

IAEA-TECDOC-1678

***Environmental Modelling for  
Radiation Safety (EMRAS) —  
A Summary Report of the Results  
of the EMRAS Programme  
(2003–2007)***



**IAEA**

International Atomic Energy Agency

# IAEA SAFETY STANDARDS AND RELATED PUBLICATIONS

## IAEA SAFETY STANDARDS

Under the terms of Article III of its Statute, the IAEA is authorized to establish or adopt standards of safety for protection of health and minimization of danger to life and property, and to provide for the application of these standards.

The publications by means of which the IAEA establishes standards are issued in the **IAEA Safety Standards Series**. This series covers nuclear safety, radiation safety, transport safety and waste safety. The publication categories in the series are **Safety Fundamentals**, **Safety Requirements** and **Safety Guides**.

Information on the IAEA's safety standards programme is available at the IAEA Internet site

<http://www-ns.iaea.org/standards/>

The site provides the texts in English of published and draft safety standards. The texts of safety standards issued in Arabic, Chinese, French, Russian and Spanish, the IAEA Safety Glossary and a status report for safety standards under development are also available. For further information, please contact the IAEA at PO Box 100, 1400 Vienna, Austria.

All users of IAEA safety standards are invited to inform the IAEA of experience in their use (e.g. as a basis for national regulations, for safety reviews and for training courses) for the purpose of ensuring that they continue to meet users' needs. Information may be provided via the IAEA Internet site or by post, as above, or by email to [Official.Mail@iaea.org](mailto:Official.Mail@iaea.org).

## RELATED PUBLICATIONS

The IAEA provides for the application of the standards and, under the terms of Articles III and VIII.C of its Statute, makes available and fosters the exchange of information relating to peaceful nuclear activities and serves as an intermediary among its Member States for this purpose.

Reports on safety and protection in nuclear activities are issued as **Safety Reports**, which provide practical examples and detailed methods that can be used in support of the safety standards.

Other safety related IAEA publications are issued as **Radiological Assessment Reports**, the International Nuclear Safety Group's **INSAG Reports**, **Technical Reports** and **TECDOCs**. The IAEA also issues reports on radiological accidents, training manuals and practical manuals, and other special safety related publications.

Security related publications are issued in the **IAEA Nuclear Security Series**.

The **IAEA Nuclear Energy Series** consists of reports designed to encourage and assist research on, and development and practical application of, nuclear energy for peaceful uses. The information is presented in guides, reports on the status of technology and advances, and best practices for peaceful uses of nuclear energy. The series complements the IAEA's safety standards, and provides detailed guidance, experience, good practices and examples in the areas of nuclear power, the nuclear fuel cycle, radioactive waste management and decommissioning.

Environmental Modelling  
for Radiation Safety  
(EMRAS)

The following States are Members of the International Atomic Energy Agency:

AFGHANISTAN	GHANA	NIGERIA
ALBANIA	GREECE	NORWAY
ALGERIA	GUATEMALA	OMAN
ANGOLA	HAITI	PAKISTAN
ARGENTINA	HOLY SEE	PALAU
ARMENIA	HONDURAS	PANAMA
AUSTRALIA	HUNGARY	PAPUA NEW GUINEA
AUSTRIA	ICELAND	PARAGUAY
AZERBAIJAN	INDIA	PERU
BAHRAIN	INDONESIA	PHILIPPINES
BANGLADESH	IRAN, ISLAMIC REPUBLIC OF	POLAND
BELARUS	IRAQ	PORTUGAL
BELGIUM	IRELAND	QATAR
BELIZE	ISRAEL	REPUBLIC OF MOLDOVA
BENIN	ITALY	ROMANIA
BOLIVIA	JAMAICA	RUSSIAN FEDERATION
BOSNIA AND HERZEGOVINA	JAPAN	RWANDA
BOTSWANA	JORDAN	SAUDI ARABIA
BRAZIL	KAZAKHSTAN	SENEGAL
BULGARIA	KENYA	SERBIA
BURKINA FASO	KOREA, REPUBLIC OF	SEYCHELLES
BURUNDI	KUWAIT	SIERRA LEONE
CAMBODIA	KYRGYZSTAN	SINGAPORE
CAMEROON	LAO PEOPLE'S DEMOCRATIC REPUBLIC	SLOVAKIA
CANADA	LATVIA	SLOVENIA
CENTRAL AFRICAN REPUBLIC	LEBANON	SOUTH AFRICA
CHAD	LESOTHO	SPAIN
CHILE	LIBERIA	SRI LANKA
CHINA	LIBYA	SUDAN
COLOMBIA	LIECHTENSTEIN	SWEDEN
CONGO	LITHUANIA	SWITZERLAND
COSTA RICA	LUXEMBOURG	SYRIAN ARAB REPUBLIC
CÔTE D'IVOIRE	MADAGASCAR	TAJIKISTAN
CROATIA	MALAWI	THAILAND
CUBA	MALAYSIA	THE FORMER YUGOSLAV REPUBLIC OF MACEDONIA
CYPRUS	MALI	TUNISIA
CZECH REPUBLIC	MALTA	TURKEY
DEMOCRATIC REPUBLIC OF THE CONGO	MARSHALL ISLANDS	UGANDA
DENMARK	MAURITANIA	UKRAINE
DOMINICA	MAURITIUS	UNITED ARAB EMIRATES
DOMINICAN REPUBLIC	MEXICO	UNITED KINGDOM OF GREAT BRITAIN AND NORTHERN IRELAND
ECUADOR	MONACO	UNITED REPUBLIC OF TANZANIA
EGYPT	MONGOLIA	UNITED STATES OF AMERICA
EL SALVADOR	MONTENEGRO	URUGUAY
ERITREA	MOROCCO	UZBEKISTAN
ESTONIA	MOZAMBIQUE	VENEZUELA
ETHIOPIA	MYANMAR	VIETNAM
FINLAND	NAMIBIA	YEMEN
FRANCE	NEPAL	ZAMBIA
GABON	NETHERLANDS	ZIMBABWE
GEORGIA	NEW ZEALAND	
GERMANY	NICARAGUA	
	NIGER	

The Agency's Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is "to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world".

IAEA-TECDOC-1678

ENVIRONMENTAL MODELLING  
FOR RADIATION SAFETY  
(EMRAS)

A SUMMARY REPORT OF THE RESULTS OF THE  
EMRAS PROGRAMME (2003–2007)

INTERNATIONAL ATOMIC ENERGY AGENCY  
VIENNA, 2012

## COPYRIGHT NOTICE

All IAEA scientific and technical publications are protected by the terms of the Universal Copyright Convention as adopted in 1952 (Berne) and as revised in 1972 (Paris). The copyright has since been extended by the World Intellectual Property Organization (Geneva) to include electronic and virtual intellectual property. Permission to use whole or parts of texts contained in IAEA publications in printed or electronic form must be obtained and is usually subject to royalty agreements. Proposals for non-commercial reproductions and translations are welcomed and considered on a case-by-case basis. Enquiries should be addressed to the IAEA Publishing Section at:

Marketing and Sales Unit, Publishing Section  
International Atomic Energy Agency  
Vienna International Centre  
PO Box 100  
1400 Vienna, Austria  
fax: +43 1 2600 29302  
tel.: +43 1 2600 22417  
email: [sales.publications@iaea.org](mailto:sales.publications@iaea.org)  
<http://www.iaea.org/books>

For further information on this publication, please contact:

Assessment and Management of Environmental Releases Unit  
International Atomic Energy Agency  
Vienna International Centre  
PO Box 100  
1400 Vienna, Austria  
Email: [Official.Mail@iaea.org](mailto:Official.Mail@iaea.org)

ENVIRONMENTAL MODELLING FOR RADIATION SAFETY  
(EMRAS)  
IAEA-TECDOC-1678  
ISBN 978-92-0-129810-2  
ISSN 1011-4289  
© IAEA, Vienna, 2012  
Printed by the IAEA in Austria  
June 2012

## FOREWORD

The IAEA's programme on Environmental Modelling for Radiation Safety (EMRAS) was launched in September 2003 and ran until 2007. The programme focused on the development, comparison and testing of environmental assessment models for estimating radiation exposure of humans and radiological impacts on flora and fauna due to actual and potential releases of radionuclides to terrestrial and aquatic environments.

Models are essential tools for use in the regulatory control of routine discharges to the environment and in planning measures to be taken in the event of accidental releases; they are also used for predicting the impact of releases which may occur far in the future, for example, from underground radioactive waste repositories. It is important to check, to the greatest extent possible, the reliability of the predictions of such models by comparison with measured values in the environment or by comparison with the predictions of other models. A special feature of the IAEA's modelling programme in this area is the possibility of testing models using 'real environmental data'. Whenever possible, priority has been given to this approach in order to support the development of validated and reliable assessment models.

The EMRAS programme focused on three themes covering fields of specific interest in relation to public exposures and environmental impacts. Within this context, altogether seven working groups were active: under Theme 1, Radioactive Release Assessment, Working Group 1 dealt with the revision of the Handbook of Parameter Values for the Prediction of Radionuclide Transfer in Temperate Environments (Technical Reports Series No. 364) Working Group 2 worked on the modelling of tritium and carbon-14 transfer to biota and humans; Working Group 3 reported on the Chernobyl I-131 release: model validation and assessment of the countermeasure effectiveness; and Working Group 4 investigated model validation for radionuclide transport in the aquatic system 'Watershed-River' and in estuaries. For Theme 2, Remediation of Sites with Radioactive Residues, Working Group 1 reported on the modelling of naturally occurring radioactive material (NORM) releases and the remediation benefits for sites contaminated by extractive industries (uranium/thorium mining and milling, oil and gas industry, phosphate industry, etc.), and Working Group 2 studied remediation assessment for urban areas contaminated with dispersed radionuclides. For Theme 3, Protection of the Environment, Working Group 1 reported on model validation for biota dose assessment.

The IAEA has been organizing programmes concerning international model testing since the 1980s. The programmes have contributed to a general improvement in models, in transfer data and in the capabilities of modellers in Member States. Due to the organization of the programme with plenary and working group meetings, EMRAS provided a well-accepted international forum for scientists, regulators and operators to exchange knowledge and experience in the field of environmental modelling.

This report summarizes the content and outcomes of the EMRAS programme. The detailed reports of all working groups are published as IAEA reports and are provided on the CD-ROM which accompanies this report.

The IAEA wishes to express its gratitude to all those who participated in the work of the EMRAS programme and gratefully acknowledges those who contributed to the preparation of the resulting reports. The IAEA officer initially responsible for the overall running of the EMRAS programme was M. Balonov and subsequently D. Louvat of the Division of Radiation, Transport and Waste Safety.

### *EDITORIAL NOTE*

*The use of particular designations of countries or territories does not imply any judgement by the publisher, the IAEA, as to the legal status of such countries or territories, of their authorities and institutions or of the delimitation of their boundaries.*

*The mention of names of specific companies or products (whether or not indicated as registered) does not imply any intention to infringe proprietary rights, nor should it be construed as an endorsement or recommendation on the part of the IAEA.*



## CONTENTS

1.	INTRODUCTION .....	1
1.1.	Background.....	1
1.2.	Objective.....	1
1.3.	Scope .....	2
1.4.	Structure.....	2
2.	INTERNATIONAL MODEL TESTING .....	3
3.	ENVIRONMENTAL MODEL TESTING AT THE IAEA .....	4
3.1.	Validation of Model Predictions Programme (VAMP).....	4
3.2.	Biosphere Modelling and Assessment (BIOMASS) .....	4
3.3.	Environmental Modelling for Radiation Safety (EMRAS).....	5
4.	CONTENT OF THE EMRAS PROGRAMME .....	6
5.	EMRAS METHODS .....	8
5.1.	Model testing .....	8
5.2.	Model comparison .....	8
5.3.	Establishing reference transfer data sets.....	8
6.	REVISION OF IAEA HANDBOOK OF PARAMETER VALUES FOR THE PREDICTION OF RADIONUCLIDE TRANSFER IN TEMPERATE ENVIRONMENTS (TRS-364).....	9
6.1.	Introduction .....	9
6.2.	Interception and retention.....	10
6.3.	Radionuclide sorption in soil.....	10
6.4.	Vertical migration in soil.....	10
6.5.	Soil-to-plant transfer.....	11
6.6.	Radionuclide transfer to rice.....	11
6.7.	Transfer to animal food products.....	12
6.8.	Transfer in forest ecosystems .....	12
6.9.	Transport in freshwater ecosystems .....	13
6.10.	Specific activity models.....	13
6.11.	Losses by food preparation methods .....	13
6.12.	Concluding remarks.....	13
7.	TESTING OF MODELS FOR THE ENVIRONMENTAL BEHAVIOUR OF TRITIUM AND CARBON-14 FOLLOWING ROUTINE AND ACCIDENTAL RELEASES .....	14
7.1.	Introduction .....	14
7.2.	Scope of work.....	14
7.3.	Summary of results .....	15
7.4.	Conclusions .....	17
8.	MODEL TESTING RELATED TO COUNTERMEASURES APPLIED TO THE INTAKE OF IODINE-131 FROM THE CHERNOBYL ACCIDENT.....	19
8.1.	Introduction .....	19

8.2.	Methods used .....	19
8.3.	Model testing scenarios .....	19
8.4.	Issues emerging from the exercises .....	20
8.5.	Conclusions .....	21
9.	TESTING OF MODELS FOR PREDICTING THE BEHAVIOUR OF RADIONUCLIDES IN FRESH WATER SYSTEMS AND COASTAL AREAS .....	22
9.1.	Introduction .....	22
9.2.	Method used .....	22
9.3.	Scope of the work .....	23
9.4.	General summary of findings .....	23
9.5.	Conclusions .....	25
10.	MODELLING THE TRANSFER OF RADIONUCLIDES FROM NATURALLY OCCURRING RADIOACTIVE MATERIAL (NORM) .....	26
10.1.	Background .....	26
10.2.	Aims of the work .....	26
10.3.	Modelling considerations .....	26
	10.3.1. Assessment types .....	26
	10.3.2. Model types .....	27
	10.3.3. Scenarios used for model testing .....	27
10.4.	Model Testing .....	28
	10.4.1. Point source .....	28
	10.4.2. Area source .....	28
	10.4.3. Area source + river .....	28
10.5.	Conclusions .....	29
11.	TESTING OF MODELS FOR THE REMEDIATION OF THE URBAN ENVIRONMENT .....	30
11.1.	Introduction .....	30
11.2.	Methods of the working group .....	30
11.3.	Results .....	31
11.4.	Conclusions .....	33
12.	REVIEW OF DATA AND TESTING OF MODELS FOR PREDICTING THE TRANSFER OF RADIONUCLIDES TO NON-HUMAN BIOLOGICAL SPECIES .....	34
12.1.	Introduction .....	34
12.2.	Model testing exercises .....	34
12.3.	Overview of results .....	34
	12.3.1. Dosimetry and transfer components of the models .....	34
	12.3.2. Scenario applications .....	35
12.4.	Conclusions .....	36
13.	OUTCOMES OF THE EMRAS PROGRAMME .....	38
	REFERENCES .....	39
	LIST OF PARTICIPANTS .....	41

## EMRAS REPORTS

### Theme 1: Radioactive Release Assessment

- ***Working Group 1: Revision of IAEA Technical Report Series No. 364 “Handbook of parameter values for the prediction of radionuclide transfer in temperate environments (TRS-364) working group***

*Technical Reports Series No. 472 (2010): Handbook of Parameter Values for the Prediction of Radionuclide Transfer in Terrestrial and Freshwater Environments.*

*IAEA-TECDOC-1616 (2009): Quantification of Radionuclide Transfer in Freshwater Environments for Radiological Assessments.*

- ***Working Group 2: Modelling of tritium and carbon-14 transfer to biota and man working group***

Modelling the Environmental Transfer of Tritium and Carbon-14 to Biota and Man

- ***Working Group 3: the Chernobyl I-131 release: model validation and assessment of the countermeasure effectiveness working group***

The Chernobyl I-131 Release: Model Validation and Assessment of the Countermeasure Effectiveness.

- ***Working Group 4: Model validation for radionuclide transport in the aquatic system “Watershed-River” and in estuaries working group***

Testing of Models for Predicting the Behaviour of Radionuclides in Freshwater Systems and Coastal Areas.

### Theme 2: Remediation of Sites with Radioactive Residues

- ***Working Group 1: Modelling of naturally occurring radioactive materials (NORM) releases and the remediation benefits for sites contaminated by extractive industries (U/Th mining and milling, oil and gas industry, phosphate industry, etc.) working group***

Modelling the Transfer of Radionuclides from Naturally Occurring Radioactive Material (NORM).

- ***Working Group 2: Remediation assessment for urban areas contaminated with dispersed radionuclides working group***

Environmental Modelling of Remediation of Urban Contaminated Areas (plus additional supporting files)

### Theme 3: Protection of the Environment

- ***Working Group 1: Model validation for biota dose assessment working group***

Modelling Radiation Exposure and Radionuclide Transfer for Non-human Species.



