IMPROVING THE ASSESSMENT OF RADIOACTIVE CONTAMINATION IN URBAN ENVIRONMENTS: "URBAN" WORKING GROUPS IN THE IAEA'S MODEL TESTING PROGRAMS

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Three recent model testing programs organized by the International Atomic Energy Agency have included Working Groups focused on assessment of radioactive contamination in urban settings: the Urban Remediation Working Group of the EMRAS program, the Urban Areas Working Group of the EMRAS II program, and the Urban Environments Working Group of the MODARIA program. Major assessment capabilities addressed by the groups include dispersion and deposition events, short- and long-term contaminant redistribution following deposition events, and use of various countermeasures or remediation efforts to reduce contamination levels or human exposures and doses. Reviews and exercises have addressed key approaches to modeling contaminant transport to and within urban environments and to modeling the effectiveness of remedial actions in terms of the dose reductions expected for members of the public in a given location. The Working Groups have identified important general considerations in modeling urban contamination situations, such as the importance of assessing the contributions to dose rate from each surface and radionuclide. General approaches to modeling remedial actions and protective actions are applicable to a variety of situations.

I. INTRODUCTION

Three recent model testing programs organized by the International Atomic Energy Agency (IAEA) have included Working Groups focused on assessment of radioactive contamination in urban settings. These include the Urban Remediation Working Group of the EMRAS program (Environmental Modelling for Radiation Safety, 2003-2007), the Urban Areas Working Group of the EMRAS II program (2009-2011), and the Urban Environments Working Group of the MODARIA program (Modelling and Data for Radiological Impact Assessments, 2012-2015). The objective of these Working Groups has been to test and improve the capabilities of models used in the assessment of radioactive contamination in urban environments. The major assessment capabilities that have been addressed include dispersion and deposition events, short- and long-term contaminant redistribution following deposition events, and use of various countermeasures or remediation efforts to reduce contamination levels or human exposures and doses.

EMRAS, EMRAS II, and MODARIA continued a series of model testing programs sponsored by the IAEA and other organizations starting in the 1980s.[1] Several of the early modeling exercises were based on data sets obtained following the Chernobyl accident in April 1986. Over the years, these programs have addressed many areas of environmental modeling, including terrestrial and aquatic food chain transfer (natural and agricultural), biosphere modeling for waste disposal, dose reconstruction, protection of biota, and various process-level situations. The general approach has been to compare model predictions (e.g., of radionuclide concentrations in various media at specified times and locations) with available measurements and to discuss agreement and discrepancies among model predictions and between model predictions and measurements. Data bases of parameter values have been developed and improved, and needs for further research and data collection have been identified. The "Urban" Working Groups of EMRAS, EMRAS II, and MODARIA have focused on modeling of urban settings, with external radiation doses characterized in terms of contributions from various surfaces (e.g., paved roads and parking lots, building walls and roofs, and grass or soil) for a given geometry. This paper describes the major efforts and findings of the three "Urban" Working Groups and discusses their overall significance.

II. THE "URBAN" WORKING GROUPS

One of the early model testing programs, the IAEA's Validation of Environmental Model Predictions (VAMP) program, included an "Urban" Working Group. The VAMP Urban Working Group produced a brief review of available information on dry and wet deposition of radionuclides in urban environments and carried out two short exercises based on Chernobyl data.[2] Major efforts in the area of urban modeling resumed in the EMRAS program in 2003. These efforts are briefly summarized here by program; individual exercises are described in Section III.

