is invariably preferred over the potassium ion on the specific sites, by a factor of two in fired clay products;

e) no specific sites are present in set cement and the specific interception of radiocaesium in mortar and concrete is related to the natural rock aggregates (containing micaceous minerals) exposed in these surfaces.

The practical significance of these results can be illustrated by the following example. The total number of specific sites for porous clay tiles present per square metre of geometrically exposed surface to a depth if 1 mm exceeds the annual caesium input through precipitation (0.1 μmole m^{-2}) by some three orders of magnitude. In turn the annual stable caesium input is equivalent to an amount of 4.10^7 Bq of ^{137}Cs. Apart from explaining the very efficient radiocaesium interception by roofs, these findings clearly demonstrate the almost limitless capacity of such surfaces for radiocaesium retention.

On the basis of ion sorption selectivity data, it is now obvious why the ammonium ion is the only realistic candidate as a decontaminating agent. Its efficacy is however severely limited not only because it is less preferred than caesium on the active sites but also by kinetic factors. This was borne out by a comprehensive study of the kinetics of desorption of radiocaesium from micaceous clays and finely ground clay products, using either stable caesium or ammonium ions as desorption agents. It was demonstrated in both cases that desorption increased linearly with the logarithm of time. This means that the desorption process is very slow indeed. In general, complete desorption required contact times of four weeks or more. The amount which was readily desorbed varies in the range from 5% to 30% of the total. Most important however is the fact that irreversibility of caesium desorption was further enhanced by long contact times and intermittent drying and wetting of the materials. It is important to note that these desorption data were obtained on powdered materials in aqueous suspension. This makes the desorption conditions optimally favourable and indicates that in the field, dealing with porous urban contact surfaces, desorption efficiencies will be further reduced by diffusion effects within the pores. (Diffusion within the pores of urban materials is examined separately.) The conclusion is that decontamination efforts are likely to result in very limited success, with respect to roofs and walls. It can be expected that the maximum desorption yield can be only 10 to 20% at best, using ammonium and keeping the time of surface treatment to some reasonable limit.

This gloomy prognosis suggests that the best conventional washing or elution decontamination procedures will be at best marginally effective. With no prospect of new efficient chemical decontamination techniques, the choices are (1) to optimise the methods presently available and (2) to seek a new philosophy as regards practical countermeasures against nuclear contamination which rejects decontamination as an option.

6. Surface Chemistry and Diffusion

a) Ionic Diffusion

The efficacy of decontamination techniques based upon ion exchange in aqueous systems, depends not only on the chemical action of the decontaminant, but also upon the rates at which the reagent and the displaced nuclide migrate into and out of the material through its porous structure, there are many field studies which show clearly the effects of porosity on nuclide interception. These factors are equally important to chemical decontamination strategies.

Methods were developed to determine porosity, diffusivity of salts and capillarity of a range of urban materials, particularly of brick and of clay and concrete roofing tiles. As a first step to classification, their porosities (percentage void volumes) were determined. Typically fired clay tiles were found to have porosities of around 25%, concrete tiles somewhat lower (12%) while fired clay bricks varied widely, the largest measured was English Fletton brick (35%) but Swedish Gävle brick was almost as porous (28%). The specification of porosities of brick vary widely and in the United Kingdom urban survey it was noted that the upper level of acceptable porosity was determined by the climatic conditions in Scotland where wind and rain levels can be higher lower porosities are required by law. Since weather and wet deposition are intimately linked, local building practice will serve to protect those walls most likely to be contaminated in proportion to risk. Porosity figures however serve to indicate the hidden excess of surface within the network of pores which lie below the exposed (geometric) surfaces of roofs and walls. These increase the available sites for caesium sorption by orders of magnitude on what would be expected if these surfaces were totally smooth.

For diffusion and capillarity, there were two objectives. The first was to establish a method for determination of salt (electrolyte) diffusion within these porous structures. The second was to study the capillary uptake of water on dry surfaces exposed to wet deposition. This latter was extended to determining the degree of wetting of urban samples treated with detergent to render them both water and caesium repellent.

To determine these parameters, 18mm diameter discs were cut from the whole tile or brick, normal to its surface. The cut edges were sealed so that diffusion or water uptake would take place through the normally exposed surfaces.

The "dipping disc" method was used to determine diffusion coefficients. Discs were filled with electrolyte (0.5M KCl) and dipped in distilled water. Only the outer surface was exposed and the rate of salt effusion was determined using conductivity measurements. The effective diffusion coefficients of salt in the roof and brick samples were then calculated by a standard method.

The diffusion coefficient of free potassium chloride in (the water filled channels of) a porous tile is typically in the range 1.5 to 2 $.10^{-6}$ cm^{-2} s^{-1} and similar values would be expected for caesium and other common ions such as ammonium. These values are only an order of magnitude lower than in free solution and are typical of what might be expected for aqueous diffusion in an open network of macropores. Even so decontaminants like aqueous ammonium nitrate would penetrate a tile or brick only slowly. For a fully wetted 1 cm tile, the half time of diffusion controlled sorption would be approximately 24 h. For a more porous structure such as a Fletton brick (commonly used for house construction in England) with thickness 10 cm and diffusion coefficient $5x10^{-6}$ cm^2 s^{-1}, the equivalent period would be about 40 days. The entry of nuclides, in the contamination step, or the decontaminant applied in aqueous solution will be much enhanced if the substrate surfaces are dry, then very rapid uptake may occur by capillary action. The results of wetting on a dry tile (from Gävle) showed that the pore structure is filled entirely in only 17 minutes. These preliminary results indicate the importance of the diffusion and wetting characteristics of surfaces in planning decontamination strategies, and further measurements on a wider range of materials would be beneficial.

b) Wetting and Protection by Surfactant Pretreatment

The field studies and the laboratory results made it clear that chemical decontamination procedures will be relatively ineffective. Accordingly, a series of experiments were made to assess the degree to which porous brick and tile might be made both water-repellent and inert to caesium sorption by pretreatment with very dilute solutions of surfactants (detergents). An extensive literature survey of the action of surfactants on mineral surfaces was made. A number of common cationic detergents were tested. The sorption characteristics of six common detergents were made. At very low concentrations, typically $\leq$ 0.001M (or $\approx$ 0.3 g l^{-1}) a protective monolayer of surfactant molecules is formed on these surfaces. Since the surfactants used are cationic, they also bind to the macrosites on the minerals which normally bind potassium, sodium, calcium (and radiocaesium). Preliminary results were very promising. Pretreatment of surfaces with these very dilute surfactants made the surfaces water repellent. In powder form the treated brick or tile was not wetted by water and these treated powders floated on the surface of water. The whole tile or brick sample discs behaved similarly excluding (rain) water penetration by up to 99%. On this basis one might expect that radiocaesium sorption would also be reduced since this treatment not only largely prevented the ingress of water into these porous materials but also, to a large degree, blocked caesium binding sites. A test using carrier free ^{134}Cs showed that the uptake of radiocaesium (on Gävle tile) was reduced by 80% on a tile treated with cetylpyridinium chloride (CPC) and by 59% with cetyl trimethylammonium bromide (CTAB), both very common surfactants widely used for industrial and household applications. The surface treatment remained effective for several weeks and through several wetting and drying cycles. The detergents so far tested are readily available in bulk and are widely used domestically (in washing powders and shampoos). Their use would create no additional chemical or biological hazard. Provided there was sufficient advance warning of impending nuclear deposition (as there might have been across most of Western Europe following the Chernobyl accident), the strategy of surfactant pretreatment could emerge as a most effective countermeasure. The techniques for spraying detergent over wide areas are already well-developed and are now used routinely for oil slicks at sea and similar techniques are used on farm land for crop spraying pesticides. The concentrations of detergent found to be effective in this study are very dilute, less than 0.001 M or depending upon the molecular weight of the detergent, approximately 0.5 g l^{-1}. Pretreatment might therefore become a well-defined option. It must be stressed however that although these results are very promising they are of a preliminary nature. Much further research and development would be needed before they could be fully evaluated, optimised and converted into a code for improved practical countermeasures.

7. Literature Review and Decontamination Tests

a) Literature Review

A literature review revealed comparatively few references to the removal of radioactive contamination from man-made surfaces in the urban environment. There was a considerable number of papers on the removal of contamination from steel, laboratory and workshop surfaces and in the context of reactor decommissioning. Almost all are aggressive and designed to remove a contaminated surface layer. Such methods are not well suited nor indeed practical to the large areas which might need treatment in an urban complex. Of those described, some would be effective for a whole range of radioactive contaminants adhering to urban surfaces, such as sand blasting, while others have been developed for specific elements, notably caesium and plutonium. Field and laboratory studies have shown that caesium remains very close to the surface of contaminated substrates (a consequence of the presence of highly selective caesium specific sites, discussed above) and therefore erosive methods would be effective as a decontamination strategy. Such methods have been used in Russia, post-Chernobyl, but with them there is the ever present problem of resuspension. The literature also indicates that prealable coatings, as used in the nuclear industry for many years, might have much to offer in the management of the contaminated urban environment.

The application of an effective decontaminant in aqueous solution would represent a more manageable system and, of those relevant to this problem, removal of caesium by displacement with ammonium salt solutions has received most attention.

Although the most attention has been paid to chemical decontamination, it is to be noted that in studies carried out as part of this research a significant fraction (up to 32%) of radiocaesium collected on air filters during the Chernobyl emergency failed to dissolve in water or aqueous solutions. It may be speculated that these correspond to mineral dust samples of micaceous clays or similar materials with strongly caesium binding sites. However their removal by filtering from air or from streets and other surfaces by sweeping and vacuuming represents a useful countermeasure.

b) Large Scale Decontamination Tests

Large scale decontamination tests were conducted on specially constructed roads at the Danish Atomic Energy Risø Laboratory where both wet and dry depositions were simulated on asphalt and on concrete roads. Using normal street cleaning practices, the efficiency of decontamination was studied at two different loadings with contaminated street dust. Sweeping with a stiff broom removed negligible amounts of caesium when the dust loading was 50 g m^{-2}, but at loadings of 200 g m^{-2} some 40-60% was removed. When a street vacuum cleaner was used immediately after sweeping with a broom, about 16% of the caesium was removed at a dust loading of 50 g m^{-2} and about 40% when the loading was 200 g m^{-2}. Application of water and vacuum cleaning simultaneously lead to inconclusive results. In some cases, an increase in contamination was recorded, probable due to uneven redistribution of the radiocaesium. A mixture of $^{132+136}Cs$ was the radioactive tracer used in these studies. These short-lived radioisotopes were prepared specially for the purpose.