# 1. INTRODUCTION

## 1.1. Background

The transfer of radionuclides through terrestrial and aquatic ecosystems can be approximated by means of mathematical models. Such models are used for assessing the radiological impact of actual and potential releases of radionuclides to the environment. They are essential tools for use in the regulatory control of routine discharges to the environment and also in planning measures to be taken in the event of accidental releases. Environmental models can also be used for predicting the impact of releases which may occur far into the future, for example, from underground radioactive waste repositories, or for assessing the impact of releases which have occurred in the past, for example, due to nuclear weapons testing or nuclear accidents.

Since environmental models are only representations of real situations in the environment, their predictions have uncertainty associated with them and before reliance can be placed on their predictions, they must be validated in some way. The preferred way of validating the models is to compare their predictions with real environmental data, that is, results obtained from measurements made after normal or accidental releases to the environment. When such data are not available, improvements in the reliability of model predictions can often be achieved by comparing model predictions with each other using artificial testing scenarios. These are the basic methods which have been used in international programmes of environmental assessment model testing.

The testing of models increases the users' understanding of models and the extent to which the model represents the actual behaviour of radionuclides in the environment. Model testing using independent data sets is the preferred approach but, in the absence of relevant data, the inter-comparison of model predictions can also yield important insights in relation to model structure and transfer parameters and about the assumptions made.

The International Atomic Energy Agency (IAEA) has been organizing programmes of international model testing since the 1980s and this publication summarises the content and outcomes of the most recent of these programmes entitled the Environmental Modelling for Radiation Safety (EMRAS) programme, which ran from 2003 until 2007.

## 1.2. Objective

The objectives of the EMRAS programmes can be summarised as follows:

- to improve models and modelling methods by model testing, model inter-comparison and other approaches;
- to develop international consensus, where appropriate, on environmental modelling philosophies, approaches, and parameter values;
- to quantify the uncertainties in environmental transport models;
- to develop data sets that can be used to test environmental transport models;
- to develop methods for the assessment of radionuclide transfer in the biosphere in areas where they do not already exist; and
- to provide an international focal point in the area of environmental assessment modelling for the exchange of knowledge and information.

### **1.3. Scope**

The scope of the EMRAS programme was on scientific, experimental and technical aspects related to the analysis and assessment of the behaviour of radionuclides in the environment and their associated impacts to the public and to flora and fauna. Special emphasis was given to improving the accuracy of model predictions, of modelling techniques and on the adequate use of experimental and monitoring as input for assessment models. Three important areas involving environmental assessment modelling were covered: (i) assessment of exposures due to releases of radionuclides; (ii) remediation of sites with radioactive residues; and (iii) protection of the environment.

### **1.4. Structure**

The role of international model testing programmes in improving assessment models is discussed in Section 2 of this report. Section 3 gives an overview of the EMRAS programme and Section 4 describes in brief the methods and approaches used with regard to model improvement. Sections 6 to 12 summarize the findings of the seven EMRAS Working Groups:

- (i) Revision of IAEA handbook of parameter values for the prediction of radionuclide transfer in temperate environments (TRS-364);
- (ii) Testing of models for the environmental behaviour of tritium and carbon-14 following routine and accidental releases;
- (iii) Model testing related to countermeasures applied to the intake of iodine-131 from the Chernobyl accident;
- (iv) Testing of models for predicting the behaviour of radionuclides in fresh water systems and coastal areas;
- (v) Modelling the transfer of radionuclides from naturally occurring radioactive material (NORM)
- (vi) Testing of models for the remediation of the urban environment;
- (vii) Review of data and testing of models for predicting the transfer of radionuclides to non-human biological species.

A summary of the outcome of the EMRAS programme is given in Section 12.

Summaries of the results of the work of each of the seven EMRAS working groups are given in Sections 5 to 11 of this report. The full reports of the outcomes of each of the working groups are given in the CD-ROM which accompanies this report.

## 2. INTERNATIONAL MODEL TESTING

The process of model testing leads to improved models and increased confidence in the reliability of predictions when the models are applied to new situations. But often there are insufficient independent data sets available in any one country to allow effective model testing. Further, in many countries environmental modelling is carried out by only a few groups of experts and in some countries by only one group, and there is therefore little possibility of organizing national model testing and comparison exercises. For these reasons, internationally organized model testing programmes provide important benefits to national groups. In summary, international exercises provide additional scenarios for model testing, greater access to experimental data and opportunities to compare with other modelling groups.

An important element in assessment modelling is knowledge of the quantitative behaviour of radionuclides in environmental systems, e.g., values of the parameters that control transfer from air to plant, soil or water to plant and plant to animal. Radioecology provides the basic information needed for assessment modelling and the reliability of model predictions has been increased over time by improvements in radionuclide transfer data. International programmes of model testing have always contained a strong element of radioecology and the working groups typically contain a mix of modellers and radioecologists.

Since the exercises began in the early 1980s, international model testing projects have led to a greater international unification and compatibility of approach. The situation is much improved as compared with the period immediately after the Chernobyl accident when the environmental modelling capability in many of the affected countries was limited. The international projects have helped to develop an 'assessment culture' in which the likely radiological impact of any new technological project is automatically assessed and evaluated prior to its approval.

In common with many other types of international programmes, participants are able to make contact with other scientists with similar interests and exchange ideas and information both during and after meetings.

There is a need for countries to maintain their capabilities in the environmental assessment field in order that new proposed facilities can be evaluated and existing facilities kept under surveillance. The small but finite threat of nuclear accidents and terrorism provides another reason that national capabilities in the field should be maintained.

The loss of experts in national organizations due to retirement and to continuous staff turnover means that assessment modelling capability and knowledge can be lost unless new persons are trained in the skills of environmental assessment. International model testing programmes serve as an effective mechanism for allowing persons new to the field to learn and to become skilled and knowledgeable in environmental assessment modelling and radioecology.

### 3. ENVIRONMENTAL MODEL TESTING AT THE IAEA

The possible benefits of carrying out model validation and testing at an international level were recognised by the Swedish Radiation Protection Institute, which sponsored the Biospheric Model Validation Study (BIOMOVS) and BIOMOVS II programmes starting in 1985. BIOMOVS was the first international exercise aimed at the testing and validation of models for the prediction of radionuclide transfer through the environment to humans.

The Chernobyl accident in 1986 created a renewed need for reliable assessments in many countries and provided an increased impetus for work in this area. It also created new data sets that could be put to use for model testing. As a consequence, the IAEA was prompted to start a programme on the Validation of Model Predictions (VAMP) in 1988, which concluded in 1996.

#### 3.1. Validation of Model Predictions Programme (VAMP)

The following topics were addressed in the VAMP programme:

Model testing related to:

- Chernobyl fallout radionuclides in terrestrial and aquatic environments.

Improvement in the modelling of:

- resuspension of radionuclides from terrestrial surfaces;
- seasonality: the influence of season on the transfer of radionuclides in foodchains;
- losses during food processing;
- deposition of airborne radionuclides in the urban environment;
- interception and loss processes in vegetation; and
- transfer in semi-natural ecosystems.

The topics addressed under ‘model improvement’ reflected areas identified as being in need of improvement in relation to transfer data, modelling approach or both. They were identified in post-Chernobyl assessments as areas in which there was a lack of information and the greatest uncertainties.

#### 3.2. Biosphere Modelling and Assessment (BIOMASS)

The VAMP programme was followed in 1996 by the IAEA's programme on Biosphere Modelling and Assessment (BIOMASS). The BIOMASS programme, which concluded in 2001, followed similar approaches to those used in the VAMP programme for the testing of models but had a different scope. The BIOMASS programme covered the following topics:

Model testing related to:

- Chernobyl fallout radionuclides in a river catchment area;
- remediation of a radium extraction site;
- historic radionuclide releases from a nuclear weapons production site; and
- tritium released from atmospheric and subsurface sources.



Improvement in the modelling of radionuclide transfer to:

- fruit; and
- forest ecosystems.

In addition, within the BIOMASS programme, a modelling approach was developed for predicting the radiological impact of releases in the far future from the underground disposal of radioactive waste ('Reference Biosphere').

### **3.3. Environmental Modelling for Radiation Safety (EMRAS)**

Starting in 2003 and concluding in 2007, the IAEA organized the Environmental Modelling for Radiation Safety (EMRAS) programme. The programme followed the pattern of the earlier environmental model testing programmes but with some new elements. The content of the EMRAS programme is described in Section 4 of this report.

#### 4. CONTENT OF THE EMRAS PROGRAMME

In selecting the topics for consideration in the EMRAS programme, the IAEA took account of several factors:

- the topics were to be related to real current safety issues in the environmental field. This could include areas known to be important in a radiological assessment context but which had received insufficient attention to enable reliable predictions to be made;
- the topics were to respond to the needs of IAEA Member States in this field. (This aspect was addressed through consultations with organizations and experts in Member States before the content of the programme was decided upon);
- the topics were to take account, to the extent possible, of international developments in the field.

Taking these considerations into account, the IAEA made proposals for the content of the EMRAS programme. A key final determinant in establishing the programme content was the need for viable working groups. Each EMRAS working group had to have a sufficient number of participating members to guarantee that it could work effectively.

The EMRAS programme contained elements which are familiar from the previous IAEA programmes but it also contained some important new elements. The programme comprised three themes:

- Theme 1: Radioactive Release Assessment;
- Theme 2: Remediation of Sites with Radioactive Residues; and
- Theme 3: Protection of the Environment.

The working groups within the themes were as follows:

##### **Theme 1: Radioactive Release Assessment**

- Working Group 1: Revision of IAEA Technical Report Series No. 364 “Handbook of parameter values for the prediction of radionuclide transfer in temperate environments (TRS-364) working group;
- Working Group 2: Modelling of tritium and carbon-14 transfer to biota and man working group;
- Working Group 3: the Chernobyl I-131 release: model validation and assessment of the countermeasure effectiveness working group;
- Working Group 4: Model validation for radionuclide transport in the aquatic system “Watershed-River” and in estuaries working group.

##### **Theme 2: Remediation of Sites with Radioactive Residues**

- Working Group 1: Modelling of naturally occurring radioactive materials (NORM) releases and the remediation benefits for sites contaminated by extractive industries (U/Th mining and milling, oil and gas industry, phosphate industry, etc.) working group;
- Working Group 2: Remediation assessment for urban areas contaminated with dispersed radionuclides working group.

### **Theme 3: Protection of the Environment**

— Working Group 1: Model validation for biota dose assessment working group.

Theme 1, Working Groups 1 to 4 concentrated on the assessment of radioactive release while, Theme 2 Working Groups 1 and 2 considered the issues of restoration of sites with radioactive residues. Additionally, Theme 3, Working Group 1 concentrated on the area of protection of the environment.

## **5. EMRAS METHODS**

### **5.1. Model testing**

In those EMRAS working groups engaged in model testing, potential test scenarios based on environmental measurements were provided by group members. The scenario information contained information about the nature of the environment and on the input of radionuclides into the environment, e.g., amount of deposition over a particular time period and the resulting concentration of the radionuclide in an environmental material, animal or human tissue, e.g., grass, milk, thyroid, etc. The group members were asked to predict the radionuclide concentration, often as a function of time, in the material or tissue. Normally, the information about the resulting concentration in the environmental components was not provided until after the working group members had made their predictions — this is termed ‘blind testing’. When all predictions had been received, they were compared and the reasons for differences from the observed values, and from other predictions, were discussed and, if possible, the reasons for mis-prediction identified. Finally, conclusions were drawn on how to improve the models and data.

### **5.2. Model comparison**

When there were no suitable scenarios based on environmental measurements available, a hypothetical scenario for model comparison was devised. The scenario was usually designed to test those parts of the model that were known to be most sensitive in relation to the endpoint. The procedure is similar to that for model testing except that results can only be compared to those of other working group members. Nevertheless, considerable benefits can be obtained from discussions about the reasons for differences in prediction; these usually include different conceptual understanding of the modelling scenario, different approaches to modelling the scenario and different transfer parameter values.

### **5.3. Establishing reference transfer data sets**

As already mentioned, a key requirement in environmental assessment modelling is appropriate information on radionuclide transfer. Ideally, this is obtained by means of measurements made in the environment to which the release of radionuclides occurs. In addition, some transfer parameter data can be obtained from studies conducted in the laboratory under controlled conditions. It is not always possible to make relevant measurements in the environment of interest mainly for reasons of cost but also because there may be public sensitivity about the use of radionuclide tracers for such purposes. However, some parameters are comparatively independent of the location in which they are made and others vary within moderate bounds. Default or reference transfer parameters can, therefore, often be used in the absence of site-specific values. The IAEA started to compile sets of default transfer parameter data for the marine environment in the 1980s and for the terrestrial and freshwater aquatic environments in the early 1990s. The compilations are based on comprehensive literature reviews by groups of national experts in each of the fields of interest. The experts summarise the information and recommend default or reference values for use in environmental assessment, together with appropriate statements on the uncertainty associated with the values. Different default values are provided to take account of the predictable variations that occur in some parameters, for example, as a result of radionuclide physical and chemical form, climate and soil type. These methods were used in the EMRAS programme in order to update the IAEA Handbook Technical Reports Series No. 472 (TRS-472), entitled “Handbook of Parameter Values for the Prediction of Radionuclide Transfer in Terrestrial and Freshwater Environments” [1].

## 6. REVISION OF IAEA HANDBOOK OF PARAMETER VALUES FOR THE PREDICTION OF RADIONUCLIDE TRANSFER IN TEMPERATE ENVIRONMENTS (TRS-364)

### 6.1. Introduction

In 1994, the IAEA published Technical Reports Series No. 364 (TRS-364) entitled, “Handbook of parameter values for the prediction of radionuclide transfer in temperate environments” [2]. Over the years, it has proved to be a valuable reference for radioecologists, environmental modellers and assessors in Member States, and has been used in numerous impact assessments.

The main goal of the original Handbook (TRS-364) is to provide default values for the use in risk assessment studies in situations where no site-specific data are available. It provides best estimate values for the most commonly used transfer parameters in radiological assessment models. However, TRS-364 was based on a review of available data up to the end of 1992. Several high quality reviews have been produced in recent years of values for some of the important transfer parameters and it was considered that there was sufficient new information available to warrant reconsideration of many of the values given in the original Handbook (TRS-364). In addition, it was considered that a number of improvements could be made by expanding the range of parameters considered, broadening the range of environments considered (to include tropical and sub-tropical environments) and by providing guidance on how to use the parameter values contained in TRS-364.

The revision of TRS-364 therefore had two main objectives:

- to revise existing transfer parameter values and to provide missing data, to the extent possible; and
- to document key transfer processes, concepts and models which have been found to be important for radiation safety.

In order to achieve these objectives, around 60 scientists from 20 countries worked jointly from 2003 to 2007 using available published information on radionuclide transfer in various environments.

The parameter values provided by the working group are based only on referenced values; values based only on expert judgment have been avoided. The working group has carried out a critical analysis of the data collected in order to qualify it and thus to reduce the associated uncertainty. In this context, some unclearly documented data were rejected because of their imprecise origin or because they were obtained under extreme environmental conditions. For example, a large set of  $K_d$  values — used in the previous version — had been obtained from data for artificial soils and is considered to produce unreliable results in real situations.

The working group aimed to guide assessors in the proper choice of values and to provide a full understanding of the implications of their choice. For example, soil and plant classifications have been introduced and used throughout the revised Handbook (TRS-472) [1] and special subsections on limitations to be considered in the use of the data accompany each section.

The general approach used in the revised Handbook (TRS-472) is to keep descriptions of the processes and relevant models as simple as possible. For this reason, certain complex processes are not included in TRS-472 and the transfer parameters usually refer to equilibrium conditions.

In addition to the revised Handbook (TRS-472), in 2009 the working group also produced IAEA-TECDOC-1616 entitled, “Quantification of radionuclide transfer in terrestrial and freshwater environments for radiological assessments” [3] which is intended to be a support to TRS-472.

In general, the revised Handbook (TRS-472) provides statistical information on each parameter value, for example, geometric mean and geometric standard deviation, minimum and maximum values, and number of observations.

A section on the use of analogues gives guidance on how to derive parameter values based on analogue data if values from other sources are not available.

## **6.2. Interception and retention**

Interception is defined as the fraction of radioactive material in the revised Handbook (TRS-472), deposited by wet and dry deposition processes, that is initially retained by plants. The main factors governing the interception of both dry and wet deposition and the existing approaches for estimating interception in models are discussed. Recommended values for the parameters governing foliar uptake are given according to the growth stages of plants. This approach provides the possibility of taking account of the processes occurring in accident conditions. The literature review of data on foliar uptake provides evidence of the lack of data on the mobility of radionuclides in plants. Most of the available data originate from experiments conducted before the 1980s and significant gaps remain to be filled.