II.A. EMRAS, Urban Remediation Working Group

The Urban Remediation Working Group of EMRAS focused on two main areas:[3,4] (1) a literature review of existing models and modeling approaches for assessing radiation exposure in contaminated urban settings, including a compilation of sources of information on countermeasures and considerations for selection of parameter values for specific situations;[5] and (2) two modeling exercises, with and without inclusion of remedial actions. One modeling exercise was based on measurements made in Pripyat, a town in Ukraine near the Chernobyl Nuclear Power Plant, including effects of various countermeasures carried out in the town.[6] The second modeling exercise was based on a hypothetical situation involving a short-term, single release to the atmosphere.[7]

II.B. EMRAS II, Urban Areas Working Group

The Urban Areas Working Group of EMRAS II developed and carried out three modeling exercises.[8,9] All exercises were designed to permit intercomparison of model predictions among participants. For one exercise, it was also possible to compare model predictions with measurements for some endpoints. This exercise was a short-range atmospheric dispersion exercise, based on data from several field tests performed in the Czech Republic. A short-lived radionuclide (Tc-99m) in liquid form was spread during a short-term atmospheric release in an open field, with or without some obstacles in the expected downwind direction. Model predictions were compared with measurements of surface contamination up to 50 m downwind. The second exercise was a mid-range atmospheric dispersion exercise based on a hypothetical accident at a nuclear power plant and the resulting predicted deposition in downwind urban areas.[10] The third exercise started with an assumed radionuclide concentration in air from an undefined hypothetical dispersion event. This exercise focused primarily on the effects of initial weather conditions (dry, light rain, or heavy rain at the time of deposition), contaminant redistribution over time, and effects of a variety of countermeasures.[11]

II.C. MODARIA, Urban Environments Working Group

The Urban Environments Working Group of MODARIA continued the short-range atmospheric dispersion exercise begun in EMRAS II, developed and carried out a new mid-range atmospheric dispersion exercise utilizing measurements of a tracer released from a thermal power plant, and developed a remediation and countermeasures exercise based on data collected after the Fukushima accident in 2011.[12] In addition, the Working Group reviewed a number of atmospheric dispersion models currently available for use with short-term or accidental releases. Several of these efforts are likely to be continued during the upcoming MODARIA II program.

III. RESULTS FROM THE "URBAN" WORKING GROUPS

The activities of the "Urban" Working Groups have included four modeling exercises for which at least some measurement data have been available (Section III.A.) and three modeling exercises based on hypothetical situations (Section III.B.). In addition, two major reviews have been conducted (Section III.C.).

III.A. Modeling Exercises with Data

III.A.1. Pripyat Scenario (EMRAS)

This modeling exercise was based on Chernobyl fallout data in the town of Pripyat, Ukraine, near the Chernobyl Nuclear Power Plant.[4,6] Pripyat was evacuated after the accident and remained largely uninhabited, although extensive remediation efforts were conducted in one area of the town where workers were to be housed temporarily. Modeling endpoints for the exercise included radionuclide concentrations and external dose rates at specified locations, contributions to the dose rates from individual surfaces and radionuclides, and annual and cumulative external doses to specified reference individuals. Model predictions were performed for a "no action" situation (no remedial measures) and for selected countermeasures (cutting and removal of grass, removal of trees and leaves, removal of soil, washing of roads, washing of roofs and exterior walls, indoor cleaning). Model predictions for several outdoor locations were compared with measured dose rates; because the town was uninhabited, measured dose rates probably included the effects of accumulated debris. Nevertheless, the exercise provided an opportunity to compare model predictions and parameterization among several participants, and to compare the predicted effectiveness of various countermeasures in terms of expected short-term and long-term reduction of predicted doses to people (Fig. 1).