Decontamination tests on whole roofs were also made. A red clay tile roof contaminated more than two years previously by wet deposition in the Chernobyl accident, was removed from the town of Gävle (Sweden) and reassembled at the Risø Laboratory. (Samples of these tiles were also included in the laboratory studies on caesium sorption and diffusion and surfactant tests.) This roof carried a thin but easily visible coating of organic matter (moss and algae). When washed with a jet of high pressure water, must of the organic matter was washed from the tiles and with it some 55% of the radiocaesium. Subsequent treatment with a solution of ammonium nitrate removed only 1-2%, and subsequent sandblasting a further 7%. Most of the displaced caesium was found to be attached to insoluble solid matter and filtration was all that was required to obtain a sufficiently low level of aqueous effluent for discharge into the drains.

In situ decontamination tests on walls contaminated more than two years previously by Chernobyl fallout showed both water and a solution of a commercial detergent to be ineffective decontaminants but a dilute solution of ammoniun nitrate displaced about 15% of the caesium for two different types of brick wall.

Prolonged tests, in which the contaminated brick and tile were steeped in solutions of ammonium nitrate, showed that, even after exposure to the weather for more than two years (during which time many wetting and drying cycles had taken place) 31% of the caesium could be displaced from the red clay tile and 45% from the brick. The greater efficiency of prolonged treatment can be ascribed, at least in part, to the provision of sufficient time for diffusion of decontaminant into the materials and for similar time scales for diffusion out. Half-times for these processes might be expected to be of the order of one day for the tile and forty days for the brick.

It is clear that the removal of particulate deposits on urban surfaces can be a useful countermeasure. Chemical decontamination procedures appear to be less so, partly because of the intrinsic inefficiency of the displacement process removing caesium from highly selective binding sites, and partly due to the porosity of these substrates and the attendant kinetic and diffusion problems which slow down the release.

8. Working Towards a Strategy for Decontamination and Reclamation of the Urban Environment

The ultimate goal of a decontamination/reclamation study is the provision of contingency plans for tackling a wide variety of scenarios for a contaminated urban environment. To provide the most cost-effective strategy, a host of factors need to be considered. Some important factors to be considered in formulating strategic countermeasures are: (1) the distribution of the deposited material with respect to differing surfaces; (2) the contribution of each type of surface to the dose rate; (3) the decontamination or dose reduction achievable on individual surfaces using the most appropriate methods; and finally (4) the practicability of the various reclamation, decontamination and perhaps now also protection or pretreatment methods.

Using existing methods of decontamination, the effects of decontamination upon a typical or model urban dweller living in a terraced suburban house and with a well defined life-style has been estimated. Having established the relative contamination on the various surfaces and incorporating attenuation factors, a table of achievable decontamination factors has been made for each surface and so it would be possible to determine where decontamination would be most beneficial and the relative efficiency of countermeasures can be estimated.

In the case of dry deposition, it was found that removal of trees and decontamination of gardens are efficient and inexpensive means of achieving very significant reductions in dose and would rate highly in a list of priorities. Street cleaning also is cost effective. Roofs are important contributors to dose but the cost of cleaning roofs is high and such a procedure would not rank highly in a list of priorities since it is not a cost-effective means of reducing dose. Walls contribute little to total dose, are expensive and difficult to decontaminate and would therefore carry a very low rating in a list of priorities.

In the case of wet deposition, the garden will be given first priority since a considerable reduction in dose can be achieved at relatively low cost. Street cleaning would also be worthwhile. Treatment of windows and walls would be a minor consideration since little could be achieved in terms of dose reduction and treatment costs would be high.

Certain practical points need to be emphasised when considering application of a developed strategy in the real situation. Firstly, although it is necessary to know the levels of contamination on the individual urban surfaces it would only be necessary to actually measure what is on the grassed area or on bare soil: the levels on other surfaces would be calculated from a knowledge of other factors such as rainfall and type of urban complex.

Knowing the distribution and levels of deposition and from considerations of the particular urban complex (e.g. height of buildings, presence or absence of parkland) the achievable reduction in dose rate could be calculated. The figure may be determined by an optimization procedure or the target for dose reduction might be based on data derived from ICRP. It may turn out in certain situations that rather simple calculations show evacuation to be unnecessary since acceptable dose levels can be achieved quite quickly or, at the other extreme it might show that attempts to reclaim the area are so cost ineffective that permanent evacuation and abandonment of the area might be the best option.

9. Conclusions and Recommendations

A survey of contamination post Chernobyl, indicated that specific sorption of caesium occurred on roofs, pavements, walls, grass and soil, indeed on all exposed urban surfaces.

Sorption varied in degree, depending upon the method of deposition (dry or wet), the porosity and texture (rough or smooth) and their position and inclination to the horizontal. Horizontal or near horizontal surfaces, such as roofs, paved areas and grass were much more contaminated than walls in both wet and dry depositions. Trees represented a special hazard with dry deposition and grass with both.

A broad correlation between sorptive capacity and differing chemical compositions was indicated from these studies together with the additional sorptive capacity of rough and porous materials.

Empirical test decontamination using hosing and washing with chemical solutions proved to be largely ineffective and caesium (the main nuclide of interest) remained absorbed on the outer surfaces.

In this work the important urban surfaces for sorption were identified. They exist in all urban areas.

An inventory of the surfaces of the urban environment was made to determine their prevalence and distribution in a quantitative manner. Such an inventory is considered to be essential to assess risk and formulate policy for decontamination or any other countermeasures needed following a nuclear emergency.

In this research a methodology was developed to create urban inventories across the Community. The United Kingdom was used as a case-study. In the seven urban centres chosen for study wide local preferences for building materials and styles were noted and quantified using statistical figures for manufacture and use of roof tiles, bricks and other construction materials. An innovation was the use of historical growth maps to assess the older parts of cities. Before 1920 local preferences in building materials were widespread and the use of natural stone, slate and locally produced materials was more common. Once identified, representative areas were photographed and their surfaces classified and catalogued. More than 400 photographs were taken in three urban areas for this purpose.

Such urban surveys must be considered essential to a proper formulation of contingency plans and countermeasures in the urban areas across the community.

Chemical studies determined the degree to which caesium bound to urban surfaces, such as roof tiles, brick, concrete and natural stone. Rapid titrimetric methods were developed to characterise these materials using a number of ion selective electrodes including a caesium specific electrode developed for this purpose in this research. The computer controlled and fully automatic procedures are much quicker than conventional (batch equilibration) methods and useful for examining the large numbers of samples needed to give an overall picture of their potential for caesium sorption. The vast majority of these sites was found to be weakly binding. It was found however, using a completely new masking technique, that a small minority (~1%) bound radiocaesium strongly and virtually irreversibly.

These sites exist on surfaces and within pores of fired clay materials and in soils and many rocks, used as building materials or as aggregates in cement or asphalt. Even under the most favourable laboratory conditions, the most complete displacement of radiocaesium from these sites proved to be impossible as such caesium as could be removed could only be displaced very slowly. Displacement was even less efficient if the sample had been exposed to wetting and drying cycles, simulating weathering. The most efficient displacement agent was found to be the ammonium ion of ammonium nitrate solution.

It was also found that these strongly binding sites, although few in number in bulk chemical terms, are in vast excess over those needed to bind radiocaesium from any conceivable fallout. The scavenging of caesium by such highly selective sites is facilitated by an initial ion exchange sorption on the very large numbers of low selectivity macrosites characterised by the titration technique. Once localised on the surface, they can migrate slowly by surface diffusion to the active sites where they subsequently will remain, effectively permanently. These experiments show that conventional decontamination using dilute solutions of chemical reagents (such as ammonium nitrate) has little or no hope of success. They also explain the field observation that radiocaesium was to be found only on the top 1-2mm of exposed surface.

Diffusion studies showed that radiocaesium would diffuse rapidly into porous brick or tile and that dry (Gävle) tiles could be extremely absorbent to wet deposition. They filled completely with water (rain) in only 17 minutes. Diffusion studies also indicated that the penetration of decontaminant and removal of caesium displaced could be a very slow process over the dimensions of a brick (10cm) or tile (1cm) half times of 40 days and 1 day respectively are typical. Such temporal considerations combine to make chemical decontamination even less attractive as an option. The most optimistic assessment, using the best decontaminant found in this study (ammonium nitrate) might be expected to remove no more that 20-30% of radiocaesium deposited. These figures are supported by field experience.

One countermeasure proved promising. This was the treatment of porous urban surfaces with a dilute solution of bio-compatible cationic surfactant to prevent absorption of radiocaesium. In use, this would require a situation in which, following a nuclear accident, the meteorology was well enough defined to predict that wet deposition might occur on an urban complex. In this case it might be possible to spray roofs and roads with a dilute solution of surfactant so that caesium would not be intercepted, but would remain in the runoff water. The mechanism for this pre-treatment has been established and laboratory experiments on weathered roof tiles, showed it to be effective, preventing 80% of uptake and also showed the treatment to be viable many days after treatment.

It must be stressed that this work is still at an early stage of development and much further research, both in the laboratory and in the field studies, would be needed to create a proved practical countermeasure.

At a practical level physical methods for decontamination can prove effective as countermeasures. Domestic cleaning equipment, street cleaning equipment, agricultural and road maintenance machinery, high pressure water jets and sandblasting methods can all prove useful.

This research showed that street sweeping with brooms and vacuum cleaning could remove 90% of radiocaesium on roads with a road dust loading of 200 g m^{-2} on an experimental road surface. In a parallel experiment simulating wet deposition, sweeping and vacuum cleaning removed no more than 11% from the asphaltic surface, but 50-60% from a similar concrete road surface.