## **6.3. Radionuclide sorption in soil**

Dissolved radionuclide ions can bind to solid surfaces as a result of a number of processes that are often classified under the broad term of sorption. The list of radionuclides for which the absorption coefficient,  $K_d$ , is specified in the revised Handbook (TRS-472) has been extended compared with the previous version and uncertainties in the  $K_d$  values have been considerably reduced. Although most of the available information relates to  $^{137}\text{Cs}$  and  $^{90}\text{Sr}$ ,  $K_d$  values have also been compiled for more than 60 natural and artificial radionuclides. The reduction in the uncertainty associated with  $K_d$  values has been made possible as a result of the adoption of a new classification of soils and by taking account of a set of simple co-factors such as pH and the mineral content of some elements. However, there are still gaps in the estimates of  $K_d$  for many radionuclides and soil types.

## **6.4. Vertical migration in soil**

Two approaches for modelling the vertical migration of radionuclides in soil are considered — a compartmental model approach and convection-dispersion equations. Information on migration rates (multi-layer compartment models) is given mainly for  $^{137}\text{Cs}$  based on both global and Chernobyl fallout data. Similarly, the majority of available data for convection-dispersion equations relates to  $^{137}\text{Cs}$ . The revised Handbook (TRS-472) provides dispersion coefficients and convection velocities for some additional radioelements: Ag, Am, Ce, Co, Eu, I, Np, Pu, Ra, Ru, Sb and Sr.

## 6.5. Soil-to-plant transfer

The soil-to-plant transfer parameter values given in the original Handbook (TRS-364) are mainly based on the database of the International Union of Radioecologists (IUR). Additional sources of information are used in the revised Handbook (TRS-472), including a new review of the literature.

Five groups of radionuclides are identified according to their physico-chemical characteristics:

- light natural radionuclides ( $^3\text{H}$ ,  $^{14}\text{C}$ ,  $^{40}\text{K}$ );
- heavy natural radionuclides ( $^{238}\text{U}$ ,  $^{232}\text{Th}$ ,  $^{226}\text{Ra}$ ,  $^{210}\text{Po}$ ,  $^{210}\text{Pb}$ );
- radionuclides of the transuranic elements (Am, Cm, Pu, Np);
- fission product radionuclides ( $^{89,90}\text{Sr}$ ,  $^{134,137}\text{Cs}$ ,  $^{129,131}\text{I}$ ,  $^{91}\text{Y}$ ,  $^{95}\text{Zr}$ ,  $^{95}\text{Nb}$ ,  $^{103,106}\text{Ru}$ ,  $^{141,144}\text{Ce}$ ); and
- activation product radionuclides ( $^{51}\text{Cr}$ ,  $^{54}\text{Mn}$ ,  $^{55,59}\text{Fe}$ ,  $^{60}\text{Co}$ ,  $^{65}\text{Zn}$ ,  $^{115}\text{Cd}$ ).

In total, 967 information sources (books, journals, conference proceedings, institutional reports, as well as international and national databases) containing data on the transfer of artificial radionuclides to plants, were reviewed. A database was created to manage and process the data derived from various literature sources. The distribution of data used for the evaluation of radionuclide transfer factors from soil to different plants is shown in Figure 1.

The most extensive information relates to cereals, vegetables and pasture grasses. Compared to TRS-364, new information is provided for radioisotopes of six elements often considered in radiological assessments, namely, Cd, K, Pm, P, Cl and Ca.

For heavy natural radionuclides, about 180 references were reviewed to provide 912 entries for U, 351 entries for Th, 594 entries for Ra, 232 entries for Pb and 73 entries for Po.

Data on soil-to-plant transfer are given for various environments: temperate, tropical, subtropical. Approximately 180 references relating to tropical ecosystems were reviewed and the associated tropical soil-to-plant transfer factor data base contains 1353 entries, mainly for radioisotopes of Cs, Ra, U, Sr and Zn, but also for radioisotopes of Co, Pb, Th, K, Pu and Am.

## 6.6. Radionuclide transfer to rice

More than half of the world's population considers rice to be one of its main food products and a specific section has been devoted to radionuclide transfer to rice. Cultivation under flooded conditions significantly modifies the chemical characteristics of the soil-plant system and consequently it has important effects on the uptake of radionuclides by plants from soil. Based on a review of more than 30 sources, information is provided for use in the assessment of the transfer of some radioelements (i.e., Sr, Cs, Mn, Co, Zn, Tc, I, Ra, Th, U) and some stable elements to rice plants.

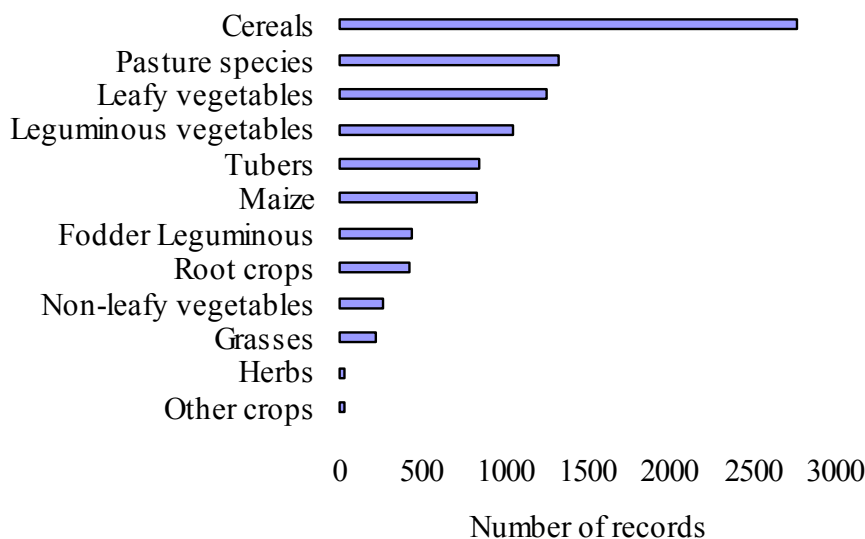


FIG. 1. Distribution of entries used for the evaluation of transfer factor values for artificial radionuclides.

### 6.7. Transfer to animal food products

Radionuclide activity concentrations in animal food products depend primarily on the rates of food intake, gastro-intestinal absorption and turnover in tissues. Data which can be used to derive animal product transfer coefficients for radionuclides have been compiled, including an extensive review of Russian language information. This included a thorough re-evaluation of data considered in the original Handbook (TRS-364). The resultant database has been used to provide recommended transfer coefficient values for a range of radionuclides to (i) cow, sheep and goat milk, (ii) meat of cattle, sheep, goats, pigs and poultry; and (iii) eggs. In addition, gastro-intestinal absorption factors have also been reviewed and recommended values presented. Most data exist on the three key radionuclides, i.e.,  $^{131}\text{I}$ ,  $^{137}\text{Cs}$ , and  $^{90}\text{Sr}$ ; for many radionuclides no suitable data were identified.

### 6.8. Transfer in forest ecosystems

The coverage of the processes governing radionuclide transfer in forest ecosystems (radionuclide transfers to trees, berries, mushrooms and game) and other semi-natural ecosystems, and the relevant transfer parameters in these ecosystems, is now much more extensive than it was in the original Handbook (TRS-364). The main contribution to dose to humans from these ecosystems is from  $^{137}\text{Cs}$  and  $^{90}\text{Sr}$  and most of the available data relates to these radionuclides. However, information on less studied radionuclides, such as isotopes of Pu, Am and some natural radionuclides, is also provided. Aggregated transfer factors (defined as the ratio of the radionuclide activity concentration in plant or any other forest products ( $\text{Bq kg}^{-1}$ ) to the total deposition on the soil ( $\text{Bq m}^{-2}$ )) are used to quantify radionuclide transfer to various types of forest vegetation and forest products. These data are given for various forest products, including trees of different types, mushrooms, berries and game.



## 6.9. Transport in freshwater ecosystems

A special section is devoted to the transport of radionuclides in freshwater ecosystems. The various routes of contamination, physical and chemical processes and radionuclide accumulation by freshwater biota species are described and quantified. Partitioning of radionuclides between water and suspended matter is normally described in terms of distribution coefficients ( $K_d$ ), expressed as the concentration ratio between the particulate phase and the dissolved phase under equilibrium conditions. The revised Handbook (TRS-472) provides  $K_d$  probability density functions for radioisotopes of Ag, Am, Co, Cs, I, Mn, Pu and Sr, for which extended data were available. For other radionuclides (isotopes of Be, Ba, Ce, Ra, Ru, Sb, and Th), probability density functions were obtained with the aid of a bootstrap statistical method.

Humans consume a variety of freshwater biota species: fish, invertebrates, amphibians, reptiles, mammalian species and waterfowl and a set of bioaccumulation factor values is given for the main freshwater biota species in the human diet.

## 6.10. Specific activity models

Specific activity models are widely used for some radiologically important radionuclides that are long lived, highly mobile in the environment and are under homeostatic control in living organisms.  $^3\text{H}$ ,  $^{14}\text{C}$  and  $^{36}\text{Cl}$  have these characteristics and are modelled using specific activity concepts in the revised Handbook (TRS-472). Because there was no comparable treatment in TRS-364, the models are described in some detail, followed by a listing of the relevant parameter values. The models and parameters considered in the revised Handbook (TRS-472) are confined to steady-state conditions for releases to air and water bodies; dynamic processes are not considered.

## 6.11. Losses by food preparation methods

The concentration of radionuclides in food is affected by industrial and domestic processes such as boiling, removal of certain parts of the raw food (e.g. bran, peel, shell, bone) and drying or dilution. 125 information sources were reviewed to provide food processing retention factors for a wide range of plant, animal, forest and aquatic food products. Again, most of the information is available for  $^{131}\text{I}$ ,  $^{137}\text{Cs}$  and  $^{90}\text{Sr}$ , but data are also given for other radioisotopes such as those of Na, K, Ca, Mg, P, Fe, Cu, Zn, Cl, Mn and Se.

## 6.12. Concluding remarks

The revised Handbook (TRS-472) is supported by IAEA-TECDOC-1616 [3] which provides more detailed information about the processes described above and references to numerous related publications and literature reviews. In the IAEA-TECDOC-1616, modellers can find the entire set of data that has been synthesized in preparing the revised Handbook (TRS-472).

In the revised Handbook (TRS-472), more processes have been considered than previously, and data have been provided for transfer to rice and other plants in tropical or subtropical environments. Nevertheless, data are lacking in many areas and gaps in knowledge have been identified in each of the sections as an indicator of the needs for further research.

## **7. TESTING OF MODELS FOR THE ENVIRONMENTAL BEHAVIOUR OF TRITIUM AND CARBON-14 FOLLOWING ROUTINE AND ACCIDENTAL RELEASES**

### **7.1. Introduction**

Hydrogen and carbon are biologically-regulated, essential elements that are highly mobile in the environment and the human body. As isotopes of these elements, tritium and  $^{14}\text{C}$  enter freely into many chemical compounds, including water (in the case of tritium), plants (through photosynthesis) and animals and humans (through various metabolic processes). This behaviour, plus the fact that tritium and  $^{14}\text{C}$  obey specific activity principles, means that the environmental transport modelling of tritium and  $^{14}\text{C}$  is complicated, and must be carried out using methods different from the partitioning and accumulation concepts used for other radionuclides. The uncertainty in the model predictions is large, particularly for accidental releases, and there is a need for improved models that will provide more reliable dose assessments. This need is particularly urgent given the expected renaissance in nuclear energy and the ongoing development of fusion reactors.

The activities of the Working Group on Modelling of tritium and carbon-14 transfer to biota and man focused on the assessment of models for organically bound tritium (OBT) formation and translocation in plants and animals, the areas where model uncertainties are largest. The working group necessarily considered models for tritiated water (HTO) as well, since an understanding of environmental HTO is needed before OBT can be modelled with any confidence. Environmental  $^{14}\text{C}$  models were also addressed because the dynamics of carbon and OBT are very similar.

### **7.2. Scope of work**

The goals of the working group were achieved primarily through nine test scenarios in which model predictions were compared with observations obtained in laboratory or field studies (Table 1). Seven of the scenarios involved tritium, covering terrestrial and aquatic ecosystems, and steady-state and dynamic conditions. The remaining two scenarios concerned  $^{14}\text{C}$ , one addressing steady-state concentrations in rice and the other time-dependent concentrations in potatoes. Five of the scenarios were based on data contributed by participants and two involved data from the literature. In the remaining two cases (the mussel uptake and depuration scenarios), new experimental work was undertaken by one participating organization in order to provide data that were otherwise not available on time-dependent OBT formation in aquatic animals.

The working group considered one further scenario, which involved the calculation of radiation doses following a hypothetical, short term release of tritium to the atmosphere in a farming area. Since suitable test data were unavailable, this scenario was carried out as a model inter-comparison exercise. It was approached in the same way as the model-data exercises except that all the information in the scenario description was hypothetical, and no conclusions could be drawn regarding the model that performed best.

TABLE 1. SCENARIOS CONSIDERED BY THE TRITIUM AND CARBON-14 WORKING GROUP

Radio-nuclide	Scenario	Number of Participants	Endpoints
Tritium	Perch Lake	8	Steady-state tritium concentrations in an aquatic ecosystem chronically contaminated with HTO
	Soybean	12	Time-dependent tritium concentrations in soybeans acutely exposed to HTO in air
	Pickering	8	Steady-state tritium concentrations in an agricultural ecosystem chronically contaminated with HTO
	Pine Tree	5	Steady-state tritium concentrations in groundwater and pine trees chronically exposed to HTO in air
	Mussel uptake	5	Time-dependent tritium concentrations in mussels exposed to an abrupt increase in ambient tritium levels
	Mussel depuration	4	Time-dependent tritium concentrations in mussels exposed to an abrupt decrease in ambient tritium levels
	Pig	6	Time-dependent tritium concentrations in pigs subject to a contaminated diet
	Hypothetical	8	Time-dependent concentrations and doses following an acute atmospheric tritium release over farmland
<sup>14</sup> C	Rice	5	Steady-state <sup>14</sup> C concentrations in rice growing near a continuous atmospheric source of <sup>14</sup> C
	Potato	4	Time-dependent <sup>14</sup> C concentrations in potatoes acutely exposed to <sup>14</sup> C in air

### 7.3. Summary of results

The models used by the various participants in a given scenario were conceptually similar in the sense that each included the key processes that control environmental tritium and <sup>14</sup>C transfer (e.g., uptake by plants, fixation in organic compounds, transfer to animals through ingestion, and so on). However, the models differed substantially in the way the processes were implemented. The simpler models were based on specific activity concepts with concentrations in a given compartment determined by the specific activities in the hydrogen or carbon pools that contributed tritium or <sup>14</sup>C to the compartment. The more complex approaches were formulated in terms of dynamic compartment models or process-oriented models in which the various transfer processes were simulated explicitly. Even here, the models differed in the number of compartments considered, the required parameters and their values, the growth curves adopted for plants and animals, the plant and animal genotypes assumed, etc.

The differences in the models led to variability in the predictions of about a factor of 2 for scenarios involving continuous releases, and a factor of 10 or more for short term releases. In the former case, performance was better for models that were driven by air concentrations averaged over the OBT or <sup>14</sup>C residence time in the compartment of interest (one or two months prior to sampling in the case of OBT concentrations in plants and animals; the period of grain formation in the case of <sup>14</sup>C concentrations in rice). The dynamics of OBT and <sup>14</sup>C concentrations were generally poorly reproduced in scenarios involving short term releases. The observed concentrations at harvest depended on the growth stage of the plant at the time of exposure, and performance was best for models with realistic growth curves. For most scenarios, the predictions tended to lie on either side of the observations, suggesting that, in an average sense, the models reflect a good conceptual understanding of the environmental transport of tritium and <sup>14</sup>C. In some scenarios, part of the difference between predictions and observations could be attributed to the uncertainty in the observations as well as in the predictions.

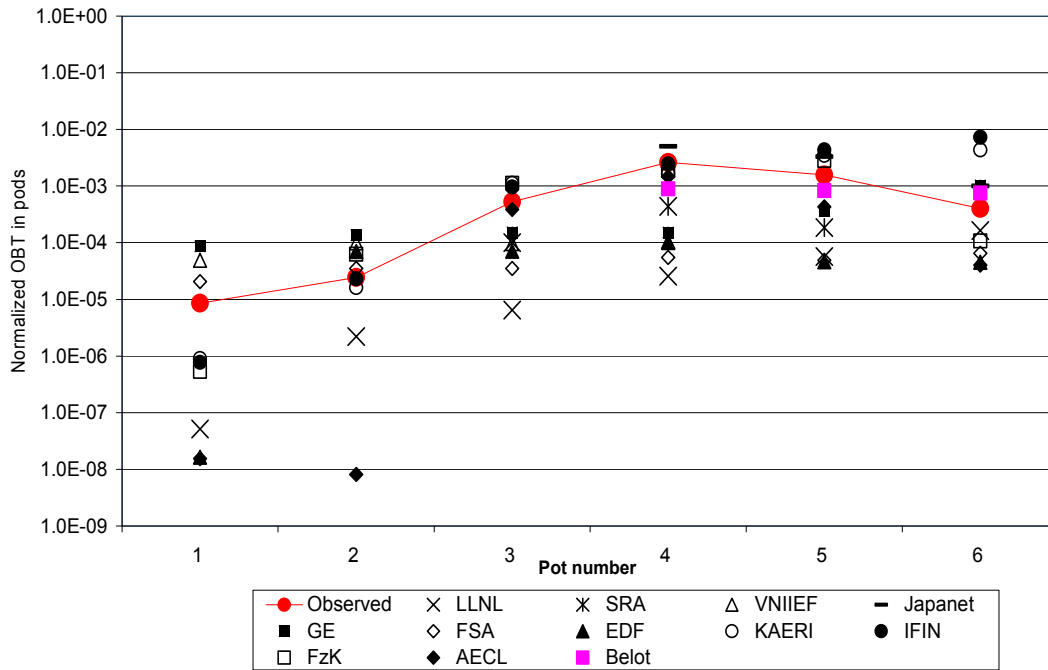


FIG. 2. Predicted and observed OBt concentrations in soybean pods at harvest.

