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European Commission

RADIATION PROTECTION RESEARCH AND TRAINING PROGRAMME

Synopsis of research results

Radiation protection programme
1990-95

Chernobyl research programme
1991-96

Report

EUR 16800 EN

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Directorate-General
Science, Research and Development

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Preface

It has been customary, in the past, for the EC Radiation Protection Research Unit to publish a summary of the results described in the Final Reports of the research projects at the end of a programme period. The immediate past publication (EUR 13200) presented a Review of the Radiation Protection Programme from 1960-1989 and a Synopsis of Results 1985-1989. This document presents a synopsis of the research results arising from projects supported during the period of the Third Framework Programme from 1990-1995 as well as the results arising from the Chernobyl Research Programme carried out from 1991-1996 with a special budget (APAS-COSU) which fell outside the normal Framework Programme.

The research done during the Third Framework Programme was divided into to distinct contractual periods covering 1990-1991, when the work was carried out as a separate Radiation Protection Research Action, and 1992-1995, when the Radiation Protection Research Unit was integrated into the Nuclear Fission Safety Programme. The dissolution of the Soviet Union made it possible to initiate collaborative research projects with institutes in the newly independent countries of Belarus, Ukraine and the Russian Federation to investigate the radiological consequences of the Chernobyl reactor accident. The Chernobyl research provided an additional challenge to the programme and the radiation protection research workers throughout the European Union and the successful execution of this programme, often under difficult administrative and practical conditions, which concluded with the "First International Conference on the Radiological Consequences of the Chernobyl Accident" held in Minsk in March 1996, bears witness to the quality of Radiatioon Protection Research in the European Union as well as to the determination and dedication of all the individual scientists involved including those from Belarus, the Ukraine and the Russian Federation.

The implementation of both aspects of the programme has been guided by the members and experts associated with the Management and Coordination Advisory Committee (CGC) "Radiation Protection". The deep interest and keen attention paid by the Committee to the developments in the programme and the wise advice given to the Commission staff has been a major factor contributing to the success of the programme.

The programme continues to stimulate radiation protection research throughout the European Union and the results constitute an important contribution to the further development of radiological protection philosophy and international recommendations issued by the International Commission for Radiological Protection (ICRP).

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CONTENTS

CHAPTER 1

EXECUTIVE SUMMARY

The Commission's radiation protection research activities are based on the Euratom Treaty which conferred on the Commission since 1957 the responsibility to establish uniform "basic standards for the protection of the health of workers and the general public against the dangers arising from ionizing radiations and ensure that they are applied" and for the "study of the harmful effects of radiation on living organisms". The Radiation Protection Research and Training Programme has therefore supported research in the Member States with the aim of providing the scientific input needed for the continuing development of radiation protection philosophy and practices. The Commission's programme plays an increasingly visible and well defined role in the work of the non-governmental international organisations, such as ICRP and ICRU which issue the recommendations on radiological protection, as well as in providing essential data to UNSCEAR.

Radiation Protection research is a Community activity with unique structure as it is concerned with a recognized hazardous agent, ionising radiation and radioactivity, and covers a wide range of complex topics from the identification of source terms, the distribution of radioactivity in the environment and the resulting exposure of the population through a quantitative and mechanistic analysis of the health effects to the continued development of risk assessment and protection policy. The specific field of radiation protection research exists because of the need to integrate all the research results coming from the wide variety of topics to form a comprehensive and coherent safety and protection culture.

The Programme has been implemented, until recently, in five-year periods via cost-shared contracts with individual institutions. The last five-year period covered 1985-1989 but then the Programme was brought into synchrony with the Third Framework Programme by a Council Decision adopting a Research and Training Programme for the European Atomic Energy Community in the Field of Radiation Protection (1990-1991). The radiation protection research was continued through a Council Decision adopting a Research and Education Programme in the Field of Nuclear Fission Safety (1990-1994) which included Area 1: Radiation Protection and Area 2: Reactor Safety. This programme of radiation protection research was extended to June 1995 by a Council Decision which provided additional funds for the Third Framework Programme. This third framework programme period heralded the introduction of multi-national, multi-partner contracts which have provided a structure for, and thus intensified, the collaboration between the different research institutions in the Programme.

In 1986 the accident at Chernobyl occurred and in 1991 a collaboration with the Chernobyl Centre for International Research (CHECIR) was launched with the Communication of the Commission to the Council. Following the dissolution of the Soviet Union, the research started via CHECIR was continued under an Agreement for International Collaboration on the Consequences of the Chernobyl Accident signed in June 1992. The research carried out under this Agreement has been supported in a series of annual non-framework programme budgets (APAS-COSU, Hors - Programme Cadre)" from 1991 to 1996. Sixteen projects covering radioactivity in the environment, counter-measures, emergency management and health effects were supported by the programme which were all implemented through multi-partner contracts with institutes in the Member States and in the three affected republics.

This synopsis provides a critical review of the progress achieved under the major headings of the programme: Human exposure to radiation and radioactivity; Consequences of radiation exposure to man; and Risk and management of radiation exposure; and it also reviews the results from the Chernobyl research under the headings: Radioactivity in the environment; Off-site emergency management and pathways of exposure; and Evaluation of the health consequences and retrospective dosimetry. The final chapter describes the development of the current programme, the changes that have occurred and the way in which the priorities of the new programme were developed.

The continuous involvement of a highly qualified scientific management staff covering all disciplines encountered in radiological protection and their constructive cooperation with research consortia significantly contributed to keep the research projects on target within the priorities laid down.

Dosimetry - Research in radiation protection dosimetry is currently based on experience gained over some decades. The current task of research in this area is to provide the methods and techniques needed to implement radiation protection concepts and regulations. One of the major tasks has been to provide the data and practical guidance for implementing the revision of the Directive for the EC Basic Safety Standards which was adopted on 13 May 1996. The efficiency with which this work - which is of benefit to radiation protection worldwide - was carried out was entirely due to the high standard of research and the level of competence within the EU Member States. This is a consequence of the continuous involvement of the EC Radiation Protection Research Programme and the high level of integration and collaboration in Europe which has been achieved in this area of research.

The collaboration and integration has also led to other developments of practical relevance. Examples are a new comprehensive approach to radiation monitoring in the workplace combining methods of ambient and individual monitoring with those of computational dosimetry. In internal dosimetry, the international collaboration ensures rapid transfer of research results into practical use. There is, however, still a need for basic research in specific areas. Examples are the basic data for high energy particle interactions and the human metabolism of incorporated radio-nuclides. The considerable progress achieved in these areas was made possible by the application of methods developed in other scientific areas, such as ultra-sensitive analytical methods for trace elements.

The progress and achievements have been good or very good in most areas. The most obvious exception is the area of mixed field neutron individual monitoring. Future research in this area will have to take account of developments in other scientific fields and adopt a more targeted approach. There will be a continued need for some basic research for exposure to high energy radiation and in internal dosimetry.

Radioecology - In the past research in radioecology has been limited to the monitoring of contamination levels in different compartments of a food-chain and its consequent modelling. During the 1990-1995 period the more traditional empirical approach of the past has gradually evolved into a more mechanistic approach with the aim of providing a structure to environmental engineering and putting environmental management on a

sound scientific basis. In this context a number of important results have had considerable influence on this development, such as the fundamental understanding of the mechanisms of absorption/desorption by components of clay and the role of organic matter; the development of the experimental and mathematical methodology to predict the true absorption of radionuclides through the gastrointestinal tract in livestock animals; and an improved description of the operative physico-chemical and biophysical factors determining the contamination load of water, sediments and biota.

With the development of the new attitude towards radioecological research in the Third Framework Programme it became clear that environmental assessments should be based on contamination loads and total inventories of contaminants as they flow through the environment, rather than on local concentrations and concentration changes. This concept forms the basis for the Fourth Framework Programme and has led to radioecological priorities where the determination of fluxes of radionuclides in different types of ecosystem has become the central objective of the investigations. The ecosystems studied include agricultural land and semi-natural ecosystems, as well as freshwater and marine environments. The flux models developed for these ecosystems will be used to evaluate their vulnerability and a Geographic Information System based classification will be produced. As an extension of these classifications, strategies of environmental restoration (exclusively dealing with large surface decontamination in contrast to site restoration) will be developed in order to create a fully comprehensive environmental strategy which can be used in the case of a future accident.

Radioecological Consequences of Chernobyl - The radioecological research carried on round Chernobyl has contributed to considerable progress in our understanding of radionuclide behaviour in different ecosystems, which has clearly demonstrated that good science leads to well-informed decisions. Such information has been acquired on the mechanisms which govern radionuclide interaction with the environment which has given a better assessment of the environmental consequences of the accident and the resulting radiation dose to the population. A wide variety of remedial measures have been developed or critically evaluated, with an assessment of their usefulness which has considered not only effectiveness but also their appropriateness for use in the contaminated regions. Although radiocaesium activity concentrations in most food products are well below intervention limits some problems remain, in particular "private" milk and some semi-natural products, especially mushrooms.

In the contaminated regions of the three republics the relative importance of different pathways of contamination varies, depending on where people live and the extent to which the applied countermeasures have reduced contamination levels in the foodstuffs which they eat. Urban residents purchase food from shops which largely originates from the collective agricultural system, whereas much of the rural population are subsistence farmers who purchase few products from shops. Since most countermeasures have been directed towards the collective system the intake of radiocaesium via this route is currently low. The contamination levels in foodstuffs grown by private farmers in rural areas will depend on many factors, including deposition rate, soil type and agricultural practices such as the extent of usage of forest areas. ^{137}Cs intake by urban residents from private farming will arise from the cultivation of private vegetable plots and food gifts from rural relatives. The significance of mushroom consumption in contributing to

radiocaesium intake and whole body burdens has been clearly demonstrated for rural inhabitants, but more data and further evaluation is needed for urban inhabitants since the tradition of collecting mushrooms in the autumn is widespread in the three republics. Similarly, the intake of radiocaesium via fish or game and possible counter-measures needs further consideration. Possible remedial measures, appropriate to private farmers, need to be evaluated further so that radiocaesium activity concentration in private milk can be reduced below intervention limits.

Health Effects - Research in this area is, in general, at the more fundamental end of the spectrum although many projects have a clearly defined goal in the short to mid-term. Examples of these more targeted projects are the development of biological dosimetry using the chromosome painting technique and the reassessment of the possibilities for the treatment of over-exposed accident victims where the application of growth factors holds great promise. Other research has, in the past and also in the Third Framework Programme, been concerned with the measurement and analysis of dose effect relationships at low radiation doses. During the 1990-1995 period the emphasis has moved somewhat towards the desire to develop an understanding of the basic processes induced in the cellular DNA by the radiation and to couple this understanding to cancer modelling and epidemiological studies to derive a better assessment of low dose radiation risk. This trend is clearly identifiable in the priorities selected for the Fourth Framework Programme.

In the health effects studies considerable progress has been achieved in many of the projects with quite remarkable progress registered in areas such as DNA repair research and early events in radiation carcinogenesis. Much of this progress is being made possible by the developments in molecular biology which finds increasing application in this area of radiation protection research. The newly available techniques stimulate not only the rapid progress but also the development of new concepts, new ideas and different paradigms, such as in the treatment of accident victims, and in radiation cytology. The areas where the research continues to press forward with great promise are the areas of prime interest for the future such as DNA repair, early events in carcinogenesis and new treatments for accident victims. In other areas of health effects research the studies have been less successful and in spite of the new methodologies certain goals have not been achieved. These areas are typically those which have had to be seriously reconsidered before inclusion as topics in the new programme.

Epidemiology - Studies in this area are crucial to the derivation of low dose radiation risk which is currently determined from the follow-up of the Japanese Atom Bomb survivors. However, the Japanese were exposed to a very short flash of radiation and it has been increasingly recognised during the last few years that the risk from an exposure protracted over the major part of a lifetime, as is the case with radiation workers and, in the case of radon, for the population, may not be simply related to the risk experienced by the Japanese. The epidemiological research has consequently been changing to include studies of populations exposed over long periods of time such as the nuclear workers study and to develop the necessary mathematical tools to analyze these populations. In addition, the risk of indoor radon exposure for the population has yet to be defined and a major European cooperation is concerned to develop sufficient statistical power to resolve this problem by means of a lung cancer case-control study in

regions with high radon levels. This study is supported by a follow-up of Uranium miners in Europe where the induction of lung cancer by high level exposure to radon decay products is well documented. Several other studies addressed particular epidemiological problems such as effect of age at exposure, internally deposited radioactivity, secondary cancers following radiotherapy and the relationship between Chernobyl and the incidence of childhood leukaemia in Western Europe. Epidemiological studies are by their nature long-term requiring meticulous data collection and verification and careful analysis. Progress in the area has been good taking into account the special nature of the studies and there has been a clear development of the strategy so that, in the new programme, epidemiological studies will concentrate on better defined populations and on the problem of the risk from a chronic protracted exposure over a major part of the lifetime.

Health Consequences of Chernobyl - This period has been successful for the health projects studied in the Chernobyl research programme and many of the original short-term objectives were met: the potential for conducting sound specific epidemiological follow-up in the republics has been demonstrated; reconstruction of organ dose or whole body dose using both physical and biological techniques appears feasible with accuracies and dose thresholds as required for epidemiological studies; the views of doctors on the treatment of bone marrow damage have drastically changed and the need for standardization of medical nomenclature and methodology has become evident; the diagnoses of thyroid cancer in children made real progress, the tumours have been classified, the subtypes identified, and cytochemical and molecular biological investigations carried out. The clinical aspects of the post-Chernobyl thyroid carcinoma also made substantial progress, even if it was not easy to discuss and come to an agreement for common protocols with the different surgeons in the CIS, since thyroid cancer was treated differently there than in the West. A protocol for diagnosis, treatment and follow-up has been devised. It is particularly gratifying that considerable humanitarian aid has been provided by the Commission to the republics in the form of specialised equipment and drugs as a direct result of the thyroid cancer research.

The studies on the health consequences of the Chernobyl accident have shown that, in 1996, the only health effect in the exposed populations which can be linked to the Chernobyl accident is the large increase of thyroid cancer in children who were living near Chernobyl at the time of the accident. However, cancer is known to appear several years after radiation exposure and it is evident that there is a need for continued surveillance of the exposed populations.

Radon research - Research in this field was focused with good progress along two main axes during the 1990-1995 period, namely: improvement of the estimation of the risk arising from inhalation of the decay products; and, in parallel, the development of efficient remedial actions to reduce the level of indoor radon, applicable to the European building stock. Research on the estimation of risk encompassed a large range of activities including the characterisation of the properties of airborne radon decay products which are important for the calculation of lung dose; deposition patterns in the respiratory tract; dose-effect relationship for the induction of lung cancers in animal experiments; case-control epidemiological studies; and retrospective assessment of radon exposure. The research for the development of efficient remedial actions included studies of correlations between soil characteristics and indoor radon concentrations;

modelling of radon movement in soil and entry into buildings; modelling of radon movement inside dwellings and studying radon permeability in and exhalation from building materials; and evaluating the efficacy, reliability and permanence of practical solutions.

Substantial efforts have been made in all Member States of the European Union in terms of basic research, in terms of surveys to map the varying level of radon exposure; and in the development of remedial actions but more research is needed to improve the understanding of the mechanisms involved in the development of lung cancer associated with radon.

The actions taken to mitigate the radon exposure situation range from the setting of action levels for dwellings, to costly investments in modifying building and work practices. The socio-economic impact of decisions taken by the society (property owners, mining industries, regulatory agencies, public health services) can be far reaching. Therefore, a careful objective estimation of the risk of radon exposure is of great importance, since, both underestimation or overestimation will have undesirable consequences in terms of either potential threats to public health or a waste of manpower and money. Therefore, in the Fourth Framework Programme, priority is given to the development of a large and comprehensive multi-disciplinary study aimed at the best possible assessment of the risk arising from the inhalation of the radon decay products.

Risk Management - Much has been achieved in this area of the programme and this is exemplified by the wide dissemination and use of a number of software products that have been developed for risk assessment, decision support in nuclear emergencies and for optimisation of radiation protection. The existence and wide use of these software products is contributing to the more uniform and consistent application of radiation protection principles and risk assessment methods within the EU. Moreover, they provide a basis or platform for the integration of new knowledge and developments in the respective areas; this should enable the more effective use and better integration of future EC and national R&D resources in these areas and help avoid unnecessary duplication. In some areas the methodological developments are now relatively mature and are largely fit for purpose (eg, optimisation of radiation protection in normal operations, probabilistic accident consequence assessment, assessing the health and environmental risks of radioactive materials released to the environment); it is important, however, that these are maintained "state of the art" given their widespread and increasing use within the EU and often within a regulatory context. Much, however, remains to be done in other areas: in particular, in improving the quality and comprehensiveness of decision support systems for managing the off-site consequences of any future nuclear accident and promoting a more coherent and integrated approach throughout Europe; in better understanding risk perceptions and improving radiation risk communication; and in developing approaches to aid the more effective allocation of resources for the management and reduction of diverse health and environmental risks. These topics are priorities within this area of the new Programme.

Off-site emergency management after Chernobyl - A number of important achievements have resulted from research carried out in the area of emergency management and pathways of exposure. Perhaps the most important has been the joint development of

the RODOS system for aiding decisions on the management of the off-site consequences of any future nuclear accident. The installation of the RODOS prototype in Belarus, Russia and Ukraine, and decisions to integrate it within national emergency arrangements in the respective countries, augurs well for a more effective and coherent response to any future accident that might affect Europe. Further developments are, however, needed to complete the system and technical assistance would greatly accelerate its implementation in the three countries. Important insights were also gained on post accident management, particularly in the longer term, from the Chernobyl experience. The importance of social and political considerations was highlighted and this has implications for both the longer term management of the contaminated environment around Chernobyl and for the development of policies and strategies for the management of any future accident. The social and psychological impact of the accident has been considerable and persistent and was largely unexpected. The extent to which this was influenced by the broader changes then occurring in the Former Soviet Union is a matter for conjecture; it is clear, however, that this aspect needs greater attention in future. Increasing social trust and enabling individuals to exercise greater personal control were identified as key issues for improving the situation for those continuing to live in contaminated areas. Means for achieving this through a decentralised approach have been identified and will be evaluated in the new programme.

Major improvements have been made in models for assessing internal and external doses in the contaminated areas. These models are more realistic than those currently used by the respective national authorities and, in general, result in significantly lower estimates of dose. The adoption of these improved models would, in principle, result in the more effective allocation of resources to the long term management of the contaminated territories and, moreover, help allay anxiety in the population consequent upon the smaller estimates of dose. Further developments are, however, still needed to assess dose distributions and to make more reliable estimates of doses from natural/wild produce. The Atlas of caesium contamination for the whole of Europe provides much needed perspective on the geographic scale and extent of the contamination; moreover, it provides a useful, albeit approximate, surrogate for the geographical variation in the (longer term) exposures from the accident. The data underlying the Atlas will be of long term value to the scientific community for research and development purposes.

Radiation Protection in Medicine - Research on the use of ionising radiation in diagnostic radiology was concerned mainly with establishing the scientific basis to combine good quality diagnostic imaging with radiation protection optimisation strategies. Special attention was given to involve the medical and technical staff in these activities. Good progress was achieved by the development and extension of the Quality Criteria concept and by the assessment of reference dose values for a series of radiological examinations. Both of these investigations prepared the ground for the standardisation of quality assurance programmes and quality control protocols, and will lead to straight-forward auditing procedures. The research results have contributed to the evaluation of patient benefit and protection measures for newly introduced radiological techniques and also to the ongoing revision of the Medical Exposure Directive (84/466/EURATOM). They will, consequently, also impact on the design and construction of new radiological equipment. As a further spin-off the research results were integrated in projects of other programmes of the EC, such as the Guidelines for Quality Assurance in Mammography

Screening of the "Europe against Cancer - Breast Screening Action". Future research actions will concentrate on the quantitative approach to defining the link between the required diagnostic information and the exposure of the patient as an operational tool for optimisation strategies, including a strong component of the expansion of safety culture.

Training Activities - The importance of continuing Training Activities in Radiation Protection has been stressed by the Council Decision on the specific programme "Nuclear Fission Safety". The main emphasis has been put on European Radiation Protection Education and Training (ERPET) activities but, in addition, a few short period fellowships have been granted. Training packages were elaborated and some 50 training courses were organised during the 1990-1996 period in subjects areas which are crucial for maintaining and developing expertise in radiation protection. It is the aim of the ERPET initiative to facilitate access to up-to-date knowledge in key areas and to contribute to the harmonisation of training programmes in the Member States. As an extension of this approach common strategies for education and training in radiation protection should be developed together with other competent international scientific organisations.

The final chapter of this synopsis presents the reasoning which has lead to the development of the priorities used for the new programme. Briefly, the reasoning rests on the need to increase the contribution of the Commission's programme to the total cost of the successful contracts coupled to a restricted budget which dictates the choice of well defined research priorities. The approach taken to maintain as comprehensive a programme as possible was to define some other topics for concerted action type of support. In this way the programme has become leaner but fitter and provides a clearly defined stable platform for the future development of the Fifth Framework programme and the maintenance of an efficient continuity in the research.

CHAPTER 2

PROGRAMME MANAGEMENT

2.1 GENERAL INTRODUCTION

The Radiation Protection activities of the European Commission are carried out within the terms of the Euratom Treaty which created the legal basis for regulation and research in the field with a responsibility to establish uniform "basic standards for the protection of the health of workers and the general public against the dangers arising from ionizing radiations and ensure that they are applied" (Article 2b, and also Articles 30 - 39) and for the "study of the harmful effects of radiation on living organisms"(Annex I, VI). The regulatory aspects of Radiation Protection defined in the form of Council Directives laying down Basic Safety Standards are the responsibility of DG XI Direction C: Nuclear Safety, Civil Protection and Industry. The research aspects of Radiation Protection which have been carried out since 1958 are currently the responsibility of DG XII Direction F : Nuclear Fission Safety Programme. There is thus a close connection between regulation and research in radiation protection which is defined in the Treaty and revealed in the regular interactions between DG XI and DG XII although there is, of course, a delay between the acquisition of research results and their application in regulation. Nevertheless, it is undeniable that the Radiation Protection Research and Training Programme has contributed to the continuing development of radiation protection philosophy, practices and regulation over the past 35 years.

Through the 1970s and 1980s the Programme was implemented in a series of five-year periods via cost-shared contracts with individual institutions. The last five-year period covered 1985-1989 and the Report EUR 13200 presents a historical review of the programme from 1960-89 and a synopsis of the results of the 1985-89 period. The Programme was then brought into synchrony with the Third Framework Programme for Community Research and Technological Development (1990-1994) by a Council Decision of 20 June 1989 adopting a Research and Training Programme for the European Atomic Energy Community in the Field of Radiation Protection (1990-1991) (89/416/Euratom) {OJ No L 200/50 of 13.7.89} with a budget of 21.2 MECU. The radiation protection research was continued after this two year programme through a Council Decision of 28 November 1991 adopting a Research and Education Programme in the Field of Nuclear Fission Safety (1990-1994) (91/626/Euratom) {OJ No L 336/42 of 7.12.91} which included Area 1: Radiation Protection with a budget of 28.64 MECU and Area 2: Reactor Safety with a budget of 7.00 MECU. This programme of radiation protection research was extended with a budget of 12.5 MECU as part of a Council Decision of 15 March 1993 (93/167/Euratom,CEE) {OJ No L 69/43 of 20.3.93} which provided additional funds for the Third Framework Programme.

During the 1985-1989 programme the accident at Chernobyl occurred and a revision of the programme supported ten "Post-Chernobyl Actions" which were concerned with the radiological consequences of the accident for the Member States. In 1991, with "glasnost and perestroika" it became possible to develop more direct research projects with the Soviet Union and a collaboration with the Chernobyl Centre for International Research (CHECIR), an initiative of the International Atomic Energy Agency (IAEA), was launched with the Communication of the Commission to the Council (SEC(91)220 DEF, 12.2.91). With the dissolution of the Soviet Union at the end of 1991 the research originally started in the frame of CHECIR was continued under an Agreement for International Collaboration on the Consequences of the Chernobyl Accident signed in

June 1992 by M Pandolfi, Vice President of the Commission and representatives of the Ministries and State Committees responsible for Chernobyl Affairs of the three affected republics, Belarus, Ukraine and the Russian Federation. The research carried out under this Agreement has been supported in a series of annual non-framework programme budgets (APAS-COSU, Hors - Programme Cadre)" from 1991 to 1996 with a total budget of 23 MECU.

Radiation Protection research has a unique structure as it has to cover a wide variety of scientific disciplines ranging from aspects of atomic physics, radiation physics and chemistry, cellular and molecular biology, animal and human carcinogenesis, animal and human metabolism, haematology, dermatology, epidemiology, radioecology, soil science, plant physiology, hydrology, marine ecology, emergency management, risk perception, assessment and management, through to diagnostic radiology. These topics cover a complete spectrum of complex problems from the identification of source terms, the distribution of radioactivity in the environment and the resulting exposure of the population through a quantitative and mechanistic analysis of the radiation induced effects, especially cancer, to the continued development of risk assessment and protection policy. The broad nature of the programme imposes certain demands on the programme managers who are all scientists with expertise and experience in one or more areas of radiation science and with basic education in different disciplines such as physics, chemistry, agriculture, plant physiology and medicine. The specific field of radiation protection research exists because of the need to integrate all the research results coming from the wide variety of topics to form a comprehensive and coherent safety culture.

The Report "Evolution, achievements, perspectives - Radiation protection programme 1987-92 - Post-Chernobyl actions 1988-89 - APAS-COSU 1991-92 {Eur 15229} presents a summary of the results arising from the research supported in the programme in the period 1990-91. Consequently, this synopsis concentrates more on the results of the research supported in the normal programme in the period from 1992 to 1995 together with a summary of the results of the research carried out under the Chernobyl programme from 1991 to 1996. In this respect it is important to note that the results of the Chernobyl research were the topic of the "First International Conference on the Radiological Consequences of the Chernobyl Accident" organised by the European Commission and the Belarus, Russian and Ukrainian Ministries of Chernobyl Affairs, Emergency Situations and Health in Minsk (Belarus) from 18 - 22 March 1996. The proceedings of the conference {The Radiological Consequences of the Chernobyl Accident, eds. A. Karaoglou, G. Desmet, G.N. Kelly, and H.G. Menzel (EUR 16544)} as well as the final reports of the 16 projects which made up the Chernobyl research programme {EUR 16527-16542} can be obtained from the Office for Official Publications of the European Communities in Luxembourg.

2.2 EVOLUTION OF RADIATION PROTECTION RESEARCH ACTION 1990 - 1995

The Radiation Protection Research Programme of the Community has developed over the years to be a wide ranging comprehensive approach to the field with newer developments, such as emergency management or cell transformation, introduced in the programme when justified. Occasionally topics have been discontinued, such as primary

radiation effects, when it was felt that continued research in that topic was no longer producing useful results for the programme. The programme makes use of multidisciplinary research in a series of inter-related topics with a long-term goal which is the provision and use of the data and understanding for an accurate assessment of low dose radiation risks and for the development and implementation of the Basic Safety Standards. The programme has achieved an appropriate balance and maturity over the years but has lost nothing in dynamism as new developments in, for instance, computer technology and molecular biology, have driven the research in a "state of the art" situation and current progress in many topics is both rapid and exciting. The programme is gradually becoming recognised to be one of the more influential and important coordinated groupings of scientists working in this field in the world, an influence which is increasingly acknowledged by the input which scientists from the programme have in international committees such as the International Commission on Radiological Protection (ICRP), the International Commission on Radiation Units and Measurements (ICRU) and the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). The Programme remains at the forefront of developments in the field and is, by design, flexible enough to be easily adapted to changing priorities.

Although some of the research in the programme is basic, much of the work undertaken is of a pre-normative nature impinging directly on the development of radiation protection standards and on their application both at the European and at the International level. The scientific contents of the Programme have been systematically modified to the needs and priorities of improving radiological protection. In the early Eighties, risk management and the radon issue became important and a sector on the evaluation of radiation risks and their management including the risks derived from exposure to radon and its daughter products was added; by the mid-Eighties, more attention was given to the reduction of patient exposure in medical diagnostic radiology and to radiation effects on the developing organism; and in the late-Eighties, cellular and molecular studies of radiation-induced cancer gained in importance. In the field of radioecology, the Chernobyl accident highlighted the need for more research on the more vulnerable natural and semi-natural ecosystems; in dosimetry, new equipment for measuring exposure has been developed and research on dosimetry of incorporated radionuclides was emphasised; and in risk management, a strong impetus was given to the planning of the management of nuclear emergencies and the development of decision support systems.

Although the 1985-1989 Programme was considered to be comprehensive and sound, it was suggested that the Programme needed to be more adventurous in its approach and adoption of more radically new developments in radiation protection. This is, of course, a laudable objective and has always been a point of consideration in the continuing evolution of the programme although the approach is not without its dangers and is thus being implemented with caution especially in view of the insufficient level of funding needed to maintain the comprehensive package of activities. Strong support is being given to research which makes use of the most up-to-date methodology and concepts and "think-tank" type of meetings are organised to advise on new research priorities.

The structure of the Programme developed for 1990-91 period was derived from the previous programmes but the topics were grouped into three newly defined

representative areas, i.e.:

1. Human exposure to radiation and radioactivity, with two sub-areas, namely measurement of radiation dose and its interpretation, and transfer and behaviour of radionuclides in the environment.

2. Consequences of radiation exposure to man; their assessment, prevention and treatment, with three sub-areas, namely the stochastic effects of radiation, the non-stochastic effects of radiation, and radiation effects on the developing organism.

3. Risks and management of radiation exposure, with two sub-areas, namely the assessment of human exposure and risks, and the optimization and management of radiation protection.

This structure has been maintained for the programme period 1992-1995 even though the contracts accepted for the 1990-91 period were finalised and a new call for proposals and evaluation procedure was undertaken to create the 1992-94 programme which led to some minor differences between the work contracted in the two periods. The contracts funded for the 1992-1994 period were extended up to July 1995 using the additional funds provided by the Council Decision (93/167/Euratom,CEE).

The changes made to the structure of the Radiation Protection Research Programme together with revisions in Programme management, have enhanced the interaction between the different subject areas and have improved the integration of data from the whole of the programme into risk evaluation.

Cooperation with other EC research programmes has been extended via contacts, for example, with the "Joint Opportunities for Unconventional or Long Form Energy supply" (JOULE) programme on external costs of energy cycles and with "Science and Technology for Environmental Protection" (STEP) programmes on atmospheric dispersion and risk assessment from pollutants released in the environment. In addition, in the frame of the cooperation with the CIS links were established with the European Community Humanitarian Office (ECHO) for the provision of special equipment for the treatment of childhood thyroid cancer in Belarus and the Ukraine and the "Technical Assistance to the Commonwealth of Independent States" (TACIS) of DG IA for training of medical personnel and for the development of emergency management systems in the CIS. The Radiation Protection Research Programme has also been actively collaborating with the programme "Europe Against Cancer" in the field of breast cancer screening by mammography.

One area of continuing concern to the programme has been the maintenance of radiation protection expertise throughout the Union. The nuclear energy industry developed intensively in the late 1950's and early 1960's. This created a boom in the development of radiation protection but now the most experienced scientists in the field are retired or rapidly reaching retirement age. This loss of experienced scientists is happening at exactly the same time when the decrease in funding jeopardises the career development of the younger scientists so that the high level expertise in radiation protection practice

and research in the Community is in danger of being irretrievably depleted. Furthermore, the variations in the level of expertise which currently exist between the different Member States need to be reduced, especially in view of the need to define European wide policies for nuclear emergency management. Increased attention has consequently been given to additional specialised training of scientists in the field. A specific training committee has been created from the Management and Coordination Advisory Committee "Radiation Protection" (CGC) and from the staff of DG XII-F-6 (previously DG XII-D-3) and DG XI-C-1 (previously DG XI-A-1). The committee advises the Commission on education and training activities including appropriate subjects and target groups and monitors the choice of proposed training courses and their organisation and success. The Commission's services have concentrated their efforts under the heading "European Radiation Protection Education and Training" (ERPET), and collaboration has been established in this respect with international scientific cooperative groups "European Late Effects Project Group" (EULEP), "International Union of Radioecologists" (IUR), and the "European Dosimetry Group" (EURADOS) which organise some of the courses. ERPET has encouraged the organisation of training courses; the development and provision of information and training packages; the allocation of fellowships for the exchange of scientists; and the promotion of the participation of young scientists in scientific conferences. In total, 52 training courses were organised during the 1990-1996 period. They covered a wide range of topics and attracted approximately 1600 participants. One extremely interesting development during the last period has been the support given to young European graduates to attend a year-long courses on Radiation Biology at St Bartholomew's Hospital Medical College for the degree of Master of Science at the University of London, UK. The participation of the programme in the European-isation of this MSc course includes the development of an advanced module as part of the curriculum with teachers taken from contractors to the programme and the teaching of certain modules of the course at universities in Germany, the Netherlands and Austria.

The programme continues to expand contacts with other countries and international organisations. Sweden became fully associated with the 1990-1991 Programme and Sweden, Norway and Switzerland applied for an association for the 92-95 period though the negotiation of the European Economic Area prevented implementation of these agreements. The special programme for Scientific and Technical Cooperation with the Countries of Central and Eastern Europe (PECO) permitted 19 projects to be attached to existing multi-national contracts for the 1992-1993 period and in the 1994-1995 period this number increased to over 50 projects.

The contacts with the Canadians and the Americans at the management of contracts level have been maintained and in 1991 and 1994 meetings were organised between the programme managers and representatives from the Atomic Energy of Canada Limited, the Atomic Energy Control Board and the Radiation Protection Bureau of Health Canada. In 1991 and 1995 comparable meetings were held with representatives of the US Department of Energy's Office of Health and Environmental Research and Office of International Health Studies and the National Institute of Health. The conclusion of Memoranda of Understanding with these organisations has been delayed because of negotiations on the problem of intellectual property rights. An exchange of letters between the Commission and the Radiation Effects Research Foundation (RERF) in

Japan signed in 1992 has helped to consolidate the existing collaboration.

Several collaborative programmes have been established with the US including a joint EC/US study of the uncertainty associated with the prediction of the consequences of accidental releases of radioactive material, an evaluation of models for predicting atmospheric dispersion in complex terrain, the integration of the CEC and US radon research programmes through common programme evaluation panels and through the creation of two DOE/CEC working groups, one on radon risk assessment and a second one, together with the Canadians, on residential radon epidemiology. The programme and the Office for Health and Environmental Research of the US DOE continue to co-organise international scientific conferences in order to improve dissemination of research results and to stimulate collaboration.

There has been increased interaction with international agencies, in particular with the International Atomic Energy Agency (IAEA) the World Health Organisation (WHO) and the Nuclear Energy Agency (NEA) of the Organisation for Economical Cooperation and Development (OECD). In 1995 the programme co-sponsored an international conference on "One Decade After Chernobyl" together with the IAEA and WHO. Collaborative programmes with international agencies include a joint NEA/CEC Benchmark Exercise on Probabilistic Accident Consequence Models and joint IAEA/CEC coordinated research on Validation and Model Performance (VAMP). Close cooperation with the IAEA Coordinated Research Programmes on "Radon in the Human Environment" and "Radiation Doses in Diagnostic Radiology" has also been established. Members of the scientific staff of the programme also participate in working groups and committee meetings of the International Commission on Radiological Protection (ICRP), the International Commission on Radiation Units and Measurements (ICRU) and the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR).

The Radiation Protection Research Action continues to produce impressive results exemplified by the many publications in quality scientific journals and the proceedings of meetings organized by the Programme. Software packages have also been developed during the programme and these are made available to all interested parties. The final reports of the 1990-1991 programme have been published in EUR 15295 and the complete texts of the final reports of the 1992-1995 programme will be published in a separate report (EUR 16769). The dissemination of the results of the programme remains an important task and staff remain alert to every possibility to improve this.

2.3 EVOLUTION OF THE CHERNOBYL RESEARCH PROGRAMME 1991-1996

The Radiation Protection Research Action has been carrying out research on the consequences of the Chernobyl Reactor accident since 1991. The collaboration was originally established when the Chernobyl Centre for International Research (CHECIR) was set up by the All-Union Ministry for Atomic Power and Industry in collaboration with the IAEA. Following the dissolution of the Soviet Union, CHECIR became an Ukrainian institute and on June 23 1992 Vice President Pandolfi, on behalf of the Commission, signed "The International Agreement for International Collaboration on the Consequences of the Chernobyl Accident" with representatives of the Ministries or State Committees of Belarus, Ukraine and the Russian Federation responsible for the

Consequences of the Chernobyl Accident. Within the terms of this Agreement a Co-ordination Board has been established with representatives from the Commission and each of the three Republics which is responsible for the oversight of the programme, the choice of projects, the coordination of the participating institutes and the general policy of the programme.

The funds provided for the Chernobyl research through the APAS-COSU (activités complémentaires de préparation d'accompagnement et de suivi) budget were renewed each year from 1991 to 1994. With the funds made available for research on the consequences of the Chernobyl Accident in 1991 a sum of 2.1 MECU was spent to establish 5 Experimental Collaboration Projects (ECP) on environmental issues and 2 Joint Study Projects (JSP) on emergency management. In 1992 this sum was increased to 4.7 MECU to continue these projects and to initiate 2 ECP and 1 JSP on health consequences. In 1993 a further 3 ECP, one each on health consequences, retrospective dosimetry and the environment, and 3 JSP, one on health consequences and two on emergency management, were initiated. The topics covered in the 16 projects are indicated by the titles given in the following list:

ECP 1: "Contamination of surfaces by resuspended material"

ECP 2: "The Transfer of radionuclides through the terrestrial environment to agricultural products and livestock, including the evaluation of agro-chemical practices"

ECP 3: "Modelling and study of the mechanisms of the transfer of radioactive material from the terrestrial ecosystems to and in water bodies"

ECP 4: "Evaluation and development of decontamination strategies for a range of environmental situations and evaluations of their efficacy and other impacts"

ECP 5: "The behaviour of radionuclides in natural and semi-natural ecosystems (forests, marshes, heather, etc.)"

ECP 6: "Biological Dosimetry including Cytogenetics"

ECP 7: "Epidemiological investigations including dose assessment and dose reconstruction"

ECP 8: "Molecular, cellular, biological characterisation of childhood thyroid cancer"

ECP 9: "Transfer of radionuclides to animals, their comparative importance under different agricultural systems and appropriate countermeasures"

ECP 10: Retrospective dosimetry and dose reconstruction"

JSP 1: "Real-time on-line decision support systems for off-site emergency management following a nuclear accident"

JSP 2: "Development and application of techniques to establish intervention levels for use in nuclear accidents"

JSP 3: "Treatment of accident victims"

JSP 4: "Development of optimal treatment and preventive measures for childhood thyroid cancer"

JSP 5: "Pathway analysis and dose distribution"

JSP 6: "European atlas of radioactive contamination and external exposures resulting from the Chernobyl accident"

These sixteen projects finished in April 1996 although final reports of the projects were prepared for the Conference in Minsk in March 1996 and have been published as EUR Reports (EUR 16527 - 16542).

The projects all operate in the same way with a coordinated group of institutes from the Community Member States working together in a consortium with a coordinated group of institutes from the three Republics. Experience has shown that, although the concept of collaboration was a difficult one to convey to the scientists in the three Republics at the start of the work, there has been a generally positive appreciation of the benefits that this sort of collaborative work can bring. In general, between 40 - 50 % of the budget is of direct benefit to the three Republics and is spent in provision of equipment, local assistance and exchange of scientists.

During the execution of this Chernobyl programme contacts have been established with other international and national programmes of a similar nature such as the World Health Organisation "International Programme on the Health Effects of the Chernobyl Accident"(IPHECA), the US NCI/DOE Programme in Ukraine and Belarus, the Council of Europe, the IAEA, and with several bilateral programmes of European countries to facilitate collaboration and avoid duplication of research effort.

2.4 MANAGEMENT AND STATISTICAL INFORMATION

The first line guaranteeing an active management of the programme lies in the eight Commission staff members who have over 160 years of scientific experience in radiation protection between them. The scientific staff, who deal with the day to day running of the programme have been supported by the members of the Management and Coordination Advisory Committee "Radiation Protection" (CGC-10) in a close collaboration both in the selection of proposals, in the development of policy and in the definition of a strategy for the programme. It is the scientific staff who have written this critical synopsis of the progress achieved by the contractors over the 1990-1995 period assessing both the strengths and weaknesses of the research and trying to indicate the future directions with the most promise for progress in the field of radiation protection.

The major change in the management of the programme in 1990-1991 was the introduction of multi-national, multi-partner contracts implemented on a cost-shared basis which have provided a structure for, and thus intensified, the collaboration between the different research institutions in the Programme. These multi-national contracts have been surprisingly successful possibly because the programme has a long history of encouraging interaction between, what were previously, individual contractors through contractors meetings, the European and International scientific collaborative groups sponsored by the programme such as EULEP, EURADOS and IUR, and the many special scientific meetings.

A second major change in the management of the programme introduced in the 1990-1991 programme was the creation of an association contract with the National Radiological Protection Board (NRPB) in UK. In the early programmes several Association contracts had been established but most of them had been discontinued except for one with the Commission d'Energie Atomique in France. Under the

Association agreement with NRPB several multi-partner contracts, each having a NRPB scientists as a coordinator, were grouped and managed through NRPB. The execution of the Association Contract was coordinated by a Steering Committee made up of three representatives each from the Commission and NRPB. The steering committee met each half-year to discuss both the scientific progress of the contracts and the financial follow-up and this allowed a very efficient and flexible management of the contracts in the Association.

In the period 1990-1991 the call for proposals resorted in the submission of 333 multi-national projects with a total of 835 partners of which 75 contracts with 351 partners, including 26 Swedish and international partners, were approved for support. In addition, 62 single partner contracts were prolonged from the previous contract period. The programme in the period 1992-1995 received 202 multi-national proposals with a total of 685 partners which led to 86 contracts with 458 partners, including 71 Swedish, Norwegian, Swiss and international partners. The Swedish, Norwegian and Swiss partners were supported by their own governments in this second contract period.

The management of the APAS-COSU Chernobyl Research programme evolved with time. The day to day responsibility for the scientific management was taken up by scientific staff members in Brussels and each project had both a western coordinator and a coordinator in one of the three republics. One member of the staff was given the responsibility of following the financial and administrative management of the programme and a Coordination Board was created made up of one representative of the relevant Ministries or State Committees for Chernobyl Affairs from each republic and three Commission staff members to oversee the running of the programme. In order to facilitate the communications with the Chernobyl area and the execution of the field work around the Chernobyl site an office was established at Zeleny Mys just outside the 30 km exclusion zone and a fully-equipped radiological laboratory was set up at Pripyat. In order to centralise the provision of equipment, local assistance, training arrangements and travel expenses for scientists in the three republics a substantial part of the programme was administered through the radiological institute Forschungszentrum Rossendorf in Dresden, Germany with the help of three local secretariats established in Kiev, Ukraine, Minsk, Belarus and Moscow, Russian Federation. An important result arising from the management of this programme was the realisation of the need to work constructively on the scientific infra-structure in each of the three republics as well as on the purely research aspects of the programme.

In the period from 1991 to 1996 some 80 research groups from the European Union and some 120 research groups from the three republics worked together on the 16 projects. The success of the programme owes a great deal to the enthusiasm of the coordinators both from the Union and the three republics as well as the great desire for cooperation expressed by all the participating scientists.

Statistical Data

The statistical breakdown of the programme is presented in the following figures for the periods from 1990-1991 and from 1992-1995 and in the table for the APAS-COSU programme from 1991 to 1996. The radiation protection programme has maintained the

same scientific structure throughout the full 1990-1995 period of the Third Framework Programme. The scientific subject areas are categorized as follows:

I. Human exposure to radiation and radioactivity
   - I.1. Measurement of radiation dose and its interpretation
   - I.2. Transfer and behaviour of radionuclides in the environment

II. Consequences of radiation exposure to man; their assessment, prevention and treatment
   - II.1. Stochastic effects of radiation
   - II.2. Non-stochastic effects of radiation
   - II.3. Radiation effects on the developing organism

III. Risk and management of radiation exposure
   - III.1. Assessment of human exposure and risks
   - III.2. Optimization and management of radiation protection.

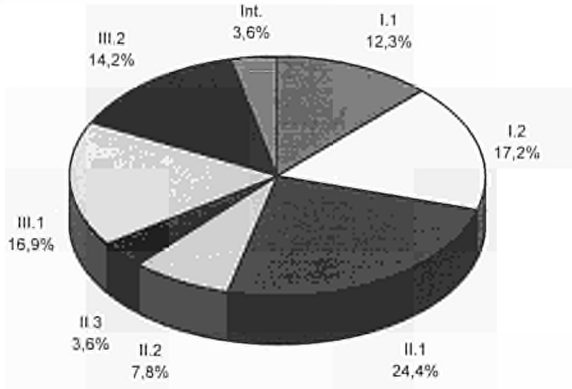
The allocation of resources, expressed in percentages, to the different subject areas of the programme is presented for both periods in the pie diagrams.

The participation of institutes from the Member States in the contracts is presented for both contract periods in the first two bar diagrams and the distribution of the total number of partners (or projects) per contract is presented in the third and fourth bar diagrams for both periods.