Decontamination of the tiled roof of a single storey building in Gävle (Sweden) two and a half years after contamination from Chernobyl, using high pressure water jets, removed 55% of activity. This (a much larger figure than expected) appeared to be due to the removal of a layer of organic matter (mosses, lichen) displaced by the water jet. Subsequent treatment with ammonium nitrate solution was ineffective, but light sandblasting displaced a further 7% due to removal of a layer of contaminated tile surface. The solid debris presented no further hazard since it could be easily recovered, the aqueous effluent was of sufficiently low activity to be discharged to the drains.

All the laboratory and field studies indicate that chemical decontamination will be ineffective and that caesium sorption will be largely irreversible. Physical methods may prove useful by removal of contaminated dust on streets (and particulate aerosols) and by physical abrasion to remove the top surfaces of contaminated materials (where most of the fallout caesium will be bound) and to remove mosses and lichens which may harbour it.

Recommendations

On the negative side all evidence suggests that application of liquid decontaminants will be substantially ineffective and cannot be used as a practical countermeasure for the removal of radiocaesium.

On the positive side the effectiveness and relative simplicity of urban sweeping and vacuuming and high pressure water hosing is proved and recommended.

At an intermediate level, a pre-treatment of roofs and pavements with surfactant gave very promising laboratory results. It might well be an extremely effective practical countermeasure after further laboratory and field research. Its preventive aspects must also be balanced by its practicality since it is dependent on meteorological predictions and the logistics of spraying: clearly a matter outside the remit of this study.

As a follow-up to this study, it is necessary to move towards the development of an all-embracing countermeasures strategy for the nuclear contaminated urban environment. To facilitate progress towards this end, the following objectives should be to acquire:

1. a better understanding of the distribution of the contamination. For example, in the case of dry deposition, the profile of the urban complex could have a marked influence on the distribution of the contamination; the distribution of the contaminant may well be different where multi-storey buildings are dominant than where the landscape is dominated by single-storey structures,
2. more accurate data are required with respect to both the efficiency and the cost of the different decontamination procedures. At present many of the estimates of efficiency and the cost are associated with large uncertainties: there is a requirement for more accurate data,
3. more and better data are required for the calculation of kerma and location factors for a variety of cases. A variety of urban scenarios can be envisaged and each would call for a different strategy in order to bring about a significant reduction in radiation dose. For example, the density, size and distribution of buildings, the presence or absence of ornamental grassed areas, trees and bushes. In all cases, calculation of kerma and location factors are required in order to formulate decontamination strategies,
4. ultimately we envisage an easily-managed computer code which would provide a clear cut guide for decision makers faced with the clean-up of any conceivable urban complex.

It should be emphasised that the remit of this study was to consider only one category of nuclear accident, namely release of volatile fission products, where the major external hazard is due to radiocaesium. Other scenarios can be envisaged where less volatile fission products, such as ^{95}Zr, ^{95}Nb and ^{144}Ce, could be important and ^{90}Sr a source of internal radiation, by ingestion. Such an accident could give rise to fuel fragments (hot particles) formed throughout Europe following the Chernobyl accident.

A third scenario in which actinides would present an inhalation and ingestion hazard could also be envisaged. This type could occur at a reprocessing plant. Contingency plans for all three should be made.

VIII Improvement of Practical Countermeasures: Preventive Medication

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2. Introduction

Since the introduction of nuclear power there have been a number of accidents involving the release of large amounts of radioactivity into the environment and associated contamination of air, soil, water, foodstuffs of a significant segment of the human population. The most important of these accidents in terms of their environmental impact are those at Windscale in 1957, Three Mile Island in 1979 and the recent accident at the fourth unit of the nuclear power station at Chernobyl in the Ukraine at 01.23 a.m. on 26 April 1986. The Chernobyl incident is the most recent and by a large margin the most significant in terms of its impact on the human population.

The pattern of release of radioactive materials from a reactor is complex. In Chernobyl, Russian scientists have estimated that almost all the noble gases from the core were released with about 10-20% of the volatile materials such as I, Te and Cs. Radioisotopes of iodine constitute a major component of such a release and are particularly important during the early period after an accident. However, the importance of this release has varied considerably from one accident to another. The Chernobyl releases of ^{131}I are much greater (440.10^3 TBq) than those at the

Windscale accident ($0.74.10^3$ TBq) and, even more, than those at Three Mile Island ($0.001.10^3$ TBq). The form of the releases and therefore the consequent response is complex with respect to its nature, time scale, travel and distribution. In Chernobyl, the releases were spread over 10 days with an initial peak, a 5-day decline, a new 4-day peak and then an abrupt stop. The ^{131}I release was particularly important towards the end of this period. The pattern of deposition in the countries of the EC was extremely complex due to the variable wind and weather conditions. Thus the depositions vary greatly from one region to another. Once ingested, radioiodine is rapidly and selectively accumulated in the thyroid gland, which therefore is its main target. Human thyroid uptake of contaminating radioiodine varies very much from one region to another depending on the relative supply of stable iodine in the diet. Thus exposures of the main target organ, the thyroid, to radioiodine are extremely heterogeneous within the population of a large geographical area such as the EC.

The consequences of radiation on the thyroid are the generation of benign and malignant tumours and hypothyroidism. At the level of response reached after nuclear accidents only tumorigenesis should be considered. It is well known from experimental studies of animals that irradiation of the thyroid by external sources of radioiodine induces tumours in this organ. In humans, numerous studies have also demonstrated the progressive appearance of nodules and cancers ≥10 years after external irradiation. Thyroid tumorigenesis after exposure to radioiodine is therefore a risk that must be considered.

However, at the present time the potential carcinogenic effects of radioiodine in man and the extent of the eventual risk remain controversial. This risk certainly depends on the amount of ingested radioiodine, on the fraction that is retained in the thyroid, on its remanence in this organ and on the potential life span after exposure. Age, sex, ethnic origin and level of thyroid stimulation and activity increase or decrease the risk for a given exposure. Foetuses in pregnant mothers and infants will be at special risk because of the higher concentration of radioiodine per gram of tissue, the ongoing proliferation of the thyroid cells and the greater life span.

Because of the short half-lives of most radioiodine isotopes, the potential exposure to the thyroid will also only be short lived once the source is under control or the plume has moved away from the area. This eventual prevention need only be temporary. Ingestion can be considerably lowered by short-term preventive measures such as avoidance of contaminated foods such as milk and protection against skin and air (masks) contamination. On the other hand the concentration of radioiodine in the thyroid can be reduced too by prior loading of the body with stable iodine before the circulating radioiodine is concentrated in the thyroid. This is the medical basis of stable iodine prophylaxis following a nuclear accident. However this type of prevention entails several risks: acute reactions to iodine, induction of hyperthyroidism in goitrous patients (this is especially important in iodine deficient areas), transient hypothyroidism which might be harmful to foetuses, etc. Induction of hyperthyroidism and thyrotoxic crises might be very dangerous in populations at risk such as old people or cardiac patients.

After uptake of radioiodine in the thyroid has occurred, various unproved methods can be proposed to accelerate the release from the thyroid of radioiodine, such as administration of drugs blocking the recycling in the thyroid of radioiodine (perchlorate, methimazole, iodine, etc).

The purpose of this programme was to study the methodology and possible consequences of the various measures used to prevent radioiodine damage to the thyroid of populations after a nuclear accident in order to propose guidelines for public health authorities.

The programme proposed to improve, by an integrated effort of the participating laboratories:

- the evaluation of risks of radioiodine release for the population,
- the evaluation of the risks of iodine treatment,
- the criteria for preventive treatment of a whole population.
- the definition of a protocol for the treatment of patients having ingested radioiodine.

The results were expected to lead to better criteria and protocols for preventive and therapeutic measures in various populations and to specific recommendations.

3. Evaluation of risks of radioiodine release

The main risk of low level irradiation of the thyroid is the induction of tumours. In the case of nuclear accidents, this risk is proportional to the cumulated uptake of radioiodine in the thyroid, on the size of the gland and on the relative biological efficiency of the emitted radiation, especially at low doses. The level of radioiodine is known to be roughly inversely related to stable iodine supply in the diet. In countries with a well developed iodine prophylaxis programme, normal iodine uptake decreases to about 20% of the ingested dose, whereas in iodine deficient areas with endemic goitre, this uptake may rise to 60% or more. Thus iodine prophylaxis could lower the radiation risk by a factor of 2 to 3. Very little is known about the uptake and kinetics in the population most at risk, the foetus and newborn. Within this framework four aspects have been considered in the programme:

- a systematic survey of iodine supply in the diet and radioiodine uptake in various European regions (Dumont, Brussels),
- an in-depth study of iodine supply in the diet and of its evolution with time in Ireland (Malone and Smyth, Dublin),
- a study of radioiodine kinetics in foetal and newborn thyroid in a model animal close to man, to be compared to in vitro and literature in vivo data in man (Van Bekkum, Rijswijk and Dumont, Brussels),
- an assessment of the risk of morbidity and mortality after diagnostic treatment with radioiodine, ^{131}I (Oberhausen, Homburg Saar).

a) Iodine supply and radioiodine uptake in Europe

A questionnaire was sent to European nuclear medicine centres. Many responses were obtained and most groups were ready to cooperate in a further study. Rather extensive data scattered in a wide literature or unpublished were communicated. In particular, the unpublished results of a cooperative European study carried out in 1975 by Prof. Lagasse (University of Brussels) were obtained. This allows to present relatively complete data on urinary iodine excretion and thyroid radioiodine uptake in the normal population of the various regions of the European Community (Table 1). Iodide daily excretion is considered as a good estimation of the daily iodine intake at least for comparative purposes.

All data presented are means from at least 50 individual measurements. However in quite a few cases, data on iodide excretion and thyroid radioiodine uptake have been obtained on different individuals. For several regions data from different groups and different sets of patients were obtained. These results in general did not vary by more than 10% and never by more than 20%. Daily urinary iodide excretions and thyroid radioiodine uptakes were measured by conventional, well accepted methodology. In the case of Prof. Lagasse's results, special care was taken to ascertain the standardisation of the methods. For instance all the iodide determinations were carried out in one central reference laboratory (Brussels). Again, when these results could be compared to data obtained by other groups in the same area, they were comparable. In a few cases, iodide urinary excretion was expressed per gram creatinine. When compared to daily urinary excretions the iodide/creatinine ratios were of the same order. For more precise calculations one can use the average European daily creatinine excretion of 1.53 g day^{-1} (Bourdoux et al).