The results for the soybean scenario illustrate many of these conclusions. This scenario was based on measurements of HTO and OBt concentrations in soybeans exposed over one hour periods to elevated levels of HTO in air in a glove box. Figure 2 shows predicted and observed OBt concentrations (normalized by the time-integrated HTO concentration in air moisture to which the plants were exposed) in the pods (the edible part of the plants) at harvest for six plants exposed at different stages of growth (Pot numbers 1–6).

The observed concentrations were low for Pots 1 and 2, which were exposed before the pods started to form. The concentrations reached a maximum for Pot 4, which was exposed when the pods were actively developing. The concentrations dropped off for the exposures closer to harvest because the OBt was diluted by the relatively large amount of uncontaminated dry matter already present in the pods. The predictions for Pots 3–6 varied by a factor of 100. They tended to lie on either side of the observations, although they showed a clear bias toward under-prediction for Pot 4. The very low predictions by some models for Pots 1 and 2 were the result of an underestimate of the HTO concentration (on which the OBt calculations were based) at the time the pods began to form. The scenario description noted that the pods were still quite wet at harvest, a situation revealing incomplete maturity. Few modellers made use of this information, which may have contributed to the difference between predictions and observations.

Uncertainty estimates were requested as part of each scenario, and most participants submitted results for the steady-state exercises. For the HTO and  $^{14}\text{C}$  endpoints, these were roughly consistent with a 95% confidence interval (97.5<sup>th</sup> percentile divided by the 2.5<sup>th</sup> percentile) of a factor 3–4. The uncertainties in the OBt concentrations were slightly higher. Few of the participants in the dynamic scenarios determined their uncertainties. However,

rough estimates were obtained from an overall assessment of the scatter in the predictions and the differences between predictions and observations. These suggest that the 95% confidence intervals on HTO and  $^{14}\text{C}$  concentrations were about a factor of 10 or more. The confidence intervals were generally smaller for OBT than for HTO, reflecting the fact that, for the dynamic scenarios, HTO varies rapidly over time whereas OBT integrates.

Much of the discussion of the definition of OBT centered on the role of buried tritium. Buried tritium is tritium in exchangeable positions in large organic molecules that is not removed when the dried sample is washed with tritium free water. It therefore appears as fixed OBT in traditional analyses although it behaves as exchangeable OBT in the body. Two organizations participating in the working group carried out experiments to determine whether buried tritium makes up a significant fraction of what is traditionally measured as OBT. The results were contradictory, with one experiment suggesting that the fraction is 50% or more and the other that the fraction is at most 5–10%. In the face of this discrepancy, the question must remain open pending new experimental data. The final definition of OBT recognizes the existence of buried tritium but remains consistent with the quantity that is measured using current analytical techniques and with existing OBT dose coefficients.

#### 7.4. Conclusions

The activities of the working group have helped to define the level of confidence that can be placed in the predictions of environmental tritium and  $^{14}\text{C}$  models. Because of the many differences in the models used by the various participants, it was often difficult to isolate the key reasons for differences in their predictions. Nevertheless, it was usually possible to identify the modelling approaches that led to the best predictions for a specific scenario. In general, the simple and complex models performed equally well for chronic releases, but complex models were required to reproduce the observations for short term releases.

The uncertainty in the predictions of environmental tritium and  $^{14}\text{C}$  models can be reduced by:

- ensuring that the air concentration data used to drive the models are of high quality and match the resolution and averaging requirements of the scenario;
- incorporating as much site-specific information as possible on land use, local soil properties and predominant crop and animal species, together with realistic assumptions concerning the habits of the maximally exposed individual;
- basing all submodels on the physical approaches available for the disciplines in question. For example, knowledge from the agricultural sciences should be used to improve models for crop growth, photosynthesis, translocation etc. Recent progress in understanding environmental carbon and hydrogen cycling should also be considered;
- recognizing and accounting for any unusual conditions (water stress, an uncommon species) in the model application.

Further work in the following areas would help to improve tritium and  $^{14}\text{C}$  dose assessments:

- testing and improving models of plant uptake of HTO at night and when it is raining; OBT formation in plants at night; translocation of OBT to fruit and roots; isotopic discrimination; tritium behaviour in soils following deposition from the atmosphere; and tritium behaviour in winter, including washout by snow, dry deposition to snow and the fate of tritium in the snow pack;

- modifying the steady-state models for chronic releases to account for the fact that fluctuations in release rates and meteorological conditions result in a state of quasi-equilibrium in the environment, rather than the complete equilibrium assumed by the models;
- developing a standard conceptual model for accidental tritium releases;
- carrying out rigorous uncertainty analyses of the dynamic models to better quantify the uncertainties in their predictions for a variety of scenarios;
- investigating and understanding the large OBT/HTO ratios that have been observed in soils, plants and fish under conditions that are ostensibly at equilibrium.

The ten scenarios developed by the working group provide a valuable source of test data for validating environmental tritium and  $^{14}\text{C}$  models.

## **8. MODEL TESTING RELATED TO COUNTERMEASURES APPLIED TO THE INTAKE OF IODINE-131 FROM THE CHERNOBYL ACCIDENT**

### **8.1. Introduction**

The studies undertaken by the Iodine-131 Working Group were targeted primarily at the evaluation of the predictive capability of environmental models, especially in relation to assessing thyroid exposure via the inhalation and ingestion pathways. Particular emphasis has been placed on improving the applicability of models to countermeasure response. Such measures include evacuation, sheltering and food controls as well as iodine prophylaxis. The rapid and reliable assessment of thyroid dose (including statistical distribution for critical groups of the population) in areas affected by the release of radioiodine is an important tool for determining whether or not medical intervention and social protection measures are required. Moreover, in the longer term, the validated assessment of thyroid doses is necessary for the purposes of epidemiological research.

### **8.2. Methods used**

The working group's activities were focused on:

- the collection of measurement data sets;
- quality checking of input and measurement data and evaluation of appropriate standard scenarios for model validation purposes;
- comparison of model outputs with independent data sets, including 'blind testing' (without disclosing observed data), assessment of discrepancies in the predictions and identification of the most important sources of bias and uncertainty.

Several end points were considered for model validation purposes:

- $^{131}\text{I}$  deposition (soil concentration);
- time dependence of  $^{131}\text{I}$  concentration in milk; and
- $^{131}\text{I}$  thyroid burden for different age groups.

The end points considered for model inter-comparison were:

- reconstruction of  $^{131}\text{I}$  air concentration based on the isotopic ratio  $^{131}\text{I}/^{137}\text{Cs}$ ;
- time dependent  $^{131}\text{I}$  concentration in fresh pasture (grass);
- committed dose to thyroid from inhalation; and
- committed dose to thyroid from ingestion.

### **8.3. Model testing scenarios**

Three scenarios were evaluated:

- (1) Data from the Plavsk district, in the Tula region of the Russian Federation, was used as the basis of the first scenario (Plavsk Scenario). The Plavsk district is located about 200 km south of Moscow and has a population of about 30 000, working mainly in agricultural production. The area was significantly contaminated with radionuclides on 29–30 April 1986 from the same Chernobyl cloud that contaminated the Bryansk region one day earlier. The maximum  $^{137}\text{Cs}$  soil contamination density of  $0.5 \text{ MBq}\cdot\text{m}^{-2}$

occurred in the town of Plavsk, at the centre of the Plavsk district. The deposition occurred during a relatively short period of rain during the cloud passage; it yielded a mixed (dry and wet) deposition and consequently an inhomogeneous  $^{137}\text{Cs}$  deposition. During this period, the time at which cows were put on pasture is not exactly known. The Plavsk scenario provided an opportunity to assess  $^{131}\text{I}$  contamination of the foodchain and to evaluate thyroid doses for urban and rural populations in the area on the basis of the isotopic ratio  $^{131}\text{I}/^{137}\text{Cs}$ . The working group participants were asked to provide an uncertainty analysis of predicted thyroid doses.

- (2) The second scenario involved the assessment of the effectiveness of short term protective measures that had been applied in the Mazovia province (Poland) during the period 29–30 April 1986 to reduce the radioiodine thyroid uptake of inhabitants. The countermeasures included: administration of stable iodine in solution form (so-called “Lugol liquid”) to children and teenagers of up to 16 years of age; putting grazing animals on stored feed; and banning potentially contaminated milk, milk products and leafy vegetables. However, it was not possible to make the animal or human diet restrictions compulsory and the protective actions were implemented only on the basis of an appeal to the public. Even if the ban had been fully effective, there was a shortage of uncontaminated feedstuff in the affected regions.
- (3) The third scenario, the Prague Scenario, was focused on the evaluation of doses to inhabitants due to the intake of  $^{131}\text{I}$  in a situation where a special cow feeding regime was being applied. Prague covers an area of 496 km<sup>2</sup>, and the first signs of the arrival of a contaminated plume were detected during the night of 29–30 April 1986. Three passages of contaminated air were detected through the territory. They resulted in locally elevated levels of  $^{137}\text{Cs}$  in soil and therefore high  $^{131}\text{I}$  deposition was also expected to have occurred at the same locations. During the period 6–8 May 1986, it was recommended that dairy cows should be kept on winter fodder, if available. Consumption of milk with an  $^{131}\text{I}$  concentration > 1000 Bq L<sup>-1</sup> was banned. The working group participants were asked to estimate the  $^{131}\text{I}$  concentration in milk for the hypothetical situation in which cows were pastured on open grassland near Prague.

#### **8.4. Issues emerging from the exercises**

Several aspects of model performance were evaluated and the following issues were identified as being in most need of attention:

- The use of the constant isotopic ratio  $^{131}\text{I}/^{137}\text{Cs}$  for the Plavsk Scenario gives a satisfactory approximation of  $^{131}\text{I}$  contamination of the foodchain. However, the results obtained for the situation of inhomogeneous  $^{137}\text{Cs}$  deposition and the relatively short period of rainfall during the cloud passage (6 hours) indicate that, when the radioactive fallout can be classified as mixed (dry and wet), it is advisable to adopt a different approach for determining the complex relationship between  $^{131}\text{I}$  deposition and  $^{137}\text{Cs}$  deposition.
- The uncertainty associated with the prediction of  $^{131}\text{I}$  concentration in air based on the average  $^{137}\text{Cs}$  content of soil over the region exceeds a factor of three and depends on the physico-chemical forms of airborne radioiodine during the passage of the radioactive cloud as well as on the meteorological conditions.



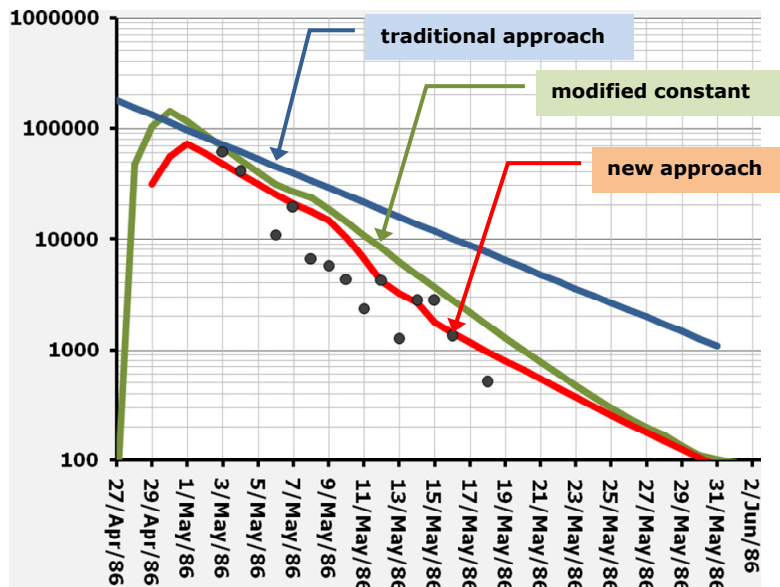


FIG. 3. Predictions of different models for interception and weathering losses by grass of mixed (dry and wet) radioiodine fallout. The ordinate is  $^{131}\text{I}$  concentration in pasture grass (Bq/Kg). Black dots represent measured values. Blue curve – model using semi-empirical constant (weathering half-time). Green curve – model with interception and weathering dependent on rainfall. Red curve – model with interception and weathering dependent on rainfall land also on different forms of radioiodine.

- The model for the interception and weathering losses of mixed (dry and wet) radioiodine fallout on grass needs to be carefully examined as the decrease with time of radioiodine concentration in grass was different for each scenario depending on the precipitation amount during the radioiodine cloud passage (see Figure 3).
- The time at which the cows from collective farms were put on to pasture seems to be the most important factor leading to the mispredictions of  $^{131}\text{I}$  concentration in milk and consequently of ingestion doses.

## 8.5. Conclusions

In general, model performance has improved significantly compared with previous international exercises involving radioiodine scenarios. The predictions of the various models were within a factor of three of the observations, and the discrepancies between the estimates of the average doses to the thyroid produced by most participants did not exceed a factor of ten. However, estimated doses differed by up to two orders of magnitude when the working group participants attempted to evaluate the effectiveness of countermeasures using different methods and conceptual approaches.

In emergency circumstances, it is difficult to effectively implement the distribution of stable iodine or the transfer of animals to stored feed. Furthermore, there are no means to make diet restrictions on milk, milk products and leafy vegetables and bans on pasture feeding for cows compulsory but only to encourage voluntary action. Therefore, for emergency response preparedness there is a need for realistic and validated dose assessment methodologies and an appreciation of the likely uncertainties. Based on the experience of this exercise, it is strongly recommended that several groups of independent experts should be involved in the dose assessment process.

## 9. TESTING OF MODELS FOR PREDICTING THE BEHAVIOUR OF RADIONUCLIDES IN FRESH WATER SYSTEMS AND COASTAL AREAS

### 9.1. Introduction

The contamination of the aquatic environment with radioactive materials causes the radiation exposure of humans through a variety of different pathways. These include the use of water for drinking and irrigation, the consumption of fish, and recreational activities such as bathing and boating.

Although in some circumstances (e.g., the aftermath of the Chernobyl accident), terrestrial pathways have been the major source of radiation exposure of humans, the public perception of risk associated with contamination of the aquatic environment is significant and must be taken into account in pre-accident planning. Obviously, in the case of direct releases of radionuclides to the aquatic environment (e.g., the releases that caused the contamination of the Tcha River from the Mayak installations, or routine discharges of radionuclides from nuclear power plants), aquatic pathways are the principal source of radiation exposure of the local population.

### 9.2. Method used

State-of-the-art models, developed by different organizations, were tested by the Aquatic Working Group, comparing their predictions with observed data. The descriptions of the environmental scenarios for model testing were developed by individual members of the working group, who also provided the measured data. Five model testing exercises were performed:

- (1) Wash-off of  $^{90}\text{Sr}$  and  $^{137}\text{Cs}$  deposits from the Pripjat floodplain, Ukraine. Modellers were asked to predict the time-dependent water concentrations of the radionuclides in the Pripjat River following the inundation of the river floodplain during the period after the Chernobyl accident. Modellers were provided with data on the deposition of radionuclides on the floodplain, the time-dependent radionuclide concentrations in the river water entering the floodplain, the water fluxes, and morphological, meteorological and hydrological data. Subsequently, concentrations of radionuclides in the water of the Pripjat River downstream of the floodplain were supplied to the modellers in order to allow the performance of the models to be evaluated.
- (2) Radionuclide discharge from the Dnieper River, Ukraine into its Black Sea estuary (the Dnieper-Southern Boug estuary). Modellers were asked to predict the time-dependent  $^{90}\text{Sr}$  and  $^{137}\text{Cs}$  concentrations in the waters of the estuary. Input information for the modellers was: the radionuclide fallout from the Chernobyl accident on to the estuarine waters, the concentrations of radionuclides in the Black Sea and in the Dnieper and Southern Boug rivers, and hydrological, morphological and environmental data (temperature, salinity, pH, etc.). The performance of the models was evaluated by comparing predictions with the observed time-dependent radionuclide concentrations in the estuary.
- (3)  $^3\text{H}$  migration in the Loire River, France. This exercise was concerned with the assessment of the dispersion of tritium released routinely from four nuclear plants at different points on the Loire River, spread over about 350 km, and over a period of six months. Modellers were provided with data on water flows from tributaries, hydrological data and information on tritium discharges from the nuclear power plants.