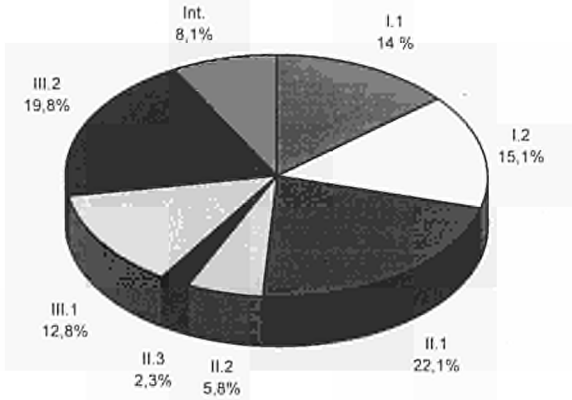
The allocation of resources in ECU, to the 16 projects which made up the Chernobyl Research Programme is presented per year in the table. This table also indicates the development of the programme with time.

Distribution by Sector, Subject Areas

1990-1991

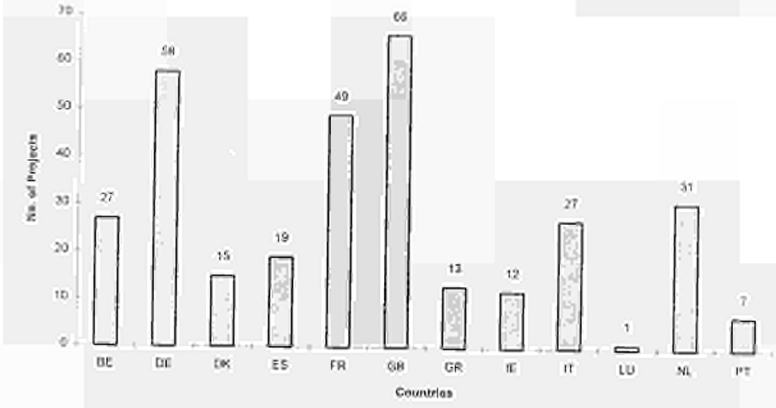


1992-1995

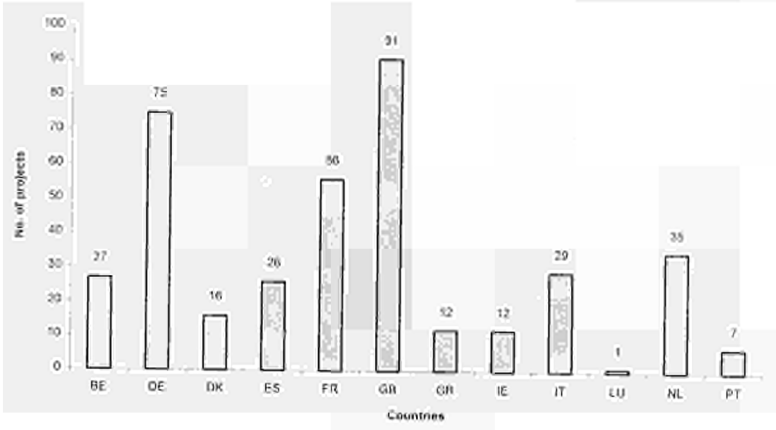


Distribution of projects over the Member States

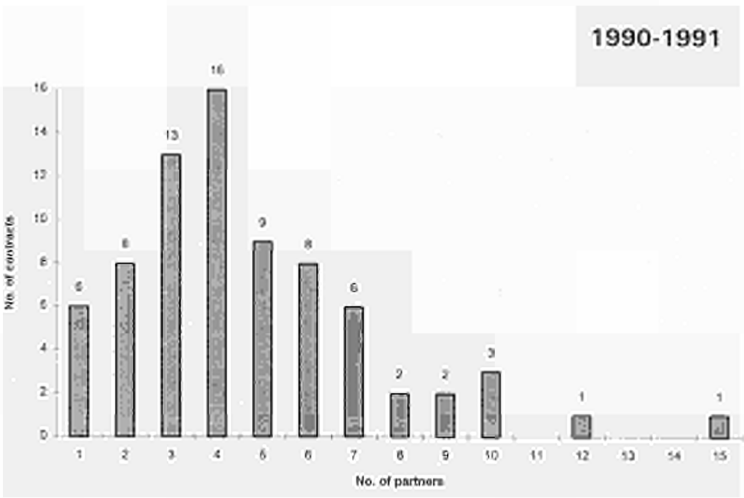
1990-1991



1992-1995



Number of partners per contract



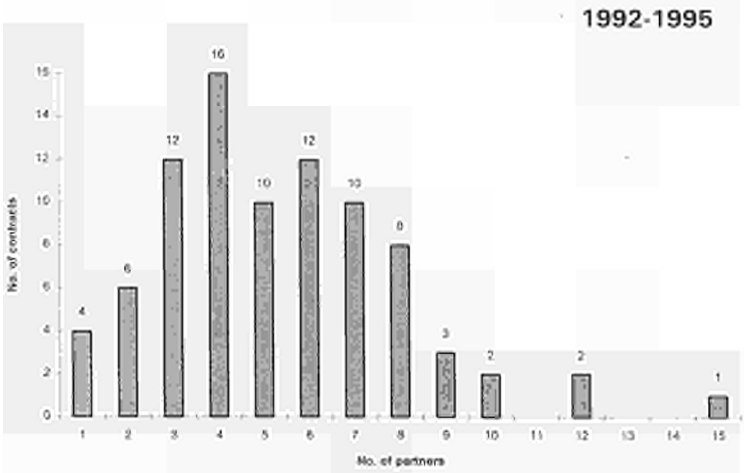


TABLE: Financial overview of the development of the Chernobyl Research Programme (ECU)

PROJECT	1991/1992	1992/1993	1993/1994	1994/1996	TOTAL
ECP 1	363000	560500	594000	353000	1870500
ECP 2	358000	665500	469000	322000	1814500
ECP 3	363000	495500	464000	327000	1649500
ECP 4	363000	560500	589000	324000	1836500
ECP 5	363000	600500	499000	372000	1834500
ECP 6		383000	406000	422000	1211000
ECP 7		340000	346000	392000	1078000
ECP 8			287000	407000	694000
ECP 9			454000	347000	801000
ECP 10			266000	412000	678000
JSP 1	137250	375500	606000	564000	1682750
JSP 2	152750	370500	571000	553000	1647250
JSP 3		389000	316000	407000	1112000
JSP 4			271000	357000	628000
JSP 5			288000	369000	657000
JSP 6			120000		120000
TOTAL	2100000	4740500	6546000	5928000	19314500

CHAPTER 3

REVIEW OF THE RESEARCH RESULTS FROM 1990 - 1995

3.1 HUMAN EXPOSURE TO RADIATION

3.1.1 MEASUREMENT OF RADIATION DOSE AND ITS INTERPRETATION

INTRODUCTION

Operational radiation protection of occupational exposure as well as the monitoring of the exposure of the general public must rely on the availability of techniques and procedures for the determination of quantities which represent a measure of the amount of energy delivered by ionising radiation to tissues and organs. Ideally, these quantities also represent a measure for the probability of the incidence of cancer induced by the radiation, the biological effect of relevance at low doses. Thus, research in radiation protection dosimetry is concerned with the development of instruments for radiation monitoring, as well as with the development of concepts and quantities suitable for risk management in a wide range of potential exposures to external and internal irradiations.

This has led to a system of risk related **protection quantities** (introduced by the International Commission on Radiological Protection, ICRP) and **operational quantities** (introduced by the International Commission on Radiation Measurements and Units, ICRU). The protection quantities are used to set exposure limits and, hence, risk limits and have, therefore, also been called "limiting quantities". Protection quantities are defined for both external and internal irradiations. The operational quantities are defined to be used as estimators for protection quantities and serve as calibration quantities for dosemeters for external irradiations. The most important protection quantity, effective dose E, explicitly takes account of differences in the susceptibility of different organs and tissues ("tissue weighting factor") and differences in the biological effectiveness of different radiations ("radiation weighting factors").

The system of protection and operational quantities provides a consistent and coherent basis for risk management and control, in particular, for occupational external radiation exposure. The practical implementation of this system, however, continues to require research work, in particular for exposures to neutrons and mixed radiations, high energy radiations (near accelerators, in civil aviation), weakly penetrating radiation and for exposure from internally deposited radionuclides.

As far as exposure to external, penetrating radiation is concerned, research work during the reporting period focused on improvements for instrumentation, especially in neutron individual monitoring where existing dosemeters have serious inadequacies in terms of sensitivity or energy response, or both. The combined use of the methods of computational dosimetry and spectrometric methods as well as improved radiation monitoring techniques at work places established in previous contract periods, have been used to prepare the implementation of the recently adopted, revised, EC Basic Safety Standards based on the 1990 ICRP recommendations (ICRP PUBLICATION 60). Responding to public concern and the recommendation of ICRP to include personnel on commercial jet aircraft in the group of occupationally exposed persons, efforts were directed towards the investigation of open questions in this field. The results of this work benefit nuclear and aviation industry because the improved accuracy and scientifically based guidance on implementation of regulation assists in optimisation of monitoring and

contributes towards cost efficiency in legally required operational radiation protection.

The assessment of dose quantities in cases of exposure to radiation from incorporated radionuclides continues to be an item for basic and applied research. The required knowledge on **human** metabolic data is improving steadily through ongoing research. During the reporting period, this work continued for various types of exposures, incorporation pathways and the most relevant radionuclides. In parallel, work on metabolic dosimetric models, which use the results of basic studies as input, were developed or improved. Much of the work in this area finds immediate access to the reference methods and reference data recommended by ICRP.

The retrospective assessment of exposures to ionising radiation after accidents involving radiations, or after uncontrolled exposures in general, has found increased interest following the Chernobyl accident. This is reflected in the research work on physical and computational methods of retrospective dosimetry which commenced during the reporting period.

The work in cost-shared actions was complemented by the organisation of symposia, workshops and training courses closely related to the topics of research in radiation protection dosimetry. The combination of coordinated multi-partner research contracts and conferences for rapid exchange of scientific information complemented by dedicated training courses within the ERPET framework is very effective for the transfer of scientific achievements into practice as well as for the identification of further research needs and priorities. The collaborative group EURADOS (European Radiation Dosimetry Group), being a contractor to the EC Radiation Protection Research Action, assisted very efficiently in this approach and in coordinating research efforts in the EU, including research funded by Member States.

The rapid and efficient transfer of scientific results into practical use was also helped by joint activities with DG XI of the EC, in particular in the areas of accident dosimetry and dosimetry for civil aviation.

3.1.1.1 EXTERNAL IRRADIATIONS

Historically, research into instrumentation has played a dominant role in the dosimetry research sector. Also in this reporting period a significant, albeit markedly reduced fraction of the research was devoted to this activity. This reflects a continuing need for improved monitoring techniques, but also the existing expertise within the EU in this field. The continued need for improvement is due to several factors; the reduction of exposure limits for occupational exposure, the increase of the quality factors and corresponding radiation weighting factors, the need to introduce optimisation procedures into operational health physics. Along with the extension of the rules of radiation protection to new professional areas, they represent individual and combined reasons for the search for instruments with improved sensitivity or energy response with respect to the relevant dose quantities.

This applies in particular for individual neutron dosimetry where the existing and well known inadequacies will become more consequential following the introduction of the

revised radiation protection regulation. In addition, the requirement for optimisation in radiation protection for occupational exposure would be met more easily if real-time readout dosemeters were available for individual dosimetry of all types of exposures, including neutrons.

Efficient and reliable radiation monitoring does not only require adequate instruments but also appropriate techniques and facilities for calibration and standards. This is still a topic for research, for example in the case of weakly penetrating radiation.

Individual neutron monitoring

In general, neutron exposures in mixed neutron-photon fields may occur in nuclear industries at work places in energy generating plants, at facilities dealing with so-called mixed-oxide (MOX) fuel elements or radionuclide neutron sources (used for calibration and safety inspections) and during the transport or storage of spent fuel elements. Outside nuclear industries, occupational neutron exposures occur in the vicinity of high energy accelerators and in aircraft at high altitudes.

Neutrons do not contribute greatly to the collective effective dose in occupational exposure. Nevertheless, the potential exposure of workers to neutrons requires adequate monitoring. In spite of 25 years of research, the performance requirements for individual monitors are still not fully met. The difficulties are due to a variety of reasons: (i) from a principal, physical point of view, the neutrons encountered in practice have energies extending over a very large range of about 8 orders of magnitude and the interactions of neutrons with biological or detector material is strongly nuclide specific and energy dependent; (ii) from a conceptual point of view, the protection quantities and the operational quantity to be used for personal monitoring, personal dose equivalent, H_p, are defined in the human body and have pronounced neutron energy dependence. Perfect individual dosemeters should have an identical or very similar energy dependence; (iii) neutron interactions with the irradiated matter are infrequent. Small personal dosemeters, therefore, often have inadequate sensitivity and thus a high detection threshold; (iv) because of the limited number of workers exposed to neutrons and the low collective effective dose, there is no significant concern in nuclear industry and in society to make research into the improvement of neutron monitoring a high priority.

The coordinated research efforts within this European research action are, therefore, still well justified and necessary. The work carried out during the reporting period focused on developmental work on several different techniques using solid state and gaseous detectors. None of the detectors used are novel by themselves. However, the research work, using experimental and computational approaches, was directed towards modifications and further developments with respect to improved energy response and sensitivity. All techniques investigated were also aimed at developing active dosemeters with real-time read out. The solid state detectors used in those investigations include silicon diodes, gallium arsenide diodes, static random access memory (SRAM), superheated drop detectors (sometimes named bubble detectors) and gas filled detectors (mainly proportional counters). This research approach of using several parallel developments reflects the principal and technical difficulties in neutron monitoring. There is an obvious risk that one or more of the avenues taken may not be successful.

However, the close coordination of the various efforts and targeted intercomparisons are expected to assist in identifying the more promising approaches as early as possible. As in the previous phase, the progress achieved during the reporting period has again been moderate. However, an important aspect is that the instruments under development are all aimed at active dosemeters which is essential because of the low frequency of neutron exposures and the general requirement for optimisation. Progress includes improvements in the energy response of silicon diodes by using hydrogenous converters loaded with ^{10}B or ^{6}L adjacent to the diode, improvement in discrimination between neutron and photon signals by pulse shape analysis and improvement in sensitivity by the use of multi-detector arrangements.

The technique of using superheated drops of liquid in a viscous or semi-viscous medium deserves a special mention. Nuclear interactions with neutrons nucleate the transition of the superheated liquid so that macroscopic bubbles are created. Two companies in North America have been commercially developing this technique for more than a decade. The bubbles are either acoustically registered (enabling active dosimetry) or visually counted (passive dosimetry). This type of detector is, in principle, attractive because of its high sensitivity and good energy response. Investigation and further development of this technique within one research contract has revealed the potential for area monitoring and even as a kind of neutron spectrometer. While the instruments can be considered to perform adequately with regard to energy response and sensitivity, they reveal serious limitations in practice due to their sensitivity to environmental temperature and physical shocks as well as other aspects of practical use.

Complementary to the development of new instruments, work has been carried out on the improved use of individual dosemeters currently in practical use, in particular etched-track detectors. Joint irradiations and intercomparisons of 27 types of neutron dosemeters were carried out involving 16 European institutions and an institute from Algeria. The irradiation fields were mono-energetic reference fields ranging from 144 keV to 66 MeV. The intercomparisons included investigations into the angular response of track-etch neutron dosemeters. This work has significantly improved the understanding of the performance of the dosimeter systems which will in turn contribute towards improved application.

The progress in research on neutron individual monitoring has been moderate and none of the methods and techniques investigated are likely to be introduced into commercial use in the near future. However, the application of some of the currently employed techniques has been consolidated by large scale European intercomparisons and related research. New developments are aiming at active dosimetry with real time read-out and use innovative approaches to overcome the inherent problems of insufficient sensitivity, inadequate energy response and discrimination between photons and neutrons.

It is questionable, however, whether the parallel development of so many different techniques and approaches is justified and beneficial. Before decisions are taken to support the development of the various techniques, they must be examined carefully, taking account also of technical developments in other research fields in which radiation detection is used. In order to stimulate such cross-fertilisation, a dedicated workshop on advanced methods in radiation measurements and dosimetry was organised in October

1994 in Chalk River, Canada. Scientists from areas such as elementary particle physics and X-ray astronomy presented their experimental methods and first cooperations have been started. Future research must concentrate on developments of dosemeters with performance criteria strictly derived from operational requirements. Developments which aim at optimisation of the performance with respect to one criterion only, for example energy response, should not be continued. The choice of performance criteria will, by necessity, have to be a compromise, as in any multi-parameter optimisation. It should be part of an overall strategy which includes the progress and possibilities in the areas of radiation field analysis at work places and computational dosimetry.

Radiation Field Analysis at Work Places

A substantial fraction of research efforts in the area of radiation protection dosimetry in preceding reporting periods had been devoted to the development of mobile spectrometers and ambient active dosemeters. Although very few of these developments led to commercial instruments, several of them are suitable for operational health physics applications and the corresponding expertise is available in several research institutions within the EU. During the reporting period, a series of joint measurements with various types of these spectrometers and ambient and individual dosemeters were carried out at different work places in nuclear industries and in reference radiation fields. This work is part of an overall strategy which includes radiation field analysis in mixed radiation fields and photon radiation fields, a systematic compilation of these results and results from other investigators throughout the world, the computation of relevant dose quantities and the detector responses in these fields, and the development of realistic calibration fields. This systematic approach will contribute towards improving the reliability and accuracy of dose assessments, especially for exposures to neutrons. It complements the efforts in developing personal dosemeters because it will provide the possibility for work place specific calibration correction factors or even work place specific dosemeter calibration.

The neutron fields at work places in nuclear industries originate from spontaneous or induced fission reactions and other nuclear reactions. Shielding with hydrogenous materials or materials with heavier elements considerably modifies the energy spectra. The energy of these neutrons does not exceed a few MeV and most of the dose equivalent is due to neutrons below 1 MeV. By contrast, neutrons originating from nuclear interactions of high energy protons (high-energy accelerators, cosmic radiation) extend to some hundred MeV. Even behind thick shielding broad energy spectra are observed.

Assisted by a EURADOS Working Group joint measurements for nuclear industries were carried out at an irradiation field designed to produce realistic work place radiation fields in the laboratory for calibration purposes (Cadarache, F) at a reactor based experimental radiation facility (Winfrith, UK), inside the containment of a PWR reactor (Ringhals, SE) and in the vicinity of a transport cask filled with spent full elements (Oskarshamn, SE). A total of 26 groups (from Member States, Canada, Czechia) participated with neutron spectrometers, area and personal dosemeters. The spectrometers employed included Bonner spheres (moderating spheres of different diameters with thermal neutron detector at their centre), recoil protein spectrometers, organic scintillation detectors, and for the

first time superheated drop detectors. The area dosemeters were moderator type instruments ("Rem-counters") and various types of tissue equivalent proportional counters(TEPC). Personal dosemeters included track-etch detectors and TLD-based systems mounted on phantoms, in order to obtain quantitative information on the directional spectral fluence. The most important results of these intercomparisons are:

- Bonner spheres are best suited for measurements at work places and allow the relevant quantities with uncertainties of less than 15% (at neutron energies less than 20 MeV) to be determined.
- The detailed analysis of all experimental results contributed substantially to the understanding of the performance of all instruments and helped to reduce uncertainties.
- The comparison of data measured by dosemeters with those calculated from spectral neutron fluence, taking account of response functions of the respective instruments, has the potential for testing the consistency and detecting deficiencies in measurements, and thus monitoring.
- Irradiation of personal dosemeters on phantoms is a useful tool to investigate the directional neutron fluence which is of great importance for the evaluation of the protection quantity, effective dose, and the operational quantity, personal dose equivalent.

The joint measurements in the reactor containment were unique in more ways than one. The number of scientists and simultaneously operating instruments presented considerable organisational and safety problems. The environmental conditions of temperatures up to over 50°C, numerous sources of electromagnetic radiation and an extreme noise level were great challenges for the investigators and their instruments. Thus, experience was also gained on whether the detectors used were truly operational at work places.

Photon spectrometry was also carried out at work places, using a suitably modified sodium iodide crystal. The objective was not only to measure energy spectra, but also to investigate angular distributions. The results were used to evaluate the quantities personal dose equivalent H_p and effective dose equivalent, H_E. The main result is that H_p is, in general, up to 20% larger than H_E. In locations where H_p underestimates H_E suitable corrections can be made.

Photon spectrometry within mixed neutron photon fields continues to be a problem yet to be adequately solved due to the neutron sensitivity of photon detectors. At present, organic liquid scintillators are most promising if the photon response is reliably calculated with radiation transport codes.

The significant progress in this area is due to the availability of suitable instruments developed in previous years, the high level of integration of European radiation dosimetry research and the explicit interest of industries (at least in one Member State). The results obtained document that work place radiation field analysis can reduce uncertainties in occupational monitoring to below 15%, thus providing the possibility to avoid undue over-conservatism in monitoring and operation and to contribute towards cost-efficiency without violation of radiation protection regulation. The results also point to possibilities for improving individual monitoring and the evaluation of protection

quantities. The latter is of importance for any dose reduction strategies and individual risk assessments. This work should continue in the future in order to exploit the technical achievements and experience gained. However, there is little need for additional research and development. The efforts should focus on promoting European collaboration and coordination.

Computational dosimetry

The use of computer codes for calculation of the transport of radiation through matter is a tool of increasing importance for the evaluation of operational and protection quantities and detector responses for all types of radiations relevant in radiation protection. Such computer codes, in particular codes using Monte Carlo techniques, have usually been developed for general purposes including, for example, shielding calculations and are readily available to interested users. Some of them exist in versions suitable for modern personal computers. Although there was no direct support of research work in this area, the coordination of work funded on national level through EURADOS contributed significantly to valuable achievements during the reporting period.

- The unique expertise represented by the members of the EURADOS Working Group on Numerical Dosemetry was the basis for a new systematic calculation and evaluation of fluence-to-dose conversion coefficients for all protection and operational quantities for neutrons up to 180 MeV, photons up to 10 MeV and electrons up to 30 MeV. This work was necessary after the introduction of new recommendations with respect to these quantities mainly by ICRP and partly by ICRU. The evaluated data were used by a joint ICRP/ICRU Task Group to prepare and publish a report on reference data for use in practical applications without which the implementation of the revised radiation protection regulation would not be possible.
- The involvement of scientists from North America and Japan in the work of the EURADOS group was important for the general acceptance of these data. The publication of the ICRP/ICRU report is foreseen for end 1996.
- The increasing frequency with which Monte Carlo general transport codes (such as MCNP and EGS4) are being used by scientists to calculate dose quantities has revealed that this application is not straightforward and considerable specific experience is required. As a first step towards developing guidance and eventually reference procedures for specific application or even quality assurance, questionnaires on application and experience gained have been sent to users of the computer codes. A first training course on the use of codes for computational dosimetry is being organised for 1996.

The dosimetry of high energy neutrons as encountered, for example, at high flight altitudes, is difficult for a number of reasons. One of them is that the nuclear interaction data, e.g. cross-sections, needed in calculations are not readily available and often associated with large uncertainties. Work has commenced on obtaining such data using high energy computer codes, among others, by performing bench mark calculations with different codes.

The expertise in computational dosimetry, as represented by the members of EURADOS Working Group on Numerical Dosimetry, is globally unique. Experts from North

America, Japan and more recently from Russia are collaborating closely with this group, so global cooperation in this area has been achieved. The substantial progress in computational dosimetry is related to the progress in computing power and its general availability and advances in general radiation transport codes. Computational dosimetry is approaching a status which is equivalent to that of experimental dosimetry. Both methods can complement each other, and any research in radiation protection dosimetry will have to include computational methods in the future. Together with the achievements in radiation field analysis at work places, computational dosimetry will play a key role in improving operational monitoring for occupational exposure and be of benefit for any retrospective exposure and risk analysis.

The EC efforts to coordinate this work and to stimulate cooperation, if possible on a global scale, will be both necessary and beneficial in the future. Future work must include efforts on developing guidance and reference methods for the specific application of radiation transport codes in computational dosimetry and, in general, on transferring the knowledge and expertise from the specialists to operational health physicists.

Implementation of protection and monitoring quantities

The EC Basic Safety Standards (BSS) for the protection of workers and the general public from detrimental effects of ionising radiation have been regularly revised to take account of the progress in scientific knowledge and developments in the conceptual framework of radiation protection. The most recent revision, adopted by Council on 13 May 1996, was mainly motivated by the recommendations of ICRP in 1990. In anticipation of this revision, a substantial fraction of the work carried out in the research contracts was devoted towards the practical implementation of the forthcoming EC directive. This included the calculation of new dose conversion coefficients (see above), a compilation of radiation field spectra at work places and investigations on the exposure and dosimetry at high altitudes in jet aircraft (see below).

The systematic evaluation of dose conversion coefficients and their application to real radiation fields was used to investigate the question to which extent operational quantities are conservative estimates of the newly recommended protection quantity and how these compare to the previously defined protection quantities. Briefly, for photons and electrons, the modifications are only of consequence for low energies. For monoenergetic neutrons below 100 keV there is an energy interval for which the operational quantities are not conservative with respect to effective dose. Applied to a wide range of different energy spectra measured at work places, however, the operational quantities were always found to be larger. On average, the ratio between the new and corresponding previous quantities is about 1.5 for neutrons.

The marked energy dependence of both the dose quantities and the detector responses is the main reason for the difficulties in operational neutron dosimetry for protection. The knowledge of the energy spectra and directional distribution of the neutrons at given work places would enable workplace specific calibration factors or corrections factors to be evaluated.

A catalogue of realistic neutron fields has been compiled which includes all available

spectra measured previously, for example, in the USA, Canada and Europe. The catalogue also includes response functions of detectors and the fluence-to-dose conversion coefficients. Computer codes have been developed to manipulate the data and evaluate dose quantities for the spectra. Furthermore, efforts are being made to categorise the neutron spectra. This work will prove extremely valuable in the future for improving operational health physics monitoring in mixed radiation fields at work places in nuclear industries. It will also be of great value if ever modifications to the dose quantities are considered because it will be possible to evaluate the consequences in realistic radiation fields easily in advance.

A closely related and complementary approach has been taken by developing "realistic" neutron calibration fields. Using the knowledge on "typical" workplace spectra and applying the methods of computational dosimetry, radiation fields have been produced in the laboratory which represent with good approximation realistic neutron spectra by using suitably arranged materials in specific irradiation arrangements based on accelerator produced neutrons. The availability of such a calibration field instead of monoenergetic reference fields or Californium reference sources for general use in Europe would contribute towards reducing the uncertainties of neutron monitoring at work places and contribute towards the practical implementation of operational quantities.

The European integration of radiation protection dosimetry research and the expertise accumulated in previous years has been the basis for highly efficient work urgently needed for the implementation of the revised Basic Safety Standards as Member States adapt their national regulation and industries have to translate that into practical radiation protection monitoring. The practical importance and economic benefit of this research should not be underestimated. It is to be noted that the work performed here will also benefit potential future modifications of radiation protection regulation. The compiled data and methods are available for advance examinations of the consequences of rules and quantities. There will be very little, if any, need for further work in the foreseeable future. However, the expertise needed to use the data must be preserved.

Cosmic ray exposure of aircraft crews

It has been recognised for some considerable time that aircraft crew and passengers are exposed to elevated levels of ionising radiation of galactic and solar origin, and dose estimates were originally made more than 20 years ago. The general interest in this phenomena and the related risk and radiation protection aspects has increased in recent years for several reasons. Chief amongst them is that the ICRP has recommended that anyone exposed to doses which exceed the dose limit of 1mSv per year for public exposure should be considered to be occupationally exposed. The exposure to cosmic radiation exposure in the operation of jet aircraft is specifically mentioned. The revised EC Directive on Basic Safety Standards has adopted this recommendation.

Two different issues were addressed in the research work:

- Consolidation of the knowledge on primary and secondary radiation fields and the related levels of exposure inside aircraft.
- Consideration of methods and techniques for assessing and, if considered

necessary, monitoring of occupational exposure to cosmic radiation.

The radiation fields encountered in aircraft at altitudes exceeding 8km are very complex and include high energy protons and heavier ions as their primary component; and neutrons, photons, pions and muons as secondary radiation from interaction with the atmosphere and the materials of the aircraft itself. This complexity and the extremely wide range of particle energies extending to the GeV region explains why conventional radiation protection instrumentation is of limited usefulness for measuring radiation field parameters and dose quantities. Techniques developed for cosmic ray physics and high energy particle physics can provide useful information and some of the instruments used in conventional radiation protection dosimetry, suitably modified, have been used to carry out measurements in commercial aircraft on different flight routes, and as a function of altitude and geographical latitude, on top of alpine mountains, in accelerator produced heavy ion beams and in a high energy stray radiation field at CERN.

Some of the conclusions are:

- Measured dose equivalent rates depend on geographical latitude, increasing from the equator towards either pole up to a latitude of 50°, remaining approximately constant at higher latitudes. The increase for the high LET component is a factor 3-5 and for the low LET component a factor of 1.5-2.5.
- The total dose equivalent rates increase with altitude for all latitudes. For example, at 12km height the dose rate is approximately twice that at 9km.
- The variation of dose equivalent rate within aircraft is negligible.
- At latitudes of 50° and greater at normal flight altitudes, the relative contributions of high and low LET components of dose equivalent are roughly the same.
- The average quality factor for the total radiation fields is approximately 2.

Computer codes exist which allow the transport of cosmic rays through the atmosphere and aircraft materials to be calculated. The research work included such calculations and comparisons with measured data. The objective is to validate the calculations and the input data with a view to be able to calculate exposure as a function of flight routes and altitudes and of the solar cycle. At the end of the contract period there were still considerable discrepancies between the results of different computer codes. More detailed data, in particular on high energy neutrons, are needed for the validation.

The measurements in the high energy stray radiation field at CERN proved to be of particular importance. It is a dedicated facility, produced at the super proton synchrotron (SPS) by 120 GeV/c protons bombarding a target surrounded by massive shielding. Outside the shielding, the radiation field resembles those encountered at high altitudes. Since 1993, CERN has made this arrangement regularly available to experimenters for testing and, in fact, calibration of detectors and instruments. CERN has also specified the radiation fields based on calculations and measurements. In the frame of experiments coordinated by EURADOS, several joint measurements have been performed by investigators from 20 institutions.

The complex composition and the high particle energies of the radiation field are the reasons for the fact that measurements on board aircraft are non-trivial. Detectors may not respond to all radiation components and the quantity measured may not correlate

with the protection quantities in a simple way. Several passive and active detectors were investigated: activation detectors, nuclear track detectors, luminescence detectors, bubble detectors, bismuth detectors and stacks of detectors (passive); G-M counters, scintillation counters, ionisation chambers, TEPC and Rem-counters (active), amongst others. The measurements included spectrometry of neutrons.

Many of these detectors provide useful data for exposure assessments and comparison with calculations. The results have shown that individual monitoring of aircrew is not required and that dose assessment can be based on determination by appropriate computer programmes. However, regular validation of such data is suggested. Only aircraft flying routinely above 15km should have permanent monitoring equipment on board. Suitable instruments include TEPC, modified Rem counter and combinations of passive detectors.

The work in this area supported by the EC and other work carried out in the Member States was an essential input to a report on guidance for the implementation of the ICRP recommendation on aircrew exposure being prepared by a EURADOS Working Group on the request of DG XI.

The work in this area was prompted by the then forthcoming regulation and public concern. The coordinated efforts included specialists for cosmic-ray physics and dosimetrists carrying out relevant measurements as well as preparing recommendations based on the results. Although the uncertainty in exposure data could be reduced within the 3 year period of research, there are still discrepancies, most probably related to the high energy radiation, in particular neutrons. Further dedicated measurements at all accessible altitudes and combined with transport calculations are needed to validate the data. The achievements include the availability of a laboratory based realistic reference and possible calibration field at CERN. This will be of great practical importance for ensuring reliability and sufficiently low uncertainty for expensive on-board measurements. The recommendations developed for practical purposes are conclusive in establishing that permanent or indeed individual monitoring is not required. Flight routes and rostering and application of an appropriate computer programme is entirely adequate. This result is of practical and, with respect to aviation industries, of economic importance.

Environmental monitoring

In general, measurements of dose equivalent rates of external photon radiation in the environment reveal the background of natural radiation of terrestrial and cosmic origin. The monitoring of changes in the level of ambient photon radiation requires instruments and dosemeters which have adequate sensitivity as well as sufficient accuracy to record small variations. Such monitoring is the basis for assessments of the exposure of the general public to natural radiation and radiation due to releases of radioactive material during normal operations in nuclear industries. In cases of accidental releases, these measurements are part of the early warning systems. The instruments applied in this area of dosimetry are, in general, conventional, and include GM counters, ionisation chambers, scintillation detectors and TL dosemeters. The research work carried out during the reporting period was aimed at determining the performance characteristics of these detectors and integrating electronic dosemeters. The investigation included the

determination of instrument characteristics at ultra-low dose rates (at 1000 m below ground in a salt mine), the establishment and commissioning of standard calibration facilities for environmental radiation detectors, international intercomparisons of dose rate meters, the assessment of external photon dose rates in the vicinity of nuclear power stations and the development of new, highly sensitive TL materials for environmental radiations.

The main achievements and results were:

- The intercomparisons showed that the calibration of instruments agreed within 2.5% if radionuclide source calibration was used. There was good agreement between the instruments and, in particular, the TLD results showed good agreement with the results of active dosemeter measurements.
- Measurements in the ultra-low dose rate laboratory can be used to determine the inherent radioactivity of the construction materials of dosemeters and the linearity of dosemeters.
- Two natural environment measurement stations were established, one for terrestrial radiation at a field site within a national research centre and another for cosmic radiation on a wooden pier extending to some distance from the shoreline of a fjord.
- The photon dose rate in the vicinity of a nuclear power station due to reactor operation is composed mainly of two components: (a) a direct irradiation from the power station, predominantly originating from the high energy gamma rays (6 MeV) emitted by the ^{16}N nuclide in the cooling water. This dose rate is roughly proportional to the reactor power levels. (b) Photons originating from ^{41}Ar released from the reactor. At a given position and time, the dose rate depends on the wind direction blowing the ^{41}Ar plume.
- The applicability of hypersensitive TL materials for environmental monitoring has been demonstrated. Periods as short as 5 hours are sufficient to measure environmental doses with adequate precision.

The results of this work contribute significantly to the accuracy and reliability of environmental monitoring. This is also of relevance for reliable early warning systems for accidental releases of radioactive materials. The involvement of institutes in Eastern Europe in this work is of obvious benefit. The continuation of the efforts to coordinate this research in Europe, including Central and Eastern Europe, will evidently be of importance for the radiation monitoring of the general public and will make a significant contribution towards reliable early warning systems.

Conclusions

Modern radiation protection dosimetry is an integral part of a comprehensive concept for risk management with respect to exposure to ionising radiation from industrial, natural and medical sources. As such, it is involved in the development of such concepts as well as in the practical implementation. Introduction of quantities such as effective dose and organ doses, protection and operational quantities designed for optimum radiation protection are meaningful only if they can be applied in practice. European research in radiation protection dosimetry has had a leading role for almost two decades. The further integration of work through multi-partner contracts has consolidated this role

and was the basis for highly efficient work during the reporting period.

During the reporting period, a horizontal integration between the special disciplines of ambient and individual monitoring, spectrometry at work places and computational dosimetry has started. This successful integration of work needs to be continued and further developed.

In addition to assisting the implementation of legally required procedures, the results obtained are also of principal economic interest. For example, the reduced uncertainties in monitoring for occupational exposures justifies a reduction of the hitherto existing practice of over-conservatism with regard to exposure. As a consequence, industrial operations may be facilitated or shielding can be made to appropriate dimensions, contributing towards the reduction of costs. Another example is the forthcoming obligation of airline industries to monitor their air crews for exposure to radiation, a potentially costly responsibility. The coordinated work in this area efficiently produced new experimental results and provided, in collaboration with scientists funded by Member States, evidence that simplified, inexpensive monitoring by calculation is entirely adequate.

The combined expertise in radiation dosimetry exemplified by the research contracts in this sector is an efficient tool for assisting industry and legal authorities in meeting their regulatory obligations which needs to be maintained to support the coordination of work in Member States.

3.1.1.2 DOSIMETRY OF INGESTED RADIONUCLIDES

Exposure of workers or members of the general public to ionising radiation emitted from radionuclides incorporated into the body is, in general, quantitatively less well understood than exposure to external irradiations. The absorbed dose to organs and the whole body are determined by the pathway of incorporation (inhalation, ingestion, wound contamination), the physical and chemical properties of the carrier for the radionuclide being incorporated, and the combination of physiological, metabolic processes within the body transporting the radionuclides, including excretion, and the type and energy of the radiation emitted by the nuclide.

In broad terms, for a given type of radionuclide, the resulting exposure of a given organ will depend on the time the nuclides reside in the body and the distribution of the radionuclides within the body. It is obvious that the doses relevant for radiation protection in general cannot be measured directly. "Internal dosimetry" has to rely on the understanding and knowledge of incorporation pathways and mechanisms, together with metabolic processes and computational models for the assessment of organ doses and effective dose. Research in internal dosimetry therefore includes experimental work to study human and animal metabolism, and theoretical work to develop metabolic-dosimetric models. In particular, with regard to potential exposures of workers, the research work also addresses studies into the relationship between quantities which can be monitored externally (e.g. radionuclide concentrations in air or bioassays) and the dose evaluations.

Experimental studies

The dose evaluations for incorporated radionuclides are based on computational models. The uncertainties of the results are obviously strongly related to the uncertainties of the input data and the knowledge of the mechanisms. The associated problems are enhanced by the fact that:

- many of the relevant experimental data have been obtained with animals and are therefore of limited significance,
- there are known variations in these data between individuals in general, as well as systematic differences, for example, as a function of age or physiological conditions.

The research work focused on human studies, either with human volunteers, or using stable isotopes and applying highly sensitive tracer techniques. The transfer of some radionuclides of relevance in radiation protection into the human body via the food chain was investigated by experimental studies using stable isotope tracer techniques. After ingestion of the chosen stable isotope sample under well defined conditions, several sensitive analytical techniques were applied to measure the amount of isotopes of interest in tissue and excretion samples. Using the methods of proton nuclear activation analysis (PNA) and inductively coupled plasma mass spectrometry (ICP-MS) stable isotopes of the elements hafnium, molybdenum, barium, neodymium, strontium, zirconium and others have been measured in biological material. For most of the radiologically relevant radionuclides, stable isotopes of the same element exist. For actinides such as americium (Am), curium (Cm) and plutonium (Pu), however, surrogates have to be found which have to have very similar chemical, physiological and, for a given compound, metabolic behaviour. Considerable effort was spent on assessing elements belonging to the group of lanthanides with respect to their suitability as surrogates for actinides. Briefly, europium (Eu) and gadolinium (Gd) mimic the behaviour of Am and Cm sufficiently well for human studies. However, the most promising candidate to mimic Pu, hafnium (Hf) is only useful for studies of the absorption from the gastrointestinal tract and not for studies of the tissue distribution. Although the work is still in progress, it can be concluded that the approach taken provides valuable human metabolic data which cannot be obtained by other methods. The results to date have confirmed some of the recommended uptake to dose conversion factors, but they have also revealed significant differences in others.

Human volunteer studies were carried out, for example, to determine physiological parameters for respiratory tract modelling (ventilation and breathing modes, nose and mouth breathing, dependence on age and ethnic origin) to measure relevant parameters for the deposition of inhaled radionuclides in the respiratory tract (by aerosol inhalation) and for the clearance of radioactive material deposited in the respiratory tract (inhalation of boluses of microscopic polystyrene particles). There were also studies with rats. The large number of different experiments carried out illustrates the large number of parameters influencing the metabolism of incorporated radionuclides and the complexity of the overall problem. The solution of the problem requires a comprehensive and systematic investigation of the mechanisms and parameters, including their variability, so that realistic and reliable dose calculation models can be made available. The experimental work carried out under this programme has again delivered a wealth of new

and coherent data which has enabled considerable progress to be made in the metabolic-dosimetric models and the efficient implementation of practical approaches to internal dosimetry.

Modelling internal exposure

Earlier work to develop and implement metabolic-dosimetric models was extended with a view to achieving more realistic models for dose estimation following intakes of radionuclides by workers and the general public, including doses to the embryo and fetus from maternal intakes. As another objective, the work also aimed at addressing more important uncertainties in the biokinetic and dosimetric models used in radiation protection.

Literature data and recent results in experimental studies, as well as results from studies of biokinetic behaviour of caesium and strontium following the Chernobyl accident were reviewed. One focus was on the characterisation of systemic behaviour of various elements, another on the kinetics of the gastrointestinal tract and their dosimetric implications. The gastrointestinal tract and urinary bladder have become more important for dosimetry following the ICRP recommendation on their respective tissue weighting factors. The excretion pathways therefore were included in the biokinetic models. A first version of a new gastrointestinal tract model has been developed.

The reliability of calculated doses depends on the knowledge of the sources of uncertainties of models and parameters. In addition to experimental studies, relevant in this respect, a systematic analysis of so-called f_1 values (fraction of activity transferred from the gastrointestinal tract to the systemic circulation) was performed. This also included the uncertainties related to the extrapolation from animal to man. An alternative method to study uncertainties under development is the use of the stochastic model instead of the conventional deterministic approach.

Two institutions independently developed codes to compute age dependent dose coefficients using the most recent biokinetic data and ICRP dosimetric models. Together with an existing code from the USA, the three independent codes offer the possibility for quality control. Intensive intercomparisons between the three groups and a further group in the Ukraine provided the possibility for quality checks of the data for several of the recent ICRP publications on dose coefficients.

Implementation of research results in practical use

The practical implementation of the recently adopted revision of the EC Directive on Basic Safety Standards also requires the appropriate data and procedures for internal dosimetry and monitoring. ICRP itself has taken the initiative by forming task groups to address various issues in this respect. Many of the scientists participating in the research work described here are actively involved in one or more of such task groups.

The current rapid development in internal dosimetry is transferred efficiently to the work of the task groups and included in the reports prepared by them. In recent years, ICRP has published six reports related to internal dosimetry (most prominently the ICRP

Respiratory Tract Model - ICRP Report No. 66) and more are in preparation. The close interaction of researchers involved in the EC Radiation Protection Research and ICRP working groups and task groups ensures that the scientific results are being included in (in fact, in several cases are the basis for) the development of recommendations and implementation of regulation. Considering the urgency with which solutions are needed for some problems in internal dosimetry, this appears to be an effective way to avoid unwanted delays. However, this approach also bears the danger that scientific results are used in a regulatory context without sufficient validation.

The implementation of new regulations and recommendations also requires practical tools for health physicists. A part of the effort on model development went into creating PC versions of codes to calculate doses, for example after inhalation. There was also a modest effort to develop instruments for monitoring intake by inhalation at work places.

As in research for external dosimetry, the high level of integration of research in internal dosimetry is the key factor for the impressive results obtained during the reporting period. Again, in this case there are two types of integrations: the collaboration of scientists on one research subject such as research using stable isotope tracers in humans and the close interaction between experimentalists and modellers. This has ensured that the transfer of scientific results into practical use was very efficient. While this approach leads to cost-efficiency in using limited resources, scientifically there is some cause for concern. The distribution of tasks avoids doubling of work but validation of results and data is difficult.

The results of the work have contributed significantly to extensive new recommendations and data for practical purposes, usually in terms of ICRP reports. An important example is the new ICRP Respiratory Tract Model, another the development of a new model for gastro-intestinal tract.

There is further need for human metabolic data for radionuclides of relevance with respect to potential occupational exposures as well as exposures of members of the general public after normal or accidental releases of radioactive materials. Priority should be given to the investigation and, if possible, the reduction of the uncertainties in the models. A further aspect for future research in this area is that integration must be improved with research in radioecology on transport of radionuclides through various pathways, including the food chain.

3.1.1.3 PHYSICAL METHODS OF RETROSPECTIVE DOSIMETRY

The work in this area has brought together within one research contract several experimental methods for retrospective assessment of radiation doses in populated areas following a radiation accident. The main methods were the application of:

- luminescence techniques with ceramic and some other natural, generally abundant materials
- Electron Paramagnetic Resonance (EPR) techniques with tooth enamel.

Both methods have to be integrated with computational modelling for comparisons and interpretation of measured values in terms of relevant dose quantities.

By virtue of the nature of the materials sampled, the two experimental approaches have different roles to play in retrospective dosimetry. The luminescence method is based on the use of crystalline materials such as quartz, feldspar and certain carbonates extracted from ceramic materials which are natural solid-state dosemeters. This class of materials includes brick, tile and porcelain and consequently has specific application to buildings and their contents, but may also include, for example, porcelain artifacts from telegraphic and power distribution networks. From the perspective of dosimetry, one of the key points concerning the application of the method is that it provides evaluations of accumulated external gamma dose at various points in fixed structures within a populated area. The method determines integrated dose to the material sampled, and this includes sources of natural radiation.

The method was originally applied in archaeological dating and much experience exists, mainly for ceramics. The suitability of other materials has been investigated within the framework of this research. Porcelain, in particular, was established as a useful and sensitive material which can be found in a range of locations inside and outside houses. Other materials including sugar, limescale, egg shells, chalk and baking powder were investigated using luminescence and EPR methods; the lower limits for dose evaluations are, however, generally in excess of 0.5 Gy.