For regions where no recent normal thyroid radioiodine uptakes were available, thyroid radioiodine uptakes were estimated using the formula of Stanbury:

$$U = \frac{57.4}{57.4+E}$$

where U is the uptake in percent of the dose administered and E the daily iodine urinary excretion in μg.

Results

As can be seen from the table, urinary iodine excretions vary in Europe from one region to another from 16 to 250 μg day^{-1}. The full spectrum from severe iodine deficiency to normal dietary intake exists in Europe. It is therefore to be expected that 24h thyroid radioiodine uptakes vary from 19 to 83%. Therefore, for a similar radioiodine contamination, the thyroid exposure will vary from one region to another by a factor of 4.

Two major findings should be pointed out:

- the mean radioiodine uptake data may vary considerably within the same country and even within the same region, depending on the iodine supply. For instance in Sicily or Greece the whole spectrum from low to high radioiodine uptake is covered within a 200km radius. In radioprotection, in these areas it would be appropriate to consider the worst case and treat the whole region as required for its most exposed population.
- the mean radioiodine uptake data are only means, which implies that for a given population a sizeable proportion of the subjects will have a higher uptake. In Stanbury's subjects in Mendoza for a mean uptake of 59% in 118 subjects, 37 (i.e. 30%) had uptakes higher than 70%. This dispersion is always wider for populations with high average uptakes. In terms of radioprotection again it might be advisable to consider the worst case.

Finally the data show how effective generalised iodine prophylaxis is. In Switzerland it has reduced the uptake from probably 70 to 22%. In the last few years the average uptake in Berne has dropped from 53 ± 13% to 22 ± 6% following the increase from 3.75 ppm to 15 ppm of iodine in the salt. In terms of radioprotection, this means that by this simple public health measure for a given radioiodine exposure the thyroid risks of this population has decreased by a factor of 3.

Conclusion

The collected data on thyroid radioiodine uptakes can now be used to set decisions criteria for iodine prophylaxis after a nuclear accident.

Table 1: Reported Iodide Urinary Excretions and 24hr Thyroid Radioiodine Uptakes in the Community

Countries and regions	Goitre prevalence %	Iodide excretion $\mu g\ day^{-1}$	Iodide secretion $\mu g\ g^{-1}$ creatinine	24hr radioiodine uptake (%)	Iodine prophylaxis
DENMARK					
Odense		85		(40)	0
GERMANY					Available
Berlin		40		48	
Hamburg		37		50	
Hannover		20		62	
Düsseldorf		84		48	
Jülich				51	
Wiesbaden		35		51	
Tübingen		16		69	
Göttingen		38		57	
Heidelberg		32		54	
Würzburg		18		67	
Bonn		-		56	
Freiburg		18		66	
Marburg		33		57	
München		32		56	
NETHERLANDS					0
Groningen		123		36	
Utrecht				38	
Amsterdam		86		43	
BELGIUM					Available
Brussels		51		43	
LUXEMBOURG					0
FRANCE					
Paris		75		43	
Rennes		115		36	
Rouen		86		44	
Lyon		113		39	
Montpellier		84		45	
ITALY					Available
Torino		108		35	
Milano				42	
Pisa				40	
Roma		87		44	
Sicily					
Catania	2.2	114		32	
Messina	6.6	76		50	
Nicosia	38.5	39		52	
St Angelo	48.7	27		70	
GREECE					Available
Athens		95		(38)	
Rural area		30		(65)	
SPAIN					
Madrid			112	(34)	
Seville			50	(53)	
Las Hurdes	86	16		(78)	New
PORTUGAL					Available
Interior	40		12	(83)	
UNITED KINGDOM	250			0	
IRELAND					0
Dublin			118	(38)	
NON EC COUNTRIES					
FINLAND		250		(19)	++
SWEDEN		110		(34)	++
DDR SOUTH		16		(78)	New
SWITZERLAND					
Bern	0	130		22	++

(U) Uptake calculated from iodide urinary excretion

b) Detailed study of iodine dietary supply in Ireland and its evaluation with time

A study of urinary iodine excretion was carried out in 821 patients attending hospital outpatient clinics in the Dublin area during 1987. Although this group cannot be taken as being representative of the total Dublin population, it is large enough to provide a reasonable indication of the iodine status of that population. The mean urinary iodine excretion value of 118 ± 82 $\mu g\ g^{-1}$ creatinine (Median 96) while excluding severe iodine deficiency in this particular cohort, obscured the fact that 250 (30%) had iodine excretion values < 70 $\mu g\ g^{-1}$ creatinine, a value approximating to the minimum daily iodine requirement.

The results provide sufficient evidence of sporadic iodine deficiency to justify a more widespread study of the iodine status of the Irish population with a view to making recommendations on the possible need for iodine prophylaxis.

In the same area (Dublin) the **evolution of 24 h ^{131}I thyroid radioiodine uptake in a comparable adult population** and thus by inference of iodine dietary supply during the last 20 years has been studied. Patients who had undergone diagnostic ^{131}I thyroid gland uptake studies during the years 1963-66 and 1983-86 were selected for study. Toxic goitres were eliminated on the basis of clinical review, results of serum PBI, 48h PB ^{131}I estimations or serum T_3 and T_4 when these become available. Results are shown in Table 2.

Period	1963-1966	1983-1986	Significance
N	435	45	
Mean ± SD	48 ± 13%	38 ± 13%	$p < 0.01$
Uptake > 50%	49%	20%	
48hr PB ^{131}I	0.12 ± 0.08%	0.15 ± 0.08%	N.S.

Table 2. Mean values ± SD for 24 h thyroid gland uptakes of ^{131}I and serum 48 h PB ^{131}I in non-toxic goitrous patients investigated during 1963-1966 and 1983-1986. p values refer to differences between the two periods.

The mean 24 h uptake of 48 ± 13% in the 1960s was significantly higher than that of 38 ± 13% observed in the 1980s. Also the number of individual values with uptake > 50%, the upper limit of the normal range, was much greater in the 1960s (49%) than in the 1980s (20%). Thus in this area the results indicate that in other European regions dietary iodine deficiency is slowly improving, reflecting the increased diversity of modern diet.

The **evolution during the year of the iodine dietary supply** was evaluated from the **milk iodine content**. Recent studies have demonstrated that milk consumption provides the most important source of dietary iodine intake in the British diet. The iodine content of milk specimens was sampled from 31 farms at different locations throughout the Republic of Ireland. These samples were obtained in November 1986 and in July 1987. Results are shown in Table 3.

Table 3: Iodine in milk in Ireland

	Milk iodine $\mu g\ kg^{-1}$	
	Summer	Winter
N Farm	31	31
Mean ± SD	61 ± 59	101 ± 65
Range	(3 - 255)	(15 - 255)

Although wide ranges were observed, the iodine content of summer milk was significantly lower than winter milk. In general Irish milk iodine levels were lower than those reported from the United Kingdom (confirming the relative iodine deficiency in Ireland).

In view of the differences in milk iodine values recorded between summer and winter it was decided to conduct sequential studies on the iodine content of bulk liquid milk provided for human consumption in the Dublin area over the period October 1987 -September 1988. Monthly mean values were calculated for individual milk samples.

The results confirm the earlier report from separate farms. The iodine content of milk was at its highest during the winter months (February - April) when cattle were housed and were receiving food supplements. Iodine values declined during the summer months when the cattle were once again put out to pasture. Assuming milk to be a major source of dietary iodine, these findings demonstrate that the iodine intake of a population must take into account the season during which figures were derived.

In the context of the Chernobyl accident the milk contribution to iodine intake in the Irish diet might have been near its minimum value during May 1986 and thus diminished the potentially available protection against uptake of radioiodine.

c) Radioiodine kinetics in foetal and newborn thyroid

Iodide uptake in the thyroid has been measured in chimpanzee foetuses and infants in vivo using ^{123}I by an adaptation of the "two peak method". Thyroid uptake of 6 adults and 7 infants were around 10%. Foetal thyroid uptake after 19 to 21 weeks of gestation varied in 6 cases from 0.8% to 4.2% of the dose (mean 1.8%). The latter values correspond to values reported in the literature for human foetal thyroids after 6 months of pregnancy (1%-3%). Considering the known weights of foetal thyroids, it can be calculated that the relative uptake per g. thyroid is 3 to 15 times higher in the foetal than in the adult thyroid. These figures correlate well with data on radionuclide uptake in vitro in one human foetal thyroid. This therefore shows that for a given uptake of radioiodine the thyroid exposure rate may be at least 3 to 15 times higher in the foetus than in the mother. Considering the higher life expectancy of the foetus and the probably higher susceptibility of the rapidly growing foetal thyroid to radiation, the relative risks may be as much as 30 times higher in the foetus than in the adult.

d) Epidemiological study of the consequences of low exposures to radioiodine on thyroid pathology

An epidemiological study of 24,063 patients having received ^{131}I iodide radiation for diagnostic purposes between 1960 and 1977 in Saarland and of suitable controls has been initiated. The results of this study, which is continuing under a new contract, are not yet available. It should be mentioned that Holm et al, in an epidemiological study of Swedish patients exposed to ^{131}I for diagnostic purposes, could not demonstrate any increase in the incidence of thyroid tumours in these patients as compared to controls. Moreover, Malone and Dumont have calculated the number of new thyroid cancers in Europe that would result from the Chernobyl accident using UNSCEAR risk estimates. The results show that this is negligible (618/50 years) compared to the natural incidence (300,000/50 years)) and would be undetectable in epidemiological studies.