The predictions were compared with downstream observations of tritium concentrations in the Loire at Angers.

- (4) Release of radionuclides into the Techa River, South Urals, Russian Federation. The objective of this exercise was to test modelling of the behaviour of  $^{90}\text{Sr}$ ,  $^{137}\text{Cs}$  and  $^{239,240}\text{Pu}$  in river water and bottom sediments. The scenario was based on data obtained from the Techa River, which was heavily contaminated, mainly in the period 1949–1952, as a result of discharges of liquid radioactive waste into the river (see Figure 4).
- (5) Behaviour of  $^{226}\text{Ra}$  in the Huelva Estuary, Spain. This estuary was affected by radionuclides released from a phosphate factory. In the exercise, the time evolution of the total  $^{226}\text{Ra}$  inventory in the bed sediments, and the time evolution of the  $^{226}\text{Ra}$  concentration in the water column, were predicted by the modellers.

Scenarios (1) and (3) were ‘blind’ exercises.

The models used in the exercises showed different degrees of complexity, ranging from those based on simple box-type approaches to those that make use of shallow-water and diffusion-transport equations. Similarly, the processes controlling the interaction of radionuclides with sediments were approached at different levels of detail in the models.

### **9.3. Scope of the work**

The activities of the working group were focused on extending the exercises of model validation to some themes that were not addressed in previous model validation projects. The activities took advantage, not only of the data from the Chernobyl accident, but also of data from other contamination events, such as the discharge of radionuclides into the Techa River and routine releases of radionuclides into the aquatic environment. In addition, the working group addressed radionuclides (e.g. tritium) and systems (e.g. coastal areas) that were not studied in previous testing projects and also aimed at modelling complex aquatic systems at a regional scale (large rivers and large catchment areas).

### **9.4. General summary of findings**

Generally, the basic components of state-of-the-art models for predicting the behaviour of radionuclides in the abiotic compartments of aquatic systems are: (i) hydrological sub-models (and related transport-dispersion sub-models); (ii) submodels for predicting the interaction of radionuclides with sediments and suspended matter; and (iii) submodels for predicting the migration of radionuclides from contaminated catchments. The uncertainty in the model predictions is related to the features of these components.

It should be noted that, as tritium does not interact with sediments, the only processes that control the migration of this radionuclide are dispersion and transport by the water current. Therefore, exercise (3) was an important test for assessing the reliability of the hydrological and dispersion-transport modules being used in state-of-the-art models. This ‘blind test’ showed that the behaviour of radionuclides that hardly react with suspended matter and sediments can usually be predicted to acceptable levels of accuracy by models even if they are based on relatively simple hydrological submodels.



FIG. 4. The Techa River. The figure shows the complex water system influenced by the constructions of canals, dams and reservoirs. The exercise concerned the migration of  $^{90}\text{Sr}$ ,  $^{137}\text{Cs}$  and  $^{239,240}\text{Pu}$  in the river.

In contrast, the predictions of models for representing the behaviour of radionuclides that interact strongly with sediment and soil particles are associated with significant levels of uncertainty. In particular, the ‘blind test’ exercise (1) showed that the models in the exercise properly predicted the remobilisation of strontium from the contaminated Pripyat River floodplain, but that they significantly overestimated the remobilisation of radiocaesium. This gave the opportunity for a re-assessment of the values of some parameters used in the models to evaluate the remobilisation process in the fresh water environment.

The modelling of the complex dynamics of extreme hydrological events, such as the inundation of large flood plains, was also recognised as an important source of uncertainty for reactive radionuclides. Indeed, the concentration of re-mobilised radionuclides in water depends on the time of inundation and on the proportion of water flowing over more or less contaminated areas. In many circumstances, these quantities cannot be predicted with sufficient accuracy and therefore have a major influence on the overall uncertainty of model predictions.

In conclusion, some dominant factors can be identified that affect the uncertainty of the model predictions. As previously noted, the submodels for predicting the interaction of radionuclides with sediments and suspended matter represent a more significant source of uncertainty as compared with the hydrological and related dispersion and transport submodels for predicting the migration of radionuclides in water. Similarly, the uncertainty in the evaluation of radionuclides migrating from a contaminated catchment to a water body can contribute significantly to the overall uncertainty of the model output.

The other important factors affecting the uncertainty of the model results are related to the availability of sufficient information concerning the circumstances and the characteristics of the contamination events, such as the input rates of radionuclides into the environment and the

conditions of the environmental system (for instance, the water flux regime). In this respect, routine controlled releases are associated with more complete and reliable input data and information than accidental events causing environmental contamination.

Scenarios (2) and (3) illustrated two extremes within the range of possible conditions for the application of models to real circumstances. Scenario (3) concerned the controlled release of tritium to river water. For this scenario, sufficient and reliable information and data regarding the hydrological conditions and the input rates of the radionuclide into the river were available for modelling purposes. In contrast, in scenario (2), which considered the contamination of the Dnieper-Southern Boug estuary due to the release of radionuclides into the environment following the Chernobyl accident, the available data were insufficient in that they did not provide the full range of information required for modelling the system properly.

## **9.5. Conclusions**

The exercises provided the opportunity to learn more about the proper application of models for the management of complex environmental problems. They showed the influences on predictions of the uncertainty in the input data and the uncertainty of the model parameters. They also showed the effects caused by the application of different kinds of models to a specific contamination scenario.

It is clear that different models can give different results when applied to the same contamination event. Nevertheless, in spite of the range of variability of the model predictions (a range that has the same order of uncertainty as that of the measured concentrations of radionuclides in water), the results of the different models were generally compatible and reproduced the time behaviour of radionuclide concentrations in the components of the analysed systems. Models that possess this ability are called 'behavioural' models.

The spread of the results reflected the various methodological approaches used to model the complex processes occurring in the aquatic environment as well as the different values used for the parameters in the models.

It is essential for applications aimed at supporting the management of the aftermath of a nuclear accident that the models are 'behavioural', even if the results may be subject to large uncertainties.

The exercise has shown the benefits of using several models for the same contamination scenario (multi-model approach). This approach is of particular value when the environmental processes are complex and when there are, therefore, difficulties in selecting appropriate site specific values of model parameters. In such circumstances, different hypotheses and approaches may be used by modellers to represent the same situation. The exercises performed in the working group showed that a multi-model approach can be useful for the management of complex problems in environmental assessment. Through this approach, the assumptions that obtain the greatest degree of consensus among modellers are clearly evident, while the aspects that are subject to dispute and which should therefore be handled carefully also become clear.

A stimulating subject for future studies would be the comparison of the performance of computerized decision support systems aimed at assessing, following the release of radionuclides into the environment, the levels of contamination of the components of complex fresh water ecosystems, the consequent radiation doses to man and the effectiveness of potential options for environmental restoration or for the reduction of radiation doses to humans and biota.

## 10. MODELLING THE TRANSFER OF RADIONUCLIDES FROM NATURALLY OCCURRING RADIOACTIVE MATERIAL (NORM)

### 10.1. Background

This working group was established to improve the modelling of the transfer of radionuclides from residues containing naturally occurring radioactive material (NORM) for the purposes of radiological assessment.

Almost all naturally occurring materials contain radionuclides from the primordial decay chains (e.g.,  $^{238}\text{U}$ ,  $^{235}\text{U}$ ,  $^{232}\text{Th}$ , and their daughter products  $^{226}\text{Ra}$  and  $^{228}\text{Ra}$ ), plus some individual long lived radionuclides such as  $^{40}\text{K}$ . Extraction and/or processing of minerals containing these materials results in waste containing such radionuclides. Often the processing can enhance the concentration of the NORM in the waste as compared with the original material. The extraction and processing of minerals usually involves large volumes of material and the resulting waste is also present in large volumes which are usually left on the earth's surface. Human exposure to radionuclides from such waste piles can occur as a result of gaseous emanation from the waste ( $^{222}\text{Rn}$ ) or as a result of the leaching by rainfall of radionuclides from the waste into water courses and, possibly, food chains.

There are a variety of situations involving NORM that require potential radiation doses to be assessed. Some of them are:

- (1) surface storage of residues from the extraction and processing of minerals;
- (2) remediation of NORM-containing waste piles; and
- (3) the use of NORM-containing waste for backfilling, building materials, road construction etc.

In all of these situations there is a need to understand the present and future behaviour of the radionuclides which may be released from NORM so that steps can be taken to ensure that humans are adequately protected from exposure to radiation. Because of the long lived nature of many of the radionuclides, the assessments must be carried out over long times into the future.

This is the first time that the modelling of NORM-containing radionuclides has been examined in this IAEA format and the working group spent much of its time exploring the global situation and determining the availability of modelling tools.

### 10.2. Aims of the work

The main aims of the work were:

- to evaluate existing models;
- to develop scenarios for testing models; and
- to develop new models.

### 10.3. Modelling considerations

#### 10.3.1. Assessment types

Models are used for different types of assessment. These include:

- existing operations;
- evaluation of past activities (legacy sites); and
- the planning of new operations or remediation strategies for existing contaminated sites.

### ***10.3.2. Model types***

Different types of models are applied for different purposes. Some of these are:

- Compliance or screening models. These models are designed to check compliance with regulatory conditions. They are usually simple models based on conservative assumptions. They should therefore overestimate radionuclide concentrations and the associated doses and risks. They can be used to determine whether radiation doses are well below regulatory limits or whether there is a need for further more detailed assessment.
- Realistic assessment models. These models are designed to assess, as accurately as possible, radioactive concentrations or radiation doses resulting from a defined scenario. For this reason, they may be fairly detailed in parts to ensure that the behaviour of the radionuclides in the system is properly represented. Accurate predictions can sometimes be obtained by fairly simple models. Such models have usually been appropriately calibrated by comparison to measurements made on the system.

### ***10.3.3. Scenarios used for model testing***

Well-documented real scenarios involving NORM were not available to the working group and so three hypothetical scenarios were developed to facilitate model testing and development.

#### ***10.3.3.1. Hypothetical scenarios***

These scenarios were designed to cover the situations most likely to be encountered in practice:

- Point source: releases of NORM from the stack discharge of a coal-burning power station is an example of this type of scenario.
- Area source: stockpiles, waste repositories (surface or near-surface), or landfills containing NORM are examples of this scenario type.
- Area source + river: this scenario is a modification of the ‘Area source’ scenario with the addition of a river flowing past the site.

#### ***10.3.3.2. Real scenarios***

Detailed model testing using real scenarios was not performed although there was some limited testing with a few models. However, data was collected on some potential scenarios for future model testing, i.e.:

- (1) Former thorium processing facility: This scenario is based on the site of a former thorium processing facility and a (physically separated) gas mantle production facility. It is an example of a legacy site and is characterized by a highly heterogeneous distribution of contaminated material in a built-up area near to a large river. The

available data indicate that there has been very little groundwater contamination even though there are several small creeks or streams in the area.

- (2) Lignite power station: This site comprises two power stations, situated close together, with a total of 5 stacks. There is a city approximately 5 km to the southeast. Values of  $^{226}\text{Ra}$  concentrations in dust and on the ground surface have been measured, and meteorological (wind rose) data are also available.
- (3) Phosphogypsum disposal – site 1: This site comprises a series of connected deposition areas under a lake, very close to the coast. A series of monitoring wells is used to collect data on  $^{226}\text{Ra}$  concentrations in surface water and groundwater. The results of measurements of groundwater flow are also available.
- (4) Phosphogypsum disposal – site 2: A single large phosphogypsum stack is located on top of a deep layer of clay approximately 1 km from the coast. A concrete wall has been built on the downstream side of the stack to restrict the flow of contaminants leached into the groundwater. A series of monitoring wells is used to measure radionuclide concentrations. Leachate is extracted from a series of wells along the downstream side of the stack and pumped back to the top of the stack.

## **10.4. Model Testing**

### ***10.4.1. Point source***

The source was specified as a single stack 100 m in height, with specified discharge rates of  $^{222}\text{Ra}$ ,  $^{210}\text{Pb}$  and  $^{210}\text{Po}$ . Wind rose and atmospheric stability data were provided, together with partition factors and other relevant environmental data. Modellers were asked to calculate the annual radiation doses to occupants of two houses at given locations and with given occupancy and dietary factors.

### ***10.4.2. Area source***

The source in this case was specified as a waste pile 1 km square and 10 m thick, with a cover layer of 2 m of clean soil. The waste was underlain by a 3 m thick layer consisting of a specified mixture of clay and sand, and this layer was immediately above a 15 m thick aquifer (see Figure 5). The direction and speed of groundwater flow in the aquifer were specified, together with other relevant environmental, dietary and water usage (drinking, irrigation) data. Modellers were asked to estimate the annual radiation doses to the occupants of three houses, one above the waste area and two others at different distances from the waste area in the direction of groundwater flow.

### ***10.4.3. Area source + river***

The source in this scenario was the same as for the area source, but a river was located 300 m from the down-gradient edge (with respect to groundwater flow) of the waste. Most of the data for this scenario were the same as the data for the area source scenario. River flow parameters and the positions of houses at different distances downstream from the waste were specified, and modellers were asked to estimate the annual radiation doses to occupants of these houses.



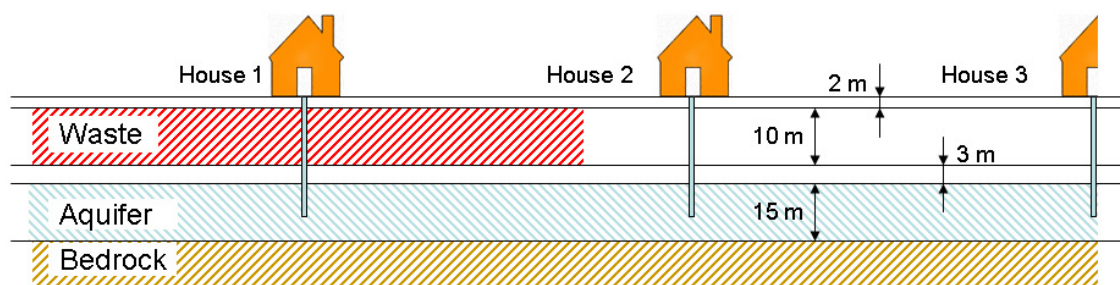


FIG. 5. Cross-section through area source and exposure points.

## 10.5. Conclusions

In contrast with other EMRAS working groups, the participants of the NORM working group generally chose to apply existing models from the literature to the test scenarios. These models had been developed by other organizations and so the participants were usually model users rather than model developers/users, as was the case in most of the other working groups. For these reasons, the issue of ‘ease of use’ of the models was an important issue for the working group. It was noted that several of the models examined were not very ‘user friendly’ with insufficient explanation provided for the user. It was concluded that ease of use could be greatly enhanced by the provision of good documentation and ‘help screens’, databases containing default values of environmental parameters, and facilities for plotting the results of calculations. It is also extremely important to provide the model user with simple procedures for changing the default values and for adding extra data to existing databases.

Predictions were made for the three hypothetical scenarios using several models. The results for the point source scenario showed that the simple models (COMPLY, CROM) predicted higher radionuclide concentrations than the more realistic model PC-CREAM.

Predictions were made for the area source scenario using two models (RESRAD-OFFSITE and DOSDIM + HYDRUS). In general, the results obtained from the two models (which use different methodologies for groundwater transport) were consistent with each other. RESRAD was ‘calibrated’ by estimating the natural background radiation level and comparing it to the existing natural background radiation levels.

The limited amount of model testing which was conducted within the working group does not allow proper conclusions to be drawn about the state of modelling in this area. It is clear that more model testing, especially using the real scenarios, is needed and that specific model components and techniques may need to be developed to allow some of the more complex features of the real scenarios to be modelled.

This is a subject of importance for many countries and for them competence in predicting the behaviour of radionuclides in situations involving NORM needs to be developed.

## **11. TESTING OF MODELS FOR THE REMEDIATION OF THE URBAN ENVIRONMENT**

### **11.1. Introduction**

The objective of the Urban Remediation Working Group was to test and improve models used for assessments related to the remediation of urban areas contaminated with radionuclides. Events that can result in the dispersal or deposition of radionuclides in an urban situation include both intentional and unintentional events, and can range from major events involving a nuclear facility or a nuclear weapon, to small events such as a transportation accident. Currently, a concern of many governmental authorities is the deliberate dispersal of radioactivity from a device, with or without an explosion.

The endpoints tested by the working group were radiation dose rates and cumulative doses to humans in urban areas contaminated with dispersed radionuclides; this included the prediction of changes in radionuclide concentrations or radiation dose rates as a function of location and time, the identification of the most important pathways for human exposure, and the prediction of the reduction in radionuclide concentrations, radiation dose rates or radiation doses resulting from various countermeasures or remediation efforts. The approach to achieving this objective was by: (i) identification of realistic scenarios for a wide variety of situations; (ii) comparison and testing of approaches and models for assessing the significance of a given contamination event, and for guiding decisions about countermeasures or remediation measures implemented to reduce radiation doses to humans or to clean up the contaminated area; and (iii) improving the understanding of processes and situations that affect the spread of contamination to aid in the development of appropriate models and parameter values for use in the assessment of these situations. The ultimate aim of the working group was to develop the capabilities of models as tools for use in decision making for addressing long term radiological concerns after an urban contamination event has occurred and for assisting in identifying appropriate remediation measures.