The technical development of this method included the use of optically stimulated luminescence (OSL) as a complement to the more conventional thermal stimulation (TL), the measurement of depth dose profiles in brick and porcelain, the development of sophisticated instruments for the semi-automated luminescence readers specifically designed for use in retrospective dosimetry.

On a number of field trips, materials were sampled which were exposed to increased levels of radiation due to fall out from radioactive materials following the Chernobyl accident. A standard procedure to evaluate the exposure due to the radiation above background, including that previous to the fall out, has been developed. The accuracy of the method is approaching a level which is adequate to provide benchmark values for modelling calculations. Together with such calculations, the luminescence technique has the potential to provide reliable data for exposures in contaminated settlements.

In terms of dose assessment for people, a step closer to determining dose received by individuals is achieved by the use of EPR. Tooth enamel comprises predominantly a crystalline mineral (hydroxyapatite) which serves as a solid-state dosemeter material. EPR has been used in the past for such determinations, but only in cases of acute dose. The focus in this area of research has been to investigate means of extending the working range to levels of dose as low as 300 mGy and to identify factors which may affect reliable evaluations of dose in typical tooth samples. The organic fraction within the enamel structure provides an intrinsic EPR signal which interferes with the dose-related signal in enamel samples and has been the subject of extended investigation.

The development of this technique concentrated on optimisation of sample preparation and the understanding and reduction of background signals. The use of chemical treatment to eliminate organic components, of appropriate mechanical grinding methods and mathematical methods in EPR signal analysis have led to a significant reduction in

the background signal. Evaluations of dose levels of approximately 100 mGy have been shown to be feasible. Confounding factors such as exposure to UV radiation and mechanical grinding have been identified and are being investigated.

During the final two years of the reporting period, the work in this area was extended by contracts in the framework of cooperation with the three Republics - Belarus, Russia and Ukraine. This gave the opportunity for direct collaboration with scientists and institutes involved in work in all areas affected by the Chernobyl fall-out. Field trips to the 30 km exclusion zone and contaminated settlements in all three republics provided realistic sampling conditions. The range of work was extended to methods for retrospective thyroid dosimetry using I-129 concentration measurements in soil samples and model calculations for external irradiations using data on surface contamination. Preliminary efforts were made to harmonise experimental techniques. As an example, a first international intercomparison of evaluating doses for tooth enamel by EPR was performed revealing several pitfalls in the use of the technique.

The progress achieved in the relatively short reporting period is remarkable. The luminescence technique has proved to be useful in particular cases, such as contaminated settlements. At present, EPR of tooth enamel is the most promising method for individual retrospective dosimetry with an acceptable detection limit of 100 mGy. Calculational methods have been developed which can use a variety of input data including questionnaires for individuals on dietary and other habits. The availability of these methods for large scale investigations, for example, in the context of epidemiological studies is, however, still restricted. Further research is needed to investigate and reduce uncertainties (in particular for EPR) and to standardise the methods so that their application is less labour intensive and can be executed by technicians. In addition, the correlation to other methods of retrospective dosimetry has to be studied, in particular to the methods of biological dosimetry, including the FISH technique.

3.1.2 TRANSFER AND BEHAVIOUR OF RADIONUCLIDES IN THE ENVIRONMENT

INTRODUCTION

The current definition of radioecology is generally accepted to be the study of the interaction between the environment and radionuclides. The definition includes the word "interaction" alluding to the impact of the environment on the geographic and physico-chemical fate of the intercepted radionuclides and to the open and dynamic structure of the environment as such. The significance of this is that ecosystems are never in a real equilibrium but only acquire their ecological stability and economic value by being in continuous development. Radioecological research in the Programme has consequently undergone a gradual transition through the Third Framework programme from concentrating on a static environmental situation to a more global approach to take the dynamic aspects of the changing environment into account.

Radioecology is a discipline that is embedded in the frame of the protection of man against harmful effects of radiation. It derives from two interconnected objectives which are the prediction of dose to man from radioactive contamination and the restoration of the contaminated environment.

The objectives of radioecology are, thus, closely connected to the definition although they have, of course, been strongly influenced by the experience gained from the evaluation of consequences that major nuclear accidents have had in altering the quality and practical usefullness of the affected environment. These objectives can be summarized as follows:

- to understand and quantify the factors which determine the fate of radionuclides in the short, medium and long term following the deposition of released radionuclides
- to allow the calculation of the dose man can incur from using his contaminated environment
- to provide methods for the mitigation of the consequences of an accident
- to restore the affected area while maintaining its ecological and economic "value".

In the programme a number of different ecosystems have been investigated by means of a set of dedicated projects which cover the terrestrial ecosystems including agricultural systems with their specific land use and animal production systems; semi-natural ecosystems considering forested regions and semi-permanent pastures; as well as aquatic systems, divided in freshwater ecosystems made up of rivers and lakes, fed by their own catchments areas; and marine ecosystems.

3.1.2.1 TERRESTRIAL ECOSYSTEMS

Basic studies of physico-chemical and biological interactions between radionuclides and ecological compartments

The project on the bio-availability of long-lived radionuclides in relation to their physico-

chemical form in soil systems has concentrated on the processes governing the availability of long-lived radionuclides in soil to biota. It is now generally assumed that the concentrations of radionuclides in soil solution are representative for the quantity that can be absorbed by animals or plants. That is why it has been important to identify the key parameters which determine the equilibrium between the solid phase and the liquid phase of the soil, the effect of measures on this equilibrium and the time-dependent changes of this distribution.

The fate of radiocaesium is defined by the fixation capacity of soils, which is determined by the Cation Exchange Capacity (Regular Exchange Complex = REC) and by its specific absorption sites, called Frayed Edge Sites (FES). In soils with a sufficient clay Caesium is entirely bound to these FES, for which a simplified and inexpensive quantification method has been developed. In soils with high organic content, however, Caesium is almost entirely reversibly bound to the REC. These organic soils are problem soils as they maintain a persistent bioavailability for Caesium. The mechanisms of fixation and release of the caesium are not fully clarified yet, although vulnerable areas can be identified, from the point of view of "bio-availability", on the basis of the existing knowledge. For Strontium sorption processes are instantaneous and no aging effects are to be expected in soils.

Potassium (K) is an "analog" for caesium (Cs) and can be used as soil treatment to reduce the caesium uptake by plants. Its efficiency has been found to depend on the soil type and agricultural practices. In organic soils, with no potassium saturation, the application of potassium can effectively reduce caesium uptake. In mineral soils with a high clay content potassium was shown to be barely effective and could even increase the Cs/K ratio leading to increased uptake and could, thus, potentially enhance the dose through the food chain. Elements like silver, americium and plutonium have a behaviour which is entirely dependent on the organic matter concentration and type of soil.

The relation between soil chemistry and uptake of radionuclides by different flora has been found to depend, to a considerable extent, on variations in the uptake and transfer factors in different species. Uptake models which have been developed to explain these differences include plant characteristics, such as growth rate and root surface of a plant, and take account of the dynamics of other key ions at the absorption sites which is, of course, dependent on the soil characteristics. As a consequence the effect of K on Cs uptake by plants was shown to depend on the fine tuning between the interaction between Cs and K at the absorbing surfaces of the soil and absorbing surfaces of the plant. The balance between these interactions determines whether K will effectively reduce the availability and uptake of radioactive caesium and, thus the dose, or not. *It will be necessary to make this type of fine tuning for every contaminated soil type before any decisions on effectivness of potassium treatments can be taken. Various conceptual models have been developed in order to be able to make such a fine tuning which have eventually be summarized in a more formalised mathematical model.*

The transfer of radionuclides in animal systems has been investigated in a number of projects to provide improved information on the metabolism of ingested radionuclides and, thus, enhance the ability to predict contamination levels in animal products under different conditions.

Both basic aspects of the transfer of radionuclides in the Gastro-Intestinal Tracts (GIT) of different animals and practical aspects of transfer in animal production systems have been investigated and quantified. The True Absorption Coefficient (TAC) of mobile radionuclides was determined in order to provide a physiological parameter which is more related to mechanisms of uptake than transfer factors. In addition, the physiological and environmental factors which affect the transfer of radionuclides to animal products have been identified and quantified.

In the case of radiocaesium a True Absorption Coefficient of 0.8 has been determined for sheep for ionic radiocaesium or that incorporated into plant material, with reported values ranging between 0.6 and 1.0. Measurements conducted within this programme suggest that a suitable recommended value for dairy goats would be close to 1.0. The measurement of True Absorption will be a powerful tool to estimate bioavailability in the case of possible future releases of radiocaesium.

Investigations have been made to find out whether it is possible to generalize models of radiocaesium behaviour in ruminants instead of developing a separate model for each different ruminant. A model developed for the transport of trace elements in animals relates the transfer coefficient $f(k)$, to any compartment k of an animal, to the feed-to-blood transfer coefficient $f(blood)$ by the simple expression

$$f(k) = a(k)f(blood)$$

in which $a(k)$ is a constant, independent of animal size or diet.

Similarly models, which were previously not applicable for sheep of different weight, have been reparameterised so that radiocaesium transfer between compartments is driven by activity concentration rather than total activity. This modification has led to a more generally applicable model that can be used to predict radiocaesium transfer in sheep with a wide range of body weights. However, experiments have shown that physiological status and feed intake rates can influence radiocaesium levels within tissues and this model still requires further development as it does not yet incorporate these effects.

Fate of radionuclides in agricultural ecosystems, mainly animal production systems: consequences for dose to man

Mechanistically based models of the transfer of radiocaesium, radiostrontium and radioiodine to food-producing animals (ruminants and poultry) have been developed with the aim of being able to take the effectiveness of countermeasures, stable element status and the influence of physiological parameters into account.

Previously published models for radioiodine behaviour in ruminants incorporate the effect of stable iodine dosing by reducing thyroid uptake rates which, consequently, increases the proportion of radioiodine which will secreted into milk. Such models, however, can not be used to predict the subsequent radioiodine output into milk. A revised model for goats has been developed which includes a saturation mechanism for the transfer of iodine from ExtraCellular Fluid (ECF) to milk which can be used to predict the effect

of using stable iodine administration as a countermeasure. The combinations of experimental and modelling studies have increased our understanding of radioiodine metabolism and countermeasures in ruminants leading to models that are better able to predict the effect of possible countermeasures. A clear conclusion is that stable iodine used as a countermeasure would be most effective if administered shortly before contamination.

The transfer of radiostrontium to ruminants is dominated by calcium metabolism and relationships between Ca intake rate and F_m, the tranfer factor to milk, have been defined. New models have been developed to account for the dependence on calcium as existing models were inadequate.

In conclusion good progress has been made and the animal transfer research has developed a new, more mechanistally based method for the measurement of transfer of radionuclides from the gastro-intestinal tract to blood, muscles and milk by measuring the True Absorption Coefficient. This has made it possible to carry out mechanistically based investigations on the fate of radiocaesium, radiostrontium and radioiodine and to search for the setting of adequate countermeasures of the above target tissues.

Fate of radionuclides in semi-natural Systems, forests and semi-permanent pastures: contribution to the dose to man

The focus in this section has been on evaluating the importance of semi-natural ecosystems as a source of radiation exposure to man by means of both experimental and modelling studies. First, experimental investigations of potentially important parameters which could govern the behaviour of radionuclides in these typical ecosystems were carried out, secondly, the acquired data was modelled, and finally an assessment of the possible dose to man from these ecosystems was made.

Forest sites in Europe have been systematically investigated and the results from different types of forest growing on different soils and under different climatic conditions have been compared. As a result of this cooperation, the knowledge of basic principles governing the behaviour of radionuclides in natural ecosystems was considerably increased. The basic mechanisms concerning ^{137}Cs migration in soils, its uptake by fungi and plants, its transfer to animals, and its cycling within forest ecosystems are all rather well understood now. Data sets have been obtained which are useful tools for site-specific long-term prognosis and helpful with respect to recommendations and considerations of countermeasures. In conclusion, the understanding of radionuclide behaviour in forest ecosystems was significantly improved. It should be realized, however, that it is still difficult to define and develop advanced explanatory models which are suitable for forest sites in general. These difficulties are due to the great complexity and wide variations in the nature of the different forest systems. To be more successful, more detailed investigations of the peculiarities of soil, plants, and animal species and of the corresponding parameters, which have been recognized to be of general importance, are required.

The vertical migration of radiocaesium and radiostrontium from plant to soil surface and in different soil layers has been investigated and the results show that the radionuclides

intercepted by the forest canopy reach the soil by mechanisms such as stemflow, wash-out and litter fall. Once in the soil a horizontal redistribution of the radionuclides occurs via transfer through mycelia of fungi (mushrooms) and accumulation in their fruit-bodies. Radiocaesium and potassium concentrations in different compartments of forest litter (leaves, needles, twigs, and seeds), their retention, and the influence of different ecological and climatic conditions on the amount of leaf and litter production have been analyzed. Seasonal amounts of litter-fall and the associated fluxes of radiocaesium have been assessed. The levels of radiocaesium arising from litter-fall have been compared with those arising from transfer through vegetation to the soil surface via ingestion by animals such as moose and rodents. Both levels appear to be comparable. Root uptake by trees becomes the dominant pathway a few years after the original deposition and there is the suggestion that ^{137}Cs migrates from the canopy to the soil surface in about 4 years.

The study of the vertical migration of radiocaesium and radiostrontium in different soil layers, has shown that the organic soil layers play a dominant role in their retention. In order to quantify the phenomena a compartmental model, representing the different horizons such as litter (OL), fermentation layer (Of), humus layer (Oh), and mineral layers (A and B) of the soil profile, was developed. The ecological half-lives, calculated from this model, suggest a stronger binding of Caesium with increasing depth.

Ecological groups of flora growing on the forest floor under the leaf canopy, the understorey, were identified and the relation between the contamination patterns in the different flora species and their ecology was established. The seasonal fluctuations of radiocaesium content in these different plant species was studied, together with the dependence of the ecological characteristics of the forest ecosystems on soil parameters and the influence of soil parameters on the transfer rates from soil to the different forest floor plants. A clustering principle can be detected such that the radiocaesium content is found to be the highest in plants whose root systems occupy the upper soil layer of acidic humus and is lowest in deep rooting plants of the forest clearings. The problem of competition between Cs and K in this ecosystem has, unfortunately, still not been resolved completely, although this may arise from a lack of adequate biological-mathematical rigidity in the research approaches.

The analysis of uptake mechanisms for caesium in different groups of mushrooms growing in different habitats revealed the gradual, but essential, difference between the existing categories of fungi where a much higher (»10 times) transfer to symbiotic species than to the saprophytic or parasitic species has been found. In order to understand the different uptake within each group, the locations of the mycelia in different soil horizons, an additional relevant parameter, were investigated. A newly developed ingenious method making use of the variation of the $^{137}Cs/^{134}Cs$ ratio with horizon level has been used to locate depth of the mycelia for 14 fungi species. The transfer factors from soil to mushrooms have been calculated taking into account the specific ^{137}Cs activities of those layers where the mycelia are located. The transfer factors calculated for 14 different species vary between 0.4 and 25.8, where the lower values are associated with saprophytes and the higher ones with mycorrhiza fungi. These transfer factors remained virtually constant over the period between 1987 and 1994. Mushrooms were found to be only slightly contaminated with ^{90}Sr.

In order to understand the wide variations in ^{137}Cs contamination of moose and bank voles, ^{137}Cs levels were measured in plants and animals from boreal forests. The range of plant species consumed varies greatly among herbivore species, both seasonally and annually and, even when the composition of diet is known in some detail, significant variations of intake rates and gut absorption are still present due to differences in the ability of the animals to digest the different plant sorts.

Sensitivity analysis using mathematical models of radionuclide transfer within ecosystems has consistently shown that the initial inputs to the system in the form of dry and wet deposition events are of major significance. The magnitude of the contamination found in the ecosystem is defined by the deposition processes which determine the transfer from a given atmospheric concentration in the boundary layer to the ecosystem taking account of the atmospheric diffusion of contamination plumes. Hence, the sensitivity analysis shows that for a successful prediction of dose in the short, medium and long-term it is essential to be able to quantify these deposition processes reliably and that deposition of radionuclides in forest ecosystems which occurs largely to the tree canopy itself, depends on a variety of factors such as tree type and seasonality and the relative interception of the deposit by leaves, needles, twigs and branches. In addition to the processes of deposition there are a variety of mechanisms and pathways which control the fate of the deposit in the short and long term. Any radioactive deposit penetrating the canopy will contaminate the underlying leaf litter and the floor growing plants, thus providing a direct contamination of the forest floor and its associated vegetation. These processes include resuspension of the deposit, which is likely to be strongly time dependent, and loss of initial deposit from tree surfaces by weathering. It has been found that the latter process provides an additional source of contamination to the litter layer on the forest floor to the extent that after 6 to 12 months following the initial deposition event more than 70% of the radionuclide inventory may reside in the litter layer. An thorough understanding of the transport processes within and below this litter layer is clearly essential for predicting the fate of radionuclides in the forest.

The rate and magnitude of all the above mentioned processes are determined by the physico-chemical form of the depositing radionuclides, and in this respect the Chernobyl accident, viewed in the context of both near-field and far-field effects, provided a particularly complex and, therefore, problematic situation. Deposits were found to consist of both sub-micron aerosols and larger 'hot particles' which were formed of either condensed volatile elements such as ruthenium or of discrete fragments of irradiated uranium oxide fuel with the associated fission and activation products. In order to investigate the physical movement of contamination in the forest ecosystem experimental techniques have been developed, such as novel methods for generating uranium based aerosols at high temperatures similar to those experienced within the reactor during the Chernobyl accident. These aerosols have been characterized using a variety of physico-chemical methods and have been used to determine the leachability of individual radionuclides contained within the UO_2 matrix and their flux rates in isolated branches of trees. With similar aerosols, dry deposition velocities in complete model canopies have been determined using a wind tunnel. Resuspension, weathering under ambient conditions and the effects of forest edges on deposition rates were quantified. The rate of vertical transport of thermogenerated aerosols also has been studied.

A site- and system- specific steady-state model has been developed for an experimental site located at Tarvisio, Italy. The model is split into two submodels, one for the proper calculation of ^{137}Cs cycling through the compartments of the ecosystem and the other to estimate variables and functions related to the uptake of radionuclides and their turnover via the vegetation pathways (foliage production, leaf area, etc.). In comparison with other radioecological models, some new aspects have been included, such as vegetation growth by photosynthesis. The model has been validated by simulating a deposition event which showed that, in general, the model gave good agreement with experimental data for the forest system chosen and time range considered. Another explanatory model was developed for a boreal site in Sweden. This model is focused on redistribution patterns with a long-term perspective, and the major regulators of energy flow, as well as of ^{137}Cs turnover, are related to primary production and its constraints on growth capacity. This approach inherently makes it possible to describe natural ecosystems in different geographical latitudes by using different growth functions. Certain fundamental processes governing the metabolism of living matter in the biotope are also taken into account and the turnover of Caesium is described by first order kinetics. The calculated time-dependent change of ^{137}Cs content in perennial vegetation has been compared to that actually observed at different localities.

The potential pathways of radionuclide transfer to man have been identified and prioritized in Sweden and in Denmark. The total mean content of ^{137}Cs in the system was 54 kBq m^{-2}. Data show that approximately 87% of total fallout is in soils, 5.5 % in the moss layer and 7% in the standing biomass of trees. Actual concentrations of ^{137}Cs in individual samples of fungi and ruminants were considerable and frequently exceeded the concentration limit of 1500 Bq kg^{-1} for consumption of wild produce which applies in Sweden. The data also demonstrate that in those countries only a small percentage of total fallout enters into food produce, that the standing crop of food produce is low, but that it may contain concentrations of radioactivity that give cause for concern. In Sweden, the three main pathways of radioactivity from the forest ecosystem to man are through the consumption of game, berries and mushrooms. The total time-integrated dose commitment from this source to the population is estimated to be between 5000 and 6000 manSv.

In order to assess our understanding of the relative dose contributions of various radionuclide pathways, after many years of radiolecological research, a system is being developed, which is capable of evaluating the level of importance and the state of knowledge of the variables which define the transport of radionuclides to man. Because of the relatively limited knowledge on semi-natural ecosystems compared to agricultural environments work has been concentrated on these ecosystems. The "critical group" associated with semi-natural systems was identified as that group of persons leading a life-style of self-subsistence, characterized by the consumption of entirely self-collected or self-produced food stuffs. When the relative importance of radionuclide pathways are being investigated it is necessary to characterize both the environment under consideration as well as the target group within a population which is expected to suffer from the highest exposure. In the normal approach, which assumes an agricultural environment as the main source of all food products, the definition of the "critical group" is well established, and apart from variations in the diet composition and in the occupational and recreational habits, is generally accepted and believed to cover both

rural and urban populations. It has to be noted, however, that in a given environment, human behaviour and the diet composition strongly influences external and internal exposure.

The sustained effort in this field, which had been almost totally neglected or ignored before this programme started, has brought a wealth of data on the interception and migration of radionuclides in forests and meadows, has stimulated modelling exercises, and has led to an approximative assessment of the contribution to the dose to man from this type of ecosystem. Similar research in the context of the Chernobyl projects has intensified and accelerated the acquisition of insights and information. This research has emphasized the need for a due consideration of the contribution of the semi-natural ecosystems to the dose to man. Their complex ecological land cover and land use has been the dominant incentive to adopt the use of Geographical Information Systems for spatial and temporal analysis of radionuclide behaviour.

3.1.2.2 RADIOECOLOGICAL ENGINEERING

Rehabilitation of contaminated areas has been described above as one of the four objectives of radioecology (see Introduction to 3.1.2). In most of the radioecological projects this objective has been taken into consideration as an obvious part of the research. Special attention has, however, been paid to the fate of "hot particles" deposited on vegetation and soils, as they occur in abundance in the near field of a nuclear accident. In order to carry out this study special types of radionuclide release and deposit experiments are being made under rigidly controlled experimental conditions using a specially designed facility.

Studies of methods for the rehabilitation of soils and surfaces after a nuclear accident (RESSAC) in a large climate controlled lysimeter installation have been made using well-characterized Western-European soils and agricultural crop production rates. This facility permitted the fate of special thermo-generated radioactive aerosols to be investigated under controlled conditions. Aerosol deposition on bare soils was compared with the deposition on plant covered soil surfaces and it was found that the surface roughness of both the soil and plants enhanced the deposition rate. The interception of the aerosols by plants depends on the species and on their developmental stage. Subsequent wash-off experiments using simulated rain showed that caesium is washed-off wheat at twice the rate of strontium and the wash-off factor for peas was higher than for lettuce, as the shape and surface morphology of both species are different.

Transfer factors were determined, using the facility, and different agricultural practices were tested to investigate their effects on the reduction of the contamination. Normal ploughing of wheat contaminated at an early growth stage followed by resowing has no effect on Caesium levels and an adverse effect on strontium transfer. Addition of cow manure (organic matter) to the arable soil layer decreased the transfer factor of ^{137}Cs to barley grain although in clover, this organic matter addition had no effect on Cs transfer, whereas Sr transfer could be reduced by a factor 3. The transfer factor depends, of course, on the soil type, and is proportional to its fixing capacity which is mainly dependent on the clay content.

3.1.2.3 AQUATIC ENVIRONMENT

Fate of radionuclides in fresh water ecosystems: consequences for dose to man

The objectives of a project set up to develop a functional model of radionuclide transport in freshwater systems are, firstly, to measure the rates of diffusional transport of radionuclides from water to bottom sediments, the mobility of radionuclides in the bottom sediments and their remobilisation from the contaminated sediments, and secondly, to develop mechanistic concepts and models for radionuclide uptake in aquatic organisms based on a fundamental appreciation of the chemical and biological processes involved.

The distribution coefficient (K_d) is a fundamental parameter in mathematical models of radionuclide transport in aquatic systems with measured values in the literature ranging from 10^2 to 10^5. This wide range means that the use of an estimated K_d is very prone to error. Previous work has shown that for radiocaesium the selectivity of the so-called Frayed Edge Sites (FES) on illite particles is so high that these sites define the sorption of caesium, even in mixed mineral systems. Under aerobic conditions K^+ is the major competing ion for these specific sites and under anaerobic conditions NH_4^+ competes.

A detailed set of measurements of K_d valuess in sediment cores taken from a number of locations, such as Hollandse Diep, Esthwaite Water etc, has confirmed that the ion-exchange equation is valid over a wide range of ammonia concentrations: a very good relationship is seen between the logarithm of the ammonia concentration and the logarithm of total diffusion coefficient K_d. A similar plot of exchangeable (ie. ammonium extractable) K_d however, which should, according to the fixation theory, be a better estimate of the field K_d, has been found to give a much lower correlation. This suggests that, contrary to expectation, over the time scale of years, the total K_d value is a better predictor of Cs mobility than the exchangeable K_d. A study of the properties of sediments taken from river waters has shown that the Cs concentration on the solid was a linear function of the proportion of fine silt and the percentage of organic matter, ie. the K_d increased with increasing fractions of fine silt and organic matter. On the basis of the FES studies it appears possible to predict values of radiocaesium K_d after short equilibration times. Following a fallout event, however, caesium slowly moves to less available sites on the solids, a process commonly known as "fixation". It appears, that the fixation of ^{137}Cs is not a truly irreversible process. Short term (days after contamination) laboratory experiments can give a measurement of that fraction of the radiocaesium which is available for transport and uptake by biota on a similar timescale. On longer timescales (years-decades), however, it is necessary to take account of the slow movement of ^{137}Cs to and from "fixed" sites.

A model based on the advection-diffusion equation has been developed to determine the fate of radiocaesium in the bottom sediments of lakes and rivers. In many freshwater systems the bottom sediments act as an important sink for radionuclides since activity in the water column accumulates in the sediments via the settling of suspended particles or direct diffusion across the sediment-water interface. Earlier work on freshwater physico-chemistry had shown that radiocaesium may be remobilised from bed sediments, particularly when sediments become anoxic, resulting in high ammonium concentrations.

The model takes account of changes in short-term K_d as ammonium concentrations change down the sediment profile, as well as the long-term movement of activity to and from "fixed" sites. Model predictions showed that *remobilisation* of activity sediments resulted in loss rates of around 2.5 % of the sediment inventory per year shortly after, for example, the Chernobyl fallout, decreasing to around 0.15 % per year 30 years later. In order to fit the observed field data, it was necessary to include a rate constant for transfer of activity from the fixed phase. The value of this constant derived by fitting the model gives a half-life for this process of around 10 years, lower than, but of the same order of magnitude as the experimentally determined value.

Radionuclide uptake depends on the biological availability of the radionuclides in the environment and the membrane systems involved in the uptake of the radionuclide by organisms. To model the effects of environmental conditions on the chemical speciation of radionuclides a model has been developed which permits the activities of radionuclide species in aquatic environments to be calculated taking into account the effects of changes in ionic composition and complexation capacity on the behaviour of the radionuclides in the environment. The model has been used to predict the effect of changes in water composition on the biological availability of radionuclides. Much of the variation in bio-availability is explained when uptake is expressed on a free metal ion activity scale rather than a total metal activity scale.

A study has been made of the influence that key environmental conditions have on the uptake of Cs by some water plants and as expected caesium was taken up by a potassium transport mechanism. As a consequence of this study a mechanistic model was constructed which can be used to predict the Cs concentration factors in freshwater plants as a function of potassium concentration in water. The effect of environmental conditions such as dissolved organic carbon, water ion composition and temperature have been determined in experimental food chains for a variety of conditions. The experiments provided essential information on the long-term accumulation kinetics and relative importance of water and food at different trophic levels.

Progress in this area has been most impressive. The models developed during the research programme provide truly mechanistic descriptions of the processes and can be used to model the long-term behaviour of radionuclides in aquatic food chains under combinations of conditions that have not been studied experimentally. The results obtained prove that it is possible to integrate the different models into one robust system that can be used to predict the fate of radionuclides in entire food chains.

Fate of radionuclides in marine ecosystems: consequences for dose to man

The overall objective of the project on mechanisms governing the behaviour and transport of transuranics (analogues) and other radionuclides in marine ecosystems was to identify the basic mechanisms and define the key parameters governing the physico-chemical speciation, vertical and horizontal mobility, biological magnification, incorporation to seabed sediments and ultimate fate of transuranium and other long-lived radionuclides in the marine environment. This was done to derive high-quality data of a universal character for use in the development and validation of predictive models based on fundamental mechanisms rather than on simple box-model approaches. It is

expected that the mechanistic models will be more likely to yield realistic predictions upon which sound decisions can be made, particularly when applied to situations involving accidental releases under unforeseen conditions.

The successful completion of these projects has led to a significant improvement in the overall understanding of radionuclide behaviour in the marine environment. Discharges of radionuclides from the spent nuclear fuel reprocessing plants are one of the major sources of radioactive contamination of the shelf seas of north-west Europe. The nuclides which have been examined include ^{99}Tc, ^{90}Sr, ^{137}Cs, $^{239,240}Pu(IV)$, $^{239,240}Pu(VI)$ and ^{241}Am and the characterization of the physico-chemical form of the more important radionuclides in the mean effluent streams has been found to be essential. In certain cases, significant fractions of the nuclides were found to be in a colloidal form. The presence of hot particles in Sellafield effluents has been well established and these hot particles could account for up to 10% of the Pu in sediments in the surface water, as they persist in the marine environment for some months before dissolving. A detailed examination of physico-chemical speciation of Pu and Am in the western Mediterranean water column and in coastal waters near the site of the Palomares accident has been carried out. In addition to being invaluable for the elucidation of the basic mechanisms governing the behaviour of Plutonium in the Western Meditterranean, these data represented an important addition to the database of radionuclide concentrations in this zone, which, when combined with conventional oceanographic data, have been used to determine radionuclide residence times and inventories, and to characterize the different water masses in the Western Meditterranean. The geochemical association of plutonium and americium in sediments was examined in the samples from the continental shelf near Palomares. Significant findings include the observation that, while fallout Pu from weapon tests is mainly associated with organic mater and sesquioxides, refractory Pu and Am from the Palomares accident appear in the residual fraction. Am from weapon tests is mainly associated with the organic and exchangeable fractions. The influence of orography on the relocation of the transuranics and, specifically, the role played by submarine canyons was investigated. At least two mechanisms of transuranic transport, one physical and the other chemical have been identified in the canyon system off Palomares. In addition the study has highlighted the importance of the land-to-sea transfer of transuranics and, in particular, terrigenous input via fluvial transport. Another objective of the work undertaken has been to estimate transit times of Pu-bearing particles in the Channel. The average velocity of the pathway for the transport of Pu with deposited sediments ranges from some kilometers per year to some tens of kilometers per year. When compared to the transit times of water masses from for example Cherbourg to Dover straits (4-8 months), those of sediments are considerably lower, ranging 10-50 years. This means that either the major part of the sediment masses remain on the sea-bed most of the time, only being disturbed by major tidal events. Evidence of elevated concentrations of Pu and Am was found in plankton and seabed sediments sampled in the Palomares/Garrucha zone, leading to the conclusion that plankton may play an important role in the cycling of sediment-associated transuranics in shallow coastal waters.

A wide ranging study of the general mechanisms governing the long-term behaviour and mass balance of long-lived radionuclides in the western Mediterranean has been undertaken. Time trends of vertical profiles in the water column, partitioning between

soluble and particulate forms, vertical transport in the water column in relation to both water mixing and sinking particles, accumulation in sediments, and fluxes through the Mediterranean Straits have been determined.

Time-series data on radiocaesium and plutonium in the surficial sediments of the Western Irish Sea mud-patch have been simulated using a semi-empirical model which assumes that the environmental material is in equilibrium with its environs. The model not only predicts future concentrations but also those in years prior to the initiation of the sampling. Predicted availability times (=radioecological half-lives) for ^{137}Cs are in the range of 7-17 years, while for $^{239,240}Pu$ they are in the order of several hundreds of years.

The work on marine environments has produced a great deal of basic physico-chemical data for a set of radionuclides released from nuclear facilities, their interaction with sediments and their fluxes with surficial and vertical water masses in western European marine waters. In the case of marine research coordinated projects have been shown to be crucial for achieving a global understanding and prediction of the behaviour of radionuclides in these highly complicated environments. In spite of the complicated nature of the topic the results became more coherent than they used to be, thanks to the coordination of the project. A validation of the knowledge gained will be undertaken in the Fourth Framework Programme in a project which aims to evaluate the risk from the release of radioactive material in the arctic waters, where harsh climate conditions prevail, but where, in some cases, rich fishing grounds are at stake.

In addition to these straightforward scientific achievements, a number of innovative analytical procedures need to be mentioned, such as a practical and relatively inexpensive technique to measure the $^{240}Pu/^{239}Pu$ ratio in environmental samples which was developed in a joint exercise by a number of the project partners.

3.1.2.4 TRITIUM RESEARCH

Five major topics have dealt with the area of tritium research investigating and modelling the dynamics of environmental tritium gas (HT), tritiated water (HTO) and organically bound tritium (OBT) levels resulting from tritium releases; namely:

- Tritium re-emission from soils
- synthesis of tritium into organic materials
- the effect of rainfall on the infiltration of tritium into soils and on tritium re-emission from soil surfaces
- activity versus distance correlations in the vicinity of a tritium-compound manufacturing facility after 20 years of HT and HTO emissions
- tritium levels in the environment before and after the start of the operation of a CANDU-type heavy water reactor.

The laboratory and small scale field experiments on tritium re-emission from bare soils have provided an answer to the question about the association between tritium re-emision and water evaporation. The importance of this problem appeared because tritium re-emision has often been modelled in terms of water evaporation as there were no better alternatives although theoretical considerations and some experimental results had indicated substantial differences between the two processes. The detailed

investigations have shown that re-emision is largely independent of evaporation and a new separate model has been developed. Furthermore an existing model based on the exchange-velocity concept has been found to reproduce the main physical mechanisms of the re-emission process. One outstanding result is the finding of high initial re-emision rates after the deposition of HTO which has initiated modifications of the broadly accepted computer code (UFOTRI) used to describe the environmental behaviour of tritium in general. If the unexpectedly high re-emision rates found in the open-air experiments for bare soil also apply for crop-grown surfaces, the consequence would be a considerable shift in the dose contributions from inhalation and ingestion.

As expected the infiltration rate of tritium into soil increases with increasing rain intensity, and tritium re-emision is reduced and delayed by rainfall after HTO deposition.

A better data base for a background situation before the start of the operation of a CANDU-reactor has been established.

The investigations on tritium fractionation processes in plants and soils have identified a variety of effects resulting from isotopic differences of the two atoms, H and T . These differences are usually neglected in natural systems but, more importantly, also in the analytical processing of environmental samples. The relevance of these studies for dose comes from the difference in the radiotoxicity of tritium whether appearing in tissue, e.g. tissue water tritium (TWT) or in organic molecules (OBT). This leads one to question whether the value of the specific activity ratio (R-value) of organically bound tritium to tritium water may exceed unity. Further research is required to define what the maximum increase of the T/H ratio could be in the different dose-relevant compartments as a consequence of the various isotopic effects. Except for the case of radio-sensitive molecules, such as DNA, it is doubtful however, that isotopic effects would increase values of the resulting dose beyond the uncertainty margins of the current dose prediction models.

3.1.2.5 AN ASSESSMENT OF THE PAST AND PRESENT RESEARCH SITUATION

Radioecology was originally rather restricted to *monitoring i.e. measurements of contamination levels in the environment*, in particular in agricultural ecosystems, which were used in modelling exercises to predict doses to man from external radiation, inhalation and ingestion. For most of the commonly released radionuclides the data are known with some statistical accuracy and only limited information is still required. An extensive literature and transfer factor tables are available. Moreover, the data can be corroborated or rejected by real time measurements.

The Chernobyl accident and other comparable accidents drew attention to some research areas and ecosystems which had not been studied very intensively or whose relative dose contribution was unsure. They include for example the behaviour of accidentally released radionuclides in semi-natural ecosystems. The Chernobyl accident also revealed flaws in environmental management and engineering.

Some important phenomena attracted the attention and concern of scientists and authorities such as the persistence of the availability of radiocaesium to animals in some

areas with high organic matter content. Another example is the ongoing discussion about the Caesium/Potassium competition with respect to their uptake from soils to plants and, consequently, the effectiveness of potassium application as a soil-related countermeasure. In addition, transfers between connected ecosystems were predominantly expressed as concentration ratios which assumes that equilibrium exists between the different compartments of these ecosystems. Although Concentration Ratios or Transfer Factors still have their place in environmental assessment, they are being steadily replaced by kinetic expressions whereby, changes in total contamination load (or inventories) are used to parameterize radionuclide behaviour, taking into account, in the meantime, total volume changes in the environment such as vegetation growth phenomena, landscape changes through erosion, water mass displacement etc rather than Concentration changes.

Important changes took place when it was realised that the factors making up most of the "black box" definitions of the transfer of radionuclides in the ecosphere needed to be unravelled and that the "uncertainty" of dose predictions could not be satisfactorily reduced by "more data of the same kind and quality".

Radioecology as a scientific discipline is special in that it draws most of its scientific information and skills from other scientific disciplines which as such have little to do directly with Radiation Protection. In addition to physics, radioecology draws information from other fundamental disciplines such as physico-chemistry and biology. Moreover, the Chernobyl accident has underlined, once more, the extent to which radioecology depends on practical sciences such as soil science, plant and animal breeding and husbandry, forestry, hydrology and geography. Ultimately, it has shown the close links between radioecology and economics, particularly when environmental restoration and rehabilition of large land areas need to be considered.

Relevance of radioecology for the calculation of dose to man

In the definition and objectives of radioecology outlined in the introduction one requirement of radioecology was to provide data to permit a reliable dose calculation and do a pertinent risk assessment for the population living in an area contaminated with radioactivity.

In this context a number of important and vital results have been realised, such as the fundamental understanding of the mechanisms of fixation of caesium by clay components of soils and the role organic matter plays in the modification of these mechanisms. The improved understanding of these complex mechanisms permits a better prediction of the long-term behaviour of Cs in the environment and will, in a forseeable time, certainly lead to a predictable control of its fate in agricultural and semi-permanent pasture land.

Another important result is the experimental and mathematical methodology developed to predict the true absorption of radionuclides through the gastro-intestinal tract in livestock animals. Again a better prediction of the fate and possibility for adequate manipulation of animal produce derive from it. Moreover, the use of the True Absorption methodology could and should be assessed in the frame of internal absorption of radionuclides by other mammals, such as humans and used for the dosimetry of internally deposited radionuclides and for "biokinetic models".

In freshwater systems the role of catchments for river and lake contamination is now being appropriately simulated in models which quantify the boundary constraints such as the face of the soils or the intercepting plant canopy. The operative physico-chemical and biophysical factors governing the contamination of sediments and biota in lakes and rivers are now defined to a large extent; inclusion of these parameters in adequate models has, very beneficially, stimulated interaction of the radioecologists with experts in the assessment of risks from such freshwater environs. The experimentalists have been getting a more precise vision of the needs for dose and risk calculations, and on the other side a better feeling for the ecological reality has developed.

The observations permit an assessment of the ratio of **external** to **internal dose** and also an assessment of the importance of the **individual dose** and **critical group dose** compared to the **collective dose.** The scientific achievements also allow for the development of scenarios for dose reduction, by implementing scientifically justified countermeasures. These countermeasures should eventually be tailored for environmental management in order to come to environmental restoration or rehabilitation, with respect for the ecological quality and economic value of the restored territories.

The developments which have occurred during the Third Framework Programme form the basis for continued radioecological research in the current programme and a more mechanistic approach is being taken to place environmental engineering and environmental management on a sound scientific footing and moving on from the more traditional empirical approach. In this respect a number of important achievements deserve a mention, such as the development of a fundamental understanding of the mechanisms of absorption/desorption by clay components in soil and the role which organic matter plays, such as the development of the experimental and mathematical methodology to predict the true absorption of radionuclides through the gastrointestinal tract in livestock animals, and such as the modelling and quantification of the role of catchments for river and lake contamination, and a better description of the operative physico-chemical and biophysical factors determining the contamination load of water, sediments and biota.

It is clear that environmental assessments should be based on contamination loads and total inventories of contaminants as they flow through the environment and these concepts provide the background for the definition of priorities for the Fourth Framework Programme. A number of radioecological projects have been defined where the fluxes of radioactivity in a variety of ecosystems are the objective of the investigations on the basis of which their ecological and economic vulnerability will be evaluated, and a GIS based classification produced. As an extension of these classifications, strategies of environmental restoration (exclusively dealing with large surface decontamination in contrast to site restoration) will be developed. In a follow-up of the Chernobyl research, previously collected information and newly acquired environmental engineering techniques will be further exploited and categorised in order to develop a fully comprehensive environmental strategy for accidents and construct an environmental decision support system.

3.2 CONSEQUENCES OF RADIATION EXPOSURE TO MAN

INTRODUCTION

Internationally applied radiation protection regulations are based on radiation risks which are derived from epidemiological studies, especially of the Atom Bomb Survivors. The Atom Bomb Survivors were exposed to acute radiation doses and several assumptions are made in the analysis of the data to derive the low dose risk from this epidemiological data. These assumptions, which contain inherent uncertainties, rely on the current understanding of radiation action and on available radiobiological data. Consequently, in order to reduce the uncertainties in these assumptions, the research effort in this sector of the programme continues to aim at a better understanding of radiation action at the molecular level and at low radiation doses on the basis of reliable experimental data. In this way the results from the research should, ultimately, provide a better basis for the estimation of risks of low dose radiation exposures.

Conceptually the programme has been designed to investigate the action of radiation starting from the deposition of energy in the nucleus of the cell and considering the types of molecular damage caused by the energy depositions, the potential repair pathways for the damage, the consequences of the damage from the point of view of mutations and chromosomal aberrations and the relevance of these effects for the induction of cancer and hereditary effects. Attention has also been given to special problems caused by internal emitters and also to ways of removing the incorporated radionuclides from the body. In addition the programme has also continued to study the effects of larger total body and partial body exposures in order to improve the treatment of accident victims.

In previous programmes studies aimed to measure dose effect relationships for the various end-points using different types of radiation, different dose rates and different irradiation conditions. In addition, the explanation of radical differences in radiation sensitivity found in cells from people with inherited medical syndromes was sought in differences in repair of radiation induced damage. In the 1980's a variety of new molecular biological techniques were developed and in the late 1980's these techniques started to find increasing use in radiation biology, firstly in the repair studies but later also in the studies of mutations, aberrations and cancer. For example, the fluorescent in situ hybridisation (FISH) technique, by which certain chromosomes are "painted" a specific colour, was developed in 1986 in USA. This method which permits the detection of stable, translocation type chromosomal aberrations has been used in radiation cytology and has led to remarkable developments in both applied and fundamental studies.

Following the Chernobyl accident in 1986, it became clear that the generally accepted method for the treatment of the acute radiation syndrome, namely, bone marrow transplantation, should not always be the first choice of treatment. In addition, the accident had drawn attention to the fact that a total body over-exposure would often be accompanied by radiation induced skin burns from beta-ray exposures and there was a need to develop new treatments which took this into account. Consequently, in the late 1980's the research on the treatment of accident victims received a stimulus to develop new methods and, here again, the revolution in molecular biology has gradually played an increasing role.

3.2.1 STOCHASTIC EFFECTS OF RADIATION

3.2.1.1 MICRODOSIMETRY AND BIOPHYSICAL MODELLING

The evaluation of risk factors for low dose and low dose rates exposures relevant for radiation protection require extrapolation from the considerably higher doses and dose rates of the exposures investigated by epidemiological studies. The extrapolation introduces significant uncertainties because of the limited knowledge of the dose-time-effect relationships at low doses, which in turn is due to the limitations in the (quantitative) understanding of the radiation induced mechanisms at the molecular, cellular and organ level.

As a complement to epidemiological studies, the EC research programme includes an approach for improving the qualitative and quantitative understanding of health hazards which is based on a detailed and comprehensive study of the physical, chemical, molecular and cellular biological processes induced by radiation. The ultimate aim is to understand the mechanisms by which mutations and chromosome aberrations are induced and how these effects lead to cancer. The fundamental objective, therefore, is to provide a sound basis for extrapolation of radiation risk to low doses accumulated over extended periods of time. The investigation of radiation quality aspects, i.e., the influence of type and energy of radiations on the biological effect, plays an important role in this approach. Variations in radiation quality in the experimental investigations provides a specific and powerful probe for studying mechanisms. Such investigations are also of direct practical importance because radiation protection requires a sound basis for quantifying differences in radiation quality with respect to the radiation risk.

The work carried out is a continuation of previous research in this area but with a significantly increased level of coordination and cooperation between the underlying disciplines of radiation physics and chemistry and cancer modelling. The coordination with relevant work in the areas of molecular and cellular radiation biology and epidemiology has been stimulated by joint contractors' meetings but needs to be extended in the future.

The objectives of this multi-disciplinary and basic research approach are necessarily of a long-term nature. During the reporting period, significant progress has been made although the achievement of the overall objectives still require further research.

The overall goal to develop an integral mechanistic model for radiation carcinogenesis was separated into the development of different models for the different levels of biological complexity: the production of primary and secondary physical and early chemical changes in the DNA, the formation of mutations and chromosome aberrations, and the induction of late somatic effects in experimental animals and man by such early effects, including the comparison with the mechanistic action of UV-light. The research included theoretical work for model development and experimental work mainly on early chemical effects in the DNA.