4. Evaluation of Risks of Iodine Treatment

Administration of pharmacological doses of stable iodine prevents radioiodine uptake by the thyroid. It has therefore been generally recommended as a preventive treatment after a nuclear accident. However, iodine administration is not innocuous; it can lead immediately to various pathological manifestations (digestive, skin pulmonary effects) called iodism. These disappear immediately after cessation of treatment. More dangerous is the appearance of hyperthyroidism. This occurs in patients with autonomous nodules which are frequent in iodine deficient areas. It has been estimated that 30 to 70% of hyperthyroidism in Germany is caused by stable iodine. The consequences of even transient thyrotoxicosis may be severe in special populations at risk (eg cardiac, older patients). It is known that the frequency of such complications varies inversely with the iodine supply in the diet, but this has not been systematically evaluated. On the other hand, in the foetus and in the newborn and in a small fraction of the adult population, pharmacological doses of iodine induce severe hypothyroidism. The blockade of iodide oxidation by iodide (the Wolff-Chaikoff effect) is not relieved by a compensatory reduction of iodide trapping (adaptation to Wolff-Chaikoff). Although there are no data available on the growth or cerebral development of children having had hypothyroidism during late pregnancy, theoretically, the consequences, even if slight, may be unacceptable for foetuses and newborns in which thyroid hormones are required for brain and general development. For obvious reasons few data are available on humans to evaluate these effects in relation to iodine doses.

a) Risk of iodide induction of hyperthyroidism

A questionnaire has been sent to various groups involved in iodine prophylaxis for endemic goitre. Although most groups answered, only a few had real data on the subject (Table 4). In fact in most surveys the endpoints measured (clinical status, goitre prevalence, iodine excretion, serum T4 levels) were only assessed one year or more after the beginning of treatment. With such protocols, transient hyperthyroidism might be missed.

In fact the only systematic survey on a sufficient number of people in Tasmania gives a risk of 0.028%. This risk greatly increases in patients with multinodular goitre when it might even rise to 33%. Obviously subjects with multinodular goitre should be omitted from any palliative iodine prophylaxis programme after a nuclear accident.

Table 4: Incidence of Hyperthyroidism after Iodine Prophylaxis

	Number of treated patients	Transient Hyperthyroidism	Incidence Percent
Goitrous Patients			
Greece			
Livadi	302	5	1.7
Askos	212	3	1.4
Other	38	1	2.5
Brazil			
Sao Paolo	23	8	33
Brasilia	103	8	7.76
Sweden	100	7	7
Normal Population			
Tasmania	390 000		0.028
Brazil	1 876	8	0.42
Malaysia	240		1.7

b) Effect of iodine treatment on foetal thyroids

The aim of this study was to study the effect of various doses and schedules of administration of iodine on the radioiodine uptake and thyroid function of foetal and infant chimpanzees as models for humans and to corroborate it in vitro on human autopsy material.

The thyroidal uptake of intravenously injected ^{123}I was stabilised after 24 hours in infant and foetal chimpanzees before and after ingestion of various doses of stable iodide. Thyroidal function was assessed by serum thyroxin, triiodothyronin, free thyroxin, thyroid stimulating hormone and thyroglobulin assays.

In five infant chimpanzees the 24h uptake varied, as in man, from 11.4 to 30% (mean 15%). All doses of iodine (0.5 to 5 mg iodide kg^{-1} day^{-1}) reduced the uptake to below 2%, ie barely at the limit of detection. In six pregnant chimpanzees the 24h thyroid uptake varied from 8.5 to 24% (mean 13%). All doses of iodide reduced the uptake to below 1%. In the 6 foetuses (19 to 21 weeks) the normal uptake varied from 0.8 to 4.2% (mean 1.9%). All doses of iodide reduced the uptake to below the detection limit of 0.2%.

In mothers and infants thyroid hormone status seemed to remain unaffected by the excess of stable iodide, although minor increases of TSH were observed. Two chimpanzee foetuses exposed to excess stable iodide during foetal life were found to be euthyroid after birth.

It can be concluded that the uptake of radioiodine in the thyroid of infant and foetus chimpanzees can be reduced substantially for at least 10 days by the daily administration of as little as 0.5 mg kg^{-1} day^{-1}. The method does not induce hypothyroidism in infant chimpanzees. However, results from the literature demonstrate hypothyroidism at birth in human newborns when the mother has received great amounts of iodine by radiographic contrast media or topical administration of iodine.

The study on foetal autopsy material was discontinued for lack of material and ethical reasons. The one experiment performed suggests that foetal thyroids exhibit the normal decrease of iodide trapping after exposure to iodide (adaptation to the Wolff-Chaikoff effect) but that its high trapping capacity, although reduced, is still sufficient to allow intracellular iodide levels that will inhibit thyroid hormone synthesis.

5. Criteria for Iodine Treatment after a Nuclear Accident

The results of the present study show that iodine deficiency is still prevalent in western Europe which by itself increases the risk of any radioiodine exposure by a factor of 2 to 3. However, this deficiency which is accompanied by a higher prevalence of goitre and of autonomous nodules also increases the risk of iodine prophylaxis after a nuclear accident.

The risks of radioiodine exposure to the thyroid can be estimated but at the level reached after Chernobyl the expected effects would be too small compared to natural incidence of thyroid neoplasia to be proved by an epidemiological study. A study by Holm which showed no demonstrable effect of diagnostic doses of ^{131}I is now independently checked on another population by Oberhausen in this programme. The results of iodine prophylaxis in monkeys confirms that this prophylaxis is highly efficient in reducing radioiodine uptake in the thyroid in adults, infants and foetal chimpanzees. The study of hyperthyroidism incidence after initiation of iodine prophylaxis in endemic goitre areas reveals quite divergent results mostly due to the fact that this risk only exists in thyroids where areas of autonomy exist, ie in goitrous thyroids. The incidence of such lesions increases with I deficiency and age. However, it is quite clear that for some segments of the population (goitrous patients over 40) the risks of iodine prophylaxis are much higher than the potential risks of radioiodine exposure. Therefore no absolute general criteria for iodine prophylaxis can be derived from studies I and II. General recommendations will be proposed in the last part of this document.

6. Protocols for Treatment of People having already ingested Radioiodine

After ^{131}I uptake in the thyroid, various therapeutic measures can be taken to reduce further radioiodine uptake, prevent its recirculation or accelerate its release. A protocol was tested on patients injected with ^{131}I for diagnostic purposes. 36 patients were administered 100 mg potassium iodide (KI) or water orally 6 hours after. ^{131}I and thyroid radioactivity were measured 6, 8, 10, 24 and 48 h after the initial injection. In KI treated patients the thyroid radioactivity only barely increased after KI administration. It was calculated that the further increase in uptake was reduced to 1/3 by the treatment. However, it must be emphasised that most of the uptake had already taken place at 6h and that the total exposure was only reduced by 15% by this therapeutic procedure. Thus KI administration after ^{131}I ingestion and uptake prevents further uptake but does not reduce exposure by previously accumulated radioiodine. The study suggests that the time window for iodine treatment should be narrowed prior to the 6th hour after contamination

7. Conclusions and Recommendations

The present programme has enabled:

- the various levels of thyroid radioiodine exposure in the different regions of the Community and in infants of pregnant mothers to be defined,
- the risks of iodine prophylaxis after a nuclear accident, particularly with regard to hyperthyroidism in adults and hypothyroidism in foetuses to be evaluated,
- the efficiency of iodine administration after radioiodine ingestion and thyroid uptake to be evaluated.

The risks of iodine administration to the foetus are still under investigation in chimpanzees. The evaluation of the risks of thyroid exposure to low radioiodine levels is still going on. These results have been presented and discussed at a WHO/CEC meeting in Brussels (4-7 July 1988). These results integrated with the available literature and with results obtained outside the EC allow the formulation of recommendations to public health authorities and suggest areas where further research would be needed.

Recommendations in the Case of a Nuclear Emergency

The following recommendations should be made:

1) Before any nuclear accident: generalisation of iodine prophylaxis.
   There exist already multiple reasons to promote the generalisation of iodine prophylaxis in European populations. Such a prophylaxis would reduce goitre prevalence and decrease the incidence and gravity of foetal and child thyroid insufficiency with its possible consequences on brain development. In the case of a nuclear accident the thyroid uptake of radioiodine and therefore its exposure and the incidence of tumours would be reduced by a factor of 2 to 3 in populations submitted to prophylaxis. Moreover, as the incidence of autonomous nodules decreases with iodine supply, such a prophylaxis would also reduce the incidence of thyrotoxicosis induced by iodine treatment. There is therefore no

doubt that the best preventive measure against the thyroid consequences of a possible nuclear accident should be the generalisation of iodide prophylaxis in Europe now.

2) After a nuclear accident:

- Immediate ban on the consumption of contaminated foods. The main source of iodine and radioiodine in food is milk. The contamination of milk by radioiodine requires prior deposition of radioiodine on the ground, absorption in plants and then in cows in pasture. Milk can be screened systematically. It is therefore quite easy to detect radioiodine contamination and to withdraw contaminated milk from the market. Withdrawal of herds from pastures and feeding with stored food, if possible, would avoid bovine and milk contamination.

- Near field: avoidance of inhalation by person displacement and other preventive measures.

- Iodine treatment: generalised iodine treatment with its risks of hypothyroidism in foetuses and infants and hyperthyroidism in goitrous people should be avoided. Over 45 years of age the delay in radiation-induced cancer and the lower susceptibility of slowly dividing thyroid cells make the potential risks insignificant. Iodine prophylaxis (100 mg KI orally per day during the period of exposure, but only during this period) should be administered to pregnant women, neonates (1 mg Iodine kg^{-1} day^{-1}), infants, children and adolescents up to 16 years old. There are few arguments for treating people over 16 years old except near the site of a nuclear accident if the predicted dose to the thyroid gland exceeds the national intervention levels of the country concerned. Older adults (over 45) should not be treated except near the site of a nuclear accident if predicted exposure is high. Even in this case, iodine prophylaxis should be avoided in people with known iodine sensitivity, in patients with cardiac or thyroid diseases and if goitre is suspected.

3) After thyroid radioiodine exposure: iodine should be administered a posteriori to the categories defined above in 2 if radioiodine has been taken up by the thyroid.

Recommendations for future action

The results of the programme emphasise the fact that our knowledge is still inadequate for the elaboration of a rational strategy on the prevention of radioiodine induced thyroid cancers. The following areas deserve further study.