### **11.2. Methods of the working group**

The activities of the working group covered three main areas. The first of these was a review of the available modelling approaches and computer models for use in evaluating the consequences of urban contamination and of potential countermeasures or remediation activities. The second was a modelling exercise based on data obtained from the town of Pripyat in the Ukraine, following the Chernobyl accident. The Pripyat scenario provided an opportunity to model a large scale contamination event and its long term effects. The scenario permitted the intercomparison of the predictions obtained from four different models (EXPURT, METRO-K, EDEM, and CPHR) as well as, for some endpoints for which measurement data were available, a comparison of model results with actual measurements. The third area was a model intercomparison based on a hypothetical scenario involving a point-release of a radionuclide in a large modern city; the release was from a dispersal device and involved an explosion. This scenario provided an opportunity for the intercomparison of predictions obtained from three models, i.e., METRO-K, CPHR, and RESRAD-RDD. For both modelling scenarios, the intent was to model the radiological impact on exposed groups of the public over time in the absence of any remediation, and then after selected remedial measures had been applied. This approach was intended to allow comparison of the short term and long term effects of various remedial measures on external radiation dose levels and on the radiation doses to humans at the locations of interest (outdoors and indoors), for the purpose of aiding decisions about when to remediate and which remedial measures to use.

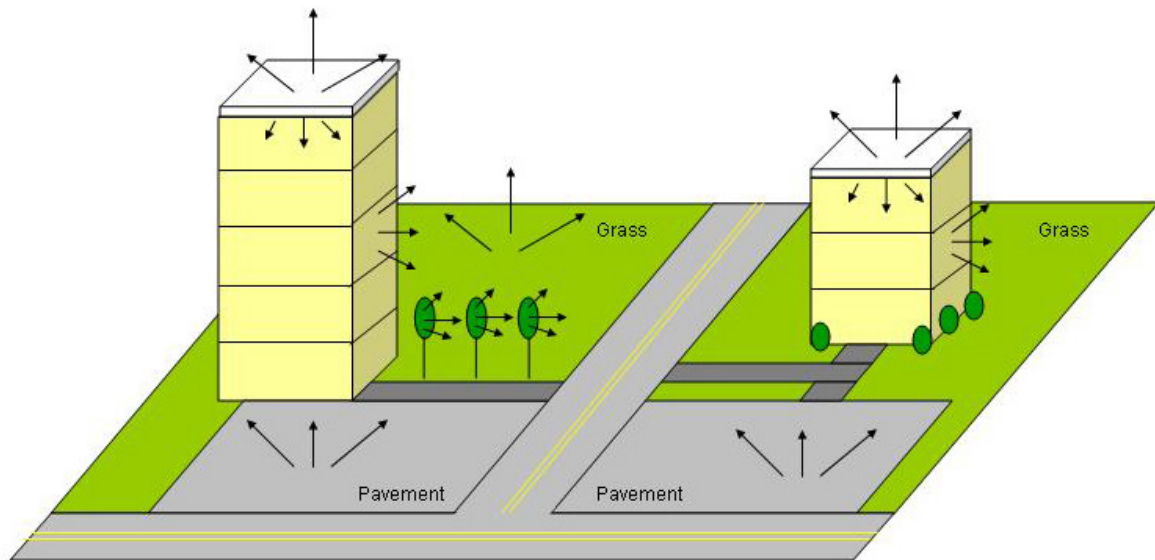
A review of the main modelling approaches and computer models presently available worldwide for use in assessing urban contamination situations has been prepared. In addition, the models used in the working group's intercomparisons have been described in detail in the working group's report entitled, "Environmental modelling of remediation of Urban contaminated areas", including the parameter values used for each of the two scenarios (Pripyat and Hypothetical scenarios).

The working group has also summarized several key considerations for characterizing an urban environment for modelling purposes. The application of computer models to assess potential countermeasures or remediation measures is considered to be incompletely developed and therefore the working group has summarized the available literature on countermeasures and their effectiveness and has developed guidance for implementing countermeasures or remediation measures in computer models. An important caveat is that much of the available information on urban modelling generally and the application of countermeasures more specifically has come from the experience of the consequences of the Chernobyl accident; for this reason some information might not be directly applicable for other types of contamination, dispersal events or geographical conditions.

### 11.3. Results

The first of the working group's two model intercomparison exercises was the Pripyat scenario, based on Chernobyl fallout data for the town of Pripyat in the Ukraine, 3 km from the site of the accident. Deposition from the accident contained a wide spectrum of nuclear fission products, activation products, and transuranium elements. The scenario involved several radionuclides ( $^{95}\text{Nb}$ ,  $^{95}\text{Zr}$ ,  $^{103}\text{Ru}$ ,  $^{106}\text{Ru}$ ,  $^{134}\text{Cs}$ ,  $^{137}\text{Cs}$ ,  $^{141}\text{Ce}$ , and  $^{144}\text{Ce}$ ). Measured deposition of these radionuclides in District 1 and District 4 was provided as input information (e.g., for  $^{137}\text{Cs}$ , 1.4 MBq m<sup>-2</sup> in District 1 and 0.52 MBq m<sup>-2</sup> in District 4). Pripyat was evacuated soon after the Chernobyl accident and has remained essentially uninhabited since that time.

The spread of the predictions from the four models for a given endpoint is more than an order of magnitude in many cases, and in some cases, up to 3–4 orders of magnitude. These large differences reflect the current uncertainty associated with modelling the behaviour of urban contamination; much of this uncertainty is likely to be related to issues such as: determining which surfaces need to be included in a model (Figure 6), the weathering of radionuclides from surfaces and transfer between surfaces, and the behaviour of different types of surface as contaminant collectors over long periods. The models used in the Pripyat scenario include different combinations of surfaces (e.g., interior surfaces of buildings were included in some models but not in others; trees were included as surfaces in some models but not in others) or treat some surfaces differently (e.g., artificial surfaces were considered permeable in some models but impermeable in others); thus even when models gave similar results for a given endpoint (e.g., radiation dose rate at a given time and location), the relative contributions of surfaces to those results were often different. The examination of predictions of interim points in the overall dose assessment (e.g., the contributions to dose rate from specified surfaces) has enabled the working group to identify and understand the differences between models.



*FIG. 6. Schematic drawing of an urban location illustrating the various surfaces that can contribute to the total dose rate to exposed persons. For example, a person spending time outdoors may receive a dose from grass, trees, paved surfaces such as streets and parking lots, and the roofs and outer walls of buildings. A person spending time indoors may receive a dose from the same surfaces (allowing for shielding effects of the building structure), plus any contaminated indoor surfaces.*

Predicted external doses to an outdoor worker (i.e., a worker employed at an outdoor job not associated with remedial activities) over the period from the accident until 1 August 1986 varied from about 85 mGy to 200 mGy; predicted cumulative doses over 20 years varied from about 160 mGy to more than 4000 mGy, in the absence of countermeasures. Individual decontamination measures (e.g., removal of the top layer of soil, cutting and removal of grass, washing of roads) were estimated to reduce the effective dose accumulated over the first time period from a few percent to as much as 79%; the variations in predicted doses were due to different assumptions about generic and scenario-specific modelling, the habits of the critical group, and the contribution of the decontaminated surface to the estimated dose. Short lived radionuclides were found to be very important contributors to total dose in this scenario. The relocation of a target person during the first 6 months after the accident produced a 70–85% reduction in the cumulative (20 year) dose according to most of the models. Decontamination measures that physically removed contamination from the scene (e.g., cutting and removal of grass, removal of soil) had lasting effects in terms of dose reduction even 20 years later.

Measurements of radiation dose rate were available for the Pripjat scenario. These were compared with the model predictions for the relevant locations and dates. Most of the models tended to underestimate the dose rates for outdoor locations, in part because the absence of human activity in the town (the population was permanently relocated after the accident) appears to have resulted in a slower loss of activity from surfaces than might be expected under normal circumstances.

The working group's second modelling exercise was a scenario based on a hypothetical dispersal event. Using computer simulations (obtained with the Hotspot code) of an explosive event involving a 50 TBq  $^{137}\text{Cs}$  source, a set of reference surface contamination

data for a part of a large modern city was prepared for use as model input, together with initial concentrations of  $^{137}\text{Cs}$  in air from the passage of the plume as a function of height at selected locations. Based on this input information, modellers were required to predict contamination densities and radiation dose rates over time at selected indoor and outdoor locations, radiation doses for defined exposure situations (e.g., residential or occupational exposure at a given location), and the effects of selected countermeasures on the effective doses to members of several critical groups. As with the Pripjat scenario, the spread of predicted values for a given endpoint was sometimes large (2–4 orders of magnitude), especially for later time points. The reasons for the variation in predictions are also similar to those for the Pripjat scenario. The predicted time-dependent behaviour of the contamination differed among models with one model showing an initial rise in contamination density or dose rate for more distant locations; this was attributed by the modeller to the continued transfer of contamination from the near-field zone for some period after the event.

#### **11.4. Conclusions**

By comparing results from the models for the same endpoints, the working group was able to identify differences in the modelling approaches or parameterization and the effects of these differences on the model endpoints, to evaluate the short term and long term effects of various countermeasures on predicted doses, and to justify selected revisions to the models. The differences in the modelling results in the two scenarios examined are due largely to differences in the conceptual models that were used. As has been found in many previous modelling exercises, such as VAMP and BIOMASS, the comparison of model results among participants and models also provides an opportunity to identify and correct errors in coding or input information and to clarify the interpretation of the scenario.

The working group has identified a number of areas where additional information would permit modellers to improve predictive capabilities and reduce uncertainties. These include improved information about the initial distribution of contamination, contaminant transport processes in urban settings, parameter information for radionuclides other than  $^{137}\text{Cs}$ , and the nature of various urban surfaces in different countries or situations, as well as human habits and patterns of movement. The working group's modelling scenarios mainly involved single countermeasures rather than combinations of them. The effectiveness of combined countermeasures is not necessarily the sum of their individual effectiveness, and may depend on the timing of the countermeasure or the order in which countermeasures are implemented. For example, it is important to wash roads and roofs before it rains. Further work on modelling combinations of countermeasures would be useful.

The Urban Remediation Working Group has also prepared general and specific practical considerations for decision-makers. For example, the types of data needed in preparation for potential urban contamination events have been identified, together with the most important information to collect at the time and place of an actual event.

## **12. REVIEW OF DATA AND TESTING OF MODELS FOR PREDICTING THE TRANSFER OF RADIONUCLIDES TO NON-HUMAN BIOLOGICAL SPECIES**

### **12.1. Introduction**

Currently, there is interest in developing guidelines for the protection of non-human biota from the harmful effects of ionizing radiation at both national and international levels, with some IAEA Member States already conducting assessments under national regulations. In response to these developments, several models and approaches have been developed for the purpose of estimating the exposure of non-human biota to ionizing radiation.

The primary objective of the Biota Working Group was: “to improve Member States’ capabilities for protection of the environment by comparing and validating models being used, or developed, for biota dose assessment (that may be used) as part of the regulatory process of licensing and compliance monitoring of authorised releases of radionuclides”.

Models and approaches being developed, and in some instances applied in a regulatory context, in the USA, Canada, France, Belgium, Russia, Lithuania and the UK and some developed in EC research programmes were tested in the working group exercises.

### **12.2. Model testing exercises**

Two model-model comparison exercises were conducted to compare the basic components of the participating models (dose conversion coefficients (DCCs) and approaches to transfer modelling).

In addition, two model-data comparisons were undertaken, utilising databases for aquatic (Perch Lake, Canada) and terrestrial (Chernobyl exclusion zone) ecosystems.

The participating models included RESRAD-BIOTA, ERICA, EA R&D128 and FASSET (see [http://www.ceh.ac.uk/protect/pages/env\\_protect\\_radio.html](http://www.ceh.ac.uk/protect/pages/env_protect_radio.html)) and in-house models being used/developed by various working group participants.

### **12.3. Overview of results**

#### ***12.3.1. Dosimetry and transfer components of the models***

The exercise to compare predicted whole body absorbed radiation dose rates (reported as DCCs) for a selection of the proposed International Commission on Radiological Protection (ICRP) Reference Animal geometries [4] demonstrated that comparable internal dose rates were obtained with all of the participating models (11 models) even though different assumptions were made. The notable exception to this conclusion was as a consequence of different daughter products being included (e.g., one approach included  $^{234}\text{U}$  in the estimation of the DCC for  $^{238}\text{U}$ ). The variation between models was greater for the estimation of external dose rates, most notably for  $\alpha$ - and  $\beta$ -emitters. However, external exposure due to most of these emitters is of little radiological significance for biota due to their low range in matter.

The comparison of predicted activity concentrations in a range of freshwater and terrestrial biota (8 models), assuming unit concentration of activity in the base medium (1 Bq per unit of soil, water or air) showed considerably more variability than the comparison of dose estimates. For many radionuclide-reference organism combinations, the variability in predictions covered three or more orders of magnitude. Predictions were often most variable

for poorly studied organisms such as fish eggs, bird eggs, ducks, amphibians and aquatic mammals. Some of the variability can be explained by the use of ‘guidance’ methodologies to estimate values in the absence of data. The guidance methodologies are generally intended to provide conservative values and, in most instances, they resulted in comparatively high (and hence conservative) predictions.

### ***12.3.2. Scenario applications***

The two scenario applications allowed model predictions to be compared to measured whole body activity concentrations of a number of radionuclides ( $^{90}\text{Sr}$ ,  $^{137}\text{Cs}$ , Pu-isotopes,  $^{241}\text{Am}$ ,  $^{60}\text{Co}$  and  $^3\text{H}$ ) in a range of freshwater and terrestrial biota. The majority of the models gave predicted activity concentrations in most organism types to within an order of magnitude of the observed data. However, in a few cases, the differences between predictions and observed values were two or more orders of magnitude. As an example, Figure 7 shows a comparison of the average predictions of whole body  $^{90}\text{Sr}$  activity concentrations for a range of organisms considered within the terrestrial (Chernobyl exclusion zone) scenario. To aid comparison, each prediction has been normalized to the measured data.

The results from the scenario model testing exercises were generally in agreement with those of the model-model testing exercises and the understanding of the different models gained in the earlier phase of the work aided the interpretation of the variability between the model predictions.

The variability between estimated radiation dose rates to biota can mainly be explained by the variability in predicted whole body activity concentrations. In the scenario testing exercises, less variability was observed in the estimated total radiation dose rates (typically less than an order of magnitude) than might have been anticipated from the observed variations in predicted activity concentrations (typically at least three orders of magnitude). This was due to compensating effects — some models under estimated for one radionuclide and over predicted for another for the same organism. Total radiation dose rate alone is, therefore, an inappropriate indicator of model performance in such model inter-comparisons.

External radiation dose generally made a small contribution to the total dose in the two scenarios considered and, therefore, differences in assumptions about the occupancy of biota had a small influence on the overall variation in estimated dose rates. In contrast, internal radiation doses made the largest contribution to total dose and the assumptions with regard to diet and concentration ratio (CR) values had an important influence on the variations between predictions.

The scenarios allowed comparison to be made of the predictions of simple CR based approaches with more complex food chain models under equilibrium conditions. Overall, the two approaches compared favourably. However, in the case of the freshwater scenario (Perch Lake), two of the models which take into account water chemistry gave the most accurate predictions of the transfer of  $^{90}\text{Sr}$  to fish.

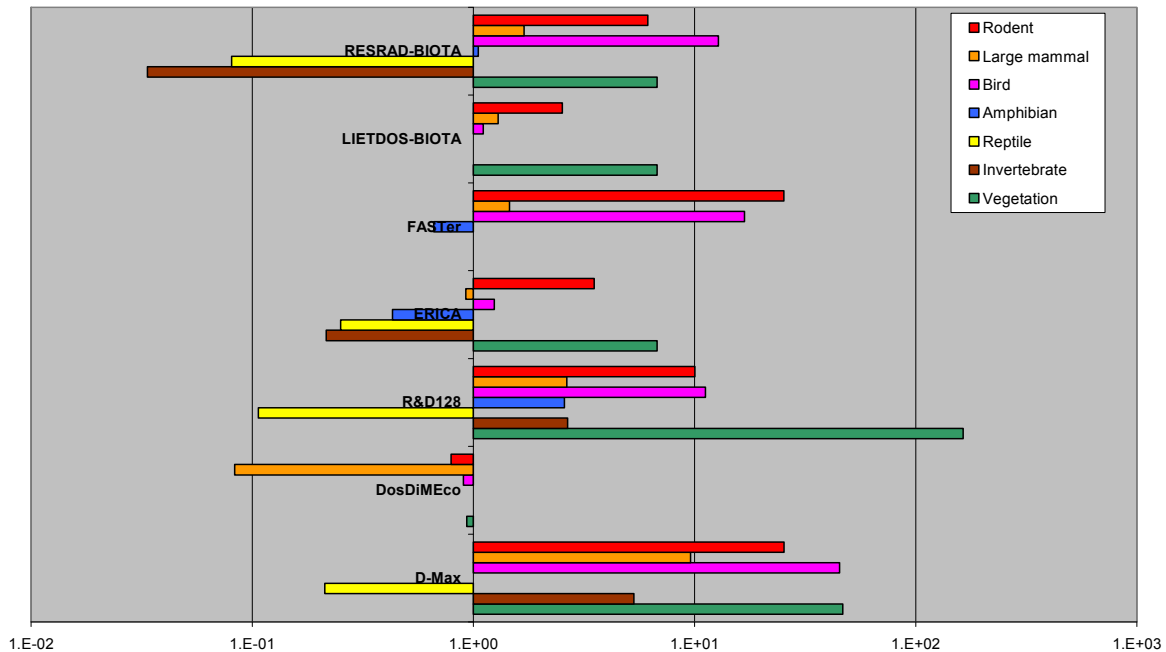


FIG. 7. A comparison of the mean normalized predicted <sup>90</sup>Sr activity concentrations by organism type for the Chernobyl (terrestrial) scenario considered by the Biota Working Group.