The modelling of tracks of ionising charged particles ("track structure calculations") is an extremely important tool in microdosimetry. During the reporting period marked

advances have been made by extending track structure codes to condensed media, and by first steps of computer simulations of DNA fibres composed of wrapped nucleosomes. The track structure calculations were used to calculate absolute yields of single and double strand breaks in DNA after irradiations with different particles and incorporation of ^{125}I in the DNA. The latter was also used to model the direct and indirect strand breaks using scavengers. An intercomparison of different available electron track simulations was performed to test the robustness of conclusions drawn from such calculations. Wide regions of quantitative agreement were found. However, over small dimensions of interactions, differences also became apparent which may be relevant for chemical modelling.

Experimental work on quantitative determination of DNA damages in mammalian cells by radiations of different quality has provided important data for mechanistic modelling. Investigations on DNA-damage complexity from direct ionisations in the DNA and as local water radiolysis products in the highly scavenging cellular environment have been measured and modelled. This and other work and the comparison to track structures have led to hypotheses on the biological importance of clustered damage at the DNA level. The investigations reveal that "clean" double-strand breaks are just one simple class of an entire spectrum of clustered DNA damage of probably widely varying molecular complexity and biological severity. The results indicate that for the quantitative modelling of damages such as mutations, chromosome aberrations and other long-term biological effects, it will be necessary to follow the track chemistry within and between clusters of ionisations.

The hprt mutation system has previously been identified as a particularly suitable paradigm for mechanistic understanding and modelling of radiation mutagenesis. The extensive quantitative information available in the literature was complemented by dedicated experiments with mammalian cells irradiated by α-particles to fill gaps in available information. The experiments were compared to chromosome aberration induction and cell inactivation under similar conditions. The results are important for the modelling of radiation mutagenesis.

The research work on radiation carcinogenesis included the investigation of a two-mutation model. Available data sets of tumour induction in animals and man from a variety of exposure conditions were analyzed. The model shows features of a relative and absolute age projection risk model and a single somatic mutation model. The two mutation model links DNA molecular and cellular damage with tumour formation. It accounts for the multistage character of carcinogenesis and links spontaneous tumour incidence with radiation risk. The model in its present form allows investigation of the involvement of radiation in different stages during carcinogenesis. The model, therefore, has the potential for the derivation of radiation risks of lifetime exposure from acute and high dose epidemiological data.

The multi-disciplinary cooperation required for the research approach to qualitative and quantitative understanding of the mechanisms of radiation carcinogenesis has been significantly intensified within the reporting period. Although much of the work in detail is primarily carried out in the scientific environment of the respective research sub-sector, the collaboration in multi-partner contracts and accompanying joint contractors' meetings

for all research contracts relevant to this topic, as well as the continuation of the series of symposia on microdosimetry contributed towards developing a common orientation and inter-disciplinary communication. The progress achieved is documented by the increasing number of molecular and cellular studies which are in close context to the model developments. They provide important input or benchmark data and serve to validate model assumptions. An important aspect here are studies using varying radiation qualities and even UV light and related investigation of effects on the DNA and cellular level. It should be noted that the work included the first attempts towards developing a mechanistic model for oncogenesis in man.

The pathway research in this area has taken in the reporting period needs to be continued and intensified by closer integration of dedicated molecular and cellular biological experimental work. The experimental work will have to concentrate on specific chemical and molecular (DNA damages of varying complexity) and cellular effects (hprt-mutation, chromosome aberrations) and their analysis. It should be performed using different radiation qualities, including single cell irradiations. This type of work is expected to validate the models and underlying hypotheses. The development of models combining cellular effects with multi-stage cancer models must be continued and results should be tested using experimental animal data.

3.2.1.2 REPAIR OF DNA DAMAGE

Although repair of radiation induced DNA damage has been an important topic in previous programmes there has been a gradual evolution of the studies from prokaryotes and lower eukaryotes to mammalian cells. This evolution has been driven by the development of the methods to investigate the induction and repair of the DNA damage in the larger mammalian genomes and the need to study cellular systems more relevant to radiation risk in man. Most of the recent work has been strictly concerned with mammalian cells but the evolution has continued in as much as the research increasingly considers the repair of damage induced by ionising radiation. The importance of molecular biology for the studies of repair cannot be stressed too much and the progress continues to be made at a most impressive rate.

The earlier work with mammalian cells concentrated on the repair of UV induced damage, essentially the nucleotide excision repair (NER) of pyrimidine dimers and 6-4 photo-products using UV sensitive cells from Xeroderma pigmentosum (XP) patients. Repair has been found to be non-homogeneous in the genome with actively transcribed genes being repaired more quickly than non-transcribed genes and with the transcribed strand of the DNA being repaired more quickly than the non-transcribed strand. Products of mammalian genes involved in NER and repair of radiation induced damage have been purified and characterised with regard to functional domains and interaction with other proteins. One NER enzyme complex has been found which functions in both NER and recombinational repair and may play a role in strand incision. Proteins from genes mutated in XP groups B and D are part of a multi-protein complex TF11H required for transcription initiation and excision repair. Several clinical symptoms associated with the corresponding disorders which were difficult to explain on the basis of a repair defect can now be explained as the result of a subtle impairment of transcription. The XPB and XPD proteins are responsible for bidirectional helix-

unwinding and it is proposed that TF11H may locally melt the DNA around the site of a lesion to facilitate repair.

The study of repair of ionising radiation damage is developing rapidly taking full advantage of all the techniques developed to study the repair of UV induced damage. Yeast artificial chromosomes (YAC) have been used to localise the defective gene in the radiation sensitive mutant *xrs* and a candidate gene Ku80 was cloned and shown to correct the defect. Ku80 is one subunit of a heterodimeric Ku protein with Ku70 as the other and the Ku protein is the DNA end-binding component of DNA dependent protein kinase DNA-PK and the suspicion that other radiation sensitive mutants with comparable defects to *xrs* might be defective in the Ku70 or DNA-PK genes led to the identification of the defective gene in the *scid* mouse as a DNA-PK gene. One interesting feature of these genes is that they are also involved in V(D)J recombination which is responsible for the development of the immune system via the processing of naturally induced double strand breaks.

Using an *in vitro* assay with cell-free extracts and plasmid DNA the repair of DNA double strand breaks induced by restriction enzymes has been studied. The repair of breaks with homologous ends is stimulated by protein REP-1 which increases ligation. The rejoining of breaks with non-homologous ends has been demonstrated to occur via different mechanisms involving either direct repeats or blunting (or filling) of single strand overhangs followed by ligation. This work has shown that the deletion of DNA between two neighbouring repeats can arise from a single DNA double strand break.

Analysis of a large number of both X-ray and alpha-particle induced mutations at the HPRT locus has revealed a predominance of large deletions extending to 3 Mb. The large deletions induced by both X-rays and alpha-particles are formed by a process of illegitimate recombination but there is some indication that the deletions induced by alpha-particles arise from complex rearrangements. Sequence analysis of the break-points in spontaneous HPRT mutants in Fanconi anaemia (FA) cells revealed features typical for V(D)J recombinase mediated cleavage and joining which suggests that illegitimate recombination may be active in FA pathology.

The isolation of several repair genes has been facilitated because of the strong conservation, and thus close homology, of repair genes in the evolutionary pathway so that a repair gene identified in yeast can be used to identify the gene in mouse and man. Using these homologies advantage can be taken of the work carried out on repair in prokaryotes and lower eukaryotes in previous programmes. It is interesting and important to realise that although the programme has evolved from the prokaryotes and lower eukaryotes to mammalian cells the work done on the lower organisms is having an unexpected pay off because of the conservation of the repair genes throughout evolution.

Several repair deficient mouse models are being developed via transgenic pathways and these mouse models will permit a deeper study of the role of the specific repair defects at the organism level and may lead to more associations between repair and other cellular processes such as transcription and V(D)J recombination.

The progress made in this area of DNA repair is quite exceptional and of very high

quality. Detailed knowledge is being gained about the genes and the protein products involved in the repair of radiation damage and in the way in which they function. The continuing development and application of molecular biological techniques in repair studies and the remarkable progress made over the past four years augurs well for the future and promises a fuller understanding of the way that cells process the DNA damage induced by ionising radiation.

3.2.1.3 CYTOGENETICS AND CELL RADIOBIOLOGY

Cytology

Some of the most important changes induced in the cell by radiation are the chromosomal aberrations which are implicated in the induction of malignancy and several tumours exhibit specific chromosome changes. Radiation induced chromosomal aberrations have been studied for many years although the actual mechanisms by which they are formed are still unknown. Chromosomal aberrations, more specifically dicentrics, induced in peripheral blood lymphocytes have been used for biological dosimetry especially after an accident although dicentrics are not suitable for dosimetry if some time has elapsed between the exposure and the measurement. The programme continues to study the formation of chromosome aberrations as an important radiation induced end point.

One of the most important developments which has influenced the research in the period 1990 - 1994 has been the technique of fluorescent in-situ hybridisation (FISH) or chromosome painting which allows certain chromosomes to be coloured along their entire length and thus easily distinguished from other chromosomes in the same nucleus. This technique coupled with the use of centromeric and telomeric stains which have also been recently developed provides a powerful method for a more detailed investigation of chromosome aberrations permitting the routine detection of many aberration types which could not be identified previously with conventional staining methods. The painting method allows, for instance the detection of reciprocal translocations which are stable aberrations and which might be useful for retrospective biological dosimetry. Another technique used more widely in the last programme period is that of Prematurely Condensed Chromosomes (PCC) where an irradiated interphase cell is fused with mitotic cells and the chromosomes of the interphase cells are condensed making their aberrations detectable.

A study using FISH techniques to compare the induction of translocations and dicentrics revealed that in addition to reciprocal translocations other types of translocations including terminal and interstitial translocations can be detected and when all translocations are taken into account there are proportionally more translocations induced than dicentrics. Dose effect relationships are linear-quadratic both for dicentrics as translocations and gamma rays appeared less effective at inducing translocations than X rays. Using five different combinations of painted chromosomes a test was made of the equation used to calculate whole genome translocations from the number detected in the painted chromosomes. The study revealed that the equation, which is based on a purely random distribution of breakage and rejoining, was not strictly valid and it appears that some chromosomes are involved more frequently in aberration formation

than would be expected on the basis of their DNA content. This result re-enforces a result showing that euchromatin which is less condensed chromatin, suffers more damage, in terms of chromosome breaks, than heterochromatin, the more condensed chromatin, and in terms of repair there also seems to be a difference in the kinetics of repair in the two different chromatins. Experiments using singly painted chromosomes revealed that, in respect of DNA content some chromosomes are over represented in translocation formation and others are under represented. These results suggest that the common assumptions made about radiation damage being randomly distributed through the nucleus are not strictly correct. A comparison of the persistence of dicentrics and translocations through several cell divisions made using FISH and differential staining of sister chromatids revealed that dicentrics and fragments did decrease with cell division although translocations were more persistent. However, there was a clear indication that more highly aberrant cells were more delayed in passing through the cell cycle and the average generation time of the lymphocytes had a clear effect on the aberration frequencies.

One important consequence of the development of the FISH technique has been that many of the aberrations previously thought to be straight forward aberrations have been found to be complex, i.e. involving more than two break points, and it has become necessary to derive a new system of nomenclature for the detected aberrations. One derived by a group of international scientists is called PAINT and should be useful for biological dosimetry. Another system developed within the programme is called CAB and is defined to facilitate the identification of the complex aberrations from the mechanistic point of view.

The finding, using the FISH technique, that many aberration types normally classed as simple actually are complex implies that there is an underestimation of damage with repercussions on the shape of dose effect curves and on inferences drawn from them. Studies of chromatid aberrations first revealed that many more aberrations are complex in nature and that the yield seems to be LET and dose dependent. Examination of chromosome aberrations also revealed that many presumed simple rearrangements were complex and these were also found to be dose dependent for low LET radiation increasing to 20% at 4 Gy but for high LET radiation the yield was about 40% independent of dose. A classification has been made of all the possible arrangements with 3 or more breaks in a system based on Chromosome number, Arm number and Break number (CAB system) from CAB 2/2/3 up to CAB 5/5/5 which covers 26 families. Inferences can be gained about under-estimation of radiation damage and mechanisms of aberration formation by painting one chromosome and examining the aberrations using the new CAB classification.

In a study of radiation sensitive cells which appear to have a normal DNA double strand break repair process experiments with restriction enzymes which produce specific types of double strand breaks at certain base sequences it was found that the sensitive cells were also sensitive to the restriction enzymes and it is concluded that these cells carry a double strand break repair defect which causes them to convert more induced double strand breaks into visible aberrations. In the same line a study of sensitive cells using PCC techniques also led to the conclusion that the increased sensitivity of these cells is associated with an increased probability for misrepair. The PCC measurements using

fusion of the irradiated cells with different strains of mitotic cells revealed that the mitotic activity of human transformed cells resulted in twice as many fragments as the mitotic activity from chinese hamster cells and led to the speculation that the level and the control of mitosis promoting factor in the cell cycle may influence the sensitivity of the cells to killing. It also implies that the comparison of yields of interphase chromosome breaks revealed by the PCC technique cannot be made between different laboratories and that the quantification of these yields must be treated with care. Results from studies of radiation induced mitotic aneuploidy using micronuclei, chromosome painting and centromeric staining are still inconclusive with respect to the shape of the dose effect relationship and also with respect to the molecular target.

Investigations of the adaptive response, mainly carried out in human lymphocytes, where a small conditioning dose given several hours before a second challenging dose appears to reduce the effect of the challenging dose, have shown that the adaptive response is variable. There seem to be variations between different donors and even differences between the same donor sampled at different times. The results have not been able to confirm that the effect arises from a repair process which is stimulated by the conditioning dose as has been proposed. What has been revealed is that very small conditioning doses of the order of 2 cGy of X-rays induce significant variations in cell progression and can, at least in some donors, change the mitotic delay induced in G2 by the challenging doses. Although these changes have not been related to the adaptive response it is not possible to exclude changes in the time progression of cells through the cycle as a possible contributor to the adaptive effect.

Attempts to develop automated analytical techniques based on flow-cytometric methods to score large numbers of aberrations for population screening in case of accident or to increase the statistical power of measurements at very low doses have failed to come up to expectations. One method proposed slit-scan examination of individual chromosomes to detect dicentric aberrations, the other methods proposed the flow cytometric analysis of micronuclei induced by radiation. In spite of elegant sophisticated technological developments both methods have drawbacks, the first with false-positives and the other with variable background, which restrict their application and do not offer improvements over conventional scoring methods. The development of an automated system for the detection of micronuclei using image analysis techniques has been hampered by problems of availability of commercial equipment but using a method to detect over-lapping binucleate cells with micronuclei has made some progress. The lower limit of dose detection is restricted by the variable level of spontaneous micronuclei which varies between donors, however, the majority of the spontaneous micronuclei contain centromeres and by combining centromere staining with micronuclei a potential lower dose detection limit of 0.1Gy was indicated in manual scoring. Other image analysis methods are being applied to the automatic detection of translocations using chromosome painting and have been developed to a promising level using two colour painting. In one system dose effect relationships have been developed and doses have been estimated for several Chernobyl liquidators and compared with doses estimated by manual scoring in another institute. The results are promising especially in view of the very much faster scoring possibilities that the automated versions offer. The other system has dose effect data using two colour painting in analysis to compare automatic and manual scoring and is under revision to increase sensitivity with the aim of using up to

six different labelled chromosome pairs.

The development and application of the FISH technique together with other specific stains has led to good progress in the research aimed at understanding the mechanisms involved in chromosome aberration formation which should be built upon in the future. In other more applied research areas, such as adaptation, the results are less impressive and future research will need to be very carefully assessed.

Cell transformation

Cell transformation studies developed rapidly in the 1980's when it was shown that one or two cell lines could be used to investigate radiation induced change to an apparently malignant phenotype at the single cell level and the methods offered the possibility of investigating radiation induced malignancy using cell cultures rather than animals. Since the mid 1980's the programme has concentrated on two aspects of the cell transformation process, namely, the use of an established immortalised cell line (C3H 10T½ cells) to investigate quantitatively the dose effect relationships especially at low doses and the development of quantitative human cell systems starting from primary human cells.

In a study to investigate the dose effect relationship at low doses in C3H 10T½ cells six groups cooperated in an extremely well coordinated and intensive collaboration over the past 5 years. The first experiences revealed that although the protocol for the use of the system had been well laid down by others the different groups were scoring the variety of radiation induced clones of cells (foci) with altered morphology differently. This led to an intercomparison of the identification of the different foci between the groups and an important deliverable from the group has been a catalogue depicting photographically the various classes of foci together with the score (transformed or non-transformed) assigned to these foci. A careful comparison of a variety of factors, such as medium, incubation time, plating density, which might affect the yield of transformed foci was made to prepare for the combined dose effect relationship studies. Using the carefully designed protocol dose effect relationships were established for cell survival and cell transformation in the dose range from 0.25 Gy to 5 Gy. The cell survival curve was found to be linear-quadratic whilst the cell transformation curve was found to be linear. Comparison with data in the literature revealed wide variations in the frequencies of transformation in the system over the years by a factor of 20 between different laboratories it is concluded that the size of this variation makes intercomparison with other work impossible but it is emphasised that the large number of transformed foci detected in this collaborative exercise makes the results the most robust, in a statistical sense, to date.

In addition to these collaborative studies the individual groups have studied certain aspects of the cell transformation process which are of radiobiological interest, such as, induction by ultrasoft X-rays, variations through the cell cycle, inverse dose rate effects for neutrons and high LET radiation, chromosomal changes on transformation, other mammalian cell transformation systems. Briefly, ultrasoft X-rays producing electron tracks of less than 7 nm, are more efficient than hard gamma rays both for cell killing and for transformation suggesting that the DNA double strand break is an important lesion for transformation; the efficiency for transformation varies through the cell cycle

with an increased sensitivity in G1-phase and a decrease in the S-phase, although the pattern is not exactly the same for high and low LET radiation; no large increase in transformation efficiency has been found when high LET radiation is either fractionated or given at reduced dose rate, this contradicts a previous publication in USA showing a large "inverse dose rate effect" for neutron exposure; although certain chromosomal changes may be associated with immortalisation no specific changes have been associated with cell transformation in these studies; no other transformation systems have been identified for quantitative studies as yet.

One of the most important results arising from this work concerns the developments which have been necessary to obtain reasonable agreement in scoring between the different laboratories in the C3H 10T½ system which has been the predominant cell transformation system for quantitative studies over the past 25 years. This result implies that it is impossible to compare published data with this system coming from different laboratories and calls into question the significance of the previously published data for radiation biology. The usefulness of the system as a whole and the wisdom of continuing support of research with the system must be doubted.

The development of a quantitative human epithelial cell transformation system starting from primary human cells has been supported by the programme since 1985 but has been frustrated by the general difficulty of transforming primary human cells. Several transfected lines of human cells were available by 1990 which provided systems for potential development to a transformation assay. The most promising of these lines have been investigated using transplantation to nude mice as a test of tumorigenicity. Urothelial, keratinocyte, bronchial and thyroid epithelial cell lines were all tested with disappointing results. The only cell line which produced positive results was the thyroid epithelial cell line which was successfully used to derive the typical bell-shaped dose effect relationship seen for cancer induction in animals. Gamma radiation was compared with alpha-particle irradiation. The RBE for alpha-particles versus the gamma rays was 4 which compares well with values found for mutation induction. In spite of these interesting results it must be pointed out that this system, which was transfected with a plasmid containing the origin defective SV40 genome, is not really a cell transformation assay as such, as the data were based on the tumorigenicity in the nude mice.

Much research in this group working on human cell transformation systems has dealt with effects of radiation on the induction of mRNA and proteins such as *c-fos* and *c-jun*, on mutations in the p53 gene and the stability of p53 protein, on the induction of apoptosis and the expression of bcl-2 and cmyc proteins but the significance of these results for cell transformation and radiation carcinogenesis is not clear.

In general, it must be concluded that it has not been possible to develop a human cell transformation system which can be used at the cell level to investigate the process of radiation induced malignancy especially from primary cells and that those systems already immortalised by virus transfection are not suitable for radiation research.

Cellular effects

In a comparable study of the effects of UV and ionising radiation on the activation of

pre-existing transcription factors such as the AP-1 factors c-jun and c-fos it has been found that UV light is far more efficient at induction of transcription of C-jun and c-fos than ionising radiation, some 50Gy being required to give a measurable effect. This effect measured in HeLa cells *in vitro* contrasts starkly with results just discussed where in pig skin effects on c-fos were detected after only 5cGy but the work *in vitro* does suggest some species or cell type specific differences. The UV induced gene transcription has been deduced to arise as a consequence of UV induced DNA damage from observations on UV DNA damage repair deficient cells, comparison of UV action spectra, injection of UV damaged DNA into unexposed cells and inhibition experiments. The UV induced activation of transcription factors has been found to be mediated via cytoplasmic signal transduction involving Src, Ras, Raf, mitogen-activated and Jun kinases. Irradiation of cells with X-rays or UV light increases the level of p53 but as there is no change in RNA levels this is assumed to arise by a stabilization of the p53 protein.

A study of the mutation spectra induced by UV light in different UV sensitive, repair deficient cells Xeroderma Pigmentosum (XP) and trichothiodystrophy (TTD) and in normal cells has revealed only minor differences. Although XP and TTD cells are both sensitive to UV the XP patients are prone to skin cancer while the TTD patients are not. It was found that the XP and TTD cells were much more sensitive to UV induced cell killing and mutations and although the mutation spectra were similar the spectra in the TTD and normal cells were most alike. The ERCC2 gene was used to complement the XP and TTD cells restoring the UV resistance to both cell killing and mutation induction showing that the ERCC2 mutations in the XP and TTD cells are the only cause of the UV sensitivity of these cells. Studies of mutations in the p53 gene in XP skin tumours and non-XP skin tumours and non-XP internal tumours revealed that in all the skin tumours the mutations were opposite pyrimidine-pyrimidine sequences while the internal tumours had mutations at random. This showed that UV induced pyrimidine dimer lesions are involved in skin tumour development even in non-XP patients. The molecular basis for differences between tumour-prone XP and non-tumour-prone TTD patients has also been investigated by looking at Enhanced Reactivation (ER). The UV-induced responses of the different cells proved to be identical in many ways, such as induction of signal transduction pathways and sensitivity to cell killing but differ in their response to ER, the XP tumour prone cells show the enhanced reactivation while the TTD cells do not. At the same time it was found that the ER^+ cells the ornithine decarboxylase (ODC) gene was also induced whereas in ER^- cells ODC was not induced. Other experiments suggested that the enhanced reactivation was also associated with enhanced recombination.

The main reservation about all this work must be that it is studying effects which are induced by UV light, not ionising radiation, and that the UV light is much more efficient at inducing these effects than ionising radiation, although some of the general conclusions from the work can be extrapolated to more general situations.

Effects of Radiation Quality

Considerable effort has been devoted to trying to resolve a discrepancy between measurements of the effectiveness of protons and deuterium ions on cell killing and

mutation induction made by two different research groups. One group has found different effectiveness between protons and deuterons having the same Linear Energy Transfer (LET) in the range 10-60 keV/μm, which is not anticipated theoretically, whereas the other group has not found a difference. In view of the implications these measurements have for the theoretical track structure calculations it is important to resolve the discrepancy. Cross checks of dosimetry have not revealed any major errors and attention has turned to a comparison of experimental protocol and data analysis. In the meantime measurements using $^{3}He^{++}$ and $^{4}He^{++}$ in a range of LET values from 40-150 kev/μm have also revealed unexpected differences for cell killing but not for mutation induction. Other work with heavy ions at high LET has shown that LET is not a unifying parameter for the comparison of these particles and that when particles with the same LET but different charge and velocity are compared track structure differences become important for differences in biological effects. The values of RBE reported for cell killing and mutation induction range up to 7 at around 100 kev/μm for light ions with values up to 20 for heavy ions.

Measurements of DNA damage, especially double strand breaks (dsb), have revealed that, in mammalian cells, the high LET radiation is less effective at inducing the dsb than low LET although the relative biological effectiveness of the high LET is higher. This difference has been proposed to be a result of the fact that the high LET radiation would induce complex lesions, that is, lesions made up of a combination of a double strand break with base damage for example, and that these complex lesions would be more difficult to repair and be more effective biologically. Attempts to study these complex lesions have concentrated on the differences in the chemical repair of single and double strand breaks induced by radiations of different LET. These measurements are attempting to look at the complexity of lesions at nanometre dimensions but it has also been found that the induction of small fragments of DNA, some 1000 base pairs long, is more efficient after high LET radiation than after low LET. These fragments appear to arise because the particle track crosses the higher order structure of the DNA in chromatin and can cause several DNA dsb in the same chromatin fibre. Conventional methods used to detect DNA dsb may not detect these fragments and may be underestimating the number of breaks. Some interesting measurements which may not be unrelated to the fragment effect show that when the DNA dsb induction by different radiation qualities is determined in Yeast there is an increase in effectiveness above unity for particles at about 100 keV/μm which decreases at higher LET values. This result is in contradiction with that found in mammalian cells and this contradiction needs to be resolved.

Experiments to measure the minimum energy deposition needed to induce single and double strand breaks have been have been made using dry plasmid DNA initially and more recently the effects of increasing hydration of the DNA has been studied. The results confirm the measurements from the dry DNA by showing that 7-8 eV is sufficient energy to induce both single and double strand breaks, the effect of hydration gives a 2-4 fold increase in yield associated with the water radicals produced in the hydration layer close to the DNA. The hydration does not have a strong effect on the threshold energy needed to induce the breaks. This result has important implications for the theoretical modelling of track structure interaction with DNA.

Other experiments looked specifically at the effect of accelerated heavy ions on cytological end points such as prematurely condensed chromosome (PCC) fragments, translocations and genetic instability. In human lymphocytes it was found that translocations were induced twice as frequently as dicentrics, reflecting to some extent that found after X-rays. Dose effect relationships were linear also for PCC but the RBE measured for PCC was close to unity. Using PCC measurements it was found that the repair after heavy ion exposure was less than after X-rays which might indicate a more difficult repair of complex lesions. In contrast the use of a DNA repair inhibitor increased the initial yield of PCC by a factor of two after both heavy ion and X-ray exposure. The studies of genetic instability, defined as the occurrence of chromosomal aberrations in cells several cell divisions after exposure, have revealed that in an immortalised Chinese hamster cell no instability was induced neither by heavy ion or by X-ray exposure when the cells were grown up in mass cultures. However, when the cells were cloned individually instability was seen in some cultures induced by both heavy ion and X-ray exposure. The reason for this difference might be that in mass cultures the normal cells grow faster than the few with an instability and dominate the cytogenetic picture. The nature of the aberrations arising in human fibroblasts several cell divisions after heavy ion exposure has shown that telomeric regions of certain chromosome arms appear to be involved and that these aberrations do not seem to be induced by X-rays. It is suggested that the differences between the genetic instability results are probably due to the differences between the cells used, the immortalised cell cultures are most probably not the best system to use for instability studies. However, it seems clear that further studies of genetic instabilities must take into account potential differences between different cell types.

Several of the studies on the effects of radiation quality have made good progress and are showing considerable innovation promising important results in the future. Care must be taken to avoid getting too bogged down in a too large investigation of experimental inconsistencies in very specific problems. It is important to realise that in the future work on the effects of radiation quality will need to be closely coordinated with the work of the theoretical biophysics groups dealing with track structure and mathematical analysis of cellular effects in order to test the theoretical models in a critical way.

3.2.1.4 ANIMAL CARCINOGENESIS

During the 1990-1995 period research has been gradually re-oriented to gain a better understanding of radiation action at the molecular level and at low radiation doses. Importance has been given to the determination and analysis of the early events of carcinogenesis. Since human data is not available, well oriented and focused animal studies to study radiation oncogenesis are both relevant and indispensable. They cannot be totally replaced by *in vitro* investigations since the basic characteristics of tumours cannot be studied and understood from purely *in vitro* studies of isolated cells.

Mouse leukaemia

The cytogenetic/molecular studies on the mechanisms and genetics of murine radiation leukaemogenesis (Acute Myeloid Leukaemia (AML)) have been focused on the characterisation of early cytogenetic events in the induction of the tumour and on specific

molecular events. Previous work between has shown that cytogenetic investigations of bone marrow cells from the affected mice commonly show specific changes in chromosome 2 (ch2) at what might be "fragile sites" and molecular studies revealed that the DNA at these sites has a special sequence which includes an inverted telomere like region. More recently attention has been given to establishing the relationship between the pattern of region-specific ch2 deletion/rearrangement and the presence of interstitial telomere-like repeat (TLR) sequence arrays on this chromosome. Statistical analysis of data demonstrates a strong correlation between interstitial ch2 TLR arrays, radiation-sensitive fragile sites and breakpoints in AML. The studies suggest that the terminal region as well as the interstitial region of ch2 may encode genes involved in myeloid leukaemogenesis. Telomeric DNA repeat sequences in chromosomal radiosensitivity, cellular immortalization and neoplasia are apparently very important and need more investigation.

Parallel studies revealed that ch2 mediated leukaemia processes do not differ significantly after high and low LET radiations; also there is no obvious contribution to myeloid leukaemogenesis from high LET induced genomic instability.

Bone-seeking alpha-emitting radionuclides

Observations in human populations exposed to bone-seeking alpha-emitting radionuclides have shown that the tumours of the bone and blood systems are the predominant radiation-induced malignancies. This has also been observed in experimental animal models. However, little is known about the target cell population affected by the alpha-irradiation. Irradiation of sensitive cells may take place in the bone itself, but also within the bone marrow. In order to define the points at which interaction between bone cells and carcinogenic radiation takes place an *in vitro* culture model of osteogenic differentiation from murine bone marrow precursors (the haematogenic bone marrow is relatively well defined, in both its lineages and location) was established. The administration of Americium-241 to mice prior to analysis of marrow cell population induces a dramatic increase in the *in vitro* proliferation of the cells of the osteogenic lineage. The *in vivo* data indicate that a significant proportion of administered Americium-241 does indeed enter the marrow cell mass. Thus the osteogenic stem cell must be considered as a potential target of osteosarcomagenic radionuclides that otherwise are deposited in the bone. A number of other radionuclides are also able to enter the skeleton, and ultimately irradiate osteogenic and haematopoietic marrow elements.

Dose distribution studies with bone-seeking radionuclides (Plutonium 239, Americium 241 and Uranium 233) show the majority of the injected radionuclide that is retained is deposited within the skeleton. There is also an approximate correlation with the bone-deposited dose and the incidence of osteosarcomagenesis in these animals. This suggests that a sensitive cell population also resides within the endosteal region of those bones with a high surface area in contact with the marrow and blood spaces.

At the same time molecular analysis of the genetic events in radiation induced carcinogenesis focused upon identifying which mutational events take place. The p53 tumour suppressor gene is implicated in the regulation of DNA repair and genome

stability. Thus, in cells subjected to DNA damage p53 mediates cell cycle transit to allow repair or to initiate cell suicide in severely damaged cells. Consequently loss of p53 function would be anticipated to have serious repercussions for the integrity of the genome in irradiated cells. Studies were oriented on the possible mutation of the p53 tumour suppressor gene locus. It was established that p53 gene mutations were a frequent occurrence - close to 100% -in radiation-induced osteosarcoma cell lines. Efforts to repeat this observation in tumour tissue was not successful, the majority of the tumours did not exhibit p53 mutation. This suggests that such mutations possess a strong growth advantage *in vitro* but not *in vivo*. It is evident that in a proportion of tumours arising after irradiation there are p53 mutations, but more work is needed to determine its importance and its degree of contribution to the carcinogenic process.

Statistical analysis

In a project dealing with the analysis of more classical types of animal studies, which are certainly diminishing in favour of the early event type of studies, two computer programmes (LifePrep and LifeStat) have been developed to provide a standard tool for the analysis of dose effect relationships. These programmes have been applied together with other statistical methods to the analysis of different series of animal data. In the same project studies designed to investigate dose rate, fractionation and inverse dose rate effects of fission neutrons on the induction of epithelial tumours in mice did not reveal any influence of the time regime on survival and tumour induction. This result confirms comparable experiments using cell transformation as an end point and contradicts previous results with cell transformation which had suggested a significant inverse dose rate effect with neutrons.

Transgenic animals

Transgenic mice Eμ-*pim-1* have been found to be sensitive to the induction of lymphoma by X-rays. Almost all the tumours are T-cell lymphomas and rearrangements of the T-cell receptor gene showed that they are monoclonal in origin. The results suggest that these transgenic mice, giving nearly identical tumours, could provide a useful model to study the involvement of oncogenes or tumour suppressor genes in the process of lymphomagenesis.

Progress in the area of radiation oncogenesis has been good demonstrating an increasing application of molecular biological techniques which is leading to a gradual evolution of the research away from the large scale animal exposure experiments towards the more detailed analysis of molecular changes in the neoplastic and pre-neoplastic tissues. Research in this field should continue since it is important to have detailed knowledge of the early events in radiation oncogenesis in order to be able to develop a better understanding of the cellular processes involved so as to be able to model human cancer risk after low dose radiation.

3.2.1.5 RADIATION EFFECTS IN GERM CELLS

Mendelian and multi-factorial hereditary risk

Studies of the effect of radiation on germ cells aim to provide a better scientific basis for the estimation of radiation risk to future generations and encompass both theoretical, as well as, experimental research. The hereditary effects of radiation have not been revealed at a statistically significant level in the offspring of the Atom bomb survivors and the data only permit an upper limit estimation of risk to be made. These risks are based on naturally occurring Mendelian diseases but some of the theoretical work suggested that this was not the best basis for the estimation of radiation risk and that the current estimates of risk for these diseases are conservative although they do provide a margin of safety. This conclusion is based on an examination of the molecular nature of the naturally occurring Mendelian diseases in over 200 genes which showed that the majority of spontaneous mutations are point mutations, some are associated with the expansion of trinucleotide repeat sequences and the rest are small deletions, while radiation tends to induce deletion type mutations. There do not appear to be many mechanistic similarities between the naturally occurring "spontaneous" and the radiation induced mutations.

Some 350 human mendelian diseases have cancer as a main feature and these diseases arise from germinal mutations in "cancer predisposing genes" so that a proportion of the population may be predisposed to cancer and also to radiation induced cancer. The question arises, therefore, of how this cancer predisposition impacts on radiation risk in the general population. A modelling study revealed that, when there is a heterogeneity in the population with respect to cancer sensitivity, irradiation results in a greater increase in the frequency of induced cancers but this increase is only detectable when the proportion of cancers due to predisposition is large. However, even though the effect expected is small in the normal population the cancers will occur in the predisposed individuals.

Many inherited diseases, the so called multifactorial diseases, arise from a number of genetic mutations coupled with environmental factors. It is only recently that the effect of radiation on these multifactorial diseases has been taken into consideration in estimating hereditary radiation risk. The problem is complex and the modelling efforts have been concerned with transforming a purely descriptive concept into mechanistic and ultimately quantitative models.

Effects in female germ cells

Experimental studies of the effects of radiation on female germ cells have concentrated on the mouse and on the guinea pig. The mouse oocytes are very sensitive to radiation and are therefore not considered to be an ideal model for the human oocyte which accounts for the effort made to develop the guinea pig system. Exposure of mouse oocytes to 1 Gy of radiation prior to mating with unirradiated males produced embryos carrying structural chromosomal abnormalities and exposure of a special strain of mouse at various oogenic stages produced malformed foetuses. Exposure of "immature" oocytes to 2.8 Gy at 0.28 Gy/h gave a significant increase in malformed foetuses but no significant

increase was found at 0.7 Gy while exposure to 1.4 Gy at the lower dose rate of 0.011 Gy/h allowed the "less mature" oocytes to survive leading to a significant increase in malformed foetuses. In the same mice exposure of the males to 2.8 Gy also led, following mating to unexposed females, to malformed foetuses. However, the fact that almost all the malformations detected were of one type is a major restriction in these results which must be kept in mind.

A major effort has been devoted to developing fluorescence in situ hybridization for the X and Y chromosome of the mouse in order to be able to study radiation induced sex-chromosome aneuploidy in germ cells of male mice. This effort was not completely rewarded as the probes developed gave diffuse signals in sperm heads making it difficult to detect sperm with two Y chromosomes. Experiments with the X chromosome probe suggested some induction of X-chromosomal aneuploidy in spermatocytes at the time of irradiation.

The studies devoted to the development of the guinea pig oocytes as a model to assess the radiosensitivity of human immature oocytes as the principal stage at risk for genetic radiation risks in human females have been successful and reproducible analyzable chromosome preparations of the cultured oocytes can now be routinely produced. The comparison between the guinea pig and the human female is based on the fact that the nuclear morphology of large oocytes present in the new born guinea pig is similar to that of the human resting oocytes. The experiments revealed that exposure of all oocyte stages induced increased frequencies of chromosomal aberrations but that oocytes irradiated as immature oocytes showed the lowest increase. Oocytes irradiated well into the oestrus cycle showed a much larger increase in aberrations and this experiment indicated that the irradiation "stimulated" meiosis I in meiotically competent oocytes. This stimulation seems to arise as an acceleration of growth and maturation of smaller follicles to compensate for the loss of large follicles in irradiated animals. The results show that there are considerable differences between the radiation response of the female mouse, used until now as a surrogate for the estimation of radiation risk in the human female germ cells, and the female guinea pig.

Dominant and recessive mutations

Radiation induced mutation rates to dominant cataract and enzyme activity alleles were determined in two different animal species, the mouse (*Mus musculus*) and the hamster (*Mesocricetus auratus*) covering various germ cell stages of both males and females. The results do not reveal any real differences in the mutation rates measured and support a major assumption needed for the extrapolation of animal experiments to derive human hereditary radiation risk, namely that there is not a difference in sensitivity to radiation induced mutagenesis in germ cells in different species. However, the hamster shows the same high sensitivity to radiation induced cell killing in immature oocytes as the mouse and in this respect both species differ from the human in their response to radiation. It has been found that the doubling dose for enzyme activity mutations in the mouse is similar to that found for the dominant cataract mutations but higher than that found for recessive specific locus mutations which leads to the conclusion that estimations of human genetic risk should be based on animal studies of comparable genetic end points.

In connection with these findings radiation induced deletions have been recovered as transmitted mutations expressing a mutant phenotype at a sub-set of the those loci which when mutated express a dominant phenotype in both the mouse and *Drosophila.* These loci are classified as haplo-insufficient, which means that both copies of the gene are required to be functional to get the normal phenotype. Thus the deletion of one allele by radiation leads to the dominant mutation phenotype. These results are important for two reasons, they confirm that radiation is essentially an inducer of deletion mutations confirming work in somatic ceils, but in addition they lead to a change in the assumption made previously that deletion mutations would induce only recessive mutations while dominant mutations were assumed to be a gain of function mutation. Now it seems that the dominant mutations are recovered at haplo-insufficient loci and this is important for the human situation as it can be predicted that dominant mutations would be expected to occur at the haplo-insufficient loci. The dominant cataract mutation is expected to be haplo-insufficient and the mutations have therefore been mapped. Both known and previously unknown loci have been found and one of these loci, the *gamma-crystallin* gene cluster encodes for structural proteins so it is something of a surprise to find that it is haplo-insufficient. A large group of multilocus deletions which express deleterious dominant phenotypes have been identified in offspring of irradiated mice and localised to different chromosomes. Their distribution is non-random suggesting that certain regions of the genome are more prone to large deletion. The homologous regions of the human genome could be very interesting for both genetic and somatic studies of radiation induced mutagenesis. In contrast, molecular analysis of an X-linked locus in the mouse revealed that the recovered mutations were all intergenic alterations and not deletions suggesting that radiation induced deletions on the X chromosome are unlikely to survive or be transmitted.

Effects in male germ cells

The effects of changes in the heterogeneity of the mouse stem cell spermatogonial population on the response to radiation have continued to be studied using a number of end points including cell killing, translocations, recessive specific locus mutations, dominant cataract mutations and enzyme activity mutations. In general, there is a correlation of the relative yields of the different effects in the altered spermatogonial populations suggesting that a common or similar mechanism of radiation induced effect leads to the different end-points, although there are one or two exceptions. Other radiation experiments using spermatogonia and dose effect relationships for killing and translocations suggest that three assumptions made by Leenhouts and Chadwick (Molecular Theory of Radiation Biology, 1981, Springer Verlag) to explain a variety of translocation dose effect relationships are incorrect and a new model to explain the results is being developed.

Experiments have also been made using human male germ cells with human-hamster *in vitro* fertilisation techniques to study radiation induced micronuclei. It has been shown that following irradiation of mature spermatozoa *in vitro* the micronuclei were of human origin and that the results parallel the induction of chromosomal aberrations. Studies with centromere and telomere staining showed that most radiation induced micronuclei lacked a centromere and were probably acentric fragments and those with centromeres usually also showed telomeres suggesting an origin from dicentrics or as whole

chromosomes. There was a suggestion that radiation was a weak inducer of aneuploidy. A FISH assay was developed for use in human sperm and applied to study aneuploidy in men exposed occupationally or for radiotherapy. The results showed no increase in aneuploidy for those exposed occupationally at low doses but an increase of 2,5 times was found in men exposed to high doses for radiotherapy. A method using mutations at microsatellite loci has been developed to provide a screening of radiation induced mutations in human spermatozoa. Initially an assay using dinucleotide repeat sequences was used but found to be unstable and unreliable but an assay using tetranucleotide repeats looks more promising.

Taken as a whole these results provide interesting perspectives for future research on germ line cells and on hereditary risk of radiation. However, results from the offspring of the Japanese Atomic Bomb survivors do not indicate a significant hereditary effect of the radiation and this finding means that the research on radiation effects in germ cells must be of lower priority when compared with the research aimed at understanding the mechanisms of radiation induced cancer and this difference in priorities is reflected in the research topics identified for cost-shared research in the Fourth Framework Programme.

3.2.1.6 METABOLISM AND EFFECTS OF RADIONUCLIDES

Decorporation

A lot of progress was made towards the reduction of risk of late effects from incorporated radionuclides. The efficacy of treatment for incorporated actinides by the administration of chelating agents was improved and guidance to those involved in the treatment of accidental overexposures was provided. Research concentrated on actinides because of their importance at the workplace. The agents recommended for enhancing the excretion of Pu, Am, Th and Np from the body are the trisodium, calcium and zinc salts of DTPA and for U is sodium bicarbonate. These substances, however, are not completely effective.

Previous work in the programme has shown that analogues of siderophores, and more specifically 3,4,3-LI(1,2-HOPO), are more effective than DTPA after the inhalation and intravenous injection of Pu; the ligands were considered equally effective for Am under these conditions. Recent studies demonstrated that of all the methods of intake investigated, the greatest differences between the efficacies of LIHOPO and DTPA for Pu and Am occurred after simulated wound contamination, LIHOPO being more effective. The comparative efficacies of LIHOPO and DTPA for Th showed that DTPA is not an effective method of treatment for Th deposited in the lungs or at simulated wound sites. Whilst considerable improvements in decorporation have been effected with LIHOPO, the differences between the efficacies of the chelates are less than after Pu administration. Research on the decorporation of U and Np with LIHOPO has shown that the ligand also has affinity for these metals although its efficacy is substantially less than for the other actinides.

The synthesis of LIHOPO is quite difficult and the chemical yield is low. Very recent

results have shown that a new siderophore analogue TREN-Me(3,2-HOPO) is as effective as LIHOPO for the decorporation of Pu and possibly other actinides. The substance was reported to be easier to synthesize and of lower toxicity in mice. Concerning the administration of LIHOPO to humans, large and comprehensive toxicity studies are necessary.

Another group analyzed the efficacy of ZnDTPA in drinking water for the treatment of inhaled forms of Pu and Am nitrate. This method of administration was as effective as twice-weekly injections of DTPA.

For the decorporation of uranium, phosphonic acid derivatives and calixarenes tested so far have been ineffective and especially the calixarenes have exhibited toxic symptoms. For the decorporation of polonium the current agents of choice dimercaptopropanol and dimercaptosuccinic acid and dithiocarbamate are only partially effective. So far the most effective have been the bisdithiocarbamates of which that code named HOETTTC has proved to be the most effective.

The decorporation of plutonium and americium by LIHOPO has been most successful and the agent appears to be very promising for practical use. However, the future use of 3,4,3-LI(1,2-HOPO) for decorporation of Pu and Am in humans will depend on the results of comprehensive toxicity testing in animals and an improved method of synthesis. The execution of such a comprehensive toxicity testing exercise is considered to be beyond the scope of the Fourth Framework Programme but is recommended for consideration by the nuclear industry. More work is needed to find an efficient agent for the decorporation of uranium, neptunium and polonium.

Eulep

The activities of the "European Late Effects Project Group" (EULEP) include promoting the training of young radiobiologists, supporting scientific exchange visits between laboratories for the purpose of acquiring technical expertise, and stimulating participation of young scientists in scientific conferences.

One of its objectives is the standardisation and development of methodology, which is carried out by three committees: external radiation dosimetry and techniques; internal radiation dosimetry and techniques; and cell and molecular pathology. A number of task groups have been created for specific problems and an archive of long-term radiobiological studies has been established consisting of a comprehensive database and decentralised specimen archive. Another task that EULEP have undertaken has been the organisation of specific workshops for instance for the annual meeting of the European Society of Radiation Biology.

The other task EULEP had during this period was to review the future structure and activities of EULEP, in the light of changing requirements and priorities for the Fourth Framework Programme in radiation protection research. The adoption of multi-national, multi-partner projects in 1990 -1991 meant that several of the activities undertaken by EULEP, and the other comparable organisations EURADOS and IUR, in the past, such as coordination and grouping of contractors in work groups, have been subsumed within

the programme.