- The relative biological efficiency of radioiodine isotopes should be defined in suitable experimental models. For this type of study the establishment of human thyroid cell lines would be of paramount importance.
- The definition of risks of a low radiation dose on thyroid cells. This subject must be approached by an epidemiological study of populations exposed to low radioiodine doses for diagnostic purposes and by the use of experimental models. These risks should be especially studied on thyroid cells from foetuses and infants as these may be more sensitive than cells from adults and are exposed to higher doses.
- The definition of thyroid cell kinetics in man which will allow the quantification of the potential risks according to the age of the patient.
- The effects of iodide on the foetal thyroid should be quantified (kinetics) and their mechanisms understood. The importance and efficiency of placental thyroxin transport should be defined in order to ascertain the effects of maternal hypothyroidism on the foetus. The interest of treating the mother concomitantly with iodine and thyroxin should be evaluated.
- The effects of iodine prophylaxis on the induction of hyperthyroidism in populations with different iodine dietary supplies should be quantified (incidence).
- Thyroid radioiodine uptake in the various regions of the EC should be monitored regularly in order to enable the assessment of the risks of accidental radioiodine exposure.

IX. Treatment and Biological Dosimetry of Exposed Persons

1. Participating Institutions

a) Treatment:

- Institut voor Toegepaste Radiobiologie en Immunologie, Hoofdgroep Gezondsheidinderzoek TNO, Lange Kleiweg 151, 2280 HV Rijswijk, the Netherlands, D.W. van Bekkum,
- Universität Ulm, Institut für Arbeitsmedizin, Oberer Eselsberg M24, 7900 Ulm, Federal Republic of Germany, T.M. Fliedner,
- Centre d'Etudes Nucléaires, Dépt. de Protection Sanitaire Service d'Hygiène Radiat. B.P.6, 92265 Fontenay-aux-Roses, France, J.C. Nenot,

b) Biological Dosimetry

- Institut Curie, Section Biologie, 16 rue de Ulm, 75005 Paris, France, B. Dutrillaux,
- Centre d'Etude Nucléaire (CEN/SCK), Boeretang 200, 2400 Mol, and Université Cathol. de Louvain, Unité TEMU, Av. E. Mounier 72, 1200 Bruxelles, Belgium, A. Léonard,
- National Radiological Protection Board (NRPB), Oxon OX11 ORQ Chilton Didcot, United Kingdom, D.I. Lloyd,
- Univ. Leiden, Lab. Straalengenetica en Chemische Mutagenese, Wassenaarseweg 72, 2333 Leiden, the Netherlands, A.T. Natarajan.

2. Introduction

The accident at the Nuclear Power Station at Chernobyl was of great concern to all countries of the EC because the radioactive emission was carried over long distances and resulted in variable fall-out of radioactive isotopes in all areas of the EC. Obviously, radiation levels were the highest inside the plant and in its immediate vicinity. At least 200 people involved in the accident itself at the installation or in efforts to control the catastrophe by bringing the reactor under control were exposed to radiation levels and/or other injuries of such an extent that immediate medical care was required. The information concerning the acute victims that was released by the Russian authorities and the subsequent results of the medical interventions proved to be of great interest to radiation experts of the EC. Although the Radiation Protection Programme of the EC had for many years included applied research on the effects of high dose radiation exposure and the treatment of its consequences, the analysis of the acute Chernobyl cases revealed several new issues, not foreseen from the experience of past reactor accidents, that were all of a much more limited extent.

These problems were analysed by experts from the Advisory Committee as the data became available and the most important ones were selected for study in the context of a crash research effort that is designated as the Post-Chernobyl programme.

The results of the projects concerned with diagnosis, prognosis and treatment of acute radiation injuries are reported in this chapter.

a) The Experience of Chernobyl

During the first hours and/or days following the accident, several hundred people were exposed to extensive radiation from the burning reactor and its emissions. A certain proportion of the victims had also suffered thermal burns and inhalation of radioactive isotopes of unknown concentration and amount had occurred as well. In the majority of the cases the body dose received by individuals could not be reliably derived from personal dosemeters carried by the victims. On the basis of calculated exposures, using time, duration of presence and location, about 200 persons were selected for immediate hospitalisation in the likelihood of need for treatment. They were transported to specialised hospitals in Moscow and Kiev for further diagnostic and prognostic evaluation. On the basis of peripheral blood counts, bone marrow puncture and chromosomal analysis, 19 patients were treated with bone marrow or foetal liver cell transplants. The clinical course and the results have been reported in a general way only and the medical community is still awaiting more detailed information. Anyhow, the effects of the transplantations have been disappointing in that a beneficial influence was not observed.

In part, this seems to be due to the mixed type of injuries suffered by the victims (in particular skin burns and intestinal damage in combination with haemopoietic injury). Other factors were the lack of HLA-identical sibling donors of bone marrow and the fact that there had been no experience with bone marrow transplantation in Russia.

This was also the first occasion that a large number of heavily irradiated people had to be treated at the same time in one hospital. Owing to the numbers of victims involved and the nature of the radiation exposure, these observations are obviously of great interest to the Radiation Protection Programme of the EC.

Within the first few days after the accident, the Commission approached the various bone marrow transplantation teams in the EC and made an inventory of the number of beds that could be made available for Russian patients possibly requiring treatment with bone marrow grafts. It was then proposed to the Russian authorities that any number of transplant candidates be transported to these highly specialised teams in Europe, but this proposal was not accepted.

During the months after the accident, experts from the EC met on a number of occasions to evaluate the data coming from Russia and to organise an emergency programme for research into the new and unforeseen questions arising from the Chernobyl experience.

b) Prognostic and Treatment of Heavily Exposed Radiation Victims

The main problem in treating such victims was the great uncertainty in establishing the risk of the individual patient developing a fatal radiation syndrome. The currently available biological indicators were lowered peripheral white blood cell counts, increased chromosomal abnormalities and the severity and rate of development of clinical sickness shortly after exposure. None of these parameters provides a very accurate risk estimate. Therefore, it was decided to reanalyse the predictive value of the changes in blood cell counts and to perform in vitro studies on dose effect relations of chromosome aberrations with emphasis on the influence of partial body irradiation. In addition, a new approach to biological prognostic dosimetry was initiated by studying the possible application of the new Hemopoietic Growth Factors (HGF) for determining the amount of surviving stem cells of the blood-forming system. These stem cells are the only cells that are important for the recovery of the blood formation. They may be activated and stimulated by the hormonal action of the HGF to produce progeny which should be reflected in the peripheral blood cell counts. If insufficient stem cells are surviving, administration of HGF would not result in a response and this would then indicate a poor prognosis.

For patients with such damage to the blood-forming system as was hitherto considered irreversible, the recommended treatment was bone marrow transplantation. However, bone marrow transplantation is effective only when the recipient has been subjected to homogeneous irradiation of the whole body and when bone marrow from a matched donor is available. It appears that these conditions were not fulfilled for the majority of the reactor accident victims.

Inhomogeneous exposure may leave a small proportion of the white blood cells responsible for the body's defence intact, which is sufficient for a bone marrow graft from another person to be rejected.

The new HGF seemed to provide possibilities for stimulating residual autochthonous stem cells following inhomogeneous irradiation or perhaps even following an otherwise lethal dose of homogeneous exposure, and thereby induce cures by endogenous regeneration of the blood-forming system. Such investigations can obviously not be carried out with patients, but it is feasible to obtain certain essential pieces of information like the doses of HGF required for a substantial response, or the occurrence of toxic side-effects, from studying patients with haematological diseases who are being treated with HGF. Other more essential data can only be acquired from experiments with subhuman primates which greatly resemble humans in their responses to irradiation.

3. Prognostic Value of Blood Cell Counts

The Ulm research group has established a Radiation Accident Data Bank in which all available data on changes in blood cells and blood cell forming tissues are being collected, in conjunction with clinical symptoms, the course of radiation sickness if it is developing and its eventual outcome. A total of 22 radiation accidents, resulting in the exposure of the whole body or a large part of the body and involving over 600 individuals is being analyzed. At the time of this report, more than 300 cases have been processed and results of calculations based on the counts of peripheral blood cells over the observation period have been related to the physically estimated dose of acute total body irradiation.

A computer-based simulation model of the formation of one class of white blood cells (the granulocytes) has been designed which allows the calculation of the number of intact blood-forming stem cells that survive the irradiation. The results so far suggest that a calculated surviving fraction of stem cells of 8.10^{-6} of the normal number is the minimum that will allow spontaneous regeneration of the blood formation.

The Rijswijk group of researchers employed a somewhat different approach to arrive at minimal surviving stem cells numbers compatible with spontaneous recovery. They compared, in rhesus monkeys, the time period required for spontaneous recovery of peripheral blood cells after total body irradiation with a range of doses with the time of recovery seen in lethally irradiated monkeys grafted with graded numbers of autologous bone marrow cells. Spontaneous recovery occurred in monkeys with a calculated surviving fraction of 10^{-5} of normal, which is very similar to the value for humans of 8.10^{-6} referred to above. However, the dose of total body irradiation which corresponds to that surviving fraction was 11.5 Gy gamma radiation in the monkeys, while in the patients studied by the Ulm group the corresponding dose was 5 Gy at the most. However, only 2 patients were available in the dose range between 10 and 12 Gy and the data between 10 and 11,5 Gy total body irradiation were derived from 4 monkeys only. The monkey data revealed that the surviving fraction of stem cells at 5 Gy total body irradiation was 10^{-3}.

Clearly, there are important, as yet unresolved, differences between the results obtained from the experiments with monkeys and those derived from human victims of radiation accidents. It cannot be excluded that the human stem cells are more radiosensitive than those of the monkey. The results with monkeys have clearly shown that regeneration of leucocyte numbers relate less dependably to the radiation dose than regeneration of reticulocytes, the former being disturbed by the occurrence of infections. It is advisable to take this into account in the interpretation of the granulocyte counts in humans. The most important problem so far, however, is the absence of human data for doses between 5 and 10 Gy and these must be obtained as a matter of urgency, if available. The major advantage of the approaches reported here is that the prognostic parameters employed are not dependent on homogeneity of the exposure, since they relate to the number of surviving stem cells irrespective of the location of those cells.