#### 12.4. Conclusions

Although the need for a system for environmental protection from ionizing radiation is now generally recognized, many aspects including the establishment of protection goals, benchmark (dose rate) values and the parameterization of models applied in the work described here are still under development.

An aim of the working group was to help in the improvement of the models used by IAEA Member States. This was achieved to the extent that the collaborative exercises led to the sharing of parameter values and/or re-parameterization in some of the participating models. However, the model-model inter-comparisons and the scenario testing exercises involved only a limited number of radionuclides. It is recognized that the sites for which extensive databases are available and which were used in the exercises may not (especially in the case of Chernobyl) be typical of situations that need to be assessed within regulatory frameworks.

The work of the working group has clearly demonstrated that the largest contribution to variability between model predictions and between model predictions and scenario values is the parameterisation of transfer components. There is a clear need to improve the sharing of knowledge on the transfer of radionuclides to biota and to provide authoritative collations of those data which are available.

The work of the working group is therefore incomplete and some of the areas still needing attention are as follows:



- The work of the working group has shown that the largest contribution to variability between model predictions and scenario values is the parameterisation of transfer components. There is a clear need to improve the sharing of knowledge on the transfer of radionuclides to biota and to provide authoritative collations of those data which are available.
- Situations which regulators/industry in most countries are having to consider should be addressed (e.g. waste repositories, NORM sites, boundary ecosystems). Scenarios based on such situations would enable the comparison of the available approaches within a regulatory context.
- The models used by the working group predict dose rates to biota but there is also a need to be able to determine the potential consequences of the predicted dose rates. A large amount of data on the effects of ionising radiation on biota has recently been collated in EC programmes (see [www.frederica-online.org](http://www.frederica-online.org)). However, this data collection covers only a portion of the available scientific literature and more efforts are needed to collate and quality assure all of the available data.

### 13. OUTCOMES OF THE EMRAS PROGRAMME

The EMRAS programme has contributed to an improved understanding of the factors affecting the reliability of environmental assessment models, that is, models used for predicting the radiological impact of radionuclides released under routine and accident conditions into the terrestrial, including urban, and the aquatic environments.

The comparison of model predictions with real data from measurements made in the environment provides a good indication of the uncertainty which exists in modelling assessments and, on this basis, the work of several of the EMRAS working groups has pointed to the areas to which attention must be addressed for improving the reliability of future predictions.

The programme has led to the documentation of new and more comprehensive reference data sets for radionuclide transfer in the environment. In comparison with the existing IAEA publication on the subject (TRS-364), the scope has been broadened beyond temperate climates and the new collection contains data on an increased number of transfer parameters (TRS-472). Data on the transfer of radionuclides to rice have been included for the first time and specific activity models and data are now given for the mobile radionuclides tritium,  $^{14}\text{C}$  and  $^{36}\text{Cl}$ .

The EMRAS programme has contributed to the development of an international system for the protection of biota by providing a forum in which models developed in Member States for this purpose were compared and tested.

Maintaining the capabilities and competence of nuclear experts is becoming an issue in Member States and the EMRAS programme has provided a valuable mechanism for transferring knowledge and expertise in the area of impact assessment modelling. Individual participants in the EMRAS programme have benefited from the opportunity to make contact with other scientists with similar interests, to exchange information and to compare models and model predictions with those of others.

In order to achieve their goals, the various EMRAS working groups organized new and existing data into a number of test or reference data sets for terrestrial and aquatic scenarios that can be used by scientists outside the programme for model testing purposes. The extensive documentation provided in the working group reports should be a valuable resource for all Member States, whether or not they participated in the programme. For example, the working group reports include the various modelling scenarios and their documentation in detail. These scenarios can be used by new modellers to gain experience of modelling generally, of a specific model, or of a new area of modelling.

The working group reports are published in the form of IAEA reports and are contained on a CD-ROM which accompanies this summary report.

## REFERENCES

- [1] INTERNATIONAL ATOMIC ENERGY AGENCY, Handbook of Parameter Values for the Prediction of Radionuclide Transfer in Terrestrial and Freshwater Environments, Technical Reports Series No. 472, IAEA, Vienna (2010).
- [2] INTERNATIONAL ATOMIC ENERGY AGENCY, Handbook of Parameter Values for the Prediction of Radionuclide Transfer in Temperate Environments, Technical Reports Series No. 364, Vienna (1994).
- [3] INTERNATIONAL ATOMIC ENERGY AGENCY, Quantification of Radionuclide Transfer in Terrestrial and Freshwater Environments for Radiological Assessments, IAEA-TECDOC-1616, IAEA, Vienna (2009).
- [4] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Environmental Protection: The concept and use of reference animals and plants, Annals of the ICRP, Volume 38, No. 4–6 (2008).



## LIST OF PARTICIPANTS

Aign, J.	Technische Universität München, Germany
Al-Khayat, T.	Ministry of Science and Technology, Iraq
Al-Masri, M.	Atomic Energy Commission of Syria, Syrian Arab Republic
Amado, V.	Autoridad Regulatoria Nuclear, Argentina
Amano, H.	Japan Atomic Energy Research Institute, Japan
Ammann, M.	STUK, Radiation and Nuclear Safety Authority, Finland
Andersson, K.G.	Risø National Laboratory, Denmark
Angeli, G.	Ente per le Nuove tecnologie e l'Ambiente, Italy
Arapis, G.	Agricultural University of Athens, Greece
Arkipov, A.	Chernobyl Center for Nuclear Safety, Ukraine
Atanassov, D.	National Institute of Meteorology and Hydrology, Bulgaria
Atarashi-Andoh, M.	Japan Atomic Energy Research Institute, Japan
Balonov, M.	International Atomic Energy Agency
Barbeau, C.	Université Laval, Canada
Barnett, C.L.	Centre for Ecology and Hydrology, United Kingdom
Barraclough, I.	Enviros Consulting Limited, United Kingdom
Barros, H.	University of Seville, Spain
Bartusková, M.	National Radiation Protection Institute, Czech Republic
Batandjjeva, B.	International Atomic Energy Agency
Baumgärtner, F.	Technische Universität München, Germany
Beaugelin-Seiller, K.	Institut de Radioprotection et de Sûreté Nucléaire, France
Belli, M.	Istituto Superiore di Ricerca per la Protezione Ambientale, Italy
Belot, Y.	Consultant, France
Benovich, I.	Ontario Power Generation, Canada
Beresford, N.A.	Centre for Ecology and Hydrology, United Kingdom
Berkovskyy, V.	International Atomic Energy Agency
Birky, B.	Florida Institute of Phosphate Research, United States of America

Bossew, P.	Institute for Environment and Sustainability, DG Joint Research Centre, European Commission, Italy
Boyer, C.	Commissariat à l'Énergie Atomique, France
Boyer, P.	Institut de Radioprotection et de Sécurité Nucléaire, France
Brennwald, M.	National Cooperative for the Disposal of Radioactive Waste, Switzerland
Brittain, J.E.	University of Oslo, Norway
Brown, J.E.	Norwegian Radiation Protection Authority, Norway
Calmon, P.	Institut de Radioprotection et de Sécurité Nucléaire, France
Cancio, D.	Centro de Investigaciones Energeticas, Mediambientales y Tecnológicas, Spain
Canoba, A.	Autoridad Regulatoria Nuclear, Argentina
Carini, F.	Università Cattolica del Sacro Cuore, Piacenza, Italy
Charnock, T.W.	Health Protection Agency, United Kingdom
Cheng, J-J.	Argonne National Laboratory, United States of America
Choi, Y.	Korea Atomic Energy Research Institute, Republic of Korea
Ciffroy, P.	Electricité de France, France
Colle, C.	Institut de Radioprotection et de Sécurité Nucléaire, France
Conney, S.	Food Standards Agency, United Kingdom
Copplestone, D.	England and Wales Environment Agency, United Kingdom
Cutts, D.	Food Standards Agency, United Kingdom
Davis, P.	Atomic Energy of Canada Limited, Canada
Doi, M. <sup>†</sup>	National Institute of Radiological Sciences, Japan
Dovlete, C.	Consultant, France
Duffa, C.	Institut de Radioprotection et de Sécurité Nucléaire, France
Durrieu, G.	Institut de Radioprotection et de Sécurité Nucléaire, France
Dzyuba, N.	Institute of Mathematical Machines and System Problems, Ukraine
Ehlken, S.	Klinikum Bremen-Mitte, Germany
Fesenko, S.	International Atomic Energy Agency
Filistovic, V.	Institute of Physics, Lithuania

---

<sup>†</sup> Deceased.

Galeriu, D.	Institute of Physics and Nuclear Engineering “Horia Hulubei”, Romania
Gallay, F.	Institut de Radioprotection et de Sûreté Nucléaire, France
Garcia-Sanchez, L.	Institut de Radioprotection et de Sûreté Nucléaire, France
García-Tenorio, R.	University of Seville, Spain
Garnier, J-M.	Institut de Radioprotection et de Sûreté Nucléaire, France
Gaschak, S.	Chernobyl Center for Nuclear Safety, Ukraine
Gehrcke, K.	Bundesamt für Strahlenschutz, Germany
Gerler, J.	Bundesamt für Strahlenschutz, Germany
Gerzabek, M.H.	University of Natural Resources and Applied Life Sciences Vienna, Austria
Gil-García, C.J.	Universitat de Barcelona, Spain
Golikov, V.	Institute for Radiation Hygiene, Russian Federation
Golovan, O.	Complexny Service, Ukraine
Golubev, A.	Russian Federal Nuclear Centre, Russian Federation
Golubeva, V.	Russian Federal Nuclear Centre, Russian Federation
Gondin da Fonseca, A.	International Atomic Energy Agency- Seibersdorf
Goutal, N.	Electricité de France, France
Guetat, P.	Commissariat à l’Energie Atomique, France
Gulden, W.	European Fusion Development Agreement, Germany
Håkanson, L.	Uppsala University, Sweden
Harris, F.	International Atomic Energy Agency
Heling, R.	Nuclear Research and Consultancy Group, Netherlands
Hilton, J.	Aleff Group, United Kingdom
Hingston, J.L.	England and Wales Environment Agency, United Kingdom
Hofman, D.	Studsvik RadWaste AB, Sweden
Homma, T.	Japan Atomic Energy Agency (JAEA), Japan
Horyna, J.	State Office for Nuclear Safety, Czech Republic
Hosseini, A.	Norwegian Radiation Protection Authority, Norway
Howard, B.J.	Centre for Ecology and Hydrology, United Kingdom

Hubmer, A.	Institute of Physics and Biophysics, University of Salzburg, Austria
Hwang, W.T.	Korea Atomic Energy Research Institute, Republic of Korea
Inaba, J.	Institute for Environmental Sciences, Japan
Inoue, Y.	National Institute of Radiological Sciences, Japan
Ioannides, K.	The University of Ioannina, Greece
Isamov, N.	Russian Institute of Agricultural Radiology and Agroecology, Russian Federation
Ivanova, K.	National Centre of Radiobiology and Radiation Protection, Bulgaria
Jackson, D.	Enviros Consulting Limited, United Kingdom
James, J.	Bhabha Atomic Research Centre, India
Jourdain, F.	Commissariat à l'Energie Atomique, France
Jova Sed, L.	International Atomic Energy Agency
Juri, Ayub, J.	Universidad Nacional de San Luis/Conicet, Argentina
Kaiser, J.C.	Institute of Radiation Protection, Germany
Kakiuchi, H.	National Institute of Radiological Sciences, Japan
Kamboj, S.	Argonne National Laboratory, United States of America
Kanyár, B.	University of Pannonia, Hungary
Kashparov, V.	Ukrainian Institute of Agricultural Radiology, Ukraine
Kawaguchi, I.	National Institute of Radiological Sciences, Japan
Kennedy, P.	Food Standards Agency, United Kingdom
Kirchner, G.	BfS Federal Office for Radiation Protection, Germany
Kivva, S.	Institute of Mathematical Machines and System Problems, Ukraine
Koarashi, J.	Japan Atomic Energy Agency, Japan
Konoplev, A.	Institute of Experimental Meteorology, SPA "Typhoon", Russian Federation
Koshebutsky, V.	Institute of Mathematical Machines and System Problems, Ukraine
Koukoulidou, V.	Greek Atomic Energy Commission, Greece
Kozar Lagar, J.	Jozef Stefan Institute, Slovenia
Krajewski, P.	Central Laboratory for Radiological Protection, Poland



Krasnov, V.	Ukrainian Institute for Forestry and Agro-Forest Amelioration, Ukraine
Krizman, M.	Slovenian Nuclear Safety Administration, Slovenia
Krylov, A.	Institute of Safety Development Atomic Energy, Russian Federation
Kryshev, A.	Institute of Experimental Meteorology, SPA "Typhoon", Russian Federation
Kryshev, I.	Institute of Experimental Meteorology, SPA "Typhoon", Russian Federation
Laptev, G.	Ukrainian Institute for Hydrometeorology, Ukraine
Leclerc, E.	Andra, Agence nationale pour la gestion des déchets radioactifs, France
LeDizès-Maurel, S.	Institut de Radioprotection et de Sûreté Nucléaire, France
Lee, C.	Korea Atomic Energy Research Institute, Republic of Korea
Lee, H.	Korea Atomic Energy Research Institute, Republic of Korea
Lettner, H.	Institute of Physics and Biophysics, University of Salzburg, Austria
Linsley, G.	Consultant, United Kingdom
Louvat, D.	International Atomic Energy Agency
Luck, M.	Electricité de France, France
Maderich, V.	Institute of Mathematical Machines and System Problems, Ukraine
Madoz-Escande, C.	Institut de Radioprotection et de Sûreté Nucléaire, France
Magro, L.	Agency for Environmental Protection and Technical Services, Italy
Malátová, I.	National Radiation Protection Institute, Czech Republic
Marks, P.	Amersham Plc, United Kingdom
Martin, P.	International Atomic Energy Agency
Masuda, T.	Institute for Environmental Sciences, Japan
Mavrin, S.	Russian Federal Nuclear Centre, Russian Federation
McDonald, P.	Westlakes Scientific Consulting Limited, United Kingdom
Melintescu, A.	Institute of Physics and Nuclear Engineering, "Horia Hulubei", Romania
Miyamoto, K.	National Institute of Radiological Sciences, Japan

Momoshima, N.	Kumamoto University, Japan
Monte, L.	ENEA, Ente per le Nuove Tecnologie, l'Energia e l'Ambiente, Italy
Montfort, M.	Commissariat á l'Energie Atomique, France
Nedveckaite, T.	Institute of Physics, Lithuania
Neves, F.	University of Evora, Portugal
Nitzsche, O.	Brenk Systemplanung GmbH, Germany
Nosov, A.	Atomenergoproject, Russian Federation
Nuccetelli, C.	Istituto Superiore di Sanita, Italy
O'Brien, R.	Australian Radiation Protection and Nuclear Safety Agency, Australia
Olyslaegers, G.	Studiecentrum voor Kernenergie (SCK/CEN), Belgium
Organo, C.	Radiological Protection Institute of Ireland, Republic of Ireland
Orlov, O.	Ukrainian Institute for Forestry and Agro-Forest Amelioration, Ukraine
Paganini Fioratti, M.	Agency for Environmental Protection and Technical Services, Italy
Palsson, S.E.	Icelandic Radiation Protection Institut, Iceland
Patryl, L.	Commissariat á l'Energie Atomique, France
Periañez, R.	University of Seville, Spain
Pérez-Sánchez, D.	Centro de Investigaciones Energeticas, Mediambientles y Tecnologicas, Spain
Peterson, S.R.	Lawrence Livermore National Laboratory, United States of America
Pröhl, G.	Helmholtz Zentrum München, Germany
Quintana, E.	Autoridad Regulatoria Nuclear, Argentina
Rantavaara, A.	STUK, Radiation and Nuclear Safety Authority, Finland
Raskob, W.	Institut für Kern und Energietechnik, Germany
Ravi, P.M.	Bhabha Atomic Research Centre, Kaiga Generating Station, India
Reed, E.	SENES Oak Ridge Inc., Centre for Risk Analysis, United States of America
Rigol, A.	Universitat de Barcelona, Spain

Rudya, K.	International Chernobyl Centre, Ukraine
Saito, M.	Kyoto University Safety Reassurance Academy, Japan
Sanina, K.	Institute of Experimental Meteorology, SPA “Typhoon”, Russian Federation
Sansone, U.	International Atomic Energy Agency
Santucci, P. †	Institut de Radioprotection et de Sûreté Nucléaire, France
Sanzharova, N.	Russian Institute of Agricultural Radiology and Agroecology, Russian Federation
Saxén, R.	STUK, Radiation and Nuclear Safety Authority, Finland
Sazykina, T.	Institute of Experimental Meteorology, SPA “Typhoon”, Russian Federation
Servant-Perrier, A.	Institut de Radioprotection et de Sûreté Nucléaire, France
Setlow, L.	US Environmental Protection Agency, United States of America
Shang, Z.R.	Nuclear Safety Centre of SEPA, China
Shaw, G.	University of Nottingham, United Kingdom
Shubina, O.	Russian Institute of Agricultural Radiology and Agroecology, Russian Federation
Siclet, F.	Electricité de France, France
Simon, S.	National Cancer Institute (NCI), United States of America
Sitnikov, S.	Federal Nuclear and Rad. Safety Authority of Russia, Russian Federation
Sizonenko, V.P.	Institute of General Energy, Ukraine
Skuterud, L.	Norwegian Radiation Protection Authority, Norway
Slávik, O.	VÚJE Trnava, Inc., Slovakia
Smith, K.	Enviros Consulting Limited., United Kingdom
Smith, J.T.	University of Portsmouth, United Kingdom
Steiner, M.	Bundesamt für Strahlenschutz, Germany
Strebl, F.	Austrian Research Centers GmbH – ARC, Austria
Suh, K.-S.	Korea Atomic Energy Research Institute, Republic of Korea
Suolanan, V.	Technical Research Centre of Finland, Finland
Sweeck, L.	Studiecentrum voor Kernenergie (SCK/CEN), Belgium

---

† Deceased.