In future, it is foreseen that these three associations should start working together in a common project, with newly developed coherent and comprehensive aims.

3.2.2 NON-STOCHASTIC EFFECTS OF RADIATION

3.2.2.1 ACCIDENTAL EXPOSURE OF LARGE PARTS OF THE BODY: IMMUNO-HAEMOPOIETIC EFFECTS

Good progress has been made in research on the treatment of accidentally exposed persons and both the existing approaches, as well as new approaches, have been developed and have successfully improved. Data bases have been set up to collect case histories of patients given irradiation and appropriate treatment. Furthermore, registries are available for recruiting stem cell donors, including a European Cord Blood Bank.

Pathophysiology of radiation induced alterations

The results achieved are quite successful in promoting the pathophysiological basis of therapeutic approaches to overcome the acute radiation syndrome in man, using the most advanced technologies available.

Assessment of the radiation sensitivity of haemopoietic stem cell subsets which are relevant for both short-term and long-term haemopoietic regeneration is a key factor in the pathophysiology of radiation-induced alterations of the immuno-haemopoietic system. Priority has been given, therefore, to the identification of those subsets both in murine systems and rhesus monkeys, as well as to the development of *in vitro* assays for immature haemopoietic cells. Using a murine competitive transplantation assay, the separation of short and long term reconstituting stem cells was established. The frequency of the long-term reconstituting stem cells was estimated at 1-2 per 10^5 bone marrow cells and their pluripotential nature was demonstrated. This means that the properties, including the radiation sensitivity, of these cell populations can be directly studied. These results have been extrapolated to rhesus monkeys and humans. The most immature cells have been tested for their *in vivo* properties using transplantation experiments. In primates, the short-term and most probably also the long-term repopulating stem cells are confined to the small (0.05% of all bone marrow cells) $CD34^+/DR^{dull}$ fraction. This fraction has been studied in detail for growth factor receptor distribution *in vitro* and growth factor responses *in vivo*. In parallel another work concentrated on the replication and differentiation of haemopoietic stem cells and on the assessment of radiation damage to the microenvironment of the bone marrow and on the radiation response characteristics of stromal progenitor cells and their modulation by growth factors. For this purpose the biological and molecular biological characterisation of stem and progenitor cells was studied extensively. Highly purified immature $CD34^+$ subsets were obtained using an improved purification strategy for the rapid isolation of pure cells. This is important for the analysis of the effects of ionising radiation at the molecular level. However, the mechanisms that control proliferation and differentiation of primitive haemopoietic stem cells/early haemopoietic precursor cells under physiological conditions as well as after exposure to ionising radiation are still poorly understood.

A technique to study expression of antigens linked to differentiation in single $CD34^+$ cells from cord blood, peripheral blood and multipotent cells from blast cell colonies (BCCs) was developed. This strategy was used to investigate the mRNA phenotype of multipotent BCCs. It is now important to investigate whether single cells from BCCs can

be induced to unilineage differentiation and proliferation because it will then be possible to investigate the cascade of gene expression that controls differentiation along a particular haemopoietic lineage.

Another goal in this field has been to design appropriate strategies to accelerate recovery of the immune system after irradiation. The results indicate that it is possible to counteract radiation-induced damage of thymus and spleen cells in mice exposed to lethal doses of X-rays. The recovery of T and B cell number and functions was complete as soon as 7 days after irradiation and could be achieved by injecting mice with a combination of recombinant interleukins, IL-11 and IL-3. The synergism of these cytokines was very efficient when a small dose of IL-11 was injected with higher doses of IL-3. More studies are necessary to see the efficacy and the side effects of this combination.

Diagnosis of the radiation syndromes: preclinical and clinical approaches

There were several innovative contributions from the different groups involved in this area of research. The use of growth factor treatment as a diagnostic tool after high dose exposure was studied. Previously it was reported that there was a disappointing correlation between radiation dose, growth factor treatment and recovery of mature peripheral blood cells. For this reason, the studies were extended to immature CD34 positive cells in both bone marrow and blood. The number of circulating CD34 positive cells appeared to be well related to bone marrow CD34 positive cells and is proposed now as a marker for residual stem cell numbers.

Since 1992 the work has advanced and is continuing on the "biomathematical granulocyte system model" developed, earlier in the programme, to be able to calculate the number of stem cells that would remain after total body radiation exposure and from which recovery could begin, using the pattern of granulocyte changes measured following exposure in accident situations.

Prevention of the radiation syndromes

In this area two questions were addressed: in what way would the administration of cytokines be useful to accelerate haemopoietic recovery to avoid the need for intensive care and in what way one can avoid graft rejection and graft-versus-host disease. *In vivo* efficacy and side effects of Interleukins as well as the combination of growth factors were tested. It could be shown that the repopulation of damaged bone marrow sites can be accelerated by the administration of two growth factors. The problem of graft rejection and graft-versus-host disease after haploid identical marrow transplantation was tested in experimental animal models by infusion of donor T cells devoid of alloreactivity towards a recipient. The results are encouraging. Another problem is the long time HLA typing takes to find the good donor. Improved technologies for a rapid and precise HLA typing in humans was studied. This technique requires a small amount of cells for DNA extraction ($5x10^6$) a reasonable time (6 hours) and is not expensive. It can be expected to improve the different approaches designed to reduce or avoid immunological consequences after bone marrow transplantation.

Therapy of the radiation syndromes

The use of combinations of growth factors to accelerate haemopoietic reconstitution after total body irradiation (TBI) was a central issue of research and led to many publications. The important thing is that pilot experiments demonstrated that thrombopoietin (TPO) is highly effective in preventing thrombopenia at the midlethal dose of 5 Gy TBI but ineffective at a dose of 8 Gy TBI, which is similar to all other growth factors studied. This leaves a "window" of about 7-10 Gy TBI where haemopoietic stem cell transplantation should still be considered and further developed as a life-saving therapy for radiation accident victims, at least to abridge the period of 4 weeks to 3 months of profound cytopenia. In this area, the transfusion of allogeneic CD34+ cells to achieve transient engraftment as a means to facilitate the management of radiation accident victims was considered to be most relevant. The use of cord blood hemopoietic stem cells as an alternative source of stem cells was considered. The cord blood stem cells, especially after *in vitro* multiplication, is set to become a very important alternative source of stem cells to reconstitute radiation induced hemopoietic failure.

The introduction of modern investigative and therapeutic tools has recently increased our knowledge of physiopathological alterations following radiation overexposure to the muscles, the lungs and the central nervous system. Therefore, new methods of diagnosis, prevention and treatment of radiation induced lesions to organs other than the haemopoietic system were studied. This work is now mainly oriented towards treatment of these lesions.

The research has developed very positively over the past years and there are exciting prospects for the early diagnosis of bone marrow damage after accidental exposure of large parts of the body as well as for new treatment modalities for different levels of total body exposure. The prospects for the future research programme look very promising.

3.2.2.2 LOCAL EXPOSURE OF SKIN AND SUB-CUTANEOUS TISSUES: EFFECTS AND TREATMENT

Cases of over-exposure of skin and underlying tissues can occur in both medicine and industry. Early diagnosis and late effects prognosis are fundamental to evaluate the extent of the injuries and to manage the treatment.

The diagnosis of early (inflammatory reaction), subacute (thrombosis and ischemia) and late (necrosis and fibrosis) effects of radiation injuries of skin and underlying tissues was performed on rabbits using ^{67}Ga scintigraphy, Nuclear Magnetic Resonance (NMR) imaging of the skin and computed tomography, and in pigs, using NMR imaging, spectroscopy and skin relief measurement.

In man, in the medical surveillance of radiation workers, telethermography (TTG) with thermostimulation was used to assess the severity of the late effects of radiation injuries in the hand and fingers.

The expression of the transforming growth factor beta-1 (TGFß1) was investigated with a view to establish its role in the pathogenesis of radiation fibrosis and skin cancer

induction after superficial beta irradiation. TGF ß1 is expressed to some degree in nearly all tissues. The results obtained on the TGF ß1 indicated that the synthesis of this growth factor was upregulated during the first clinical phase of erythema, which occurred 3 weeks after irradiation of the pig thigh. The possible induction of growth factor was then investigated at various times after irradiation of pig skin. It was found that both TGF ß1 and collagen type I mRNA were highly induced at 6 hours in the irradiated pig skin during the first wave of gene response. These early inductions were found only after doses high enough to induce fibrotic lesions several months thereafter. These *in vivo* results suggest a role for the induction of early response genes in the pathophysiologic affects of ionising radiation on skin. The molecular mechanisms underlying the response of the skin to radiation remain unclear. TGF ß1 is important in cell proliferation, differentiation, cell migration and the synthesis of extracellular matrix by fibroblasts. It should therefore be a significant cytokine in the radiobiological response of the skin.

The pathogeny of early and late effects was approached by measuring the expression of AP1 and p53 genes in pig skin irradiated with low and high doses. After either ß or γ ray irradiation, the prevalent role of TGF ß1 in the development of fibrosis was demonstrated in pigs and mice.

In pigs, beneficial effects of liposomal bovine Cu/Zn-SuperOxy-Dismutase (Cu/Zn-SOD) on skin and muscular tissue fibrosis were demonstrated after administration via a systemic pathway. In man, a study using the liposomal bovine Cu/Zn-SOD as topical application gave positive results in skin biopsies in 44 patients, with respect to the reduction of the fibrosis grade. In 132 patients treated by topical SOD for radiation-induced fibrosis for 90 days and followed by telethermography with cryostimulation for a period ranging from 18 to 72 months, 50 % showed a continuous improvement of the fibrotic lesion, 30 % a durable stabilisation and 20 % a slight deterioration.

Further progress in the area of over-exposure of skin and subcutaneous tissues is dependent on a more profound understanding of the cellular and molecular mechanisms involved, which will lead to the development of new, more effective methods for the treatment of skin lesions in exposed individuals.

3.2.2.3 RADIATION EFFECTS TO THE THYROID AND ITS PROXIMATE TISSUES

In this area, thyroid dosimetry, new models for radiation carcinogenesis and the expression of different oncogenes have been defined.

Dietary iodine and thyroid dose

Some progress was made in fetal and neonatal thyroid dosimetry and the dosimetry for sensitive target organs or tissues, like the brain, liable to be irradiated by radionuclides taken up in the fetal thyroid or maternal organs. In this context thyroid mass and iodine kinetics have been defined in pregnant women and neonatals as a basis for this dosimetry. Fetal and neonatal dosimetry have been defined using phantoms. Results from these phantoms will prove to be very useful for estimating detriment to the fetus from ingestion of I-131.

In Europe there is a marked variation in the dietary intake of iodine and hence in the mass and uptake of the thyroid. Thyroid dose maps have been established for all European countries allowing an estimation of doses for the population in case of a nuclear accident. Iodine deficiency manifests itself in a population in the form of elevated thyroid mass/volume and increased iodine uptake. In the wake of a nuclear accident, this would imply the elevated uptake of radioiodines and hence an increased dose to the thyroid.

A new dosimetry unit has been proposed; further investigation is needed to examine how useful it would be if applied to the estimation of risk coefficients.

Search for *in vivo* and *in vitro* models

New models of transgenic mice expressing all types of thyroid tumours have been created for radiation studies. In all cases I-131 (1μCi at 15 days of age) induces invasive tumours.

Human thyroid cell lines have also been created but they dedifferentiated. An ideal immortalized human thyroid cell line has not yet been produced.

Molecular biological studies have recently suggested that papillary and follicular carcinomas in humans show different oncogene involvement; ras genes being more frequently mutated in follicular carcinoma and translocations of the ret and trk oncogenes being more frequent in papillary carcinomas. Interestingly the ret oncogene has been shown to be frequently mutated, rather than translocated, in medullary carcinoma. Further results suggest that radiation may not cause any particular changes in the patterns of the expression of the oncogenes so far studied. This does not exclude the possibility that other oncogenes, not yet studied, may show different patterns of expression.

3.2.3. RADIATION EFFECTS ON DEVELOPING ORGANISM

3.2.3.1 BRAIN DAMAGE

The rather limited project of the 1990-1991 programme has grown out into a panel of investigations encompassing many aspects of the special radiobiology of the foetal brain.

During the last period it had been found, in contrast with current radiobiological observations, that the susceptibility of the foetal brain to prenatal irradiation did not decrease when the dose-rate was attenuated during a protracted exposure. This raised the question of defining the minimal dose limit of such an unexpected phenomenon. Previous work also revealed that the cingulum volume is for any mode of irradiation a more sensitive criterion than brain atrophy. However, more recent work shows that the cingulum volume endpoint is not found to be as radiosensitive in chronic exposures as it was in acute ones. It can be assumed that the radiosensitive period of the cingulum is restricted to a very small period of the cerebrogenesis, 15 days post-conception, and in consequence, only lasts for 1/4 of the total chronic exposure time. An alternative explanation would be that the cingulum atrophy does not show below a certain threshold dose, at least for chronic exposures. These points are important and should be considered in future work on early effects of prenatal irradiations.

With respect to the question whether there is an increase in the effects of protracted irradiation, very low protracted prenatal irradiation (PPI) with gamma rays (5 and 10cGy) did not induce a measurable brain atrophy in the 3 month old rat after an exposure during the critical 12-16 day post conception period. This observation had been a first indication for the existence of a threshold in the dose-effect relationship of the developing brain after protracted gamma rays. It is therefore concluded that ageing does not amplify microcephaly.

The neutron-induced brain atrophy is significant down to a dose of 1 cGy per day during a 4 day exposure. The question "can a 5 cGy protracted prenatal irradiation induce brain atrophy" has to be given a positive answer for neutrons from day 12 to 16 post conception and a negative answer for gamma rays. Severe brain alterations arise after high dose only. The critical foetal period is undoubtedly day 12 to 16 post conception.

Optimal conditions for cultivating nerve cells have been developed. This will be of great help for future *in vitro* research work in this field.

The effects of low doses of radiation on functions of the central nervous system were investigated. Deficits were assessed using both conventional and behaviourial techniques. It is known that exposure of unborn humans during corticogenesis is associated with an increased incidence of severe mental retardation, and with reductions in both intelligence and performance at school, although the precise aetiology and dose-response relationships for these endpoints remain uncertain. The association between dose on gestational day 18 and deficit in performance as adult using doses of between 0.1 Gy and 1.0 Gy were investigated. It seems probable that a "functional" threshold does exist since only with doses above about 0.25 Gy were the deficits in performance large enough to allow the behaviour of the exposed animals to be distinguished from that of the controls.

Research in this field will be reinforced in the future by molecular biology assessments. The problem of DNA repair in the prenatal brain will be central in these studies. Work should concentrate essentially on the understanding of the mechanisms of low dose (rate) lesions; development of in situ molecular indicators and definition of the threshold doses for functional damage.

3.2.3.2 STUDIES ON TRANSFER OF RADIONUCLIDES IN UTERO

The information obtained in studies on biokinetics and dosimetry of the transfer of radionuclides to the fetus is being used in current ICRP work on the estimation of doses to the human fetus.

Studies of the transfer of ^{210}Po to the fetus in guinea pigs have been reported previously. Other sources of ^{210}Po in the fetus are transfer after formation from ^{210}Pb accumulated in the maternal skeleton and in-growth after transfer of ^{210}Pb. For ^{210}Pb administered to rats and guinea pigs during pregnancy, transfer was largely influenced by skeletal formation in the fetus and showed significant increases shortly before birth.

Autoradiographic studies using a beta emitter, ^{241}Pu have been undertaken to obtain information on the microdistribution of Pu in relation to sensitive cells in the yolk sac and other tissues. At 11 days of gestation, when haemopoiesis is established in the yolk sac, the greatest concentrations of ^{241}Pu were in the columnar epithelium of the endodermal layer with less activity associated with the primitive erythroblasts arising from the mesodermal layer.

Other work has focused on the uptake of radionuclides by the skull with the aim of studying the effects on the brain. Studies of the distribution of ^{141}Ce in fetal and neonatal rats showed that the skeleton accounted for 60-85 % of total fetal or neonatal activity at one day after administration. Other organs, including the brain did not accumulate significant ^{141}Ce activity.

Studies have also been conducted on the effects of exposure to incorporated radionuclides and external radiation on haemopoietic development in utero and after birth.

Although some results were interesting, no definite conclusions were drawn from the results of these experiments. This aspect of the work is likely to fall into an area of lower priority in the future.

3.3 RISK AND MANAGEMENT OF RADIATION PROTECTION

INTRODUCTION

Risk assessment and risk management have important roles in the development and subsequent implementation of well conceived policies on health, safety and environmental protection. The adequacy of these policies and the efficacy of their implementation will depend, *inter alia*, on the reliability with which risks can be quantified and assessed, and on the techniques or processes available for their evaluation and management. These different aspects have been the focus of research carried out within this area of the Programme.

The assessment of risk has been an important element of the Programme since its inception. It was given increasing attention through the 1970's when major progress was made internationally both in the quantification of the risks of radiation exposure, through epidemiological studies and in the increasing attention given to the radon exposure of the population, and in the development of methods to assess the health and environmental risks of nuclear installations in both normal operation and in accident conditions.

The quantification of low dose radiation risk is derived, essentially, from epidemiological studies of the Japanese atom bomb survivors. Although the involvement of European scientists in the study of the Japanese is increasing certain questions with respect to risk quantification cannot be addressed through the Japanese population, such as exposure duration and indoor radon risks. There are, therefore, good reasons for studying other exposed cohorts, for example, uranium miners, people exposed as children, nuclear workers, etc which can provide guidance and quantification of risk for these different exposure situations. The epidemiological studies undertaken in the Programme gradually increased through the 1980s to investigate the relevant cohorts although a stabilisation is clearly discernible in the Third Framework Programme.

One of the largest contributions to population dose arises from the unavoidable exposure to radon gas and its progeny in the home environment. The assessment of the level of exposure in homes throughout Europe has been an important part of the programme with early emphasis on the mapping of high radon areas and the measurement of radon levels in typical European houses. The programme has matured to investigations of radon diffusion from the soil into houses, the study of the physico-chemical properties of the radon progeny in homes and the development of methods to reduce the levels of radon in houses. Although the focus of considerable concern the demonstration of an adverse effect of indoor radon exposure on man using epidemiological studies remains equivocal and there is consequently an on-going series of animal experiments which have gradually evolved from studies of lung cancer induction from relatively short high exposures in a simulated mine environment to consider the effect of more protracted exposures in a simulated home environment.

Increased resources within the Programme were allocated to the assessment and management of risks in the early 1980s when the topic was formally included as a separate programme sector. Attention initially focused on risk assessment but shifted with time to risk management as the methods for assessing risks have become relatively

mature.

The Programme has focused on five main areas: the optimisation of radiation exposure (or the reduction of exposures to as low as reasonably achievable (ALARA)), the development of methods to assess the off-site consequences and risks of potential accidents at nuclear installations, the development of decision support systems for off-site emergency response in the event of a nuclear accident; comparative risk assessment and risk perception and communication. Major progress has been achieved, both conceptually and methodologically, in each of these areas and particular attention has been given to the practical application of what has been developed. The ever increasing power and availability of personal computers has enabled the results of the research to be widely disseminated in the form of software products; these are being used extensively in the EU and beyond and, inter alia, are contributing to the more uniform and consistent application of radiation protection principles and risk assessment methods. In some areas the state of knowledge and/or the methodologies developed are now relatively mature, at least in the contexts in which they are to be applied; in other areas further development is still needed and this is indicated below.

3.3.1 ASSESSMENT OF HUMAN EXPOSURE AND RISK

3.3.1.1 EPIDEMIOLOGY

The epidemiological studies taken up in the programme are selected to address certain areas of concern, such as the radon risk question, or to add pieces to the jig-saw puzzle which must be completed so that optimal use can be made of large studies, like that of the atom bomb survivors, to derive an accurate assessment of low dose radiation risk. Consequently, the programme is made up of five projects which address a specific topic or exposed population and one project of more analytical nature.

The atom bomb survivor study in Japan provides the most important data for the current derivation of radiation risks to low LET external radiation. However, the Japanese survivors were exposed to an acute flash of radiation which is quite different from the very protracted radiation exposure by which both nuclear workers and the general public are exposed. The extrapolation from the atom bomb survivor data to derive risk for workers and the public contains inherent uncertainties, such as the dose and dose rate effectiveness factor (DDREF) and one way to gain information about this factor and also a direct estimate of the risk of very protracted exposure is to study populations which have been exposed in this way.

Nuclear Workers

One of these studies is that of the nuclear workers themselves as the industry is some 50 years old and many of the pioneers in the industry received higher, though not large doses, of low LET external radiation than are currently allowed. An international collaborative study of cancer risk has been set up as a retrospective cohort exercise in 12 countries including 7 from the European Union and to coordinate the data collection using a common core protocol. Construction of cohorts has been completed in all 12 countries except Spain and mortality follow-up has started in most countries. Follow-up for mortality is nearly complete in Finland, Japan, Sweden and the UK and analyses are about to start. Considerable attention has been paid to dosimetry as all workers have carried physical dosimeters throughout their working career. Protocols have been prepared to assess and ensure the comparability of the dosimetry systems used in the different countries and over the 50 year history of the industry. An initial analysis of workers in Canada, UK and USA has shown a strong healthy worker effect but within the worker population there is a dose effect for leukaemia which gives risk value of the same order as that derived from the atom bomb survivors but with large errors.

Childhood Leukaemia

As a consequence of recommendations coming from a Post-Chernobyl study on the "Feasibility of studies on health effects in western Europe due to the reactor accident at Chernobyl" an epidemiological study was established to study the incidence of childhood leukaemia and lymphoma in Europe as a function of time and geographic location taking advantage of the data routinely available from a variety of regional and national cancer registries throughout Western Europe. The study began in 1988 with the aim to collect data starting from 1980 to develop a background incidence prior to the accident. Most

participating centres have submitted data up to the end of 1992 and the data has been verified. The analysis of the data covers a classical analysis of incidence rates by sex, age group and geographical area based on all leukaemia, acute lymphocytic leukaemia, acute Non-lymphocytic leukaemia and Non-Hodgkin lymphoma. An alternate analysis allocates an excess radiation dose for all cases and for the populations at risk based on birthdate and place of residence using dosimetry information from UNSCEAR and trends with dose are sought. The data up to the end of 1991 show a small increase in incidence of childhood leukaemia on a Europe wide basis but the patterns of increase by age and place of residence suggest that radiation from the Chernobyl accident is not an important factor.

Indoor Radon

Radon in homes has been recognised as an important contributor to population dose from natural radiation and a potential lung cancer risk. Consequently, epidemiological studies have set out to try to determine the risk of indoor radon but most studies have been to small to draw definite conclusions and results have often been contradictory. In an attempt to overcome the limitations of restricted national studies an European epidemiological case-control study has been started with a common protocol both for the case and control questionnaire as well as the dosimetric measurements. The study covers areas in Europe with high levels of indoor radon, such as the Ardennes in Belgium, the Eiffel region in Germany, Brittany-Vendee and the Massif Central in France, and South-west England. In the Ardennes-Eiffel study 1000 cases and 1400 controls have been interviewed with the aim of having 1200 cases and 2400 controls. The controls are matched as closely as possible from patients attending the same hospital as the cases but for non-lung complaints. In the French study 270 cases with 540 matched controls have been registered and in the UK 965 cases with 1400 controls taken from the community as well as hospital have been registered. When the originally planned number of cases and controls have been reached, probably in 1996 then a pooling exercise of all the data will be carried out. Steps are already in hand to coordinate this pooling exercise. The pooling study and the eventual determination of risk depends on the estimations of exposure and comparison measurements between the different detectors used in the different studies have been made. One type of detector was found to be out of range and has been excluded from further use. In the other 4 detectors good agreement was found in houses having radon levels commonly encountered in the study but a study in houses having higher radon levels showed that attention will need to be given to variations in response of detectors in epidemiological field conditions. It is intended that measurements should be made in the houses currently occupied by the cases and controls and also in former residences but this is not always possible and details of past exposure will be derived from information on construction and geological data. One major confounding factor in this study is smoking as some 94% of the cases are smokers and smoking habits may vary from one area of Europe to another.

Uranium Miners

An alternate approach to try to derive the risk from indoor radon makes use of a wide range of data on Uranium miners where the association between lung cancer and radon exposure has been clearly established. The association has, however, only been

established at radon levels far in excess of those found in the home where the indoor atmosphere is considerably different from that in a mine. The problem of deriving indoor radon risk from the uranium miner studies is thus one of interpretation and extrapolation. Three sets of miner data have been available to the group, a French miner cohort of 1785 miners followed up to 1985 exposed at low levels, a Czech cohort of 4320 miners followed up to 1990 with higher exposure levels and the Colorado Plateau miners from the USA. The project concentrated on further improvement of the French and Czech cohort data and analysis of the lung cancer incidences using different models. Both cohorts show an increased rate of lung cancer and excess relative risks vary considerably from 0.35% for the French cohort to O.71% for the Czech cohort S, but it is concluded that the use of a single figure for excess relative risk is too crude and that risk must be considered as a function of various confounders. The Czech data show an "inverse dose rate" or "exposure period" effect especially at higher exposure rates which cause fewer lung cancers than the same cumulative exposure over a longer time period. The French data exposed at lower rates do not show the "inverse dose rate" effect. It is conceivable that other cancers are also caused by radon exposure but examinations of the data have not revealed any excess of cancers such as of the larynx and excesses of stomach, liver and leukaemia found in a pooled study of 11 cohorts could not be related to radon exposure levels. Thus, it is concluded that protection standards for radon should be based on considerations of lung cancer risk only.

An interesting development in the Uranium miner studies has been the application of multi-step models of carcinogenesis to the cohort analysis. The multi-step models are variations of the model proposed by Armitage and Doll often including the two mutation with clonal expansion of intermediate cells model as developed by Moolgavkar, Venzon and Knudsen. A version of the MVK model was applied to the Colorado Plateau miner cohort which also allows some consideration of smoking and radon interaction. It was found that the radon and smoking affect the first mutation step but not the second mutation and radon and smoking affect the cell kinetics of the intermediate cells where the radon dose enters as a dose squared term. In another exercise with the cancer models two analyses of the same animal data on radon effects using very similar models but getting rather different parameters for comparable fitting of the data were assessed. It was concluded that the models carry so many fitting parameters that comparable fits can be made with widely differing parameters and that a better understanding of the biological significance of the models is needed in order to try to rationalise the interpretations and predictions which the models can provide. This is a good example of the application of developments in the "biophysical modelling" part of the programme and though the carcinogenesis model development is in an early stage the approach deserves to be taken forward in a well coordinated way.

Thorotrast

Thorotrast is a colloidal suspension of thorium dioxide which was used as a radiographic contrast medium in various countries from the 1930's to about 1955. It contains long-lived ^{232}Th and its decay daughters, persists in the body, and therefore thorotrast chronically exposes the organs where it deposits which are the liver, spleen, lymph nodes and bone marrow. Many of the patients injected with thorotrast have developed radiation induced cancers and a study of these populations can be used to indicate the

risk of chronic exposure to high LET radiation. Three important thorotrast injected populations have been followed up through the programme, the German population is the subject of a long running epidemiological study with clinical examinations, the Danish population study was reactivated in 1989 and the Portuguese population study was reactivated in 1993. Another important study population is in Japan. All studies show the same results the most important of which is the tremendous induction of liver cancer by the deposited thorotrast, with a relative risk of 160 determined from the German population compared with appropriate matched controls. There is a clear dependence of the liver cancer incidence on the volume of thorotrast injected with larger injected volumes associated with earlier appearance. Volumes are usually based on hospital records but comparison of whole body counting and hospital records suggests that some records overestimate the amount of thorotrast injected. These measurements affect the dose rate calculations for the liver which are made assuming an ideal organ weight based on body surface area, however, measurements of liver volume in thorotrast patients have shown that the liver shrinks and this leads to corrections in the order of 30% for the dose rate to the liver.

Both the German and the Danish study show an excess of leukaemia in thorotrast patients but only the Danish study shows a dose effect relationship for leukaemia. There is considerable interest to derive the risk of leukaemia from chronic high LET exposure of the bone marrow because of the comparable behaviour of plutonium and thorotrast in the bone marrow. A detailed study of the distribution of thorotrast in the bone marrow has been undertaken to obtain good dosimetric data and use has been made of analysis of complete tissues removed from the cadaver of a whole body donation to the United States Uranium Registry together with experiments with monkeys. One important result from this work shows that some 25% of injected thorotrast deposits in the bone marrow compared with 8% derived in earlier measurements made at autopsy which suggests that the leukaemia risk derived previously in the Danish study should be reduced by a factor of at least 2. Another factor affecting bone marrow dose is the uniformity of the distribution of the thorotrast in the bone marrow as measurements in human bones collected many years after injection show non-uniform distribution in the bone marrow at the microscopic level although at the organ level the thorotrast distribution is rather uniform. The monkey experiments were done to study the short term distribution of the thorotrast in the red bone marrow and the results show that at early times after injection the thorotrast is uniformly distributed but at later times some local accumulations are present. Other experiments indicated that there are no time dependent changes in the organ distribution of thorotrast. All these results lead to a risk estimate for thorotrast related leukaemia from the Danish study corrected for the factor two higher fraction of thorotrast in the bone marrow of 100 per 10^4 persons per Gy which is about the same as that estimated from the Japanese atom bomb survivors for whole body low LET exposure. This lower risk estimate could explain why so few leukaemias are seen in the radium dial painters and the thorotrast patients.

Other interesting results from the thorotrast studies demonstrate that liver cancer arises solely as a result of the radiation and not as a result of the foreign body effect of the colloid. In contrast the additional treatment of thorotrast injected rats with quartz increased the number of lung tumours significantly. This is interesting as, in spite of a permanent exposure of the lungs of thorotrast patients from exhalation of ^{220}Rn in breath,

no excess rate of lung cancers have been recorded. Point mutations in the p53 gene in liver and lung tumours and in malignant mesotheliomas from thorotrast patients seem to be lower than in the same tumours with other etiology. Children from patients injected with thorotrast had no elevated risk of cancer.

The reactivated Danish study has been concluded with the evaluation of the data and the Portuguese study has progressed well with a final report of the reactivated study promised for 1996. The German study has some 70 survivors and is also coming to an end. The studies have been very informative and well supported by the programme but it remains important that the studies are fully documented and reported. A scientific workshop on "Health effects of internally deposited radionuclides: Emphasis on radium and thorium" was organised with the support of the programme in 1994 in Heidelberg and proceedings published in 1995. It seems appropriate, therefore, that in order to stimulate the proper documentation of this thorotrast study the topic has been given a priority for concerted action in the Fourth Framework Programme.

Medical Cohorts and Mathematical Developments

One further large multi-partner project on epidemiology studied a series of medically irradiated cohorts, continued to develop models for the analysis of data on populations such as the Japanese atom bomb survivors, created 'probability of causation' tables specific to the European countries, analyzed the geographical distribution of cancer in relation to a number of variables, and extended a study of occupational radiation workers in the UK.

In the medically exposed cohorts the follow-up of 900 patients injected with ^{224}Ra for treatment of tuberculosis and ankylosing spondylitis has revealed, in addition to the 54 bone cancers which occurred rather early after treatment (none since 1988), an excess of breast cancers (26 against 7 expected) but estimates of dose to breast from the ^{224}Ra only explain a small amount of the excess and repeated X-ray fluoroscopy examinations during the treatment may also be relevant. Follow-up of a later cohort of 1500 ankylosing spondylitis patients injected with lower levels of ^{224}Ra has revealed a small excess of myeloid leukaemia but no excess of breast cancer has been found. 17 thyroid cancers (mean thyroid dose of 0.26 Gy) are reported in a cohort of 14000 patients irradiated in infancy for skin haemangioma. There was an increasing trend with dose and an excess relative risk of 4.92 per Gy has been found. In the same cohort a positive dose-response relationship for breast cancer was found especially in the period more than 50 years after exposure. 31 cases of thyroid cancer were found in a cohort of 11000 patients treated with ^{131}I with some indication of the rates varying with level of ^{131}I administered as well as the condition being treated. In just over 1000 patients given radiotherapy for first cancer in childhood 26 solid cancers were observed as secondary cancers compared with 5.6 expected with a follow-up period of 30 years.There was an indication that relative risk decreased with time. Data on new malignancies arising in patients treated by bone marrow transplantation show that 41 cancers have been seen in 982 patients given whole body irradiation compared with 7 cancers in 229 non-irradiated patients. All these results show that the various medical studies, while undertaken to examine specific problems in radiation epidemiology, have low statistical resolution. It seems desirable, in future, to restrict the choice of cohorts to be studied

to those which are large enough to provide a good resolution and a powerful data base for the testing of models.

Tables of probability of causation for Member States of the European union are well advanced. The tables are based on BEIR V models derived from mortality studies of the atom bomb survivors although separate models have been developed for cancers with high cure rates. Diagrams have been used to show how probability of causation varies with age at exposure and attained age. The Armitage-Doll multi-stage model has been shown not to give a good fit to data for breast cancer and leukaemia based on mortality in the Japanese atom bomb survivors. A generalised two-mutation model has been fitted to data on base line incidence of leukaemia in England and Wales with adequate descriptions of acute and chronic lymphatic leukaemia. A study of childhood leukaemia with respect to paternal preconception irradiation in Sellafield workers, other workers and atom bomb survivors showed that, apart from the Seascale born children of Sellafield workers all other data gave no association with paternal preconception irradiation. The programme supported a scientific workshop on the topic of paternal preconception irradiation in 1993 which also led to the conclusion that there was no substantiation of the effect and consequently the topic is not included in the priorities chosen for the Fourth Framework Programme.

An investigation of mortality around nuclear installations in France has been extended by considering an additional 13 facilities with follow up to 1989. Overall leukaemia rates among young persons living near these installations were lower than national values and no association with proximity to the sites or with the type of site was found. Other cancers in persons less than 65 years old showed that rates near installations were close to or less than national values. The geographical variation in childhood leukaemia in Great Britain has been investigated with respect to natural radiation levels and socio-economic status. No significant association was found between average levels of gamma radiation or from indoor radon. Leukaemia rates were significantly higher in districts of high socio-economic status. The cohort of Nuclear workers in the UK has been expanded from 95000 used in the first analysis to over 120000 workers for the second analysis and this is expected to provide more information on cancer risks following chronic low-dose exposure. This topic is clearly becoming more important with the realisation that the radiation risks derived from the atom bomb survivors exposed to high dose-rate high dose irradiation may not be directly applicable to populations exposed over many years of life to low doses of radiation.

In the future epidemiological studies will have to be concentrated on fewer large cohorts with a long follow-up history and reasonably well defined exposure patterns to give reliable retrospective dosimetry chosen to address specific problems, such as the estimation of risk after long term exposure to low dose rates and low doses of radiation. In addition, epidemiological and carcinogenic modelling will have to be developed on good radiobiological principles to address and analyze the data arising from the specific epidemiological studies.

3.3.1.2 COMPARATIVE RISK ASSESSMENT

Comparative assessments of the environmental impact of generating electricity by

different means have been the subject of increasing interest since the early 1970s. The earliest studies were limited in the range of impacts assessed, for example death and injury, and also in the methodology used. Various methodological improvements have since been made and the more recent assessments take account of a diverse range of potentially important health and environmental impacts. By the end of the 1980s increasing attention was being given to assessing the costs of energy generation that were imposed on society and the environment but which were not explicitly included in the market price of energy, the so-called "external costs". This culminated in a major joint project ("ExternE"), which began in the early 1990s, between the European Commission (Joule Programme) and the United States Department of Energy to assess the environmental externalities of energy use. This project has resulted in the development of a common comprehensive methodology for environmental impact assessment and has produced an operational accounting framework for assessing the external costs of different fuel cycles.

Comparative risk assessment has been an important element of the Commission's Radiation Protection Research Programme for a number of years. This research has made an important contribution to improvements that have been achieved in assessing the risks and environmental impacts of energy generation. Research carried out within the Third Framework Programme had two main objectives: firstly, to further improve the methodologies for assessing the risks and environmental impacts of the coal and nuclear fuel cycles for use within the ExternE project (see above) and, secondly, to explore various evaluation techniques that could aid decisions on the effective allocation of resources for the reduction of a diverse range of health and environmental impacts.

An improved methodological framework was developed for use within the ExternE project. One of its key and novel features was the development and use of a "time and space" matrix for the assessment and presentation of different impacts. Health and environmental impacts occur to differing population groups, over different periods of time and with differing geographic extents and the methodology enables a clear distinction to be maintained between these different aspects (eg, effects occurring on a local, regional and global scale; effects occurring immediately, within a year, within a lifetime, etc). Such disaggregation is particularly important, indeed essential, as an input to informed judgements on the absolute and relative significance of different impacts. Other aspects addressed in the methodology included the assessment of large consequence-low probability accidents (including considerations of public attitudes and aversion to such events) and the relative importance of impacts to workers and the public. While further improvements in the methodology would be beneficial in some areas, the current version represents a sound and robust basis for comparative risk assessments.

Cost-benefit and multi-attribute analysis were investigated as aids to policy formation and decision making in this area. Cost benefit analysis clearly has the merit of simplicity but suffers from the inherent difficulty of transforming diverse environmental impacts into monetary cost. Multi-attribute techniques are now well established and can be readily applied using commercially available software. They largely overcome the difficulties of cost benefit analysis and their particular strengths are the ease with which problems can be structured and disaggregated (which greatly aids their resolution) and the transparency

given to the key issues and the value judgements exercised on them. Inevitably value judgements differ between different stakeholders or interest groups with the result that different conclusions are reached on particular issues. This is sometimes perceived as a limitation or problem associated with the use of multi-attribute analyses. On the contrary, this is not a limitation but rather a strength of the approach, as it provides a clear indication of the origins of any differences, in particular in value judgements, which can then be the subject of further more detailed and focused evaluation and discussion.

The methodology for assessing the risks and environmental impacts of energy generation are now judged to be relatively mature and largely fit for purpose. Improvements in a few areas are, however, warranted, in particular in the valuation of large consequence-low probability accidents within an accounting framework, in taking account of broader social issues such as public attitudes and aversion to particular outcomes and in the handling of uncertainties which, for some environmental impacts, are and are likely to remain very large. The use of the results of comparative risk assessments as an input to policy formation and the effective allocation of resources to risk reduction (ie, risk management) is, however, relatively immature by comparison. Much greater attention needs to be given to this aspect in future if full benefit is to be taken of the considerable progress and developments made in the assessment of risks and environmental impacts. This need is reflected within Four Framework Programme-Nuclear Fission Safety where, in the area of comparative risk, this topic is the focus of further research.

3.3.1.3 RADON AND NATURAL RADIOACTIVE SOURCES

Geological factors controlling the availability of radon in the ground

It was recognised at an early stage that most radon problems were caused by a flow of air from the ground into buildings and that the probability of high radon levels indoors depended on local geology. Therefore, research was funded into what geological factors result in high indoor radon levels, including uranium, gamma rays, radon in soil gas. The results have shown that measurements of uranium or gamma-ray dose rates are of little use, and that radon in soil gas and permeability are the most important parameters. However, the results have also shown that this is a very complex problem and that there is apparently no direct correlation between soil gas radon concentration and indoor radon level; as a consequence an index must be developed with most parameters susceptible to assess regions at risk.

Techniques for mapping radon-prone areas

Areas prone to high radon levels in homes have been mapped either by the use of geological information or by the use of the results of measurements in existing homes. Both of these techniques have been improved, in particular by applying lognormal modelling to the results of radon measurements in homes. The research has also pointed the way ahead, indicating that combining geological information with that derived from measurements in homes is likely to give more accurate and detailed information than either of these techniques alone.

Factors affecting the movement of radon in the ground and into buildings

The influence of the meteorological parameters on the transport of radon-laden soil gas to indoor and outdoor air was recently studied experimentally. Two completely different houses were continuously monitored during several weeks. It was shown that the radon concentration indoors is mainly governed by the convective entry of soil air into the building. The pressure difference itself is governed by meteorological parameters, such as atmospheric pressure variations, wind speed, temperature, etc. Research on the parameters affecting transport has been carried out by mathematical modelling and by the construction of physical models. Mathematical models have been amended in the light of experimental findings, resulting in models that can be used to determine soil gas transport through soil and into buildings.

Movement of radon within buildings

Inter-zonal movement of air in buildings affects the spatial variation in radon concentrations. Infiltrating air dilutes radon entering from the ground and thus affects the radon concentration existing in the various zones. Interzonal air movement and infiltration result from pressure differences occurring across the structure of the building and between zones. These effects have been studied by modelling and measurements in real buildings. Again, the models have been amended to overcome differences between model prediction and real-world behaviour as demonstrated by measurement.

Remedial techniques

Several case studies allowed an evaluation of different mitigation techniques (room pressurization, crawl space ventilation, soil depressurization). Appropriate remedial actions were selected after a number of specific investigations including a detailed visual inspection of the buildings, tracer gas experiments, pressurization experiments, etc. The arguments used for the selection were, among others, the applicability of the mitigation technique to the given building, its simplicity, its ability to solve other problems (e.g. other indoor air quality problems). The most successful methods require the use of a fan, with underfloor depressurisation, or sump, the latter system being the method most likely to be successful and to bring about the greatest reduction in indoor radon level.

Estimation of past exposures to radon

Retrospective epidemiological studies of radon-related disease require estimates of the historical exposures of study participants. This is generally achieved by measuring current radon levels in as many as possible of the homes in which participants have lived. It is known, however, that generally indoor radon levels have changed over time, and especially they are dependent on occupier behaviour. Radon decay products plate out on glass surfaces, resulting in the accumulation of lead-210 being embedded in the surface layer by recoil of alpha-emitting precursors. Measurement of the lead-210 (or more easily the polonium-210 decay product) in well-chosen glass, offers the prospect of assessing past exposures to radon decay products.

Characteristics of the decay products

The deposition of radon decay products in the respiratory tract depends strongly on the activity size distribution of the decay product aerosol, and the fraction of Potential Alpha Energy Concentration (PAEC) not attached to the ambient aerosol. In general terms, the devices and methods for measurements of specific or large range of radioactive aerosol sizes (diffusion batteries, cascade impactors, etc.) are now tuned and reliable. New information and data were recently obtained, for example in the unattached fraction also called the cluster mode (aerosol size from 0.5 to 10 nanometres). An intercomparison of the aerosol size measurements was performed in a house with elevated radon concentrations in Northern Bavaria (Germany). The conclusions of this exercise were that a general agreement on the main points (averaged size distributions) was attained and that a significant amount of activity was found in the nucleus mode (10-100 nm); this will have a major influence on the calculated dose.

Animal experiments

Experiments carried out on rats showed that measurement of initial alterations might be used for biological dosimetry in the different lung compartments. The measurement of induced chromosomal alterations after stimulation of cell proliferation (by acute ozone exposure), appears to be an appropriate method, nearly as sensitive as the most accurate dosimetric tests used in cell culture models following in-vitro irradiation. It was also shown, that a dose-rate effect for low doses and low levels of radon exposure must exist (exposure around 25 WLM). It has been concluded that further studies are needed to understand the role of the age effect or of the damage-repair mechanisms in lung cancer induction, especially at doses and dose-rates found in the domestic environment.

Surveys of radon in homes

Extensive surveys of radon in homes have been carried out in most countries of the European Union. These have revealed the wide range of exposure received, and have identified previously unsuspected areas where members of the public receive high radon exposures. The results of these surveys have been compiled in the "Radiation Atlas of Europe" which will be updated regularly.

The progress made in the field of radon research was very good, leading to the conclusion of certain studies and to the promise of important results for other studies in the future. The understanding of the availability of radon in the ground, of the movement of radon into dwellings and within buildings is very well advanced and does not require further support. The emphasis is now being given to the development of a large and comprehensive multi-disciplinary study aiming at the best assessment possible of the risk arising from the inhalation of the radon decay products.

3.3.2 OPTIMIZATION AND MANAGEMENT OF RADIATION PROTECTION

3.3.2.1 PROBABILISTIC ACCIDENT CONSEQUENCE ASSESSMENT (MARIA AND COSYMA)

The MARIA (Methods for Assessing the Radiological Impact of Accidents) project was initiated by the Commission in the mid 1980s. The main objective of the project was to develop methods for assessing, in a probabilistic framework, the consequences of potential accidents. Such assessments are an integral part of probabilistic safety assessments (PSA), in particular of Level 3 PSA, used to evaluate the risks presented by nuclear installations. They also have other uses, for example in studies on siting of nuclear installations and in the development of policy for intervention following an accident. A large number of institutes have been involved in the MARIA project which culminated in the issue of the COSYMA (COde SYstem MAria) software package for assessing, *inter alia*, the risks presented by nuclear installations. The COSYMA software was issued in the late 1980s for use on a main frame computer and was distributed to and used by several tens of institutes in Europe and beyond.

During the most recent phase of the MARIA project, the main objectives were:

- to ensure that the models within COSYMA, and the code system overall, remained "state of the art" - an important consideration given the widespread and increasing use of COSYMA within Europe for risk assessments
- to make COSYMA available to a wider group of potential users through the development of a version that could be used on a personal computer (PC)
- to enhance the quality assurance of the code through comparison with similar codes developed elsewhere
- to establish a COSYMA Users' Group to provide feedback between model developers and users and to provide a quality check on the use of the code
- to assess the uncertainties associated with the predictions of the COSYMA code, an increasingly important consideration when such codes are used to estimate risks for comparison with safety goals.