4. Prognostic Value of Administration of Hemopoietic Growth Factors (HGF)

Recombinant HGF have been evaluated as a means of determining the number of surviving stem cells in irradiated subjects. The main data were obtained with GM-CSF and interleukin 3. Since a special barrier was discovered for r. Hum. IL-3, it was necessary to produce r. Rhesus IL-3 for the studies in irradiated monkeys. This was accomplished by the Rijswijk group under this programme.

The French team at Fontenay-aux-Roses has made extensive studies in vitro on GM-CSF added to long-term human bone marrow cultures. They observed no adverse effects on either the stromal cells or on the proliferation capacity of hemopoietic precursor cells. GM-CSF has a broad range of actions on hemopoietic progenitor cells, including pluripotent stem cells. It stimulates the proliferation of cells in many of the differentiated lineages. Therefore, an investigation was made to determine whether early post-irradiation treatment with GM-CSF might cause a detectable response of the peripheral blood cell counts and whether the capacity for endogenous hemopoietic recovery could be reliably determined by such a response.

It was found that GM-CSF can indeed serve that purpose in the dose range between 4 Gy and 8 Gy (6 MeV X-rays). However, the variations are considerable and at least 8 days of observation are required for a reaction. Responses were not seen after doses greater than 8 Gy (more than 4 log cell kill), although the residual stem cell numbers are sufficient for endogenous regeneration. Preliminary data with IL-3 treatment of irradiated monkeys are similar to those seen with GM-CSF. Therefore, it has to be concluded that treatment with these factors cannot result in a clear-cut distinction between those who will and those who cannot regenerate spontaneously.

5. Biological Dosimetry by quantitative analysis of Chromosomal Damage

a) As chromosomal analysis is particularly labour-intensive and time-consuming, there are considerable logistical problems in dealing with large numbers of patients. The new micronucleus assay that utilises cytochalasin B to block cytokinesis offers an alternative to scoring for dicentrics. Because the images are far simpler, the analysis could be completed significantly faster and by less skilled technicians. This technique was not available to the Soviet laboratories that responded to the Chernobyl accident.

There is usually an urgent need to provide an estimate of dose as quickly as possible. The present techniques are not ideal in this respect because for dicentric analysis the microscopy cannot begin until 2 days after receipt of the blood sample. This is because the lymphocytes need to be stimulated with a mitogen and cultured for 48 hours so that they can be analyzed at first metaphase. For the micronucleus assay the culture time is even longer, 72 hours, although as indicated above, once the preparations are made, the analysis time is much shorter. In practice, therefore, a dose estimate is not available until three or four days after receipt of a blood specimen.

The relatively new method of Prematurely Condensed Chromosomes (PCC), however, opens up the possibility of scoring aberrations within a few hours of blood sampling. The technique is maintained at present as a routine test only in Leiden. It has the potential for overcoming the complications of interphase death and mitotic delay which apply to conventional metaphase analysis with no loss of sensitivity or accuracy. The technique, being new, requires further background research.

b) The Chernobyl experience was notable for highlighting two important features of biological dosimetry that are particularly relevant to high, life-threatening exposures. Firstly, for highly over-exposed subjects, lymphocyte cultures yield a low mitotic index and there are two reasons for this: (a) the rapid decline in the number of lymphocytes in the peripheral circulation; and (b) highly irradiated cells respond in culture less readily to mitogens and proceed more slowly through the cell cycle to metaphase. Thus, in order to increase the number of cells available for analysis, there is a need to improve the mitotic index in such circumstances and to quantify the mitotic delay. Secondly, accidental irradiation is usually inhomogeneous and this can often be detected cytogenetically because the distribution of aberrations among the scored cells is over-dispersed with respect to the Poisson distribution that characterises a uniform whole-body exposure.

c) Acute partial body irradiations to 5 or 8 Gy X-rays were simulated at Chilton by in vitro irradiation of blood which was then mixed with non-irradiated blood from the same donor. The irradiated fractions of the mixtures ranged from 0.5 to 0.1. The mixtures were coded for blind analysis and shared between Chilton and Leiden and cultured for chromosomal aberrations and micronuclei in cytokinesis blocked cells. In Leiden only, prematurely condensed chromosomal fragments were analyzed in mixtures of irradiated and non-irradiated cells.

d) The analysis applied to the dicentric distributions scored at both Leiden and Chilton showed that for most mixtures both the estimates of the irradiated fraction and their doses agreed well with the true values. It was noted that even for 95% of cells irradiated at 5 Gy there were still about 35% of cells seen that did not contain any aberrations and so were apparently undamaged. At 8 Gy and 99% irradiated, about 20% of cells seen were normal. By contrast, for 100% irradiated at both doses, no cells were seen to be free from aberrations. This information in itself is of immediate value as an indication that some proportion of the cells has been spared. The implication from this is that there is likely to be natural recovery of bone marrow. For the analysis of a highly irradiated subject, this would be apparent after relatively few cells had been scored.

e) Culture techniques were extensively compared between the participating teams in Paris, Brussels, Leiden and Chilton and this has resulted in notable improvements and optimal standardisation. In this respect, addition of thymidine to the culture medium generally used by the numerous laboratories performing medical cytogenetics increased greatly the number of dividing and analysable cells. Such a technique could be useful if a large population were to be monitored as rapidly as possible after an accident. Two relatively new methods were also investigated in depth: the micronuclei technique and the assay based on prematurely condensed chromosomes. The latter technique turned out to yield comparable values to those of the estimation of dicentric chromosomes and to possess several important advantages: results can be scored within a few hours of blood sampling and there is no interference from interphase death and mitotic delay.

6. Therapeutic Implications

Our present inability to arrive at a dependable estimate of the number of residual stem cells at low stem cells numbers, i.e. at high doses of irradiation, implies that a reliable distinction cannot yet be made between subjects with a high probability of spontaneous recovery and those with a low probability. The experiments with rhesus monkeys indicate that spontaneous hemopoietic regeneration can always be expected provided that intestinal radiation damage is sublethal. In the homogeneously irradiated monkeys there was no significant dose interval between spontaneous recovery and death from intestinal damage. If these observations apply to humans, it should be safe not to attempt treatment with bone marrow transplants, in view of the fact that in accident cases more marrow is spared because of the inhomogeneous distribution of the dose over the body. Treatment with the hemopoietic growth factors GM-CSF, possibly in combination with IL-3, is recommended soon after the exposure in all patients who are expected to develop pancytopenia. Such treatment will shorten the pancytopenic period and reduce the associated risks in patients who will eventually recover spontaneously and it is not expected to do any harm to patients who cannot regenerate from their residual stem cells.

Indications for a substantial degree of inhomogeneous exposure can be obtained from dicentric chromosome counts and at an early time after the exposure from the PCC technique.

Such indications when obtained with high dose estimates, favour the probability of endogenous recovery and should discourage the use of bone marrow transplantation. The absence of signs of inhomogeneous exposure in conjunction with high dose should favour attempts at rescue with bone marrow grafts. In such cases, perhaps very rare, rejection of the allogenic graft is much less likely than in the case of inhomogeneous exposure when surviving lymphatic cells can react against the graft. Where strong indications are present for bone marrow transplantation, the chances of finding an HLA-identical sibling donor will be small. Other donors are not recommended because of the high risks of rejection or fatal graft versus host disease. Most of these dilemmas could be avoided if the patient's own non-irradiated bone marrow were available for reinfusion. Collection and storage of bone marrow from nuclear plant personnel prior to an accident is not feasible. On the other hand, collection of stem cells from the peripheral blood of personnel who are sent on rescue missions is worth considering.

7. Recommendations

The duration of the special post-Chernobyl research projects has obviously been insufficient to solve all the problems that were selected for study. However, the results thus far obtained have permitted a number of conclusions to be drawn regarding further research and organisational measures of high priority. These concern problems related to diagnosis and prognosis, treatment and logistics of operations following the identification of accident victims.

a) Diagnostic Procedures with Prognostic Relevance

Further analysis of the prognostic significance of blood cell counts is required in particular for total body doses of between 5 Gy and 12 Gy. For these purposes the data bank operated at Ulm and the mathematical models of myelopoiesis should be further expanded.

The results so far obtained with GM-CSF administration as a means of evaluating the size of the surviving hemopoietic stem cell compartment should be continued with IL-3 and combinations of IL-3 and GM-CSF. Separate studies should be carried out in rhesus monkeys subjected to inhomogeneous total body irradiation, with and without growth factor administration.

The techniques to determine chromosome damage by counting of dicentrics and prematurely condensed chromosome estimates in particular have to be established in a larger number of European laboratories than were involved in the present study. Training courses have to be organised to disseminate the PCC technique. Separate investigations are needed for the evaluation of these methods in determining the degree of inhomogeneity of the exposure, by setting up in vivo experiments, preferably with subhuman primates.

Finally, increased efforts are recommended to achieve a better understanding of the interaction between extensive thermal and/or radiation damage to the skin and the damage to hemopoietic tissues so that prognostic parameters in cases of combined injury may be obtained. For all the methods referred to above, it is necessary to increase our knowledge about their usefulness in cases of protracted exposure to radiation.

b) Improvement of therapeutic means

Further research both in preclinical animal models and in patients is needed to improve the therapeutic potential of hemopoietic growth factors. Combinations of factors and variations of the doses have as yet been insufficiently explored. Also, their therapeutic value in cases of inhomogeneous exposure has to be established in vivo. The use of HGF in combination with allogenic bone marrow transplantation also deserves much attention. It is possible that HGF would promote the proliferation of the grafted cells and thereby overcome the problems of graft rejection imposed by inhomogeneous exposure. In this respect, it is important to investigate, in monkeys, whether the residual immune capacity following inhomogeneous exposure may be neutralised by pretreatment of the patient with appropriate anti-lymphocyte antibodies, as it has been shown in rodents that they allow a reduction of approximately 2 Gy of the total body dose required for bone marrow takes. Similar studies are recommended with some of the new immunosuppressive drugs. The importance of continued research on the use of autologous stem cells derived from the peripheral blood can hardly be overestimated. If safe and reliable technology could be developed for harvesting an adequate number of stem cells from the peripheral blood of healthy people, this would be a method of choice to protect individuals at risk in the case of a nuclear accident.

c) Organisation and Logistics

Although there is currently an increasing number of well equipped hospitals where patients are treated with high dose total body irradiation and bone marrow transplantation on a regular basis, the medical staff in these places are not usually trained in the handling of victims of radiation accidents. It is recommended that the Commission takes the initiative for organising courses in Europe to bring these medical groups up to date, in particular with regard to the handling of contaminated patients and to the medical problems arising in patients with combined injuries.