Tagami, K.	National Institute of Radiological Sciences, Japan
Takeda, H.	National Institute of Radiological Sciences, Japan
Tamponnet, C.	Institut de Radioprotection et de Sûreté Nucléaire, France
Telleria, D.	International Atomic Energy Agency
Thiessen, K.M.	SENES Oak Ridge, Inc., United States of America
Thiry, Y.	Studiecentrum voor Kernenergie (SCK/CEN), Belgium
Thorne, M.	Mike Thorne and Associates Limited, United Kingdom
Tomás Zerquera, J.	Centro de Protección e Higiene de las Radiaciones, Cuba
Torri, G.	Agency for Environmental Protection and Technical Services, Italy
Treebushny, D.	Institute of Mathematical Machines and System Problems, Ukraine
Trifunovic, D.	State Office for Radiation Protection, Croatia
Tsatsi, L.	National Nuclear Regulator, South Africa
Uchida, S.	National Institute of Radiological Sciences, Japan
Vandenhove, H.	Studiecentrum voor Kernenergie (SCK/CEN), Belgium
Varga, B.	Agricultural Authority, Hungary
Velasco, H.	GEA-IMASL, Universidad Nacional de San Luis/Conicet, Argentina
Venter, A.	Enviros Consulting Limited, United Kingdom
Vichot, L.	Commissariat à l'Energie Atomique, France
Vidal, M.	Universitat de Barcelona, Spain
Vives i Batlle, J.	Westlakes Scientific Consulting Limited, United Kingdom
Vives-Lynch, S.	Westlakes Scientific Consulting Limited, United Kingdom
Vlasov, O.	Medical Radiological Research, Russian Federation
Voigt, G.	International Atomic Energy Agency
Waggitt, P.	International Atomic Energy Agency
Webbe-Wood, D.	Food Standards Agency, United Kingdom
Wierczinski, B.	Technische Universität München, Germany
Wood, M.D.	University of Liverpool, United Kingdom
Yamamoto, K.	Yfirst Inc., Japan

Yankovich, T.	Chalk River Laboratories, Atomic Energy of Canada Limited, Canada
Yu, C.	Argonne National Laboratory, United States of America
Zeevaert, T. <sup>†</sup>	Studiecentrum für Kernenergie, Belgium
Zeiller, L.	International Atomic Energy Agency
Zelmer, R.	Atomic Energy of Canada Limited, Canada
Zheleznyak, M.	Institute of Mathematical Machines and System Problems, Ukraine
Zibold, G.	Hochschule Ravensburg-Weingarten, Germany
Zlobenko, B.	Institute of Environmental Geochemistry, Ukraine
Zvonova, I.	Institute of Radiation Hygiene of the Ministry of Public Health, Russian Federation

### **EMRAS Combined Meetings**

1–5 September 2003 (78 participants, from 24 countries)  
8–11 November 2004 (84 participants, from 24 countries)  
21–25 November 2005 (106 participants, from 31 countries)  
6–10 November 2006 (101 participants, from 32 countries)  
5–9 November 2007 (99 participants, from 30 countries)

### **Interim Working Group Meetings**

#### Theme 1, Working Group 1:

Aix-en-Provence, France: 1–3 June 2004; Aix-en-Provence, France: 6–9 June 2005;  
IAEA, Vienna: 12–16 June 2006; Paris, France: 6–8 June 2007

#### Theme 1, Working Group 2:

California, USA: 19–22 April 2004; Baden-Baden, Germany: 13–17 September 2004;  
Cardiff, Wales, UK: 12/13–15 April 2005; Chatou Cedex, France: 7–9 June 2006;  
Bucharest, Romania: 30 May – 1 June 2007

#### Theme 1, Working Group 3:

Madrid, Spain: 31 May – 2 June 2004; Warsaw, Poland: 29–31 August 2005;  
Prague, Czech Republic: 6–9 June 2006;  
St. Petersburg, Russian Federation: 3–7 September 2007

#### Theme 1, Working Group 4

IAEA, Vienna: 5–7 May 2004; IAEA, Vienna: 8–10 June 2005;  
IAEA, Vienna: 14–15 June 2006

#### Theme 2, Working Group 1:

IAEA, Vienna: 8–11 November 2004; Seville, Spain: 9–12 May 2005;  
Nicosia, Cyprus: 25–28 April 2006; Catania, Italy: 7–10 May 2007

---

<sup>†</sup> Deceased.

Theme 2, Working Group 2:

IAEA, Vienna: 21–23 April 2004; IAEA, Vienna: 30 May – 1 June 2005;  
IAEA, Vienna: 19–21 June 2006; IAEA, Vienna: 18–20 April 2007;  
IAEA, Vienna: 15–19 October 2007

Theme 3, Working Group 1:

IAEA, Vienna: 1–3 June 2005; IAEA, Vienna: 12–14 June 2006;  
IAEA, Vienna: 25–27 June 2007



# IAEA

International Atomic Energy Agency

No. 22

## Where to order IAEA publications

In the following countries IAEA publications may be purchased from the sources listed below, or from major local booksellers. Payment may be made in local currency or with UNESCO coupons.

### AUSTRALIA

DA Information Services, 648 Whitehorse Road, MITCHAM 3132  
Telephone: +61 3 9210 7777 • Fax: +61 3 9210 7788  
Email: [service@dadirect.com.au](mailto:service@dadirect.com.au) • Web site: <http://www.dadirect.com.au>

### BELGIUM

Jean de Lannoy, avenue du Roi 202, B-1190 Brussels  
Telephone: +32 2 538 43 08 • Fax: +32 2 538 08 41  
Email: [jean.de.lannoy@infoboard.be](mailto:jean.de.lannoy@infoboard.be) • Web site: <http://www.jean-de-lannoy.be>

### CANADA

Bernan Associates, 4501 Forbes Blvd, Suite 200, Lanham, MD 20706-4346, USA  
Telephone: 1-800-865-3457 • Fax: 1-800-865-3450  
Email: [customercare@bernan.com](mailto:customercare@bernan.com) • Web site: <http://www.bernan.com>

Renouf Publishing Company Ltd., 1-5369 Canotek Rd., Ottawa, Ontario, K1J 9J3  
Telephone: +613 745 2665 • Fax: +613 745 7660  
Email: [order.dept@renoufbooks.com](mailto:order.dept@renoufbooks.com) • Web site: <http://www.renoufbooks.com>

### CHINA

IAEA Publications in Chinese: China Nuclear Energy Industry Corporation, Translation Section, P.O. Box 2103, Beijing

### CZECH REPUBLIC

Suweco CZ, S.R.O., Klecakova 347, 180 21 Praha 9  
Telephone: +420 26603 5364 • Fax: +420 28482 1646  
Email: [nakup@suweco.cz](mailto:nakup@suweco.cz) • Web site: <http://www.suweco.cz>

### FINLAND

Akateeminen Kirjakauppa, PO BOX 128 (Keskuskatu 1), FIN-00101 Helsinki  
Telephone: +358 9 121 41 • Fax: +358 9 121 4450  
Email: [akatilaus@akateeminen.com](mailto:akatilaus@akateeminen.com) • Web site: <http://www.akateeminen.com>

### FRANCE

Form-Edit, 5, rue Janssen, P.O. Box 25, F-75921 Paris Cedex 19  
Telephone: +33 1 42 01 49 49 • Fax: +33 1 42 01 90 90  
Email: [formedit@formedit.fr](mailto:formedit@formedit.fr) • Web site: <http://www.formedit.fr>

Lavoisier SAS, 145 rue de Provigny, 94236 Cachan Cedex  
Telephone: + 33 1 47 40 67 02 • Fax +33 1 47 40 67 02  
Email: [romuald.verrier@lavoisier.fr](mailto:romuald.verrier@lavoisier.fr) • Web site: <http://www.lavoisier.fr>

### GERMANY

UNO-Verlag, Vertriebs- und Verlags GmbH, Am Hofgarten 10, D-53113 Bonn  
Telephone: + 49 228 94 90 20 • Fax: +49 228 94 90 20 or +49 228 94 90 222  
Email: [bestellung@uno-verlag.de](mailto:bestellung@uno-verlag.de) • Web site: <http://www.uno-verlag.de>

### HUNGARY

Librotrade Ltd., Book Import, P.O. Box 126, H-1656 Budapest  
Telephone: +36 1 257 7777 • Fax: +36 1 257 7472 • Email: [books@librotrade.hu](mailto:books@librotrade.hu)

### INDIA

Allied Publishers Group, 1st Floor, Dubash House, 15, J. N. Heredia Marg, Ballard Estate, Mumbai 400 001,  
Telephone: +91 22 22617926/27 • Fax: +91 22 22617928  
Email: [alliedpl@vsnl.com](mailto:alliedpl@vsnl.com) • Web site: <http://www.alliedpublishers.com>

Bookwell, 2/72, Nirankari Colony, Delhi 110009  
Telephone: +91 11 23268786, +91 11 23257264 • Fax: +91 11 23281315  
Email: [bookwell@vsnl.net](mailto:bookwell@vsnl.net)

### ITALY

Libreria Scientifica Dott. Lucio di Biasio "AEIOU", Via Coronelli 6, I-20146 Milan  
Telephone: +39 02 48 95 45 52 or 48 95 45 62 • Fax: +39 02 48 95 45 48  
Email: [info@libreriaaeiou.eu](mailto:info@libreriaaeiou.eu) • Website: [www.libreriaaeiou.eu](http://www.libreriaaeiou.eu)

## **JAPAN**

Maruzen Company Ltd, 1-9-18, Kaigan, Minato-ku, Tokyo, 105-0022  
Telephone: +81 3 6367 6079 • Fax: +81 3 6367 6207  
Email: [journal@maruzen.co.jp](mailto:journal@maruzen.co.jp) • Web site: <http://www.maruzen.co.jp>

## **REPUBLIC OF KOREA**

KINS Inc., Information Business Dept. Samho Bldg. 2nd Floor, 275-1 Yang Jae-dong SeoCho-G, Seoul 137-130  
Telephone: +02 589 1740 • Fax: +02 589 1746 • Web site: <http://www.kins.re.kr>

## **NETHERLANDS**

De Lindeboom Internationale Publicaties B.V., M.A. de Ruyterstraat 20A, NL-7482 BZ Haaksbergen  
Telephone: +31 (0) 53 5740004 • Fax: +31 (0) 53 5729296  
Email: [books@delindeboom.com](mailto:books@delindeboom.com) • Web site: <http://www.delindeboom.com>

Martinus Nijhoff International, Koraalrood 50, P.O. Box 1853, 2700 CZ Zoetermeer  
Telephone: +31 793 684 400 • Fax: +31 793 615 698  
Email: [info@nijhoff.nl](mailto:info@nijhoff.nl) • Web site: <http://www.nijhoff.nl>

Swets and Zeitlinger b.v., P.O. Box 830, 2160 SZ Lisse  
Telephone: +31 252 435 111 • Fax: +31 252 415 888  
Email: [info@swets.nl](mailto:info@swets.nl) • Web site: <http://www.swets.nl>

## **NEW ZEALAND**

DA Information Services, 648 Whitehorse Road, MITCHAM 3132, Australia  
Telephone: +61 3 9210 7777 • Fax: +61 3 9210 7788  
Email: [service@dadirect.com.au](mailto:service@dadirect.com.au) • Web site: <http://www.dadirect.com.au>

## **SLOVENIA**

Cankarjeva Zalozba d.d., Kopitarjeva 2, SI-1512 Ljubljana  
Telephone: +386 1 432 31 44 • Fax: +386 1 230 14 35  
Email: [import.books@cankarjeva-z.si](mailto:import.books@cankarjeva-z.si) • Web site: <http://www.cankarjeva-z.si/uvoz>

## **SPAIN**

Díaz de Santos, S.A., c/ Juan Bravo, 3A, E-28006 Madrid  
Telephone: +34 91 781 94 80 • Fax: +34 91 575 55 63  
Email: [compras@diazdesantos.es](mailto:compras@diazdesantos.es), [carmela@diazdesantos.es](mailto:carmela@diazdesantos.es), [barcelona@diazdesantos.es](mailto:barcelona@diazdesantos.es), [julio@diazdesantos.es](mailto:julio@diazdesantos.es)  
Web site: <http://www.diazdesantos.es>

## **UNITED KINGDOM**

The Stationery Office Ltd, International Sales Agency, PO Box 29, Norwich, NR3 1 GN  
Telephone (orders): +44 870 600 5552 • (enquiries): +44 207 873 8372 • Fax: +44 207 873 8203  
Email (orders): [book.orders@tso.co.uk](mailto:book.orders@tso.co.uk) • (enquiries): [book.enquiries@tso.co.uk](mailto:book.enquiries@tso.co.uk) • Web site: <http://www.tso.co.uk>

### **On-line orders**

DELTA Int. Book Wholesalers Ltd., 39 Alexandra Road, Addlestone, Surrey, KT15 2PQ  
Email: [info@profbooks.com](mailto:info@profbooks.com) • Web site: <http://www.profbooks.com>

### **Books on the Environment**

Earthprint Ltd., P.O. Box 119, Stevenage SG1 4TP  
Telephone: +44 1438748111 • Fax: +44 1438748844  
Email: [orders@earthprint.com](mailto:orders@earthprint.com) • Web site: <http://www.earthprint.com>

## **UNITED NATIONS**

Dept. I004, Room DC2-0853, First Avenue at 46th Street, New York, N.Y. 10017, USA  
(UN) Telephone: +800 253-9646 or +212 963-8302 • Fax: +212 963-3489  
Email: [publications@un.org](mailto:publications@un.org) • Web site: <http://www.un.org>

## **UNITED STATES OF AMERICA**

Bernan Associates, 4501 Forbes Blvd., Suite 200, Lanham, MD 20706-4346  
Telephone: 1-800-865-3457 • Fax: 1-800-865-3450  
Email: [customercare@bernan.com](mailto:customercare@bernan.com) • Web site: <http://www.bernan.com>

Renouf Publishing Company Ltd., 812 Proctor Ave., Ogdensburg, NY, 13669  
Telephone: +888 551 7470 (toll-free) • Fax: +888 568 8546 (toll-free)  
Email: [order.dept@renoufbooks.com](mailto:order.dept@renoufbooks.com) • Web site: <http://www.renoufbooks.com>

**Orders and requests for information may also be addressed directly to:**

### **Marketing and Sales Unit, International Atomic Energy Agency**

Vienna International Centre, PO Box 100, 1400 Vienna, Austria  
Telephone: +43 1 2600 22529 (or 22530) • Fax: +43 1 2600 29302  
Email: [sales.publications@iaea.org](mailto:sales.publications@iaea.org) • Web site: <http://www.iaea.org/books>







INTERNATIONAL ATOMIC ENERGY AGENCY  
VIENNA  
ISBN 978-92-0-129810-2  
ISSN 1011-4289