Considerable interest has also been shown in COSYMA by institutes in Eastern and Central Europe and, with support from the PECO programme, several institutes from this geographic region were formally integrated into the project.

Code developments and improvements

With one exception few major changes have been made to the COSYMA code during the latest phase of the project, a reflection of its relative maturity. Most changes have involved the updating of data libraries used in the code but obtained from external models (e.g., internal dosimetry, transfer through food chains, etc.) and/or of code parameter values consequent upon new research findings in the many and diverse areas which feature in an accident consequence code (e.g., atmospheric transport, transfer through the terrestrial environment, dosimetry and metabolism, health effects models, economic models, countermeasures, etc.). The exception concerns the modelling of economic consequences. This is widely recognized as the least mature area in accident consequence assessments and a number of more substantial improvements have been

made in this area. An improved model has been developed for estimating the costs of evacuating and/or relocating people following an accident; account is now taken of the distribution of different economic activities within an affected area rather than the previous use of a value averaged over a large region or country. In addition a new model, based on an input-output approach, has been developed that is capable of assessing both the direct (i.e., in the area directly affected by the accident) and indirect (e.g., through loss of tourism in adjacent but not directly affected areas, etc.) costs of an accident; previous models were only capable of assessing direct costs.

Main frame and PC versions of COSYMA

Two updates of the main frame version of COSYMA were issued during the period in question, the first in 1993 and the second at the end of 1995. The first version of PC COSYMA was also completed in 1993 and a second updated version was issued in 1995 (EUR 16239, 16240). Some of the flexibility of the models in the main frame version has been removed in the PC version. However, for the great majority of users, other than those with primarily a research interest, this is not an undue hindrance and indeed may be advantageous. There has been considerable demand, as expected, for the PC version and more than 150 copies of the software have already been issued with demand continuing. This demand exemplifies the success of the MARIA programme and the COSYMA code. The common development of COSYMA at a European level has led to the more effective use of resources in this area. Moreover, through the widespread use of the code, greater harmonization or standardization has been achieved in the assessment of risks from nuclear installations, an important consideration in a regulatory context.

International intercomparison of accident consequence predictions

With the increasing use of quantitative risk assessment in the evaluation of safety, greater attention has been given to, and demands placed on, the reliability of the methods used and the inherent uncertainties associated with their predictions. In this context the Commission, together with the Nuclear Energy Agency of OECD, initiated a international study to compare the predictions of probabilistic consequence assessment codes. Some seven codes, including COSYMA, participated in the intercomparison. Differences were observed in the predictions of the various codes consequent upon differences in modelling approaches; in general, however, these differences were small in comparison with the inherent uncertainties in the predictions of each code. COSYMA performed particularly well in the intercomparison which also served to further enhance the quality assurance of the code. In a parallel exercise, an intercomparison was made of predictions by different users of the COSYMA code. This proved to be a particularly valuable exercise and it contributed greatly to the reliable use of the code by its many users. The importance of and need for a COSYMA Users Group was recognized as a result of this exercise, in particular to provide a forum for exchange between users, to provide feedback between modellers and developers and to contribute to quality assurance in the application of the code. A Users Group has since been established with support from the Commission and it has been most successful in achieving the objectives set for it.

Uncertainties in COSYMA predictions

The Commission and the United States Nuclear Regulatory Commission (USNRC) initiated a major joint study to assess uncertainties in the predictions of probabilistic accident consequence codes, in particular COSYMA and MACCS, the two codes which have found widespread use in Europe and the US, respectively. The MACCS and COSYMA codes are broadly comparable, although there are many detailed differences between them in the modelling approaches and parameter values used. The joint study was initiated against a background of increasing use of these codes for assessing risks as an input to judgements on risk acceptability and on where further reductions in risk might be achieved at reasonable cost. An important consideration for making sound judgements in these areas is the level of uncertainty associated with the risk estimates.

The broad objectives of the joint study were:

- to formulate a generic, state-of-the-art methodology for uncertainty estimation which is capable of finding broad acceptance
- to apply the methodology to estimate uncertainties associated with the predictions of the probabilistic accident consequence codes, COSYMA and MACCS
- to contribute to the regulatory process, for instance, to decision making on risk acceptability
- to provide an input to the identification of research priorities.

The emphasis placed on the respective objectives and on the subsequent use of the results of the study differed between the two sponsoring organizations. The emphasis within the EC is primarily on methodological development and its generic application; while sharing this interest, the USNRC also has an interest in the potential use of the methods and results as an input to the regulatory process.

Undertaking the study jointly had several important benefits:

- enabling a more effective use of resources than two independent studies (ie, cost saving and minimisation of duplication)
- providing access to a greater pool of experts
- enabling the use of diverse methods of elicitation and evaluation, thus averting potential criticisms regarding reproducibility of results when using such techniques
- giving the outcome of the study greater credibility both technically and politically.

The analysis is being carried out in modular way, with consideration being given separately to each of the major processes modelled in the two codes. These models address, *inter alia*, the dispersion of radioactive material in the atmosphere, deposition by wet and dry processes, transfer of deposited material through food chains to man, estimation of doses from external radiation and from intakes from inhalation and ingestion, estimation of the probabilities of deterministic and stochastic health effects and the impact of countermeasures (e.g., issue of stable iodine, evacuation, food restrictions, relocation, etc.). The final step in the analysis is to combine the uncertainty estimates for each of the modules to estimate the overall level of uncertainty in the code predictions taking due account of correlations between the respective modules.

Uncertainties in each of the code modules were estimated using formal expert judgement

elicitation. The use of expert judgement is commonplace in the resolution of complex issues, in particular when data are unavailable or sparse, when models do not apply directly or in contexts where uncertainties are very large; in general, however, it is used informally and rarely made explicit. The main benefits of using formal expert judgement are that it provides an improved expression of uncertainty, greater clarity and consistency of judgements and an analysis that is more open to scrutiny. The process is not without disadvantages, however, the more important of which is the significant cost involved.

The methods used to elicit, and subsequently process, expert judgements were an amalgam of the best features of the approaches developed independently in Europe and the US. For each code module the process comprised the following steps: specification of the elicitation variables (case structure); identification and selection of experts; first meeting of experts for introducing case structure and providing training in encoding uncertainty judgements; preparation by individual experts of their uncertainty estimates and their rationales; second meeting of experts to share their rationales but not quantitative estimates followed by individual elicitations; processing of elicited results to obtain uncertainty distributions on code module parameters.

Within the present phase of the MARIA project, expert elicitations were jointly carried out for the following code modules/topic areas:

- atmospheric dispersion
- deposition of airborne material by wet and dry processes
- transfer of material between soil and plants
- transfer of material between soil/plants and animals
- internal dosimetry including metabolic processes
- stochastic health effects
- deterministic health effects.

Libraries of uncertainty distributions have been developed for each of the important parameters in the respective code modules. These represent a valuable resource with a use far beyond the narrower context in which they were established (e.g., input for identifying future R&D priorities, etc.). Moreover, they have the potential to be updated over time as new knowledge is obtained.

Elicitations have yet to be carried out on one remaining module, that concerned with countermeasures that may be taken to mitigate the off-site consequences of an accident. These will be performed under the auspices of the Fourth Framework Programme - Nuclear Fission Safety; unlike the previous elicitations they will be carried out independently in Europe and the US because of the variability in emergency arrangements between countries. The final step in the process is to combine the uncertainties in the individual code modules and estimate the overall uncertainties in the COSYMA predictions and will be completed early in 1998.

Probabilistic accident consequence assessment codes, such as COSYMA, have reached a fairly mature stage of development and are broadly fit for the various purposes for which they were designed. Changes will, however, need to be made periodically both to take account of new knowledge (e.g., revised health effects models, new data on deposition on skin, etc.) and of changing concepts and/or practice in radiological

protection (e.g., use of averted dose as a basis for implementing countermeasures, etc.). Given the major resources invested in the development of COSYMA and its widespread usage within the EU (often within a regulatory context), it is imperative that appropriate resources are directed to ensuring that it continues to reflect the "state of the art". The existence of the COSYMA Users Group which is being supported by the Commission will be important in this respect as it will provide an effective forum for identifying limitations in the code and/or where new developments may be required to meet practical needs. The completion of the ongoing uncertainty analysis, foreseen in early 1998, will be an important milestone and will provide valuable input to determining future research priorities in this area.

3.3.2.2 DECISION SUPPORT SYSTEM FOR OFF-SITE EMERGENCY MANAGEMENT (RODOS REAL-TIME ON-LINE DECISION SUPPORT)

Background

Following the Chernobyl accident, increased resources were allocated in many countries to improve systems to aid the off-site management of any future nuclear accident. Much has since been achieved but much yet remains to be done to ensure an integrated, coherent and consistent response to any accident that might in future affect Europe. The need for and importance of a coherent response were amply demonstrated following the Chernobyl accident when differences in the countermeasures taken by national authorities contributed greatly to a loss of public confidence. The development of a Decision Support System (DSS) for off-site emergency management, that would be comprehensive and capable of finding broad application across Europe, was included as a major item in the Commission's research programme based on the following considerations:

- to make better use of resources in the EU for further improving off-site emergency management (e.g., minimise unnecessary duplication, integrate best features of systems developed at national levels, etc.)
- to benefit from the development of a comprehensive (i.e., applicable at all distances, all times and to all important countermeasures) and fully integrated decision support system that was generally applicable across Europe (e.g., seamless transition between different stages of an accident, greater continuity and consistency in decision support, etc.)
- to provide greater transparency in the decision process as one input to improving public understanding and acceptance of off-site emergency actions
- to provide a common platform or framework for incorporating the best features of existing and future DSS
- to provide a basis for improved communication between countries of monitoring data, predictions of consequences, etc., in the event of any future accident
- the overriding consideration, to promote, through the development and use of the system, a more coherent and harmonized response to any future accident that may affect Europe.

Objectives and potential users

Decision support can be provided at various levels ranging, in increasing sophistication, from the largely descriptive, to providing an evaluation of the benefits and disadvantages

of different countermeasures' options, to ranking them according to the decisions makers' expressed preferences for different outcomes. Most decision support systems, developed to an operational state, are limited to providing analyses and predictions of the current and future radiological situation. Some extend to the simulation of countermeasures but are often limited in the range of countermeasures they address or in the completeness of the benefits and disadvantages that are considered. The few systems that have progressed to the evaluation and ranking of alternative countermeasures' options are limited in the range of countermeasures they address. RODOS is unique in that it will provide comprehensive support (i.e., at all levels) for each potentially useful countermeasure at all times following an accident.

The system is being designed to fulfil a number of roles, the more important of which are:

- full or partial integration into emergency arrangements at local, regional, national or supra-national levels (i.e., subject to interfacing with radiological monitoring and meteorological networks and with the decision making process)
- providing a more effective means for communication and exchange of monitoring data, prognoses of accident consequences, etc., between countries
- a stand alone interactive training tool for use, inter alia, by those responsible for making decisions on off-site emergency management and their technical advisers at local, regional, national and supra-national levels
- a more general interactive training and educational tool for radiation protection, nuclear safety and emergency planning personnel with a professional interest in and/or responsibility for off-site emergency management
- contributing to improvements in existing decision support systems through the development and dissemination of improved stand alone modules
- a research and development tool to explore the merits and limitations of new techniques or approaches prior to their integration into operational decision support systems
- providing greater transparency in the decision process as a contribution to better public understanding and acceptance of emergency actions
- a basis or framework for decision support systems for the management of non-nuclear emergencies with potential widespread off-site consequences.

The system has been designed in a modular way so that it can be tailored to the user's particular needs. Potential users include those responsible at local, regional, national and supra-national levels for off-site emergency management and related training, for the operation of nuclear installations, for public information, or for communication and exchange of information (e.g., in accord with bi-lateral or international agreements); the research and development community concerned with improving decision support for off-site emergency management; and developers of decision support systems for the off-site management of non-nuclear emergencies.

Development status

Development of the RODOS system began in late 1990. About 10 EU institutes were initially involved increasing since to almost 20. In addition, about 10 institutes from Belarus, Russia and the Ukraine were formally integrated within the project in 1992

under the auspices of a collaborative programme on the consequences of the Chernobyl accident between the EC and the State Committees on Chernobyl Affairs in the respective countries (see Section 4.2). More recently, institutes from Poland, Hungary, Romania and the Slovak Republic have joined the project under the auspices of the Commission's PECO programme (**P**ays d'**E**urope **C**entrale et **O**rientale - Scientific and Technical Cooperation with Central and East European Countries) and requests to participate have been received from others.

Development of the system has been carried out within four closely integrated projects which focused, respectively, on system development (excluding atmospheric dispersion); atmospheric dispersion and meteorology; decision aiding techniques and joint developments with the Former Soviet Union (see Section 4.2). In addition, less formal links were made with two other projects (one concerned with the development of improved models for predicting the migration of radionuclides deposited in catchment basins of fresh water systems and the other with the use of multi-fractal analysis to better describe the deposition of radionuclides released in an accident), both of which have contributed to the development of the system.

Given the size and complexity of the RODOS project, formal arrangements have been put in place for its management. A RODOS Management Group (RMG), comprising representatives from the Commission and the contractors, has been established, *inter alia*, to monitor progress. The project is coordinated and progressed through nine Working Groups, established by the RMG, on the following topics:

- system development and quality assurance
- meteorology and atmospheric dispersion
- countermeasures and consequences
- hydrological modelling
- source term estimation, data assimilation and uncertainties
- evaluation techniques
- training and exercises
- international data exchange
- RODOS Users Group

A first prototype (PRTY 1.0) of the RODOS system was completed in 1992 and has since been installed in institutes in Belarus, Germany, Greece, Hungary, Russia, Poland, Romania, the Slovak Republic and the Ukraine; requests for the system have also been received from institutes in other EU and East European countries. The latest prototype (PRTY 1.3) and a first pilot version (PV1) of the system were completed at the end of 1995. The latest prototype has greater functionality through the integration of software developed by the various EU and East European partners and expansion of the user interface. The first pilot version (PV1), with functionality limited to the early and intermediate stages of an accident, has been developed specifically for on-line testing in emergency centres where it will be interfaced with meteorological and radiation monitoring networks and the decision making process itself, albeit in a pre-operational mode.

The current version of the system comprises the following fully integrated modules or elements:

- the operating system for overall system control, data management and user interface
- the geographical information system, RoGIS
- a meteorological model chain comprising
  - the meteorological pre-processor, PAD
  - the mass consistent wind field models, MCF and LINCOM
  - the Lagrangian puff model, RIMPUFF, and
  - the simplified Gaussian puff code, ATSTEP
- the module, DOSBAU, for calculating potential doses in the early stages of an accident
- the module, ECOAMOR, for calculating internal and external doses by various exposure pathways
- the module, EMERSIM, for simulating early emergency actions and the consequential effects on doses
- the module, FRODO, for simulating intermediate and late countermeasures and the consequential effects on doses
- the modules, HEALTH and ECONOM, for estimating health and economic consequences.

In addition, the following modules have been completed as stand alone programmes but have yet to be fully integrated within the system:

- the module, RETRACE, for modelling run-off processes after deposition of radionuclides in catchment areas
- the one- and two-dimensional modules, RIVTOX and COASTOX, for describing the behaviour of radionuclides in rivers
- the module, LAKECO, for describing the behaviour of radionuclides in lakes, including biota
- the module, EVSIM, for simulating the temporal and spatial movement of people on traffic networks during evacuation
- the module, STOP, for identifying the best routes for evacuation
- the multi-attribute decision analysis software tools, HERESY and M-Crit.

Significant methodological progress has also been made in each of the following areas: development of a model chain for atmospheric dispersion over intermediate and long ranges, treatment of uncertainties and data assimilation. More work is required in each of these areas prior to the specification and development of software to be included in the system in the respective areas. Recent summaries of the overall design of the system, its software/hardware environment and the technical content of its major modules can be found in the Proceedings of the Minsk Conference (EUR 16544). Current developments and progress with the system are reported in periodic issues of the RODOS Newsletter, copies of which are available on request.

The system is being further developed with support from the Fourth Framework Programme - Nuclear Fission Safety. Further developments will focus on extending the applicability of the system to encompass all stages of an accident (i.e., to the late stage including the long term management of contaminated land and the subsequent return to "normality" after an accident) and making improvements in those areas where there is a demonstrable need. Two topics will receive particular attention in the latter context:

firstly, the development of an integrated approach for the handling of uncertainties and their effective communication to decision makers (an important issue that has received insufficient attention in the past) and, secondly, the development of improved methods for assimilating and making better use of expert judgement, model predictions and monitoring data. Improvements will also be made in response to experience gained in the pre-operational use and testing of the system in several European countries, in particular the interface with the decision making process. Important feedback has already been obtained from using the prototype system in exercises with decision makers and this aspect will receive increasing attention in future. A fully operational and comprehensive version of RODOS, applicable throughout Europe, is scheduled for completion by mid-1999, the end of the second phase of the project.

With the completion of the pilot version and a commitment from the Commission to support the further development of RODOS, potential users are increasingly recognising the many benefits which the system offers. In particular, its potential role as part of a wider European network has become evident. The existence of such a network would promote a more effective and coherent response to any future emergency in Europe. Three factors will largely determine how far and how quickly the RODOS system (or elements of it) finds operational use as part of emergency arrangements within Europe: firstly, the results of pre-operational testing of the pilot version in 1996; secondly, the extent to which the technical objectives of the second phase of the project are achieved; and, thirdly, a commitment by countries in Europe to take advantage of these new developments, a matter which will be influenced by broader and largely non-technical considerations. The interest currently being shown in the system by many EU and East European countries does, however, augur well for its future use.

3.3.2.3 DEPOSITION OF RADIONUCLIDES IN URBAN ENVIRONMENTS AND THEIR RADIOLOGICAL IMPACT

The deposition and subsequent behaviour of radionuclides in urban or semi-urban areas following an accident represents a long term source of external exposure of the population. Where the deposition is large and/or persistent intervention may be needed to reduce or avoid the exposure, e.g., decontamination of surfaces, temporary or permanent relocation of people from affected areas. A good understanding of the processes of deposition of radionuclides from the atmosphere to urban surfaces and their subsequent behaviour is, therefore, of great importance for the effective management of urban/semi-urban areas contaminated following an accident. Notwithstanding previous research and investigations, major uncertainties remained in a number or areas and these were inhibiting the establishment of soundly based post-accident management strategies. The focus of research in this area was, therefore, to reduce these uncertainties and develop improved models for describing the behaviour of deposited radionuclides in urban areas and how their impact could be mitigated. A multi-disciplinary approach was adopted and the effective integration of the experimental and modelling communities was largely responsible for the success of this project. Institutes from both the EU and Central and Eastern Europe (the latter with support from the PECO programme) participated in the project and benefit was taken of experience of urban contamination in Europe following the Chernobyl accident and in Brazil following the Goiania accident.

Advantage was also taken of input from the projects on Exposure Pathways and Dose Distributions carried out within the Research Programme on the Consequences of the Chernobyl Accident.

Experimental investigations of deposition of radionuclides by rain have demonstrated the importance of both particle size and the size distribution of rain droplets and also the importance of fog as a source of deposition. Comparisons with modelling approaches currently used in accident consequence assessments showed that deposition levels were being under-estimated for lower intensities of precipitation but over-estimated at higher intensities. The development of a model parameterised on the basis of particle and rain droplet size would overcome these deficiencies.

Deposition of radionuclides on indoor surfaces can be an important source of exposure particularly in buildings which provide high levels of shielding from material deposited on external surfaces. Measurements have been made of deposition on indoor surfaces in a variety of buildings as a function of particle size and differing levels of furnishing. An empirical relationship has been developed between deposition level and particle size which can be used as a basis for dose estimation. Deposition of radionuclides on skin, hair and clothing is also a potentially important source of exposure, particularly for large accidents. However, few quantitative data existed on either typical levels of deposition or its rate of removal from such surfaces. An extensive programme of measurements has now been made of deposition to skin, hair and clothing. Typically the levels of deposition were about an order of magnitude greater than those to indoor surfaces in buildings; body heat may be the major reason for this difference. For aerosol particles in the size range of a few microns the deposition velocity to skin was estimated to be about 10^{-2} ms^{-1} although there was considerable variation between individuals. More limited measurements have been made of the removal of material deposited on skin and hair and these indicate that about half the material (at least for the deposit of silica particles) can be removed by normal washing; however, more extensive measurements are needed to determine the more general applicability of these findings.

Extensive measurements of the depth distributions of caesium-137 in undisturbed soils and *in situ* gamma spectrometry have been used to derive an improved analytical expression for estimating external gamma dose rates in open undisturbed areas. This new analytical approximation provides a better fit with the measured data at both medium and longer times after deposition. The weathering or removal of caesium deposited on urban surfaces has now been investigated for almost a decade following the Chernobyl accident. Broadly comparable results were obtained in investigations carried out in Sweden, Germany and Russia. These have been used to make robust estimates of location factors (i.e., the ratio of the dose indoors to that outdoors over undisturbed land) for occupancy of different types of building and patterns of urban development. These estimates have been partially validated by *in situ* gamma spectrometry.

Measurements of the levels and physico-chemical forms of caesium-137 resuspended in air following the Chernobyl and Goiania accidents have been evaluated. While local and seasonal effects have been observed the data exhibit a general decline in concentration with time and are consistent with an average resuspension factor of about 10^{-9} m^{-1} almost a decade after the initial deposition. For resuspended Chernobyl caesium, the dominant

physico-chemical form appears to vary with season; in the winter the dominant form is water soluble, acid soluble in the summer and insoluble around the end of spring and beginning of summer.

Two models, URGENT (URban Gamma Exposure Normative Tool) and PARATI (Program for the Assessment of RAdiological consequences in a Town after a radioactive contamination), have been developed for assessing the consequences of deposition in urban areas and the efficacy of remedial measures; both have made use of the results of the experimental research carried out within the project. A further important objective of this research was to evaluate the adequacy of the modelling currently used for assessing external exposures from deposited radionuclides in the COSYMA code for probabilistic accident consequence assessment and in the RODOS decision support system for off-site emergency management. Both the COSYMA code and the RODOS decision support system were developed within the framework of the Commission's Nuclear Safety Research Programme and are being widely used in Europe and beyond; given this widespread use the need to ensure that the models remain reliable and reflect current knowledge is self-evident. As a consequence of this evaluation, the values of a number of parameters in the COSYMA code have been revised; in addition, more detailed investigations, largely of a confirmatory nature, were recommended in several areas prior to other changes being made.

This research project has significantly enhanced understanding of the deposition of radionuclides onto urban surfaces and their subsequent behaviour. The quantification of deposition onto skin, hair and clothing represents the most substantive and needed development as few, if any, data were previously available in this important area. Consequent upon the results of this project improvements have been made in models used to estimate external doses from deposited material and to evaluate the efficacy of remedial measures, especially in the Commission sponsored and widely used codes and systems such as COSYMA and RODOS. These models are now relatively mature and are largely fit for purpose. While further research in this area would doubtless improve these models further, such improvements would be unlikely to be significant within the context in which the models are used. There are two main exceptions to this generalisation. Firstly, further investigations are required on the deposition and retention of material on skin; confirmation of the existing results are needed and the investigations need to be extended to a wider range of physico-chemical forms of potential interest. This would provide a better understanding of the processes involved and provide a sounder basis for their modelling. Secondly, models for predicting external doses from deposited material have so far only been validated over the short and medium term (i.e., over about 10 years). Validation of longer term predictions will require continuing, albeit infrequent, measurements of dose rates at previously monitored sites over an extended period; few resources would be needed for this and it would be an important opportunity lost were such measurements not continued.

Within the Fourth Framework Programme - Nuclear Fission Safety, further research in this area is being supported on the deposition and retention of material on skin, hair and clothing.

3.3.2.4 ASQRAD (ASSESSMENT SYSTEM FOR THE QUANTIFICATION OF RADIATION DETRIMENT)

A user friendly PC based software package, ASQRAD, has been developed which provides a common framework for studying the detriment associated with radiation exposure. The software runs under Windows and includes the main health effects models which have been proposed by national and international bodies (e.g., UNSCEAR, BEIR, RERF, NRPB, etc). The risks to different populations, including age and sex specific groups, can be investigated as a function of time for different patterns and levels of exposure. The ASQRAD database contains data on demography, cancer rates, morbidity, fertility, etc, for several countries with a facility to include data for others. Various measures of detriment are estimated, e.g., incidence of each significant health effect over time, loss of life expectancy, etc. The software has a number of roles; these include training, sensitivity analyses to different modelling assumptions, evaluating the importance of the various contributors to detriment (i.e., fatal and non-fatal cancers, hereditary effects) and investigating the impact on detriment of new control regimes or dose reduction strategies. The package has been peer reviewed and a training course held on its use.

3.3.2.5 ALARA IN INSTALLATIONS

Optimization of radiation protection (or commonly referred to as "As Low As Reasonably Achievable" - ALARA) has been an important element of the Radiation Protection Research Programme since the early 1980s and, indeed, has become one of its major successes. Initially, attention focused on fundamental conceptual issues (e.g., detriment, monetary cost of unit dose, equity, etc.) with subsequent progression to methodological issues and then to aspects of more practical import. The achievements of this programme have been considerable. Perhaps the most important, yet least tangible, achievement has been the major contribution made to the establishment of an ALARA culture throughout the European radiation protection community. This has led to better protection, often at a lower cost consequent upon the better planning and execution of work. A more harmonized approach to protection within Europe has been a further important benefit.

The most recent phase of this programme focused largely on consolidation of what had gone before and, in particular, helping bring the previous research findings to greater practical effect. In addition, limited resources were expended on further conceptual developments in those areas where the ALARA methodology remains relatively immature, in particular its application to potential sources of exposure and to exposures that may occur far in the future. This, however, was secondary to developments aimed at the wider dissemination and more effective use of the existing methodologies which, for most practices, are fit for purpose.

In the context of demonstrating the applicability of the ALARA methodology to a wider range of practices, consideration was given, *inter alia*, to decommissioning. The optimization of decommissioning is complex and, in general, trade-offs need to be made between technical, radiological, economic and social factors. In such circumstances cost

benefit analysis was judged to have little value as a decision aid and multi-attribute techniques are more appropriate. The latter have been applied to a specific decommissioning problem to demonstrate their applicability. The lack of adequate radiological data on particular operations (e.g., dose and dose distributions, costs, waste arisings, etc.) proved to be a major uncertainty and constraint in determining optimum decommissioning strategies. This highlighted the importance of the systematic collection of data on dismantling operations and greater attention needs to be given to this in future. As a first step, the structure of a data base (DECOM) has been developed using MS-ACCESS and data input for dismantling operations at the BR3 reactor at Mol.

The effective application of ALARA depends both on the adequacy of relevant data and tools to simplify the application of the methodology. In addition to the DECOM database, two further important developments were made in this area. Firstly, the IRID (Ionising Radiation Incident Database) database was developed for radiological incidents in industry, medical research and teaching. Secondly, a user friendly software package, OPTI-RP, has been developed to aid the non-specialist in performing ALARA or optimization studies. The software is available in both the French and English languages. The software guides the user on the data that must be input and provides a number of decision aiding techniques, based on cost benefit analysis, that can be readily applied to evaluate the problem.

The conceptual and methodological basis of ALARA is now relatively mature, as is its application to most practices involving the use of radiation, at least during their normal operation (i.e., excluding accident). There is, therefore, little priority for further research in this area, although there is a need to ensure that the ALARA network that has been established over the past decade is maintained and that important data continue to be collected systematically. Some conceptual and ethical issues remain in the application of ALARA to accidents and intervention and to exposures that may occur far in the future and it is in these areas that any further research should be focused.

3.3.2.6 RISK PERCEPTION AND COMMUNICATION

Risk perception and communication studies have an important role in the development of effective approaches for risk management. They provide a basis for assessing the likely response of the public to advice and information they receive and for evaluating the efficacy with which it is communicated. The results of such studies can be used, *inter alia*, to develop improved approaches for dealing with the problems of risk amplification and attenuation which are evident in the public's response to risks of comparable magnitude but different origin. Risk perception and communication is a diverse and expanding research area with relevance to most technological activities, especially if they are novel or perceived as hazardous. Research undertaken within the narrower confines of the Nuclear Fission Safety Programme must, therefore, be seen within this broader context and its limited scope recognized. The main objectives of the research undertaken within this programme were twofold: firstly, to gain a better understanding of risk perception with regard to ionising radiation and, secondly, to evaluate current approaches in radiation risk communication with a view to identifying possible improvements.

The two main theories or approaches that have been developed to explain risk

perceptions, the so called psychometric approach and cultural theory, have been reviewed and their performance tested by empirical surveys. The results showed that the psychometric approach accounted for a modest but important part of the variance in perceived risks but that little or no improvement was obtained when cultural factors (eg, hierarchy, egalitarianism, individualism, fatalism) were also included. These findings, which are supported by other evidence, cast serious doubts on whether cultural factors have a major influence on risk perceptions. More recent work has indicated that including "attitudes" into the psychometric approach greatly enhances the explanatory power of this model, indicating that attitudes may be a major determinant of perceptions. The concept of social representation has also been explored to explain the process of opinion formation with regard to particular risks; representations were categorised into the following six groups: traditional indifferent, individual distant, rational economic, intellectual civic, environmental apprehensive and progressive modern. An important finding was that an individual does not have a unique representation for all situations but adopts one or other depending on the situation. Investigations were also made of group differences in risk perception of various technological hazards. A particularly important conclusion to emerge from these, albeit limited, surveys was that the perceptions of politicians were broadly comparable with those of the public but different from those of experts.

Four case studies were developed for evaluating risk communication in different countries. These were chosen to cover quite different radiation situations, namely, radon in homes, the use of X-rays in diagnostic medicine, food irradiation and disposal of nuclear wastes. One major conclusion to emerge is that many information or communication programmes, especially in the radon and waste disposal areas, have been relatively ineffective, albeit for different reasons. In the case of radon much of the information has in general been met with apathy on the part of the public with little personal motivation to reduce radon levels in homes. Concerning waste disposal, the available evidence indicates that fairly extensive information campaigns have not significantly affected perceptions that radioactive wastes represent a high risk. These findings have important implications for future communication strategies and suggestions have been made for improvements or alternative approaches in the different areas.

It is clear that current understanding of risk perception and effective communication is far from complete and is a subject that warrants continuing investigation, both in the area of nuclear safety and more widely. Major progress in this complex area is, however, unlikely to be rapid; nonetheless, it should be recognized that even modest progress has the potential for far reaching beneficial effects in the more effective allocation of resources to risk management. In this context the topic has remained a priority in the Fourth Framework Programme - Nuclear Fission Safety. The identification and characterisation of the key factors which influence risk perception and effective communication will continue to be the main focus of future research in this area.

3.3.3 OPTIMIZATION OF RADIATION PROTECTION IN MEDICINE

INTRODUCTION

In order to present an overview of the research activities on the Optimisation of Radiation Protection in Medicine for the period 1990 - 1994 and an indication of future initiatives, the previous activities will be briefly reviewed and their impact on the present and future situations will be highlighted. This is especially relevant in view of the changing philosophy inherent throughout all the major European activities in the fields of Health Care, Education and Welfare as well as in the commercial and industrial domains. This changing philosophy will certainly influence the nature and extent of the European-wide research and development initiatives funded by the European Commission (EC) in this field.

The EC first funded research and development projects in the field of radiation protection in medicine in the late 1970's. At that time research projects concentrated on large-scale patient-dose surveys, dose measurement techniques and mathematical modelling for organ dose assessments. These studies determined the genetically and somatically significant population doses from medical exposures. At that time the staff involved with diagnostic radiology were more concerned with the diagnostic information and image quality than with the level of the dose to the patient and radiographers. The differences in patient doses measured for similar examinations which varied by up to two orders of magnitude implied that changes in attitudes and behaviour were badly needed.

In 1984, a Council Directive was issued laying down basic measures for the radiation protection of persons undergoing medical examination or treatment (84/466/ EURATOM). This Directive gave further impetus to research on the radiation protection of the patient since guidance was needed for its implementation and the scientific background for a potential up-date had to be provided.

In order to increase awareness of the need to take the dose to patient and medical staff into account in relation to good practice in diagnostic radiology, research priorities were chosen that would contribute to establish links between the clinical and technical requirements of the medical staff and radiation protection principles. The broad range of topics investigated during 1985-1989 consequently included initial studies on general aspects of quality assurance and dose reduction measures introducing the concept of Quality Criteria. In addition, research projects dealt with dose and risk related investigations, surveys of patient doses, and assessment of radiological practice.

As an ancillary activity a Study Group was established in order to develop a set of Quality Criteria for Diagnostic Radiographic Images of adult patients for six conventional examinations. This first set of Quality Criteria covered three groups of criteria: Image Criteria as diagnostic requirements; Criteria for Good Imaging Performance, including important image details and dose to the patient; and an Example of Good Radiographic Technique.

The preliminary set of Quality Criteria was tested, refined and submitted for comments to representatives of medical and radiation protection professions as well as to health

care authorities in all Member States and the improved list of Quality Criteria was published as a Working Document in 1990.

3.3.3.1 GENERAL OVERVIEW OF CONCEPTS AND ACHIEVEMENTS

Optimisation of radiation protection in diagnostic radiology aims to use the available technical means in the most efficient way to achieve an optimal diagnostic image with a reasonable dose to the patient and staff. The adjustment of several technical parameters or the appropriate use of equipment components can contribute to reduce dose to the patient and as such can be considered as radiation protection measures. A new component of optimisation, introduced by the 1990 Recommendations of the International Commission on Radiological Protection (ICRP), is the consideration of dose reference levels in diagnostic radiology which could serve as "investigation levels" for inadequate procedures or faulty equipment function.

Throughout the 1990-1995 period development of the programme was quite dynamic with an approximate doubling of the number individual research projects, some modification of partnerships and project titles, but with a trend to provide a clearer distinction between different areas of research leading to a topic related grouping. Research projects were represented under two main headings:

Quality Assurance and Dose Reduction included projects on:
- Optimisation of image quality and reduction of patient exposure in medical imaging
- Quality Criteria and dose reduction in CT and paediatric radiology
- Digital medical imaging; optimisation of the dose for the examination
- Reduction of dose in x-ray diagnostics by the choice of the optimal screen film systems which was finalised during the programme period.

Dose and Risk Assessment included projects on:
- Medical dose assessment and evaluation of risk
- Patient dose from new radiopharmaceuticals
- Evaluation of dose and risk due to interventional radiology techniques.
- Diagnosis related doses: a comparative investigation in some European hospitals

A gradual evolution of philosophy from dose assessment and quality assurance towards optimisation took place during this period. The changing and evolving situation makes it difficult to trace clearly the evolution of projects, both individually as well as collectively. The assessment of the relevance and contribution of individual constituent projects to their goals is therefore not straightforward. These apparent operational problems, which were revealed in the research programme during this period, have been addressed within the Fourth Framework Programme of the Commission.

The Quality Criteria Concept

In addition to the central research work, many contractors accepted supplementary work to sustain the new research orientations. This included a second and more comprehensive assessment of the methodologies defined in the Quality Criteria

Document for adult patients under-going medical radiographic examinations, and the development and evaluation of the Quality Criteria for Paediatric Patients. In cooperation with the EC action "Europe against Cancer" European Guidelines for Quality Assurance in Mammography Screening were elaborated, including a chapter on: "The European Protocol for the Quality Control of the Technical Aspects of Mammography Screening".

These activities formed a corollary to the main programme and represent major deliverables from this research period. Also, since the Quality Criteria approach involved a clinical assessment of image quality defined by radiologists, a major link to practical radiation protection of the patient was addressed.

3.3.3.2 QUALITY ASSURANCE IN MAMMOGRAPHY

One of the larger projects programme was involved in the general field of quality assurance and reduction of patient exposure with the main area of activity lying within the field of mammography. The scope of the work was wide ranging with research projects covering the:

- establishment of quality assurance programmes in countries where this activity was not previously well established
- development of an expert system to support quality control initiatives
- assessment of test phantom results
- mathematical modelling of the imaging process (physical-technical parameters)
- electronic instrumentation for quality control measurements
- data analysis of the results of Quality Criteria Trials

These projects were a mixture of continued and new activities, for example those projects concerned with establishing quality assurance programmes tended to follow existing initiatives in order to transfer the know-how from one part of Europe to another.

The assessment of relevance, validity and accuracy of test phantom measurements was essential for their use in quality control programmes for breast screening programmes throughout Europe. In this respect the Radiation Protection Research Action has provided scientific support to the EC's "Europe against Cancer" initiatives. The work helped to define the important characteristics required for the appropriate phantom design as well as to evaluate the role that phantoms play in checking equipment performance for optimum image quality. The role of phantoms was also extremely relevant to the project concerned with the development of Expert Systems, in the first instance for assessing quality control data in mammography. A consistently reported limitation was the lack of sensitivity of test phantom measurements to changes in radiological system performance. However, this limitation is inherent to the purpose of the usual test phantoms, that are not designed for the primary diagnosis of system faults but as a verification that quality control has been carried out properly. This particular project also highlighted problems which can be encountered when developing Expert Systems, the concept of which is still evolving. It was therefore difficult, initially, both to define clear and concise objectives as well as to verify their achievement. This project did lead to a clearer understanding of the role and possibilities of using computer based technology in the overall field of quality control and radiation protection of the patient.

3.3.3.3 QUALITY ASSURANCE IN PAEDIATRIC RADIOLOGY

The group working in this field involved predominantly paediatric radiologists from throughout Europe in contrast with other projects where contractors have mainly a training in the physical sciences. The group developed the Quality Criteria for paediatric radiology starting from the practical procedures in day to day routine work. They demonstrated the important variety of radiation protection measures, such as restraining movement, specific shielding and careful selection of technical parameters, which could be taken to reduce patient dose and achieve optimisation bearing in mind the great variety of size, weight and different organ and tissue sensitivity as well as the often unpredictable behaviour of most of the paediatric patients.

3.3.3.4 QUALITY CONTROL IN DIGITAL RADIOLOGY

A co-ordinated group working within the field of digital fluoroscopy and radiography concentrated on physical measurements such as noise, resolution, threshold contrast and signal to noise ratio, as well as dose measurements in relation to image quality. Unfortunately, this work was carried out without reference to the quality criteria developed for conventional radiological techniques and consequently, the data obtained have not been used fully to develop quality assurance and optimisation strategies needed for this new technology. However, some progress was made in the further development of the theoretical basis of the threshold contrast detection process. There remains a need for the adaptation of clinical quality criteria to this type of technology and for the improvements made at the technical level to be more closely related to the clinical requirements.

3.3.3.5 DOSE RELATED FACTORS IN DIAGNOSTIC RADIOLOGY

In order to broaden the approach to those factors which influence dose during the whole diagnostic process a project was established which attempted to develop a framework for assessing and comparing the diagnosis related doses associated with a series of administrative, managerial, educational and operational parameters. Although this approach is a logical step in developing overall radiation protection strategies in medicine it requires effective data collection and management approaches. The concept of a Diagnostic Group was used in order to define the patient pathway through the relevant diagnostic radiological process to study the influence of department practice on related dose. Consequently much of the early work of this project was concerned with evaluating possible diagnostic outcomes of examination protocols within which there was a well defined but varied radiological, clinical component. Three Diagnostic Groups were eventually found to meet the necessary criteria for the study (lumbar hernia discalis, renal cell carcinoma and vesico-ureteral reflux). Also there was a necessity to establish a clear structure within the diagnostic Group for collection of information on patients and examinations. Although the preliminary results were promising the time and resource allocation for this type of project was probably underestimated given the logistical problems posed.

3.3.3.6 DOSE AND RISK ASSESSMENT

The evaluation and application of dosimetric techniques and quantities as well as organ dose assessment through mathematical phantom modelling and Monte Carlo studies continued throughout the whole programme period 1990 -1995. One project concerned with patient dose from radiopharmaceuticals was pursued which involved the mathematical modelling expertise developed within this contract. Part of this work has underpinned the radiation protection of patients undergoing clinical investigations involving new radiopharmaceuticals in both adults and paediatric patients. The biokinetic data were established and the impact on patient dose was assessed. This project clearly indicates the need to maintain some form of research initiative within this area mainly with regard to paediatric examinations.

The need to implement standardised and routine patient dose measurements evolved from the programme as well as means for achieving this aim. These were incorporated in a Patient Dose Protocol for Mammography and used to support the routine implementation of the Quality Criteria.

More refined mathematical modelling techniques were applied to both the radiological imaging process as well as organ dose and risk evaluations. In the case of the imaging process, work on the optimisation of the radiographic technique, in terms of tube voltage and grid parameters, clearly supported the development of the Quality Criteria concept. Modelling of the imaging process will continue to play a supporting role in effective optimisation strategies.

The evaluation of organ dose and risk improved the framework for the intercomparison of risks from different types of radiological examinations involving different groups of organs and hence the refinement of protection strategy in relation to cost-benefits. Work on the effect of age at exposure on lifetime risk led to the broad conclusion that children exposed to typical X-ray examinations are at about twice the risk per unit effective dose than the general population, and that patients over 70 years old are at less than one fifth of the risk. This lends support to the decision to pay particular attention to paediatric patients.

3.3.3.7 OPTIMISATION OF RADIATION PROTECTION

The large co-ordinated project on "Optimisation of image quality and reduction of patient exposure in medical imaging", developed from a project which had originally been pursuing work in the general field of quality assurance and reduction of patient exposure. A number of contracts which had previously been co-ordinated within this group developed into independent activities. In particular, work in the field of paediatric radiology and computed tomography became separate activities reflecting their individual importance. This has been demonstrated with the evolution of separate Quality Criteria listings for both of these areas. This facet has been a major progressive aspect of the research activities and has helped to broaden the clinical framework for European research initiatives.

Computer assisted radiation protection

Another evolution from the earlier activities of this particular group concerned the development of a different approach to the application of computers in radiation protection rather than through the development of expert systems. This evolution concerned the assessment of computer based data management systems for quality control programmes including patient dose assessments on a routine basis. This work highlighted both the need for, and feasibility of, employing such systems within an individual x-ray department as well as in centralised scientific support centres. In this way operational radiation protection tools aimed at users of ionising radiation in medicine can be developed.

Work in support of developing expert systems also continued and a prototype system was produced. However, the amount of knowledge encoded in the system prototype, especially for mammography, was not sufficient to cover the whole range of practical situations. This project did bring concepts of expert system and artificial intelligence into the domain of radiation protection. Very recently the prototype has been reported to have become suitably developed for practical use.

The application of computer systems in the field of medical radiation protection has been evaluated and shown to offer great potential for routine implementation of radiation protection strategies by collecting and managing data of system performance and the behaviour of the sensitive parameters which are most relevant for image quality and dose to the patient. This will contribute to standardise and optimise radiation protection of the patient. The development of routine computer based tools now seems highly probable and desirable.

3.3.3.8 EUROPEAN TRIALS WITH THE QUALITY CRITERIA FOR DIAGNOSTIC RADIOGRAPHIC IMAGES

The evaluation of the results of the 1991 European-wide trial of the Quality Criteria for adult patients has contributed to the further development of the Quality Criteria through 1992 - 1995. These Criteria allowed a preliminary list of reference dose levels established previously to be checked for three types of conventional X-ray examinations; of high frequency, e.g. the chest; of rather high exposure to the patient, e.g. lumbar spine and pelvis; and of more sensitive tissue, e.g. the breast (see Table 1).

These reference dose values form a base line for initiatives to establish other reference dose values for specific diagnostic procedures and under selected conditions. Moreover, the Quality Criteria could be used as an efficient tool for auditing the radiological practice.

Table 1

Reference Dose Values as part of the Quality Criteria
for Diagnostic Radiographic Images (mGy)

Chest		Skull		Lumbar Spine			Pelvis	Urinary tract		Breast	
PA	Lat	PA or AP	Lat	AP or PA	Lat	L5-S1	AP	AP before Contrast	AP after medium	MLO	CC
0.3	1.5	5	3	10	30	40	10	10	10/radgr	10	10

Several scientific publications have demonstrated that the use of the Quality Criteria in day to day practice has led to an optimised relationship between image quality and dose to the patient. This was achieved by changing from low tube voltage to high tube voltage techniques in chest radiography, by regularly checking the performance of the automatic exposure control, by using the recommended screen film system of high speed and the appropriate rare earth screens, by strictly controlling the film processor temperature and the processing time and by respecting the recommended viewing conditions. In this way, dose reductions by 10 to 30% have been reported for some conventional diagnostic examinations with image quality remaining satisfactory.

The first steps have been taken to assess image quality using computer analysis of digitised images. The computer assessment can reproduce the average of the scores of 5 human observers but with a reduced variability than that of the humans.

The Quality Criteria for Diagnostic Radiographic Images of adult patients were greatly improved during this period as a result of feedback from Trials and other scientific initiatives and the Quality Criteria for paediatric patients were developed significantly. In order to strengthen links between the ongoing developments in adult and paediatric Quality Criteria a joint project was established towards the end of this period. This enabled both projects to be harmonised conceptually as well as operationally, leading to a common format for the presentation of the two Quality Criteria documents. The resulting documents will form a template for further Quality Criteria development, for instance in Computed Tomography. The feasibility of developing preliminary Quality Criteria for digital radiology remains to be assessed.

The research projects reflected the changing attitudes to radiation protection in medicine and the need to tailor these projects specifically for this particular area. As a consequence concepts of quality assurance, quality control, measurement of image quality and standard operational dosimetric measurement techniques became a more prominent aspect of the research.