It is recommended that these hospitals establish formal connections with laboratories capable of performing analysis of chromosomal damage, so that immediate action can be taken in cases of exposed individuals. To support such a network of "stand-by" medical and laboratory facilities to be used in cases of accidents, an expert system should be established that is available to all. A special effort is required to establish such an international (European) expert system and to guarantee its maintenance by adding pertinent new information as it becomes available. An excellent basis for this expert system is obviously provided by the data bank of radiation accidents which has been established in Ulm.

Finally, it is recommended that basic research on the effects of ionising radiation on the hemopoietic system and factors that modify this damage continues to be stimulated by the Commission.

X. Feasibility of Studies on Health Effects in Western Europe due to the Reactor Accident at Chernobyl

1. Introduction

A report on the feasibility of studies on health effects in the Community as a consequence of the accident at Chernobyl has been prepared by a task group made up of Prof. A.M. Kellerer and Dr. J. Breckow of the University of Würzburg, Prof. E.G. Knox of the University of Birmingham and Dr. S. Richardson of INSERM, Villejuif. The report reviews the radiation exposure of the Community population to internal and external radiation arising from the radioactive contamination caused by the Chernobyl accident and compares this radiation exposure with that due to natural background radiation. It discusses the health effects of radiation, taking into account malformations and mental retardation as potential effects occurring soon after exposure, and cancer, including leukaemia in children, and genetic effects such as those occurring late after exposure. These effects are reviewed as potential research targets which could form the subject of a study of health effects and in this respect the report also considered the currently available registration facilities which could be used in a health effects study.

The report has been reviewed by an International Panel of Independent Experts made up of:

Sir Richard Doll, Imperial Cancer Research Fund, Oxford University, United Kingdom;
Dr. J.D. Boice, National Cancer Institute, Bethesda MD, USA;
Dr. J. Estève, International Agency for Research on Cancer, Lyon, France;
Prof. G. Silini, Secretary of UNSCEAR (retired at Lovere, Italy);
Dr. J.W. Thiessen, Radiation Effects Research Foundation, Hiroshima, Japan.

The Panel has considered whether studies of health effects potentially related to environmental releases from the Chernobyl reactor accident would be useful. In doing so, it has evaluated the exposure patterns of the dose levels within the European Community, the different health effects that might be induced by such doses and the likelihood that epidemiological studies could produce scientifically useful information. The Panel indicates below the conclusions of these evaluations and recommends a course of action that it considers to be prudent and scientifically reasonable.

2. Exposures in the European Community

Doses to populations of Member States due to the Chernobyl accident vary from 0.05 mSv to 0.9 mSv in the first year after the accident, with a total exposure in all following years not exceeding that in the first year. Averaged over the population, such exposure levels are less than the normal background radiation levels that result in annual doses of the order of 1 mSv. As a consequence, epidemiological (or, for that matter, any) health effect studies comparing populations of entire Member States could not be expected to be productive and the Panel recommends that no consideration be given to them.

Within Member States, and especially in those with the highest depositions of radioactive substances from the accident, smaller areas exist where the doses to the population considerably exceed the average for the country as a whole. If any study is to have a chance of detecting any effect it will only be one in which comparisons are made between relatively small areas within Member States that have experienced the biggest differences in exposure.

3. Possible Health Studies

The Task Group report discusses the health effects in humans that have been shown to be related to previous radiation exposure. These health effects are:

- short-term effects in the exposed, including developmental effects induced in the foetus or embryo, occurring within a few weeks;
- long-term effects, i.e. cancer and possibly heritable genetic effects that become demonstrable years after exposure, or in future generations.

Most short-term effects require substantially elevated doses of radiation, i.e. of the order of grays, and are therefore not expected in the situation discussed here. Some developmental effects, expressed as congenital malformations, could conceivably be induced by doses less than 1 gray, but the low probability of such effects being induced, given the post-Chernobyl exposure situation, precludes their being detected in any of the exposed populations in the European Community.

Cancer is well known as a late effect of radiation exposure and some estimates of the cancer relationship with dose are available. Given the exposure situation described earlier, it is extremely unlikely that any study on the post-Chernobyl cancer rates in adults within the Community will produce useful information and the Panel considers such a study to have no merit. The study of heritable genetic effects in the offspring of those exposed would also be a totally unproductive effort.

Cancers in children differ from cancers in adults in four important respects relevant to the Panel's task. First, they are likely, in the majority of instances, to be related to events that occur during the period of gestation. Secondly, they are normally so rare and the foetus is so susceptible to radiation damage that associations have been reported following exposure of the foetus to excess doses of ionising radiation of the order of 10 to 50 mSv. Thirdly, the occurrence of the disease can be related to the area in which the mother resided during pregnancy and to the time of birth. Fourthly, the disease occurs relatively soon after birth. For these reasons, the Panel believes that studies of childhood cancer might offer some opportunity for detecting an effect of the Chernobyl accident.

Despite the above considerations, it is the opinion of the Panel, based on current estimates of radiation risks, that even a study of childhood cancer following in utero exposure would be unlikely to demonstrate any attributable increase in risk. The estimated foetal doses resulting from the Chernobyl accident are too low for such an increase to be reliably detected. Moreover, the complexity introduced by the need to allow for the higher doses experienced from natural background radiation or medical X-rays would conceivably mask any possible effect or produce spurious findings. Nevertheless, there is clear public concern about the health consequences of increased radiation exposure from the Chernobyl accident and it might be possible to detect an effect if our estimates of risk were too low by a factor of about five. The Panel therefore recommends, as a check on our ability to predict risks from doses of the order received, to contribute to our understanding of the occurrence of childhood leukaemia, and to allay public anxiety, that a small epidemiological survey of childhood cancer be conducted within areas where selected cancer registration was in existence at the time of the Chernobyl accident.

4. Study Design and Methodological Considerations

A study of the kind that the Panel recommends requires the ongoing registration of childhood cancers, i.e. those occurring in early life. As stated before, such registration must have been well established before the Chernobyl accident in order to have confidence in the completeness of registration that is necessary for the study of cancer trends with time to be interpretable. One possible approach would compare childhood cancer rates in areas of high and low exposures, or, if adequate dosimetric information is available, as a function of dose, but again, only if the reliability of the registration data has been established before the accident occurred.

In order to improve the statistical power of these studies, joint analysis of data sets from different registration areas needs to be considered. This, however, will require a high degree of uniformity among the registration procedures, a condition that may need special efforts to accomplish, and one that may be hard to meet for some of the existing registries within the European Community. An additional problem is created by the fact that the areas receiving the highest exposures are not included in registration areas.

For all of these reasons, it would not be advisable to initiate ad hoc studies. The Panel recommends, however, that the Commission give serious consideration to the promotion of comparable studies already going on elsewhere. Excellent registries are operated in countries outside the Community, e.g. in Nordic countries and in countries of Central Europe, some of which have areas where exposures have been high. The International Agency for Research on Cancer (IARC) is organising a collaborative effort for the monitoring of childhood leukaemia in which particular attention is given to comparability of registry data in different areas. Although much of the information to be obtained is not derived from population groups within the Community, the data obtained should be considered extremely useful, particularly if the study could be extended to include all childhood cancer. Finally, close collaboration with scientists carrying out studies in the USSR, i.e. on people exposed in areas much closer to the accident site and therefore much more likely to result in scientifically useful information, ought to be seriously considered.

5. Limitations of Epidemiologiocal Studies

The Panel is aware that the above suggestions are not easily implemented and that in all likelihood results from the study envisaged might be open to many and varied interpretations. In order to minimise this possibility, the Panel recommends that if any study is to be undertaken, it be planned in detail, before any data are examined, with precise definition of the boundaries of high and low dose areas, exposure and control cohorts and statistical methodology. This will diminish misinterpretation of results which occurred purely by chance.

The Panel also recognises that such a study may require a long-term commitment and that its duration should be kept to the minimum required for obtaining reliable results. As most childhood cancers following in utero exposure may be expected to occur within a period of 8-10 years after exposure, the Panel recommends that a first evaluation of the childhood cancer cohort-specific incidence be made after five years, at which point a decision can be made as to whether to extend the observations by another period of five years.

Finally, the Panel notes that some of the difficulties of setting up a well designed investigation arise from the inadequacies of existing cancer registration mechanisms in areas of high exposure within the Community and in comparable adjacent areas. These inadequacies spring partly from inadequate investment - for which remedies could be found - but also from less tractable problems surrounding the release of clinical diagnoses for public health purposes, going beyond the confines of the clinical consultation. The Panel recommends that Member States review their arrangements for releasing such information to qualified scientists, for defining its custodianship and for reconciling confidentiality with the effective utilisation of data that may be useful for the detection of environmental hazards.

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The CEC radiation protection research programme has taken several important initiatives to address the scientific problems created by the Chernobyl accident. It has defined additional research requirements, reoriented some existing research contracts and strategically placed some new contracts. It also asked for a revision of the current 1985-89 programme to deal with some particularly urgent issues:

(i) evaluation of data on the transfer of radionuclides in the food chain;
(ii) improvement of reliable long-distance atmospheric transport models;
(iii) radiological aspects of nuclear accident scenarios:
 (a) real-time emergency response systems,
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(iv) monitoring and surveillance in accident situations;
(v) underlying data for derived emergency reference levels;
(vi) improvement of practical countermeasures against nuclear contamination in the agricultural environment;
(vii) improvement of practical countermeasures against nuclear contamination in the urban environment;
(viii) improvement of practical countermeasures: preventive medication;
(ix) treatment and biological dosimetry of exposed persons;
(x) feasibility of studies on health effects due to the reactor accident at Chernobyl.

This synopsis aims to present, in an easily understandable way, the rationale for and the principal results of the research undertaken in this area. As a whole, this research has considerably improved Community ability to handle such emergency situations and has developed the cohesion of Community science.

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