In addition to these research activities, some important horizontal initiatives at the European level deserve mention:

Coordination Action

In order to harmonise the medical use of whole-body counters, a special activity was started to establish a common protocol by interested laboratories from 4 Member States which led to a programme of calibration and intercomparison for whole-body counters throughout the European Union. This programme was carried out by the Directorate General for Environment, Nuclear Safety and Civil Protection.

Dissemination of Research Results

Three Workshops were organised to provide a forum for the discussion and dissemination of the results of the on-going research projects. Each workshop dealt primarily with an important and distinct facet of radiation protection research and its application in medical practice. They were:

- Dosimetry in diagnostic radiology (March 1991)
- Test phantoms and optimisation in diagnostic radiology and nuclear medicine (June 1992)
- Quality control and radiation protection of the patient in diagnostic radiology and nuclear medicine (October 1993)

These three meetings highlighted the range, variability and also to some extent the overlap of the ongoing research in medical radiation protection in the Union.

General Conclusions and Future Perspectives

During the 1990-1995 period a number of goals were achieved which are important for the further development of the research in the Fourth Framework Programme.

- A larger number of medically oriented scientists are now involved in the projects improving the balance between the clinical and the technical nature of the work.
- A transfer of expertise took place among Member States, whereby quality control programmes and measurement strategies already established within some Member States were disseminated throughout Europe by the cooperative structure of the contracts.
- Work within the projects helped further development and extension of the concept of Quality Criteria for radiological examinations. This activity represents a major supporting action for effective implementation of the EURATOM Directive dealing with patient protection and contributed significantly to its revision.
- The Quality Criteria framework has established a mechanism for incorporating the quality of the final diagnostic image within medical radiation protection strategies which directly involves the radiologist.

For the future research activities it is important to bear in mind that:

- The inclusion of a consideration of the clinical image in the overall radiation protection strategy for medical practice requires ongoing and further development. In particular the ability to predict the outcome of an X-ray examination in terms of both image quality and patient dose once a set of

given technical factors are selected needs to be firmly established in routine practice.

- Effective training programmes for both radiologists and radiographers need to be established which are based upon the Quality Criteria concepts and can help establish quality audit programmes throughout Europe.
- Routine operational radiation protection tools need to be developed, assessed and implemented which aid or replace the human controls which presently provide the major source of patient protection initiatives.
- In terms of the justification of radiological practice an assessment needs to be made of referral patterns and criteria as well as the quality of clinical results.
- A clear framework for avoiding uninformative or unnecessary X-ray examinations needs to be established.

The European Guidelines on Quality Criteria for Diagnostic Radiographic Images for adult and paediatric patients in conventional radiology and the European Protocol for Dosimetry in Mammography will be published in the near future. The Working Document on Quality Criteria for Computer Tomography will be circulated to competent professional bodies and individuals for comments.

These guidelines and protocols are progressively introduced into training programmes for radiologists, radiographers and medical physicists and will, therefore, increase and extend the safety culture in the use of ionising radiation in diagnostic radiology.

3.4 EDUCATION AND TRAINING IN RADIATION PROTECTION

INTRODUCTION

The Training Activities of the EURATOM Research and Training Programme on Radiation Protection include two parts: grants and fellowships on the one hand, in order to allow young research workers to study in a foreign laboratory for a period of maximum 6 months, to specialise in scientific areas of specific importance for radiation protection or to help to improve the scientific and technological competence in certain regions or research milieus. On the other hand the European Radiation Protection and Training Action (ERPET) has been created in order to promote up-to-date concepts and know-how on key problems for which a consistent approach at European level is crucial and urgent in order to maintain and extend expertise in specific areas of radiation protection in the European Union.

3.4.1 FELLOWSHIPS

In the 1990 - 1996 period seventeen fellowships were allocated for a 6 months duration each. The research work granted was carried out in the following research sectors of the Radiation Protection Research Action:

-	Radiation Biology	:	7
-	Dosimetry	:	4
-	Radiation Carcinogenesis	:	3
-	Radioecology	:	2
-	Medical Exposures	:	1

Of these seventeen fellowships, six went to Italian students, three each to French and Spanish students, two each to Greek and Belgian students and one to a Dutch student.

3.4.2 EUROPEAN RADIATION PROTECTION EDUCATION AND TRAINING ACTIVITIES (ERPET)

The ERPET activities were set up in 1990 (see Doc.XII-23-1991) and have included a series of specific training actions, covering the establishment of training programmes and packages, the organisation of training courses and specific guidance in training and education in radiation protection. The ERPET activities are dealt with in a common effort by the DG XI-C-1 (Regulatory Actions in Radiation Protection) and DG XII-F-6 (Radiation Protection Research Action) and where appropriate with the Joint Research Centre in ISPRA.

Since 1990, 52 training courses have been organised, in most cases with contractors of the respective EC services acting as local organiser. These 52 courses are listed below in Tables with some details.

These 52 training courses can be sub-divided into the following categories:

Type A: 16 Courses

Establishment of training packages, preparation and organisation of courses to be made available for regions and on subject areas where knowledge and know-how need to be increased and where access to training or relevant training programmes is insufficient. The organisers must ensure that A-type courses will be attended by about 50 participants; they should rely on the advice and support of competent authorities, scientific institutions, advisory bodies etc in order to meet the target groups in the Member States.

Type B: 11 Courses

Updated standard courses in some Member States which present the state of the art of specific subject areas in radiation protection and which are adapted to selected groups of participants. B-courses can be repeated periodically. Some of them are partly conceived for participants from Eastern and Central Europe.

A special case of the type-B course is the MSc-course in Radiation Biology held at St Bartholomew's Hospital Medical College at the University of London, where 3 to 4 candidates from Member States receive grants to study for one year to obtain a university degree in this area of special importance for radiation protection. The MSc course in radiation biology at St Bartholomew's dates back to the 1960s and is the only comparable post-graduate course within the Member States leading to a full university degree after one year of study. The involvement of the ERPET activities with this course started in the academic year 1993/1994. During the past three years considerable changes have been made to the curriculum making it more European in character. The lecture course has been divided up into two parts, a basic course and an advanced course which is made up of lectures presented mainly by contractors to the programme who give an up-to-date account of their special research area. In this way lecturers from several Member States are directly involved in the course and a closer cooperation with research institutes in other Member States is being progressively developed. The 1996/1997 course is consequently proposed as a cooperative action between the most competent departments of Universities in four Member States (Austria, Germany, the Netherlands and the UK). This new module of the MSc course could be considered as a model of European integrated training efforts.

Type C: 4 Courses

Individual training courses of institutions which present specific know-how and can be adapted to participants of various educational levels. These courses are concentrating on experiences with new technologies.

Type D: 21 Courses

Special courses on recent concepts, methodology and research results for the advanced training of interested scientists. These courses emphasise, beside up-dated theoretical training, the practical demonstration of complex situations in radiation protection.

Participants

During the 1990-1996 period a total of about 1600 participants from all over Europe attended the 52 courses. Except when the course has been conceived for a special region, the organisers try to get a balanced mixture of nationalities among the participants. It was anticipated that a certain number of the courses will be organised mainly for those who are involved in teaching in the specific subject area.

One of the problems that has to be dealt with constantly centres around the difficulty of contacting the target group for whom the course has been conceived. This also includes identifying a rather homogeneous level of background education of the participants. The EC's services therefore must rely on the help of the advisory bodies or national and governmental institutions for getting in contact with the appropriate target groups.

Funding

The Training Activities are funded by about 2 % of the budget of the Radiation Protection Research programme. The greatest part of these funds are used for the procurement of eminent lecturers, for the preparation of the training packages and course notes, and for the local organisation. Beside the 17 fellowships for specific research work only few grants are available for young scientists to attend the ERPET courses. Here again, it is expected that the national or governmental bodies are contributing some financial support to those who need to get access to this advanced training at European level.

Perspectives

The training activities will continue in the same framework. About 2 to 3 fellowships will be granted and about 7 to 8 courses will be organised per year. The selection of the training activities to be granted is done by an ad hoc Training Committee which should contain representatives of the involved EC's services and of the Consultative Committee for the Specific Programme in the field of Nuclear Fission Safety. In special cases one or two invited experts should assist the committee, mainly in order to integrate the evaluation of preceding activities into the selection criteria of a new training project.

European Radiation Protection Education and Training - ERPET

1990 - 1996 Training Courses and Other Initiatives

- 1990 -

CEC • DG XI/C/1 - DGXII/F/6

Type	Subject Area	Organised how many times	Place/Date	Proposed by/Organiser	Remarks
A	Summer School on Radioecology	1	Mol (B), 8-20.7.1990	IUR + CEC	25 participants
D	The Use of the Probabilistic Accident Consequence Code COSYMA	1	Karlsruhe (D), 17-21.9.1990	KfK Karlsruhe (D) + CEC	22 participants
A	Optimization of Radiological Protection in the Design and Operation of Nuclear and Industrial Facilities	1	Saclay (F), 19-23.11.1990	CEC	26 participants, in EN

- 1991 -

Type	Subject Area	Organised how many times	Place/Date	Proposed by/Organiser	Remarks
B	Radiological Protection in the Event of Accidents	1	Saclay (F), 18-22.3.1991	INSTN, Saclay (F) + CEC	27 participants
A	Assurance et Contrôle de Qualité en Radiodiagnostic: Qualité d'Images et Réduction de la Dose	1	Paris (F), 3-7.6.1991	CAATS-INSERM, Cachan (F), IRS Liverpool (UK) + CEC	45 participants

A	Optimization of Radiological Protection in the Design and Operation of Nuclear and Industrial Facilities	2	Saclay (F), 3-7.6.1991	CEC	28 participants, in FR
D	Planning for Nuclear Emergency	1	Prague (CZ), 25-29.6.1991	CEC	42 participants from Eastern and Central Europe
A	Summer School in Radiophysics (Nuclear Medicine)	1	Dublin (IRL), 30.6-6.7.1991	EFOMP + CEC	32 participants
A	Optimisation-Decision Aiding in Radiation Protection	3	Moscow (URSS), 1-5.7.1991	CEC	55 participants from NIS and Eastern and Central Europe
D	Off-site Emergency Planning and Response	1	Mol (B), 9-13.9.1991	CEN Mol (B) + CEC	25 participants

- 1992 -

Type	Subject Area	Organised how many times	Place/Date	Proposed by/Organiser	Remarks
B	Radiation Protection of the Patient	1	Neuherberg (D) 06-10.4.92	BfS (D) + CEC	24 participants from 14 countries, 2nd course proposed 1994, Berlin
A	Radiation Protection in Radiation Therapy	1	Sevilla (E) 14-21.06.92	EFOMP + CEC	29 participants from 11 countries
D	Off-site Emergency Planning for and Response to Nuclear Accidents	2	Mol (B) 29/06-03.07.92	CEN/SCK Mol (B) + CEC	25 participants
D	Handling of Cyclotron produced Radiopharmaceuticals	1	ISPRA (I) 30/06-02.07.92	JRC ISPRA + CEC	24 participants, 2nd course proposed 1994 at a more central place
D	Radiation Protection in Dental Practice	1	Amsterdam (NL) 26-27.11.92	Univ Newcastle (UK), Fed Vol Hosp (IRL), Univ Amsterdam (NL) + CEC	35 participants from 10 countries

D	Off-site Emergency Planning for and Response to Nuclear Accidents	1*	Athens (GR) 12-16.10.92	Greek Atomic Energy Commission (GR), CEN/SCK (B) + CEC	*Limited number (25) of participants. Nomination by Greek and Bulgarian Governments
A	Optimisation of Radiological Protection in the Design and Operation of Nuclear and Industrial Facilities	4	Saclay (F) 16-20.11.92	CEPN INSTN (F), NRPB (UK) + CEC	23 participants from 10 countries
A	Quality Assurance & Quality Control in Diagnostic Radiology	2	Madrid (E) 16-20.11.92	CIEMAT (E), IRS (UK) + CEC	66 participants
D	Modern Methods in Radiation Dosimetry	1	Bad Honnef (D) 23-26.11.92	EURADOS, IARR + CEC	42 participants from 14 countries
D	Modern Techniques in Radiation Cytology and DNA Repair	1	Leiden (NL) 23.11-04.12.92	Univ Leiden (NL) + CEC	12 participants from 6 countries

- 1993 -

Type	Subject Area	Organised how many times	Place/Date	Proposed by/Organiser	Remarks
A	Quality Assurance & Quality Control in Diagnostic Radiology	3	Udine (I) 31.05-04.06.93	USL N° 7, Udine (I) IRS (UK) + CEC	65 participants from all regions of Italy
D	Off-site Emergency Planning for & Response to Nuclear Accidents	3	Mol (B) 21-25.06.93	CEN/SCK Mol (B) + CEC	57 participants from 23 countries
D	The Use of the PC Version of the Probabilistic Accident Consequences Code COSYMA	2	Oxfordshire/Wallingford 28.06-02.07.93	KFK Karlsruhe (D), NRPB (UK) + CEC	38 participants from 19 countries
D	Decision Aided Techniques for Optimising Radiological Protection	1	Leeds (UK) 6-8.9.93	University of Leeds (UK), TNO (NL)	13 participants from 4 countries
D	Off-site Emergency Planning for & Response to Nuclear Accidents	2*	Chalkida (GR), 25-29.10.93	GAEC (GR), CEN/SCK Mol + CEC	*25 participants from Greece, Bulgaria, Cyprus (only Eastern Europe)

A	Optimisation of Radiological Protection in the Design and Operation of Nuclear and Industrial Facilities	3	Ringhals (S) 8-12.11.93	CEPN (F), NRPB (UK), NPP Vattenfall (S) + CEC	Organised, 25 participants from 11 countries
B	Diagnostic and Treatment of Radiation Victims	1	Saclay (F) 15-19.11.93	INSTN (F), NRPB (UK), BfS (D) + CEC	Organised, 23 participants from 14 countries

- 1994 -

Type	Subject Area	Organised how many times	Place/Date	Proposed by/Organiser	Remarks
B	Dosimetry in Diagnostic Radiology	2	Trieste (I), 14-18.3.94	ICTP, PTB (D) + CEC	27 participants from 11 countries
D	Dose Assessment from Intakes of Radionuclides	1	Cadarache (F), 18-22.4.94	EURADOS, IPSN (F) + CEC	40 participants from all over Europe
C	The Use of the PC Version of the Probabilistic Accident Consequence Code COSYMA	2	Kiev (CIS) 16-20.5.94	KFK (D), NRPB (UK) State Committee for Chernobyl (CIS)	50 participants (Ukraine, Russia, Belarussia, Rumania, Slovania, Slovak Rep.)
A	Summer School for Medical Physicists in Diagnostic Radiology	1	Nancy (F), 19-25.6.94	EFOMP, S.F.P.H. (F) + CEC	43 participants from 14 European countries (incl. Eastern Europe)
D	Off-site Emergency Planning for & Response to Nuclear Accidents	4	Mol (B), 27.6 - 1.7.94	CEN/SCK Mol (B) +CEC	45 participants from 11 countries (Western/Eastern Europe, Canada, China, Sweden, Finland, Switzerland)
B	Application of Modern Methods of Radiation Dosimetry	2	Munich (D), 12-16.9.94	GSF (D), EURADOS + CEC	30 participants from all over Europe
D	Off-site Emergency Planning for & Response to Nuclear Accidents	3	Prague (CS), 10-14.10.94	University of Prague (CS) CEN/SCK (B) + CEC	25 participants (Czech Rep., Rumania, Russia, Hungary, Slovania, Poland, Slovak Rep., Ukraine)

A	Optimisation of Radiological Protection in the Design and Operation of Nuclear Facilities	4	Karlsruhe (D), 7-11.11.94	Kernforschungszentrum Karlsruhe (D), CEPN (F), NRPB (UK) + CEC	29 participants from the Member States, Czech Rep., Slovak Rep. and Switzerland
B	MSc. Course in Radiation Biology	2	London (UK), academic year 94/95	University of London + CEC	8 participants (4 grants from the EC) and 10-12 European lecturers from 4 countries.

- 1995 -

Type	Subject Area	Organised how many times	Place/Date	Proposed by/Organiser	Remarks
C	Clinical Optimisation and Radiation Protection in Digital Radiography	1	Trier (D), 22-25.2.95 4 days	University of Heidelberg + CEC	32 participants from 12 countries
C	The Use of a PC Version of the Probabilistic Accident Consequence Code COSYMA	3	Madrid (E), 20-25.3.95 5 days	CIEMAT, KFK (D), NRPB (UK) + CEC	26 participants from 11 countries
B	Radiation Protection of the Patient	2	Berlin (D), 8-12.5.95 5 days	BfS (D), NRPB (UK), INSTN (F) + CEC	Subvention for 10 participants from Eastern Europe
D	Geographical Information System for Radioecology	1	Grange-over-Sands (UK), 15-20.6.95	ITE (Inst. of Terrestial Radioecology) + CEC	21 participants from Member States, 1 participant from Obninsk.
D	Off-Site Emergency Response to Nuclear Accidents	5	Mol (B), 26-30.6.95	CEN/SCK Mol (B) + CEC	39 participants from 18 countries (incl. Eastern Europe)
A	Radon Indoor Risk and Remedial Actions	1	Stockholm (S), 10-15.9.95 95, 1 week	SSI (S) + CEC	37 participants from 20 countries (incl. Eastern Europe)
B	Dosimetry in Diagnostic Radiology	3	Tallinn (Estland) 23-25.9.95	CEC	81 participants from 3 Baltic States
A	Optimisation of Radiological Protection in the Design and Operation of Nuclear Facilities	5	Madrid (E), 25-29.9.95	UNESA/AMYS, CEPN (F), NRPB (UK) + CEC	35 participants from 9 countries

A	Training Course of Russian Personnel Working in Nuclear Research Reactors	1	4.10-8.12.95	Forschungszentrum Karlsruhe (D) + CEC	26 participants from NIS
D	Off-site Emergency Planning for and Response to Nuclear Accidents	4	Athens (GR) 11-15.12.95	Greek Atomic Energy Commission (GR), CEN/SCK (B) + CEC	25 participants from 8 countries (incl. Eastern Europe)

- 1996 -

Type	Subject Area	Organised how many times	Place/Date	Proposed by/Organiser	Remarks
B	MSc. Course in Radiation Biology	3	London (UK), academic year 95/96 with extended European cooperation	University of London + CEC	9 participants (4 grants from EC) + 12 European lecturers from 5 countries
B	Dosimetry in Diagnostic Radiology	4	Vilnus (Lithuania) 12-15.2.96	SSI (S) + CEC	Organised for Eastern and Central Europe
B	Diagnostic and Treatment of Radiation Victims	2	Reisenburg (D), 29.2.-1.3.96	University of Ulm (D), BfS (D), NRPB (UK) INSTN (F) + CEC	25 participants from 11 countries (incl. 4 Eastern and Central European countries)
D	Health Physics Managers Course on Emergency Planning	1	Karlsruhe (D) 22-26.4.96	FZK (D), NRPB (UK) + CEC	26 participants from 12 countries (incl. Eastern Europe)
D	Numerical Dosimetry	1	Bologna (I), 13-16.5.96	ENEA (I) + CEC	30 participants

Training Material for Students in Medicine and the Sciences

CEC • DG XI/C/1 - DGXII/F/6

Type	Subject Area	Type of Document	Authors	Remarks
E	Radiation Protection for the Transport of Radioactive Materials	Publication	Course Manual by R.M. Guest	1993: EN version 1995: FR + DE versions
E	Radiation and Radiation Protection for Primary and Secondary Schools	Publication	Course Manual for Teachers by J. Draijer and J. Lakey	1993: EN version 1994: FR version + NL version 1995: DE + ES Discussions 1996: IT
E	Radiation Protection and Quality Assurance in Dental Radiology	Publication	Manual by P.F. van der Stelt and J. Garsou	1994: Draft of EN version 1995: 9 languages available 1996: Swedish + Finnish versions available
E	Educational Objectives in Radiological Protection and Quality Assurance for Diagnostic Radiology Installation Personnel	Report	VALUE Project PA 012/90E CCM - 317, E. Vano	1993: Spanish version + preliminary EN, FR, IT versions Follow-up 1995 by CEC and official representatives from the Member States
E	Off-site Emergency Response to Nuclear Accidents	Text book	CEC	1995

Type A: Establishment of training packages, preparation of organisation of training courses, to be made available for regions and on subject areas where knowledge and practical know-how need to be increased (for not more than 60 participants).

Type B: Updated standard courses in Member States which present the state of the art in specific subject areas (for 20 - 30 participants).

Type C: Individual courses of institutions which present some specific know-how (for about 20 participants).

Type D: Special courses on recent concepts, methods and research results for interested scientists (for 10 - 50 participants).

Type E: Establishment of training material for students in medicine and the sciences (manuals, audio visual material).

CHAPTER 4

THE CHERNOBYL RESEARCH PROGRAMME 1991 - 1996

4.1 RADIOACTIVITY IN THE ENVIRONMENT

4.2 OFF-SITE EMERGENCY MANAGEMENT AND PATHWAYS OF EXPOSURE

4.3 EVALUATION OF THE HEALTH CONSEQUENCES AND RETROSPECTIVE DOSIMETRY

4. THE CHERNOBYL RESEARCH PROGRAMME 1991 - 1996

The results of the 16 projects executed under the Chernobyl Research programme have been published in a series of Final Reports specially prepared for the Conference held in Minsk to commemorate the tenth anniversary of the accident. The synopsis made here is presented in three sections on radioecology, risk and emergency management, and health effects which cover all 16 projects although the results from some projects relate to, and are included in, more than one of these three sections. Consequently, the different projects are not identified as such in the text.

4.1 RADIOACTIVITY IN THE ENVIRONMENT

INTRODUCTION

The science of radioecology has a number of important objectives relevant to the radioactive contamination of land arising from the Chernobyl accident. A prime objective of radioecology is to understand how the interaction between radionuclides and the environment affects radiation dose. Such an understanding then permits a second major objective of radioecology, which is to provide suitable rehabilitation methodology to reduce radiation dose so that it is possible to restore the ecological and economic value of contaminated land. The achievements of such a multi-national programme are dependent on the extent of constructive collaboration between all participants, and cannot be measured solely in terms of their scientific output. In both the Union and the three republics the rate of progress in radioecology has been greatly increased by the collaboration.

In this text the main achievements of a comprehensive environmental research programme, conducted from 1991 to 1996, are briefly summarised. This has only been possible through the active collaboration of the co-ordinators and participants of the relevant experimental collaborative projects (ECP) and joint study projects (JSP), each of whom summarised the work of their own programmes as an input to this text. The aim of the following text is to highlight some of the major achievements of the programme; readers are strongly advised to consult the final reports of the different projects and the Minsk conference proceedings for further details.

4.1.1 QUALITY ASSURANCE

An important aspect of the collaboration has been that it has enabled scientists in many different Member States and Belarus, Ukraine and the Russian Federation to compare and standardise methodologies. An improved understanding of radionuclide behaviour, coupled with extensive discussion of techniques, has ensured that the most appropriate and useful methods have been utilised. Comparison and scrutiny of data has helped to identify current deficiencies and consequently improve data quality where necessary.

4.1.2 DEPOSITION

Information on deposition rates is fundamentally important to dose assessment, and the collation of deposition data has highlighted where there are current deficiencies and

identified difficulties in comparing values because of different collection techniques and reporting procedures. Geostatistical techniques have been applied on a small scale to identify where there is the greatest uncertainty in current information on deposition. Furthermore, it has become clear that deposition values acquired in 1986 may not be representative for current contamination patterns, since both catchment drainage and flooding can modify deposition patterns.

4.1.3 URBAN ENVIRONMENTS

Studies on urban environments have quantified how different surfaces contribute to external radiation dose, and how this changes with time. Furthermore, radioactive contamination on buildings and adjacent areas has been shown to contribute significantly to radiation dose. An initial model has been developed to predict external doses for urban areas. Testing of various decontamination techniques for different urban surfaces has shown that some previously recommended techniques such as fire-hosing are ineffective. Cost-effective decontamination techniques have been developed and tested and recommended methods include:

- high pressure systems
- sand blasters
- rotary brushes
- triple digging

An example of the reduction of the dose rate that was achieved inside a detached house using the above mentioned decontamination methods shows that decontamination of soil and roofs is particularly important. Only a few detailed studies of this nature currently exist.

Overall the study of the urban area has shown that the dose rate in and around semi-detached houses (i.e. in villages, suburban areas, etc.) can be reduced by a factor of 4-5. In view of the many abandoned buildings in the contaminated urban areas in the three republics there appears to be real potential for cost efficient reclamation even 10 years after the original contamination event. Considering that most of the external dose to people arises from contamination in the urban area, it is surprising how little effort has been paid to mapping the deposition pattern in urban environments, and estimating the composition of the dose rate.

4.1.4 RESUSPENSION

Current levels of airborne radioactive material arising from natural and man-made resuspension processes have been found to be small and therefore radiation doses from this pathway are small compared with other pathways. Furthermore, transfer by resuspension from more highly contaminated to less contaminated regions has not been found to be significant. However, forest fires can cause the release of several percent of the radionuclide inventory in soils, as was demonstrated by a 2 km^2 forest fire which resulted in a 4% loss of the total ^{137}Cs inventory and a 1000 fold enhancement of radiocaesium levels at a 20km distance from the fire.

Resuspension is a non-linear process, and a two fold increase in wind speed leads to a much greater (30 fold) increase in resuspension. This has important consequences, since a single high wind speed event can dominate long term average flux estimates. Hence, it is inappropriate to extrapolate from average resuspension values for predictive purposes.

Resuspension in the immediate aftermath of a nuclear accident may be much greater than measured during this investigation period, and, therefore, this process must be considered in the early phase.

Resuspension of soil onto plant surfaces can contribute a significant proportion of plant contamination, especially of non-mobile radionuclides such as plutonium, but also for mobile radionuclides in certain circumstances. This pathway can be substantially reduced by mulching around plants to reduce soil splash onto plants.

4.1.5 FRESHWATER ECOSYSTEMS

Peat bogs have been identified as a major secondary sources of radioactive contamination of water bodies. Furthermore, radiocaesium remains available for long periods in peaty catchments. Run-off from various catchments can now be quantified using radioecological knowledge of the hydrological regimes and sorption properties. In addition, the distribution and risk of remobilisation of radiocaesium between sediments and water can be predicted from water chemistry and underlying sorption, using knowledge of the interaction between radiocaesium and ammonium ions with the illitic frayed edge sites.

The dissolution of fuel particles near the Chernobyl reactor constitutes a major secondary source for remobilisation of both radiocaesium and radiostrontium. A validated model has been used to predict the effect of flooding on the dissolution of radiostrontium and consequent ^{90}Sr activity concentrations in water of the Kiev reservoir. This has enabled prior warning to be given of the possible excess of ^{90}Sr intervention limit for drinking water in 1996 in time for the relevant authorities to take appropriate action.

Lakes are more ecologically vulnerable to radioactive contamination than rivers because of the longer residence time of radionuclides. Edible fish generally contained maximum radiocaesium activity concentrations in the period one to three years after the Chernobyl accident. Fish contamination rates are inversely related to potassium concentrations in water and the uptake of radiocaesium by fish has been modelled using a pseudo-equilibrium approach. The highest concentrations of radiocaesium activity have been found to occur in the top predator species. The consumption of fish can make a significant contribution to radiocaesium intake by humans in certain areas, especially those with peat catchments where radiocaesium activity concentrations currently still exceed intervention limits.

4.1.6 SEMI-NATURAL ECOSYSTEMS

Semi-natural ecosystems, which in the three republics are largely represented by forests and unimproved meadows often in forest clearings, are inherently complex since they are

ecologically much more diverse than agricultural areas. Radiocaesium activity concentrations in semi-natural foods in the study period have been much higher and more variable, both spatially and temporally, than those of agricultural products, both between and within species. The highest radiocaesium activity concentrations in semi-natural products have been recorded for various fungal species fruiting bodies (hereafter referred to as mushrooms) and for game animals, specifically roe deer and wild boar. The rate of transfer of radiocaesium to different mushroom species has been shown to be related to the depth in the forest soil at which the fungal mycelium are located. High transfer rates of radiocaesium from soil to forest vegetation have been measured.

Chernobyl fallout radionuclides have been largely retained in the upper organic horizon of forest soils, in which they have been shown to have a long residence time. Of several radionuclides studied (including ^{60}Co, ^{106}Ru, ^{144}Ce, ^{125}Sb and ^{154}Eu) radiocaesium is the most mobile and the two isotopes, ^{134}Cs and ^{137}Cs, are equally mobile. The bioavailability of radiocaesium, combined with its long residence time in the organic horizons, is associated with low amounts of clay minerals in organic soils and the high, but reversible, sorbing capacity of organic matter. In addition, radiocaesium uptake by fungal mycelia in the upper organic horizons, have also been identified as a mechanism which retards the downward migration of radiocaesium in forest soils.

A database of radiocaesium transfer parameter values has been collated for forest and meadow ecosystems for the contaminated areas. Initial forest models have been developed which consider both near field (with fuel particle deposition) and far field (with condensed particles or soluble) radionuclide behaviour. These models are yet to be validated, but indicate that important differences occur in the partitioning of fallout within forest ecosystems and in the dynamics of radionuclide behaviour close to and far away from sites of nuclear accidents.

4.1.7 AGRICULTURAL ECOSYSTEMS

Transfer parameter values have been measured under controlled field conditions for a range of key soil/crop combinations in each of the three republics. The distribution of parameter values has been critically assessed and recommended values derived. Long-term ecological half-lives have been estimated for agricultural products, but most data sets include periods where countermeasures have been applied.

Geographical information systems have been found to be a powerful tool which can help to identify areas which should not be used for supplying dairy cow fodder or as pasture for summer grazing. By combining information on deposition rates, soil types and transfer rates from soil to grass and milk, maps were constructed to show predicted milk radiocaesium activity concentrations in selected collective farm areas. Using this technique pastures which would give rise to milk with radiocaesium levels exceeding the EC intervention limit were identified.

4.1.8 SOIL TYPES

The soil type in contaminated areas is fundamentally important in determining contamination levels in both plant and animal food products. The behaviour of

radiocaesium and radiostrontium in soil has therefore been the focus of attention in several programmes. The key parameters governing radiocaesium and radiostrontium behaviour in soils have been identified and pseudo-equilibrium models developed.

It has been clearly shown that "conventional" Kd values, comparing radionuclide activity concentrations in soil solids with those in solution, overestimate radionuclide availability since they assume that all the radionuclide on the solid is exchangeable and hence available. In many soils a significant proportion of radioactivity becomes fixed within the solid matter and is unavailable for plant uptake or remobilization. A better alternative is to use an "available" Kd, which only includes the exchangeable fraction of solid-associated radionuclides.

Comparisons have been made of bioavailability estimated from laboratory-based methods with measured transfer parameter values. In general, there is a reasonable relationship between *in-vitro* and *in-vivo* transfer estimates, with the notable exception of organic soils, where further work is needed.

Some data has been obtained on the rate of fuel particle breakdown and subsequent release of radionuclides, in particular of radiostrontium, but more information will be needed over longer time periods.

4.1.9 CHANGES WITH TIME

Radiocaesium and radiostrontium levels in biota will generally decrease after the deposition of Chernobyl fallout due to a number of different factors:

- natural ecological processes
- the influence of countermeasures
- physical decay

However, fuel particle decomposition has been found to lead to an increase in the bioavailability, particularly of radiostrontium in the 30km zone. Experience within the programmes has shown that it is difficult to obtain effective half-lives which are not affected by the application of countermeasures. Because of the gradual fixation of radiocaesium in soils, the bioavailability of radiocaesium in terrestrial and aquatic systems will change for several years after an accident, until an equilibrium level is achieved. Thus, the effective half life commonly increases over time following a fallout event. More work is required to determine this rate of decrease in availability, and at what stage equilibrium levels (and therefore constant half-lives) may be reached.

In semi-natural ecosystems long effective half-lives have been recorded for many species. For instance in the Chernobyl exclusion zone, during the period 1992-1995, there was no observable decrease in radiocaesium activity concentrations in the meat of either wild boar of roe deer. Similarly, no observed decrease has occurred in some species of mushroom. This means that for some species we expect the effective half-life to be equivalent to the physical half-life, which for ^{137}Cs is 30.2 years. In order to acquire suitable data for estimation of long-term trends measurements of biota will need to be continued for many more years. The long effective half-lives in many semi-natural

products compared with agricultural products means that the comparative importance of semi-natural products as sources of radiocaesium in the diet increases with time.

In some circumstances, radiocaesium activity concentrations in food products may increase. For instance, contamination of milk in one study site dramatically increased from 400-500 Bq l^{-1} to over 1,000 Bq l^{-1} due to flooding of a peaty-soil pasture in 1993. In 1995, ^{137}Cs activity concentrations in milk in Russia increased for both collective and private milk, due to an extended drought, which reduced fodder biomass.

4.1.10 FLUXES OF RADIONUCLIDES

Extensive use has been made of the calculation of total fluxes of radiocaesium within the research programme. Fluxes are calculated by multiplying the active concentration of radiocaesium in a product by the total quantity of the product produced, and therefore have units of Bq y^{-1}. The total flux can be integrated over many years to give a total output of radionuclides over a long time period. Flux estimates take into account the total production or harvesting rate of different foodstuffs and highlight the relative importance of different foodstuffs as sources of radiocaesium or radiostrontium. Furthermore, total production can be expressed both in radioactivity and energy terms which allows a comparison of the relative importance of foodstuffs as energy sources as well as sources of contamination. In rural communities it has been shown that it is important to consider both the energy flux (and therefore the availability of calories from each foodstuff) as well as the radiocaesium flux for various products.

4.1.11 COMPARATIVE IMPORTANCE OF DIFFERENT FOOD SOURCES

There are three main sources of radioactive contamination of people in the areas of the three republics which were heavily contaminated by the Chernobyl accident, namely:
- Collective farm produce
- private agriculture (subsistence farming)
- collection from forests

The importance of the three different sources varies with different categories such as:
- rural versus urban habitation
- degree of forest utilisation
- special groups, such as game eaters, mushroom foragers and fish eaters.

In rural areas, village inhabitants are mostly subsistence farmers who also work on the collective farms. For these people, studies in all three republics have shown that private farming (largely through milk, meat and potatoes) and collection from semi-natural ecosystems significantly contributes to their total radiocaesium intake. The contribution of collective products to radiocaesium intake by rural inhabitants is small. Furthermore, a clear correlation was observed between the consumption rate of mushrooms and the whole-body radiocaesium content of rural inhabitants. Providing clear, well illustrated information on which mushrooms species are most highly contaminated would be one method of reducing radiocaesium intake via semi-natural products whilst avoiding a total ban on a valued culinary product.

For radiostrontium, the relative importance of semi-natural ecosystems is low compared with radiocaesium, because it is not accumulated in either fungi or meat.

4.1.12 REMEDIATION

One aim of radioecology is to reduce radiation dose, and remediation is considered when radionuclide activity concentrations exceed intervention limits. In this text, intervention limits will be considered to be those prevailing in EU countries, since the limits in each of the three republics vary. Radioecology aims to reduce both individual and collective dose of populations.

Rapid and effective intervention in collective agricultural environments during the first two years after the Chernobyl accident, and ensuing policies since then have ensured that the vast majority of collective produce has contamination levels which are well below intervention limits. In contrast, radiocaesium activity concentration in milk produced by private farmers continues to exceed intervention limits in certain Oblasts of the three republics. A wide range of effective agricultural and household treatments are available, but their effectiveness varies according to techniques of application and local conditions. A comprehensive analysis of the available countermeasures has clearly shown that a generic ranking of countermeasures is inappropriate, the selection of suitable countermeasures should be site-specific.

Soil treatment to reduce radionuclide uptake by plants has been, and continues to be, among the most important and extensively used remediation measures after the Chernobyl accident. Such treatment includes various forms of ploughing and soil amelioration using fertilisers, liming and manure. There are now good laboratory-based procedures available for predicting the effectiveness of various soil treatments. However, some soil-based treatments have been found to be more effective in the laboratory than in the field, suggesting that application methods in the field could be improved.

Despite the wide range of currently available remediation measures, there are remaining problems. Recent and current issues with regard to remediation include:

- ^{137}Cs contamination of private milk
- ^{137}Cs intake via semi-natural products, especially via mushrooms, where intervention limits are substantially exceeded
- transitory increases in contamination levels due to seasonal or flooding events
- a reduction in effectiveness with time in soil-based treatments

Some of these remaining problems arise because, for varying reasons, the currently available countermeasures cannot be used successfully. It is apparent that the usefulness of remediation measures needs to be considered with regard to many factors including:

- effectiveness
- cost
- ease of use
- local availability
- social acceptability

Overall, an important final consideration is whether they would be used by the target community. In the case of private milk it is therefore important to consider the views and attitudes of private farmers. Thus, the application of remedial measures needs to be considered with regard to socio-economic considerations as well as agricultural and efficiency factors. It is evident that the authorities must be aware that transitory increases in product contamination levels can occur and the mechanisms which give rise to such increases need to be clearly defined.

The potential long-term consequences of a reduced effectiveness of soil treatment needs to be evaluated, given the importance of widespread application of soil ameliorants. Furthermore, possible ecological side effects arising from current treatments rates, or required increases in treatment rates must be considered. There are initial indications that deficiencies are occurring in certain trace metals in regions which already have a low trace elements status, such as the Poleysee region. In addition, possible detrimental effects on water quality and ecologically sensitive ecosystems such as peat bogs must be considered.

4.1.13 RECLAMATION

Our improved understanding of the practical use of countermeasures could in future be applied to aid the reclamation of abandoned contaminated land. People returning to contaminated territories would need information on how they can reduce contamination levels to reduce both external and internal dose. The results of psycho-social studies clearly show that it is important to provide people with the ability to "self-help" by the provision of appropriate information. Provision of clear, well presented site-relevant information which enables them to make their own decisions about remedial measures would be required. Clearly, reclamation would require an integrated approach requiring expertise on administrative, radioecological, dose estimation and social aspects.

There has been a considerable advance in our understanding of radionuclide behaviour arising from this programme, which has clearly demonstrated that good science allows well informed decisions. Much basic mechanistic information has been acquired on how radionuclides interact with the environment allowing a better appreciation of the environmental consequences of the accident and the resulting radiation dose to the population.

A wide variety of remedial measures have been developed or critically evaluated, with a consideration of their usefulness which has taken into account not only effectiveness but also their appropriateness for use in the contaminated regions. Although radiocaesium activity concentrations in most food products are well below intervention limits some problems remain, in particular private milk and some semi-natural products, especially mushrooms.

In the contaminated regions of the three republics the relative importance of different pathways of contamination varies, depending on where people live and the extent to which the applied countermeasures have reduced contamination levels in the foodstuffs which they eat. Urban residents purchase food from shops which largely originates from the collective agricultural system, whereas much of the rural population are subsistence farmers who purchase few products from shops. Since most countermeasures have been directed towards the collective system the intake of radiocaesium via this route is currently low. The contamination levels in foodstuffs grown by private farmers in rural areas will depend on many factors, including deposition rate, soil type and agricultural practices such as the extent of usage of forest areas. Cs-137 intake by urban residents from private farming will arise from the cultivation of private vegetable plots and food gifts from rural relatives. The significance of mushroom consumption in contributing to radiocaesium intake and whole body burdens has been clearly demonstrated for rural inhabitants, but more data and further evaluation is needed for urban inhabitants since the tradition of collecting mushrooms in the autumn is widespread in the three republics. Similarly, the intake of radiocaesium via fish or game and possible countermeasures needs further consideration. Possible remedial measures, appropriate to private farmers, need to be evaluated further so that radiocaesium activity concentration in private milk can be reduced below intervention limits.

It has become evident that there is a need for integrated environmental management after a nuclear accident. Remaining or future problems will best be solved by an interdisciplinary approach considering chemical, biological, agricultural and socio-economic aspects of each issue.

4.2 OFF-SITE EMERGENCY MANAGEMENT AND PATHWAYS OF EXPOSURE

4.2.1 REAL-TIME, ON-LINE DECISION SUPPORT SYSTEMS FOR OFF-SITE EMERGENCY MANAGEMENT FOLLOWING A NUCLEAR ACCIDENT ("RODOS")

This topic was a priority item in both the Commission's research programme (see Section 3.3.2.2) and those of the other three countries and it was clear that mutual benefit would result from closer collaboration. Two major benefits, in addition to those of a more general and obvious nature (i.e., increase in project resources and their better utilisation, minimizing duplication, sharing knowledge and experience, etc) were foreseen from the collaboration; these were:

- the first hand, practical experience obtained from responding to the Chernobyl and other nuclear accidents in the former Soviet Union would provide a valuable input to the development/improvement of the models, methods and data bases making up a decision support system
- the development of a commonly agreed decision support system would, if subsequently implemented and networked, greatly facilitate the timely and effective exchange of information in the event of any future accident and contribute to more coherent and consistent emergency response within Europe

From the outset of this project a goal-oriented approach was established (ie, the common development of a decision support system for nuclear emergency management that would be applicable throughout Europe)(Kelly et al. Rad. Prot. Dos.,64(1/2) 129-141,1996). This determined the nature and dynamics of the cooperation and was instrumental to the success achieved. The early agreement to use RODOS as a platform for the collaboration was an important step forward as it established, from the outset, a framework within which the individual scientific investigations and software developments could be effectively integrated and managed. Moreover, this enabled the work within this project to be fully integrated with that of the ongoing RODOS development programme with obvious project management benefits.

Progress on the RODOS project as a whole is summarised in Section 3.3.2.2. Consideration here is limited to work carried out specifically within the collaborative project. The main technical achievements of the collaborative project include:

- the transfer and installation of the hardware and software components of the RODOS system (including periodic updates) to Russia, Ukraine and Belarus
- on-line connection of RODOS to meteorological and radiological monitoring data
- the installation of Internet connections between all participating institutes
- the common development of RoGIS, the geographical information system of RODOS, and its data base
- the development of mathematical methods and computer software for reconstructing the characteristics of radioactive material released in an accident
- the development of a module for optimising evacuation routes within the traffic network around sites of nuclear power plants
- the generation of a data base on the efficiency and costs of agricultural countermeasures for general application in Europe

- the development of a hydrological model chain for describing the transfer of radionuclides deposited on catchment areas to river systems and lakes (run-off) together with modules for assessing doses to man via the relevant exposure pathways
- the development of a decision support tool, M-Crit, based on multi-attribute decision analysis

These achievements enhanced the quality of the system and accelerated its progress towards completion. Notwithstanding these major technical achievements, the agreement in principle to integrate RODOS within national emergency arrangements in Belarus, Russia and Ukraine is, by far, the most important outcome. Significant progress has already been made in this context.

Belarus - The development of RODOS is carried out under the auspices of the Ministry for Emergency Situations and Protection of the Population from the Consequences of the Chernobyl Accident. A workstation HP-9000/735 has been installed in the Centre for Radiological and Environmental Monitoring of the Committee on Hydrometeorology which is responsible to the Ministry for Emergency Situations.

Customisation and adaptation of the RODOS software, models and data bases to specific Belarus conditions, together with their verification, is being carried out at a number of Belarussian institutes. The first application of RODOS is likely to be in the region adjacent to the Ignalina NPP which is in Lithuania but close to the border of Belarus. In this region, with support from the European Commission, an automatic system of radiation monitoring (GAMMA-1 Project) is being installed and interfaces will be established with the RODOS system. Subsequently, the system will be extended to other regions of Belarus that are in relatively close proximity to nuclear power plants in neighbouring countries. Interfaces with RODOS systems operating in neighbouring countries will be developed in parallel.

Russia - The development and implementation of RODOS in Russia is being carried out by the Russian Federal Service on Hydrometeorology and Environmental Monitoring (Rosgydromet). Rosgydromet has established a special Emergency Centre for providing real-time and prognostic information on the radiological situation within Russia. The Centre is installed at SPA "TYPHOON", Obninsk. The Centre works in close collaboration with the other organisations with responsibility for emergency management in Russia.

Rosgydromet has an extensive network of meteorological and radiation monitoring stations in Russia. The information from this network is input to and processed by the Radiological Analysis Support System (RECASS) developed by SPA Typhoon. The RECASS system was already at an advanced stage of development when the joint project, between the EC and the respective State Committees on Chernobyl Affairs on the consequences of the Chernobyl accident, began. Following the agreement to use RODOS as the platform for the development of the joint decision support system, considerable effort was directed towards achieving coherence and consistency between the RECASS and RODOS systems. Effective integration of the

two systems has been achieved within the Emergency Operations Centre at Typhoon, in particular:

- the management of data transmission lines
- the management of real time data from meteorological and radiological monitoring networks, and
- modelling processes of trans-boundary transport of contaminated air masses from an affected area

Experience gained in interfacing the RECASS and RODOS systems has indicated that the establishment of an integrated network of RODOS systems, with common data formats, data structures and rules of access to distributed data bases, would be the quickest and most practicable way to achieve the main objectives of the RODOS project.

Ukraine - In the Ukraine the Cybernetics Centre, Institute of Mathematical Machines and Systems (IMMS CC) has played a major role in the development of RODOS, in particular in the areas of hydrological modelling, system development and optimisation of early emergency actions. The hardware and software components of RODOS PRTY 1.0 were installed at IMMS CC in early 1994. Following the demonstration of the prototype system and its capabilities to the various governmental organisations responsible for emergency preparedness, a decision has been taken to implement RODOS for decision support at the upper level of data processing and monitoring systems in the Ukraine. Two major steps have been taken in this context.

Firstly, a joint programme between the Administration of the Chernobyl Exclusion Zone (ACEZ) and IMMS CC was begun in October 1995 to use RODOS to support off-site emergency response in the event of a nuclear accident in the Chernobyl Exclusion Zone. The programme foresees the test-operation of RODOS in late 1996 with it being brought into operational use in late 1997. The system will be customised for two distinct situations - potential accidental releases from the Chernobyl reactors still in operation and from the sarcophagus around the damaged reactor (unit 4).

Secondly, an agreement was signed, in October 1995, between the Committee of Nuclear Power Production (GOSATOM) and IMMS CC to develop, in cooperation with other Ukrainian institutes, decision support systems for the Emergency Centres at Nuclear Power Plants (NPP) and at the National Crisis Centre of GOSATOM; RODOS would be used as the basis for these systems. The first or pilot decision support system will be implemented at the Emergency Centre at Zaporozhe NPP.

Practical application of RODOS

Notwithstanding the fact that RODOS is still under development, elements of the system have already found practical application on two occasions in the former Soviet Union. The Emergency Operations Centre at Typhoon was involved in the processing of monitoring data and environmental modelling following the accident

at the Siberian chemical plant, Tomsk-7 (Shershakov, et al. Rad. Prot. Dosim., 59, 93-126, 1995). Predictions were rapidly made of environmental contamination from Nb-95 and Pu-239 using the RIMPUFF code which is the model used in RODOS for dispersion over short and intermediate distances, and in predicting the exposure of the population from the accident.

The hydrological module of RODOS was used in the Ukraine to evaluate and aid the management of the consequences of an accidental release (non-radiological) from the Kharkov municipal waste treatment facility. Following a heavy rainstorm in June 1995, the pumps at the Dikanki Sewer Water Treatment Station (responsible for processing municipal waste water collected from the whole of Kharkov, a city of about 2-million people) were flooded. During the following month, the waste water was directly released into the rivers in the Kharkov region and dispersed downstream. The hydrological module of RODOS was adapted to this emergency situation at IMMS CC within several days to simulate the chemical and bacteriological contamination of the river system. Based on the predicted levels of pollution, the State Emergency Commission determined the amounts of water that had to be pumped from elsewhere so that the water quality in the Kharkov region could be kept within permissible levels. The proposed countermeasures, based on predictions of the RODOS' hydrological module, were successfully implemented by the Ukrainian State Committee on Water Resources.

This latter experience is a clear demonstration of the wider potential of the RODOS system. Notwithstanding its specific development for application to potential future nuclear accidents, it could be readily applied to aid the management of accidents from industrial facilities generally, in particular those resulting in the widespread contamination of the air or water bodies.

4.2.2 DECISION AIDING SYSTEMS FOR THE MANAGEMENT OF POST ACCIDENT SITUATIONS

Major difficulties were experienced in the late 1980s by the former Soviet authorities in managing the longer term consequences of the Chernobyl accident. Criteria proposed for continued habitation of, or relocation of people from, affected areas were subject to much criticism, the origins of which were not wholly unassociated with the broader social and political changes then occurring in response to "glasnost" and "perestroika". These difficulties led the former Soviet authorities to ask the IAEA to organise the International Chernobyl Project to evaluate, *inter alia*, the criteria or intervention levels being proposed for the long term management of the contaminated areas. Notwithstanding the conclusion of the Project that the proposed intervention levels were unduly cautious (i.e., levels too low), even more restrictive levels were formally adopted by the authorities in both the former Soviet Union and, following its break up, the three affected countries. It was evident that social and political considerations, rather than the narrower radiological protection factors, were of overriding importance in determining intervention policy and levels. These findings had potentially important implications for existing international guidance on intervention in the medium and longer term following an accident, in particular as the

quantitative criteria developed took little or no account of broader social and political factors. It was against this background that this project was launched with the following objectives:

- to analyse the longer term management of the Chernobyl accident with particular reference to the policy adopted for intervention
- to highlight the factors that influenced decisions on intervention and determined the efficacy of countermeasures taken
- to clarify the conceptual basis for establishing intervention levels
- to develop decision aiding systems to assist the relevant authorities in the long term management of the affected territories.

The project was carried out in four separate but fully integrated tasks.

Historic portrayal

The historic portrayal of the decisions and actions taken by the former Soviet authorities (up to the break up of the Soviet Union in 1991) to mitigate the consequences of the Chernobyl accident provides essential background for reaching informed judgements on the policies adopted and on the reasons why these failed to receive broad acceptance by the population. The response to the accident is set out chronologically with particular reference to the political, social, economic and regulatory factors which influenced the intervention policy and the efficacy of the countermeasures taken. An analysis is made of the decisions taken; this shows that scientific and/or radiological factors played a minor role in comparison with broader social and political considerations. While the problems experienced by the authorities were undoubtedly exacerbated by the economic and political changes then occurring in the former Soviet Union, it is clear that the policies themselves and how they were implemented were also major contributors to these difficulties (e.g., the failure to inform the population of the potential risks before the accident and the incomplete information provided after the accident resulted in a loss of confidence by the population in both the policies and the authorities).

Social and psychological factors

The accident and its aftermath have resulted in considerably enhanced levels of stress and anxiety which appear to be at the origins of an increased level of ill-health in the affected populations. These effects doubtless had an influence on the intervention policies adopted for the long term management of the affected areas, in particular the adoption of lower intervention levels than could be justified on strictly radiological protection grounds.

Surveys were carried out in all three countries to identify the major factors that influenced (and still influence) people's attitudes and opinions on the risks they face consequent upon continuing to live in contaminated areas and on the countermeasures that ostensibly are being taken for their protection. The surveys showed that the levels of stress were significantly higher in contaminated settlements compared with those essentially unaffected by the accident and used as controls; moreover, the level of stress had continued to increase since 1992. The level of stress

or anxiety is not, however, well correlated with the level of contamination in affected settlements but is more influenced by the people's state of mind. Some of the major factors determining the level of stress were distrust of the authorities and experts, a general feeling of helplessness and loss of personal control over their well-being, inadequate information and its lack of credibility. Inadvertently, the levels of stress may also have been increased by some of the measures taken to mitigate the consequences of the accident (e.g., the payment of compensation based on the level of contamination).

Conceptual basis for setting intervention levels

The response, both within the former Soviet Union and elsewhere, to the Chernobyl accident indicated that, while the conceptual basis of existing guidance was largely sound, insufficient attention had been given to its practical implementation (e.g., how to take account of factors of a more social and political nature). Major reviews have since been made, both nationally and internationally, of guidance on intervention, in particular that concerned with intervention in the medium to long term (e.g., food restrictions, relocation, resettlement of evacuated or relocated populations, etc). A critical analysis has been made within this project of how guidance and/or policy on intervention has developed over the past decade, in particular in three former Soviet countries most affected by the Chernobyl accident. Current international guidance on relocation is contrasted with the social protection policies implemented by the three former Soviet countries. Significant differences are apparent and are largely due to the differences in the nature (generic versus specific) of the respective guidance/policy and the extent to which account has been taken of broader factors of a more social and political nature.

Distributions of dose in contaminated settlements were analyzed as part of a wider and ongoing assessment of the implications of using average dose in a population group as the basis for decisions on intervention. While this practice is justifiable where the dose distribution is relatively narrow, greater caution is needed in its application when the dose distribution is wide and/or exhibits multiple peaks.

Conceptual basis for decision aiding system

The basic framework for a decision aiding system that could assist authorities in the long term management of contaminated territories has been developed. A number of modules are at various stages of development. The more significant are: BARD - a risk module and data base for estimating the health risks and loss of life expectancy consequent upon exposure of a specified population; PRANA (Protection action and Rehabilitation of Agrosphere after a Nuclear Accident) which assesses the efficacy and costs of different agricultural countermeasures at different levels (e.g., farm, settlement, district, region); and a module on indirect countermeasures (i.e., actions that improve the situation without changing the exposure of the population).

In future, greater attention needs to be given to modules that take account of a number of broader factors (e.g., social, political, etc.) in addition to those of a more tangible nature such as cost and affect on health.

Important lessons have been learnt from this project which, if heeded, could improve the long term management of areas affected by the Chernobyl accident and, indeed, areas affected by any future accident. Increasing social trust and enabling individuals to exercise greater personal control have been identified as key issues for improving the situation for those continuing to live in contaminated areas. This whole topic, however, warrants further research.

The main conclusion of the project is that new strategies need to be established for the effective long term management of contaminated areas. A new and promising approach, that has emerged from this project, is to promote changes in the social infrastructure and economic life in the affected regions. The complexity of the existing situation calls for a decentralised and pragmatic approach of public action to enable the population to actively participate in the rehabilitation of the affected areas. New psychological and social conditions need to be established to restore trust among the affected population to enable greater "normality" to return to everyday life, notwithstanding the residual contamination of their environment. The potential of this approach will be evaluated within the Fourth Framework Programme - Nuclear Fission Safety, through its pilot application at a contaminated settlement in Belarus.

4.2.3 PATHWAY ANALYSIS AND DOSE DISTRIBUTIONS

The main objective of this project was to develop improved and more reliable models for predicting the internal and external exposure of the population living in areas contaminated by the Chernobyl accident. In general, the models currently used for this purpose contain a number of cautious assumptions (i.e., result in over-estimates of exposure) which were deliberately introduced to ensure adequate protection of the population in the immediate aftermath of the accident. While the adoption of such an approach in the past is understandable, there is an increasing need for more realistic estimates for application both now and in the future (e.g. to aid the better allocation of resources, for use in epidemiological studies, to avoid over-stating exposures of people, etc.). Many current models are also limited in the sense that they are only able to estimate average doses in relatively large population groups. The estimation and analysis of dose distributions in the affected populations was a further important objective of this project.

The project was carried out in five sub-projects:

External exposure

A validated and generally agreed model has been developed to predict the external radiation exposure of different social and occupational groups continuing to live in areas affected by the Chernobyl accident. The model was validated with TLD measurements of external doses in various population groups and has been used to estimate annual doses for particular population groups (e.g. as a function of age, occupation, house type, etc) for the period 1990 - 2056. The most exposed groups in the population were found to be outdoor workers, in particular forestry workers, living in wood frame houses.

Transfer of radioactivity to foodstuffs

An extensive review of the available data on transfer factors was carried out and these were classified on the basis of soil characteristics, crop and type of animal. Best estimates, together with 95% confidence intervals, have been made of transfer factors for each of the classifications. Analyses were also made of how the transfer factors varied as a function of time after the Chernobyl accident and of how transfer was affected by the use of fertilizers on different types of soil and other types of countermeasure. Surveys were also made of the levels of caesium in foodstuffs in shops, markets and in public catering systems as an input to assessing human intake and to providing an indication of the efficacy of system of foodstuff control.

Natural/wild foodstuffs and effects of culinary practice

Detailed and extensive analyses were made of the transfer of ^{137}Cs to natural or wild foodstuffs, principally to mushrooms, berries and game obtained from forest environments. Transfer factors have been derived for different species of mushroom and berries and, for selected species, as a function of time and soil type. Surveys have also been made of the dietary intakes of wild/natural products in Belarus and of how these are prepared prior to consumption and the effect of culinary practice on caesium levels has also been investigated. Based on these analyses a 'state of the art' model has been developed to estimate the intake of caesium from wild/natural products.

Internal exposure

A model has been developed to estimate doses from the intake of ^{137}Cs in foodstuffs. The model is based on surveys of dietary intakes in the three countries and of their origins (i.e., fraction produced locally, regionally, etc.) and on whole body measurements of ^{137}Cs in the population. For the purposes of the model the population has been classified into groups who are low, moderate and high consumers of locally produced milk and mushrooms.

Computer versions of models

Software has been developed for estimating average external and internal doses as a function of time for each settlement in the Ukraine. Account is taken of the pattern of caesium deposition in the settlement, external dose rates in air, size and structure of the population, levels of caesium in locally produced foodstuffs, nature and extent of countermeasures imposed, measurements of caesium body burdens, etc. Software has also been developed to estimate the distribution of external doses in settlements. Estimates can be made for rural and urban settlements and for 15 sub-groups within the population divided according to age and or occupation and type of housing.

The models developed within this project contain a number of improvements compared with those currently used by the respective national authorities as input to the management and control of the longer term consequences of the accident. The adoption of these improved models would, in principle, result in the more effective

allocation of resources to the long term management of the contaminated territories; moreover, they may help allay some of the anxiety prevalent in the population consequent upon the generally lower (and more reliable) estimates of dose which they indicate. The models also provide a sound basis for estimating exposures in the event of any future accident. Notwithstanding these major improvements, further developments are needed in a few areas. The more significant include refinement of the models for the purposes of retrospective dosimetry, further improvement of the model for internal exposure (in particular for natural/wild produce and for assessing dose distributions), seasonal dependence and the more reliable estimation of doses averted by countermeasures.

4.2.4 ATLAS OF CAESIUM DEPOSITION ON EUROPE AFTER THE CHERNOBYL ACCIDENT

Various compilations have been made of the deposition of radioactive material in particular countries or regions in Europe as a result of the Chernobyl accident. These compilations were made for a variety of different purposes and consequently there are significant differences in their resolution and quality. The objective of this project was to prepare a comprehensive atlas of the deposition of radioactive material across the whole of Europe consequent upon the Chernobyl accident. In addition to the more obvious interest in and use of the more factual content of the atlas, it would provide most useful and needed perspective for judging the significance of the deposited material, especially for those continuing to live in areas that are formally designated as "contaminated".

The focus of the atlas is the deposition of ^{137}Cs, the radionuclide which largely determines the long term radiological impact of the accident; consequently, it provides a good, albeit approximate, surrogate for the spatial variation in this impact. Other long lived radionuclides (e.g., ^{90}Sr, ^{239}Pu, etc.) were also released and widely dispersed in the environment but their radiological significance is small in comparison with that of ^{137}Cs. The short term impact of the accident was largely determined by shorter lived nuclides (e.g., ^{131}I etc.) but the deposition of these is outside the scope of this atlas.

The atlas was compiled from the most comprehensive and up to date monitoring data available from each country in Europe. The data, after being subjected to various quality checks, were compiled within a data base in a Geographical Information System (GIS). Geostatistical techniques were applied to the data to determine isolines of caesium deposition.

The atlas (De Cort, et al, Atlas of Caesium Deposition on Europe after the Chernobyl Accident, EUR 16733, (EC, Office for Official Publications, Luxembourg), 1996.) contains more than sixty full colour maps (mostly A2 format) of ^{137}Cs deposition. The deposition levels reported are normalised to May 1986 and comprise the total (ie, from Chernobyl, weapons fallout, other accidents, etc.) deposition of ^{137}Cs at that time irrespective of its origin. Maps are presented at three geographic levels with each on a different scale: European (1 to 10 million), national or regional (1 to 1 million to 1 to 2.5 million) and local. The "local" maps are limited to those areas with enhanced

deposition, in particular areas with deposition in excess of 40 kBq m^{-2} (1 to 500 thousand) and 1480 kBq m^{-2} (1 to 200 thousand), respectively. Based on the interpolated patterns of deposition, estimates have been made of the amount of Chernobyl ^{137}Cs deposited on each country and over Europe as a whole. Some perspective is provided on the radiological significance of the deposited levels. The atlas also contains an accompanying explanatory text together with several annexes which contain information central to the understanding of the deposition patterns (e.g., meteorological data during the release, precipitation, topography, soil characteristics, etc.).

Within the framework of the project Geographical Information Systems were transferred to each of the three countries to facilitate the processing and management of the underlying deposition data and the development of maps based on them.

These systems will find continuing use in future for the effective management and processing of both the deposition and other data (e.g. deposition of other nuclides, internal and external doses, land cover and usage, population distribution, agricultural production, health statistics, economic and social statistics, etc.) relevant to the health and environmental impact of the accident. Moreover, the existence of such extensive and quality assured data bases will be of long term value to the scientific community, for example for model development and validation, and optimisation of monitoring networks.

4.3 EVALUATION OF THE HEALTH CONSEQUENCES AND RETROSPECTIVE DOSIMETRY

Projects in this important area were integrated within the collaborative programme during its second year in December 1992 and during its third year in December 1993. The first three projects initiated in 1992 are: Biological dosimetry for the persons irradiated by the Chernobyl accident; Epidemiological investigations including dose assessment and dose reconstruction; and Treatment of accident victims. To these projects three new ones were added in 1993: Molecular, cellular, biological characterisation of childhood thyroid cancer; Development of optimal treatment and preventive measures for childhood thyroid cancer; Dose reconstruction and retrospective dosimetry.

For the projects on the health consequences of the Chernobyl accident it is important to evaluate the medium (1-10 years) and long term (10-50 years) consequences of the accident, to evaluate the health consequences of the accident for the public and the "liquidators", and to establish international guidelines for treatment of victims (e.g. children with thyroid cancer, overexposed people).

4.3.1 EPIDEMIOLOGY

The project on "epidemiological investigations" was essentially aimed to determine whether a detailed follow-up of the more exposed populations, e.g., liquidators, would be possible and was structured along 3 main activities: education, training and exchange of scientists; routine monitoring systems - cancer registration; and follow-up and analysis of exposed cohorts. In training and exchange of scientists, the most important achievement was the very successful course in epidemiology, radiation epidemiology and cancer registration. This activity reached a broad audience of experienced scientists and young researchers in the three republics at the beginning of their career. The pilot follow-up studies (the feasibility for follow-up of liquidators; dosimetry on a stratified sample of liquidator bloods; and a case-control study on leukaemia among liquidators in Belarus and Russia (Ukraine is doing this with US-researchers) proved also to be very successful with respect to increasing knowledge of what is needed to do such a follow-up properly. The maintenance and use of the Chernobyl registries, and the importance of maintaining linkage possibilities to the general registries kept by the health authorities is obvious after the different pilot projects were carried out. The initial phase has demonstrated the potential for conducting specific types of epidemiological follow-up in the republics successfully.

4.3.2 BIODOSIMETRY AND DOSE RECONSTRUCTION

The general objective of "biological dosimetry" was to assist in quantifying exposure of irradiated persons by the analysis for chromosomal damage in lymphocytes using the newly developed fluorescent in situ hybridization (FISH) technique. The material that was necessary for this work includes a data bank on several thousand persons comprising those who are heavily irradiated; liquidators; and surveys of exposed communities, particularly of children. The final aim of this project was to build the infrastructure in the three republics for the use of the FISH technique in order to complement

epidemiology studies. As expected it was very time consuming to get the FISH technique started in the laboratories in the three republics for several technical reasons and data for this project did not begin to emerge until mid-1995. One success of this project is that a number of scientists in the three republics have now been well trained in the FISH technique. The study showed clearly that the FISH technique is not going to be an individual dosemeter for persons exposed to low doses of current interest to the epidemiologists. FISH is still not properly validated as a retrospective biological dosemeter and there are questions still needing resolution. An important way to determine the extent to which different factors may confound biological dosimetry would be to study, by FISH, persons who were irradiated to doses that were, at the time, reliably defined by other methods. Potentially the Chernobyl accident victims who were exposed in 1986 to life threatening doses of radiation would be a valuable group to examine. In all, there may be 100-150 persons still available whose blood could be usefully used for cytogenetic studies. This sort of study has already been started in the Ukraine.

The project on "retrospective dosimetry and dose reconstruction" was based on a comprehensive approach using a variety of methods including determination of a long-lived radioactive iodine isotope in soil samples for thyroid dose reconstruction; "Electron Spin Resonance" (ESR) measurements of tooth enamel for retrospective dosimetry of individuals;"Luminescence Dosimetry" using house and household materials (ceramics, tiles) and environmental material for assessment of population doses accumulated over longer periods; and mathematical modelling of exposures taking account of exposure pathways, individual living and consumption habits and measurement data (see section 3.1.1.3). The study has shown that reconstruction of organ dose or whole body dose is feasible with accuracies and dose thresholds (of the order of 200 mGy) as required for epidemiological studies, and, in fact, has been carried out for several groups such as the evacuees of Pripyat and, in addition, thyroid doses for a restricted number of people have been estimated.

4.3.4 PATIENT TREATMENT

For the "diagnosis and treatment of patients with acute radiation syndromes" project, new insights in understanding stem cell biology and radiation sensitivity, the emergence of new drugs, as well as the new developments in stem cell transplantation technology, have drastically changed the views of doctors on the treatment of bone marrow damage. It is unlikely, that in a future accident, allogeneic bone marrow transplantation will be considered a first choice of treatment. Rather, an approach in which a combination of growth factors is administered, both to accelerate hemopoietic reconstitution as well to obtain an indication of the extent of the damage will be favoured. Concerning the patient evaluation a Radiation Accident Data Base (MURAD) has been developed. The essential prerequisite for successful work was the drafting of a pre-computer case report. The last version is now finished and can be used in a paper form or in a disk form.Also, considerable progress has been made, in general, in the surgical treatment of extensive skin lesions. Early diagnosis and prognosis of the extent of the damage is of critical importance to establish early therapy. The newer imaging techniques may to a certain extent provide the diagnostic tools required. The careful description of the patient data of the acute phase has been completed as well as the questionnaires and corresponding

clinical database. The results emphasized the need for standardization of medical nomenclature and methodology.

4.3.5 THYROID CANCER IN CHILDREN LIVING NEAR CHERNOBYL: THE INITIATIVES TAKEN BY THE EC

In January 1992, under the Radiation Protection Research Action, a Panel of experts was set up to evaluate the situation concerning the reported increased incidence of thyroid cancer in children living near Chernobyl at the time of the nuclear reactor accident on 26 April 1986.

The report written by this Panel "Thyroid Cancer in Children living near Chernobyl", and published by the EC, (EUR 15248) documents their findings with respect to the occurrence of childhood thyroid cancer in Belarus and the Northern Ukraine. The Panel arrives at a consensus opinion and makes strong recommendations for urgent technical and humanitarian assistance and research cooperation.

The Consensus Opinion of the Panel Members and Observers documents the agreement reached that there is a true increase in childhood thyroid cancer in areas around Chernobyl, that intensive screening programmes are unlikely to account for much of the increase in cancer incidence, and that exposure to radioactive isotopes of iodine from the Chernobyl accident is the most likely cause of this increase. The report therefore proposed that urgent action be undertaken to deal with both the humanitarian and scientific aspects of the problem. The recommendation for Technical Assistance proposes a complete package of facilities and training to provide optimal treatment for the childhood thyroid cancer patients.

The report explains the situation concerning the children suffering from thyroid cancer. Childhood thyroid cancer is a rare disease but if optimally treated does not have to be fatal.

The Panel was of the opinion that the situation was serious and the children were not receiving optimum treatment despite all the efforts of the Medical Authorities in Belarus and the Ukraine because of the lack of adequate surgical and therapeutic facilities. Humanitarian aid would have an immediate impact on the health of these young victims. The magnitude of this health problem should not be underestimated and may persist for decades.

The European Commission's reaction to this situation and to the Panel recommendations was to deal quickly with the three most important aspects of the problem, namely, Humanitarian aid, Technical assistance and Research cooperation.

Humanitarian Aid

In March 1994, the European Office for Humanitarian Aid (ECHO/2) of the European Commission launched a humanitarian project to supply specialist equipment and medicines for the diagnosis, treatment and follow-up of the children suffering from thyroid cancer in Belarus and the Ukraine.

The facilities include:

- Nuclear medical facilities for radioactive iodine for diagnosis and treatment of metastases (e.g., scanners or gamma cameras for radioiodine scans)
- Modern equipment for diagnostic use i.e. microtomes, microscopes, consumables and material (glass slides, etc), (These needs will necessarily be accompanied by training of anaesthetists, surgeons and other specialists, and assistance in the quality control of the equipment)
- Continuing provision of replacement therapy drugs after surgery since the children adequately treated will be hypothyroid. Centres will be provided with drugs of sufficient quality necessary for medical treatment or trained to be able to produce these drugs independently, in their own countries
- High quality reagent kits for laboratory analysis, for the follow-up of the children.

Technical assistance

Through the Commission's activity on Technical Assistance for the CIS (TACIS) a training programme for 80 specialists was launched, as well as designing and installing facilities for forming and packaging L-thyroxine tablets in the Chernobyl affected regions and defining and implementing measures to improve the production, packaging, storage and distribution of iodised table salt in the Chernobyl affected regions.

Research cooperation

Following the publication of the thyroid report in October 1993, the Radiation Protection Research Action initiated two thyroid research projects 2 months later within the Chernobyl research collaboration framework. The two projects deal with the molecular, cellular, biological characterisation of childhood thyroid cancer and the development of optimal treatment and preventive measures for childhood thyroid cancer.

The project on the pathological characterization of the tumours led to the conclusions that there has been an important increase in the incidence of childhood thyroid cancer in Belarus and the Ukraine during the years 1990-1994, and that this increase is not due to screening identifying a reservoir of papillary microcarcinomas. Simple analysis suggests that this increase is related to exposure to fallout from Chernobyl; the fact that the only type of tumour so far reported with a major increase in the exposed areas is thyroid cancer, and that there was a large component of radioisotopes of iodine in the release from the accident and the fallout points strongly to exposure to radioiodine as the probable major cause. The most compelling evidence which links the radioactive iodine released in the accident with the increase in childhood thyroid cancers is an analysis which shows that children who were conceived after the accident have the low incidence of thyroid cancer normally found before the accident and comparable with that in countries not affected by the accident. Analyses by cohort at age of exposure shows that there is a great increase in sensitivity in very young children. This suggests that there will be a continuing increase in the incidence of thyroid cancer. This will make the thyroid cancer an extremely common tumour, and require major resources to deal with the increase. Therefore, consideration should be given now to the resources needed for dealing with a large increase. With very few exceptions the diagnoses of thyroid cancer in children made in the CIS over the last 5 years have been substantiated by joint studies

with EU scientists, the tumours have been classified, the subtypes identified, and cytochemical and molecular biological investigations carried out.

The project on the clinical aspects of the post-Chernobyl thyroid carcinoma also made substantial progress, even if it was not easy to discuss and come to an agreement for common protocols with the different surgeons in the three republics since thyroid cancer was treated differently there than in the West. The major difference consists in doing a partial thyroidectomy, which is not practised any more in the West since it leads more often to recurrence of disease. One of the reasons for practising this kind of surgery was due to the fact that no L-Thyroxine drug, needed for lifelong treatment after a total thyroidectomy, was available in Belarus and the Ukraine. The action of ECHO to procure this drug for two years and the action of TACIS to design and install facilities for forming and packaging this drug in the Ukraine has changed the situation and made discussions on surgical treatment easier. A protocol for diagnosis, treatment and follow-up of the children has been devised. It is expected that the adoption of such protocol in its final version by all treatment centres will greatly facilitate an optimisation of the management of thyroid cancer.

In general this phase, which can be considered as an initial one for the health projects, has been a success and many of the original objectives were met within the project period. The collaboration has provided important early results. For all of these projects a solid basis has been laid for a continuation of this type of research collaboration in a further development of the programme.

The studies on the health consequences of the Chernobyl accident have shown during these three years that the only health consequence to date that can be directly linked to the Chernobyl accident is thyroid cancer in children. It is evident that there is a need for continued surveillance of the exposed populations.

CHAPTER 5

PROSPECTS FOR THE FOURTH FRAMEWORK PROGRAMME

5. PROSPECTS FOR THE FOURTH FRAMEWORK PROGRAMME

5.1 POLICIES AND PRIORITIES

The Radiation Protection Research Programme has always maintained a comprehensive approach attempting to cover all the different areas which make up radiological protection science. This has been increasingly difficult with the gradual but serious reduction in funding which has taken place throughout the 1980s and into the 1990s. In the early eighties the area of "Primary Radiation Effects" which dealt with radiation chemistry and free radical induction was taken out of the programme as a result of the reduced funding but this was the only concession which was made to the deteriorating budget situation. The consequence of the continued reduction in funding and the aim of the programme to maintain as comprehensive approach to radiological protection as possible has been the gradual marginalisation of the support which has been given to the successful projects compared with the support given at the national level. The response at the management level in the planning for the specific programme "Nuclear Fission Safety" for the Fourth Framework Programme has been to reconsider the desire for a comprehensive approach and to examine the different possibilities to increase the participation level in the successful projects while still maintaining a broad programme.

The solution which was eventually chosen was to select a restricted number of priority areas for strong support via cost-shared contracts complemented by a series of topics which could be addressed via concerted action projects where funding is provided to coordinate the research by bringing the scientists together to discuss progress but where there would not be direct support for research. Concerted Actions have been used by other programmes within DG XII but have not previously been utilised in the field of radiation protection research.

The selection of research priorities for the new programme has been achieved with the help of the members of the Management and Advisory Committee "Radiation Protection" (CGC 10) and with the help of national experts. The programme selected has been driven by the desire to follow-up the main themes demonstrating clear progress from the 1992-1995 programme and might be considered somewhat conventional. However, elements of innovation with respect to topics in the programme were introduced via areas proposed for the concerted actions. The research topics selected for the area D of the specific programme "Nuclear Fission Safety" of the Fourth Framework Programme are listed below in section 5.2. under the heading "Radiological impact on man and the environment".

In addition to the continuation of the normal research programme there was a desire to formalise the research carried out under the "Chernobyl Research" APAS-COSU programme within the Fourth Framework Programme and this led to the development of an additional section with the title "Mastering Events of the Past" which aims to continue the research programme started under the Chernobyl Research expanding it to cover other radiological accidents which have occurred in the past in other parts of the Russian Federation. The research topics selected for this area E of the specific programme "Nuclear Fission Safety" are listed below in section 5.3. Under the terms of the Euratom Treaty the budget allocated to the "Nuclear Fission Safety" programme can

only be utilised to support research carried out within the European Union. This meant that it was impossible to support the scientists working in Belarus, Ukraine and the Russian Federation at anything other than a sub-contractors level and certainly not at the level that had been possible under the APAS-COSU programme. In order to overcome this difficulty a clause was introduced in the Council Decision on the Fourth Framework Programme to permit research on the radiological consequences of nuclear accidents in countries outside the Union to be supported under the Activity 2 - Cooperation with third countries and international organisations. It is intended that a close coordination of the projects selected for support under the Area E of the Nuclear Fission Safety programme and the Inco-Copernicus programme from Activity 2 will permit an extension of the Chernobyl Research to include other nuclear accident sites with equitable funding for institutes in the Union and in the other countries concerned.

5.2 RADIOLOGICAL IMPACT ON MAN AND THE ENVIRONMENT

Improved radiation protection of man and the environment requires better **understanding of mechanisms of radiation action** in the low dose range and reliable methods for the **evaluation of radiation risk** related to external and internal irradiations, including improved knowledge of environmental transfer of radionuclides for the evaluation and management of radiation risks. These may contribute to further **reduction of exposures** in the light of social and economic considerations. The evaluation of the consequences of previous nuclear accidents will be used to advance and test current knowledge and radiation protection concepts under realistic conditions and contribute towards meeting the related **Mastering Events of the Past**.

Understanding Radiation Mechanisms and Epidemiology

The approach adopted here for improving the qualitative and quantitative knowledge of health hazards, such as cancer, related to human exposure to low doses and low dose rates of ionising radiation is based on an integrated and comprehensive study of the physical, chemical, molecular and cellular biological processes induced by radiation. The ultimate aim is to understand the mechanism by which mutations and chromosome aberrations are induced by radiation and quantify how these events lead to cancer. Epidemiological studies of groups of exposed people are the necessary complement of the study of basic mechanisms and provide direct information on the risk of radiation induced cancer in man, but mainly at high doses. A combination of epidemiological and mechanistic studies will provide a sound basis for the quantification of radiation risks at low doses accumulated over long periods of time.

The research is grouped under the following priorities:

- Modelling of radiation oncogenesis and of related biological effects
- Repair of, and recovery from, DNA damage and radiation sensitivity
- Molecular studies of radiation oncogenesis and predisposition to cancer
- Epidemiology of exposed populations
- *In utero* radiation effects on the brain
- Treatment of exposed individuals

Evaluation of Radiation Risks

Risk assessment and risk management have important roles in the development and subsequent implementation of objectively conceived policies on health and safety and environmental protection. The evaluation of risks of real or potential human exposure to ionising radiation depends critically on the quality of the methods available for the assessment of the level of exposure to external and internal irradiations. Dose reconstruction is especially important for the quantification of risk using epidemiology. The study of the behaviour of radionuclides in the ecosphere is important for the assessment of present and future exposure to radionuclides and to allow the planning and implementation of restoration techniques.

The research is grouped under the following priorities:

- Quantification of parameters which determine the fluxes of radionuclides in ecosystems
- Long term consequences of accidental contamination in semi-natural environments
- Fluxes of artificial radionuclides in surface and ground waters
- Intakes of radionuclides and their dosimetry
- Monitoring of external irradiation
- Uncertainty in the predictions of probabilistic accident consequence codes
- Development of a decision support system for off-site emergency management
- Risk perception and communication
- Comparative risk assessment of different energy systems

Reduction of Exposures

Radiological protection requires that the radiation risk to individuals and the population should be kept "As Low As Reasonably Achievable" (ALARA - principle). The correct estimation of the risk of exposure is of great importance, since both underestimation or overestimation will have undesirable socio-economic consequences. The complexity of the problems and the diversity of disciplines involved in the development of criteria, methods and strategies for effective optimisation procedures demands a basic research approach. Exposure to ionising radiation from natural sources, especially the radon decay products and the assessment of radon risk continues to require further clarification. A targeted research approach will be used for the development of techniques for environmental remedial actions in contaminated ecosystems and the assessment of their consequences. In medical diagnostic radiology the development of optimisation strategies and measures must be based on the correlation between patient dose, radiological techniques and procedures and the diagnostic information content.

The research is grouped under the following priorities:

- Optimisation of radiological protection for complex exposure situations
- Risk assessment of exposure to Radon decay products
- Techniques and management strategies for environmental restoration and their ecological consequences
- Optimisation strategies for radiation protection of the patient in diagnostic radiology

Coordination Activities (Concerted actions)

The concerted actions will be concerned with issues of global interest for which a continuous exchange of information is sufficient to stay abreast of developments and maintain expertise. These actions will bring together work in the three areas, will contribute to the transfer of research results to the implementation of radiation protection practices. These actions will include concertation and cooperation with European collaborative research groups and international organisations for the exploitation and dissemination of results.

Understanding Radiation Mechanisms and Epidemiology

- Hereditary effects
- Genetic instability
- Adaptive Responses
- Epidemiology of medically treated patients
- Treatment protocols
- Decorporation of incorporated radionuclides

Evaluation of Radiation Risks

- Radiation field analysis at the workplace
- Environmental dosimetry
- Risk from tritium
- COSYMA - Users' Group and code updating
- Assessment of health and environmental impacts

Reduction of Exposures

- Radioecological assessment of the consequences of the contamination of marine areas and of their drainage areas
- ALARA network
- Radon (sources-pathways-countermeasures)
- Areas affected by Uranium mining activities
- The adaptation of quality criteria concepts to other radiological examinations
- Elaboration of quantities for risk assessment related to radiation protection of the patient
- New developments with potential for optimisation in diagnostic radiology

5.3 MASTERING EVENTS OF THE PAST

The broad aims are, firstly, to contribute to improvements in the longer term management of territories contaminated by radioactive material in the former Soviet Union and in the health and well being of the exposed populations and, secondly, to use this experience as an input to developing more effective means for managing the radiological consequences of any future nuclear accident and, more generally, to improve radiological protection through a better understanding of the behaviour of radionuclides in the environment and of the effects of radiation on man. The research will be a continuation of that begun in 1991 under the auspices of an Agreement for International Collaboration on the Consequences of the Chernobyl Accident between the Commission and the Ministries for Chernobyl Affairs in Belarus, Russia and the Ukraine. Its scope,

however, will now be extended to encompass other significantly contaminated territories in the former Soviet Union, in particular those regions of Siberia and Kazakhstan.

Recognition and amelioration of health effects

The main aims are to investigate the feasibility of improving current estimates of the risks of radiation exposure (based on evaluations of the doses received by, and health effects expressed in, the affected populations); to develop optimal protocols for the diagnosis and treatment of exposed individuals, in particular where the exposures may result in deterministic effects or where it may lead to a major increase in the risk of thyroid cancer; and to validate the basic work done in the main research programme (see Section 5.2) by studies concerning childhood thyroid cancer and populations exposed to chronic radiation.

The research is grouped under the following priorities:
- Molecular studies of radiation oncogenesis and predisposition to cancer
- Epidemiology of exposed populations
- Treatment of exposed individuals
- Dose Reconstruction

Restoration of severely contaminated territories

The aim is to develop guidance that will be of practical value for the longer term management and restoration of contaminated sites with differing characteristics (e.g., urban, rural, agricultural, semi-natural, aquatic, etc.).

The research is grouped under the following priorities:
- Bases for developing criteria for restoration of contaminated sites
- Methodological approaches for evaluating restoration options
- Consolidation and evaluation of practicable restoration techniques
- Further investigation, where necessary, of potentially promising or new restoration techniques

Emergency management approaches

The aim is to develop a comprehensive decision support system to aid decisions on how best to mitigate the off-site consequences of future radiological accidents and of residual contamination from past events. This research would be complementary to that in the main research programme (see Section 5.2) and take advantage of former Soviet experience in this area.

The research is grouped under the following priorities:
- Development and/or improvement of system modules
- Adaptation of the system to local conditions. Integration of the system with radiological monitoring and meteorological networks
- The role and influence of social factors
- Development of guidance on the return to normality after an accident

Data management

The aim is to establish data management centres in Belarus, Russia and Ukraine to bring together, in an integrated, coherent and validated form the many and diverse data on the health, environmental and economic impacts of the Chernobyl accident. These centres will, inter alia, provide a sound basis for evaluating the future management of contaminated areas, provide a more reliable basis for estimating past and future doses, provide a basis for improved understanding and modelling of the transfer of radionuclides in the environment, and contribute to increased public acceptance of official advice on the radiological impact of continuing to live in contaminated areas.

The research is grouped under the following priorities:
- Specification of the content and structure of the data base and hardware requirements
- Development of the component parts of the data base

Public Information

The aim is to improve, through public information, understanding of the nature and magnitude of the risks from living in contaminated areas and of how these risks can be influenced by diet, lifestyle, etc. This is expected to provide a measure of reassurance to the population and help re-gain their trust in the measures taken to achieve safe living conditions in the affected areas.

The research is grouped under the following priorities:
- Identification and evaluation of the major factors influencing the attitudes/beliefs of the affected population
- Evaluation of major factors influencing effective communication with the affected population
- Development, implementation and evaluation of the potentially most useful information strategies

5.4 PROGRAMME IMPLEMENTATION

Two calls for proposals to this programme have been made in March 1995 and February 1996. The proposals submitted have been evaluated by panels of independent experts and the successful projects from the first call have already started. The successful contracts from the second call will soon be the subject of contract negotiations. The clear definition of the priority areas in this new programme has resulted in a leaner but fitter programme as the more productive laboratories are certainly to be found amongst the successful contractors. This streamlining of the new programme holds great promise for the development of the Fifth Framework Programme and the research continuity so essential to the field.

Real-time Computing of the Environmental Consequences of an Accidental Release to the Atmosphere from a Nuclear Installation - Decision Aids to Offsite Emergency Management (2 Volumes)
EUR 12320 - 1990

Feasibility of studies on health effects in Western Europe due to the reactor accident at Chernobyl and Recommendations for research. Post-Chernobyl Action
EUR 12551 - 1990

Monograph on Environmental Radioactivity in the European Community (1984-1985-1986)
EUR 12254 - 1990

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EUR 12483 - 1990

Radioactivity Transfer to Animal Products
EUR 12608 - 1990

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EUR 12682 - 1990

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EUR 12864 - 1990

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Statistics of Human Exposure to Ionising Radiation
EUR 13781 - 1991

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ALARA: From theory towards practice.
EUR 13796 - 1991

Improvement of long-distance atmospheric transfer models.
EUR 12549 - 1991

Improvement of practical countermeasures: The urban environment.
Post-Chernobyl Action.
EUR 12555 - 1991

Improvement of practical countermeasures: Preventive medication.
Post-Chernobyl Action.
EUR 12556 - 1991

Treatment and biological dosimetry of exposed persons.
Post-Chernobyl Action.
EUR 12558 - 1991

Impact Radioécologique de l'Accident de Tchernobyl sur les Ecosystèmes Aquatiques Continentaux (Radioecological Impact of the Chernobyl Accident on Continental Aquatic Ecosystems)
DOC XI/3522/9 - 1991

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EUR 13298 - 1991

COSYMA - a New Programme Package for Accident Consequence Assessment
EUR 13028 - 1991

COSYMA Users' Guide
EUR 13045 - 1991

Radiological Aspects of Nuclear Accident Scenarios. Vol I & Vol. II
EUR 12552 - 1991

Underlying Data for Derived Emergency Reference Levels
EUR 12553 - 1991

Improvement of Practical Countermeasures against Nuclear Contamination in the Agricultural Environment
EUR 12554 - 1991

The future of human radiation research
EUR 14096 - 1991

Skin Dosimetry
EUR 14092 - 1991

Respiratory Tract Dosimetry
EUR 14108 - 1991

Environmental Radioactivity in the European Community: 1987 - 1990
EUR 15699 - 1991

Radiation Protection research and training programme 1990-1991
EUR 13387 - 1991

Seminar on methods and codes for assessing the off-site consequences of nuclear accidents (2 volumes)
EUR 13013 - 1991

International Seminar on Intervention Levels and Countermeasures for Nuclear Accidents
EUR 14469 - 1992

Guidebook for the Treatment of Accidental Internal Radionuclide Contamination of Workers
EUR 14320 - 1992

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DOC XI/3539/92 - 1992

Evaluation of data on the transfer of radionuclides in the food chain. Post-Chernobyl Action
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Age-dependent factors in the biokinetics and dosimetry of radionuclides
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EUR 13892 - 1992

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Radiation protection series No. 67 - 1993

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EUR 14821 - 1993

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EUR 15248 - 1993

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Radiation Protection Series No. 65 - 1993

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Radiation Protection Series No. 64 - 1993

Radiation Protection Research Action 1992-94
Technical description of scientific projects
EUR 15238 - 1994

Radiation Protection Programme 1990-1991 (Vol. 1 & 2)
EUR 15295 - 1994

Radiation protection optimization "Achievements and Opportunities"
EUR 15234 - 1994

PC COSYMA: an Accident Consequence Assessment Package for Use on a PC
EUR 14916 - 1994

COSYMA: Users Intercomparison Exercise
EUR 15108 - 1994

Probabilistic Accident Consequence Assessment Codes: Second International Comparison - Technical Report
EUR 15109 - 1994

Probabilistic Accident Consequence Assessment Codes: Second International Comparison - Overview Report
EUR 15237 - 1994

A European intercomparison of methods used for the assessment of intakes of internally deposited radionuclides.
EUR 14195 - 1994

Guidance notes on the calibration of whole-body counters and on the interpretation of the measured results
EUR 15395 - 1994

Molecular Mechanisms in Radiation Mutagenesis and Carcinogenesis
EUR 15294 - 1994

Individual Monitoring of Ionising Radiation
EUR 15394 - 1994

Intakes of Radionuclides. Detection, Assessment and Limitation of Occupational Exposure
EUR 15714 - 1994

Indoor Radon Remedial Action
EUR 16005 - 1994

Radiation Protection for the transport of radioactive substances
Radiation Protection series No. 68 - 1994

Technical recommendations for monitoring individuals occupationally exposed to external radiation
Radiation protection series No. 73
EUR 14852 - 1994

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EUR 15855 SAND94-1453, 1994, 3 vols

Health effects of internally deposited radionuclides: emphasis on radium and thorium
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EUR 15564 - 1995

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Advances in Radiation Measurements
EUR 16177 - 1995

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EUR 16604 - 1995

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Radioactive effluents from nuclear power stations and nuclear fuel reprocessing plants in the European Community, 1977-86
Part 1: Discharge date 1977-86
Part 2: Radiological aspects
Radiation protection series No. 77
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Radiation protection series No. 76
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EUR 16545 - 1996

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EUR 16239 - 1996

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EUR 16644 - 1996

European Guidelines on Quality Criteria for Diagnostic Radiographic Images
EUR 16260 - 1996, in press

European Guidelines on Quality Criteria for Diagnostic Radiographic Images in Paediatrics
EUR 16261 - 1996, in press

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EUR 16263 - 1996, in press

The 1991 Trial on Quality Criteria for Diagnostic Radiographic Images: Detailed Results and Findings
EUR 16635 - 1996, in press

Present status of practical aspects of individual dosimetry
Part I: EU Member States
Part II: East European Countries
Radiation Protection series No. 78 - 1996

Contamination of surfaces by resuspended material
EUR 16527 - 1996

The transfer of radionuclides through the terrestrial environment to agricultural products, including the evaluation of agrochemical practices
EUR 16528 - 1996

Modelling and study of the mechanisms of the transfer of radioactive material from terrestrial ecosystems to and in water bodies
EUR 16529 - 1996

Evaluation and Development of decontamination strategies for a range of environmental situations and evaluations to their efficacy and other impacts
EUR 16530 - 1996

The behaviour of radionuclides in natural and semi-natural ecosystems
EUR 16531 - 1996

Biological dosimetry for irradiated persons
EUR 16532 - 1996

Epidemiological investigations including dose assessment and dose reconstruction
EUR 16537 - 1996

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