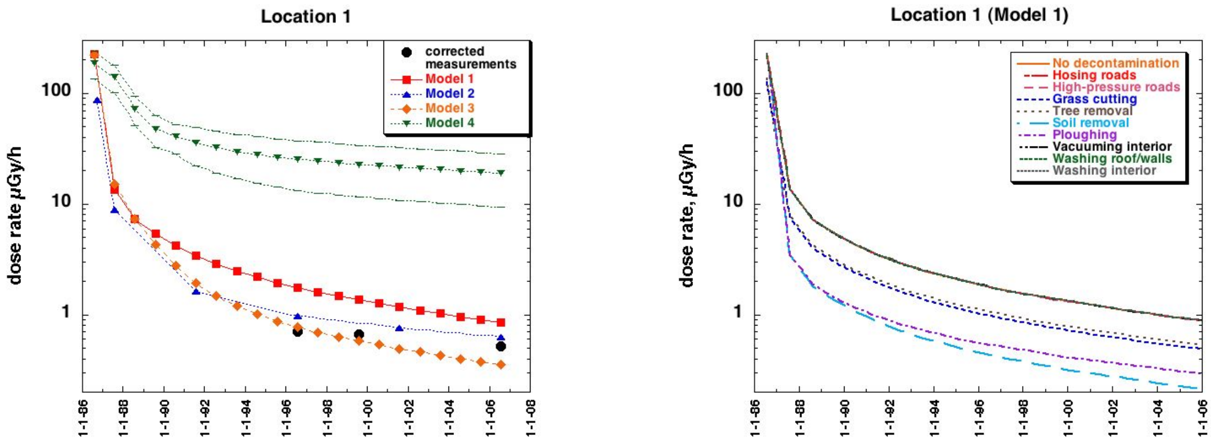

Fig. 1. Predicted and measured dose rates for an outdoor location in Pripyat in the absence of countermeasures (left). Predicted effects of countermeasures on dose rates over time at the same location (right).

III.A.2. Short-range Atmospheric Dispersion Exercise, Field Tests (EMRAS II and MODARIA)

The short-range atmospheric dispersion scenario was based on experimental data obtained from a series of field tests performed by the Czech National Radiation Protection Institute (SÚRO), involving the dispersal of a short-lived radionuclide (Tc-99m) during short-term, single release events.[9,12,13] The scenario was intended to provide an opportunity to test model predictions of atmospheric dispersion and deposition for a short-range dispersion event. The scenario included six field tests; Tests 3 and 4 were used for blind model testing during the EMRAS II Program,[9] and Tests 5 and 6 were used for blind model testing during the MODARIA Program.[12] Input information for each event included the amount of radioactivity involved, the arrangement of the various detectors in the vicinity of the release point, meteorological information, and particle size information. Available measurements included dose rates, surface contamination, air concentrations, particle size distribution, time-distribution of dust particles in air, and thermo-camera snapshots. The primary endpoint modeled and analyzed during the exercises was the surface contamination (Bq m^{-2}) as a function of distance. The scenario was also used by one participant for estimation of a source term from measurements.

Fig. 2 shows the predicted deposition from three models in comparison to the measurements for Test 5. Predicted amounts of deposition within the measurement grid area for Test 5 ranged from 67 to 330 MBq, compared with the measured total of 202 MBq. Although the test area was selected for a stable wind direction under usual meteorological conditions, the plot of the measurements indicated that the plume was not stable in direction during the deposition event, and the models did not fully reproduce this effect. Possible explanations for differences among model predictions include differences in selection of parameter values (e.g., deposition velocity, atmospheric stability class), and differences in handling of the meteorological data (e.g., use of average vs. time-dependent wind speeds and directions).

III.A.3. Mid-range Atmospheric Dispersion Exercise, Tracer Releases from a Power Plant (MODARIA)

This modeling exercise was based on an extensive set of measurements from the Šoštanj thermal power plant in Slovenia (Fig. 3, left).[12] The data set includes meteorological data, measurements of tracer emissions from point sources (three stacks), measurements of airborne tracer at a set of regional monitoring stations, and descriptions of the complex terrain in the region. The exercise involved comparison of predicted airborne concentrations of the tracer at the monitoring locations with the measurements at those locations (Fig. 3, right). The first situation was relatively simple, with only one operating emissions point and a strong wind blowing directly toward a monitoring location. The second situation was more complex, involving two emissions sources, a night temperature inversion, convective mixing on the following day, and the spreading and accumulation of air pollution in all directions. This exercise has led to important recommendations for modeling situations with complex meteorology and complex terrain.

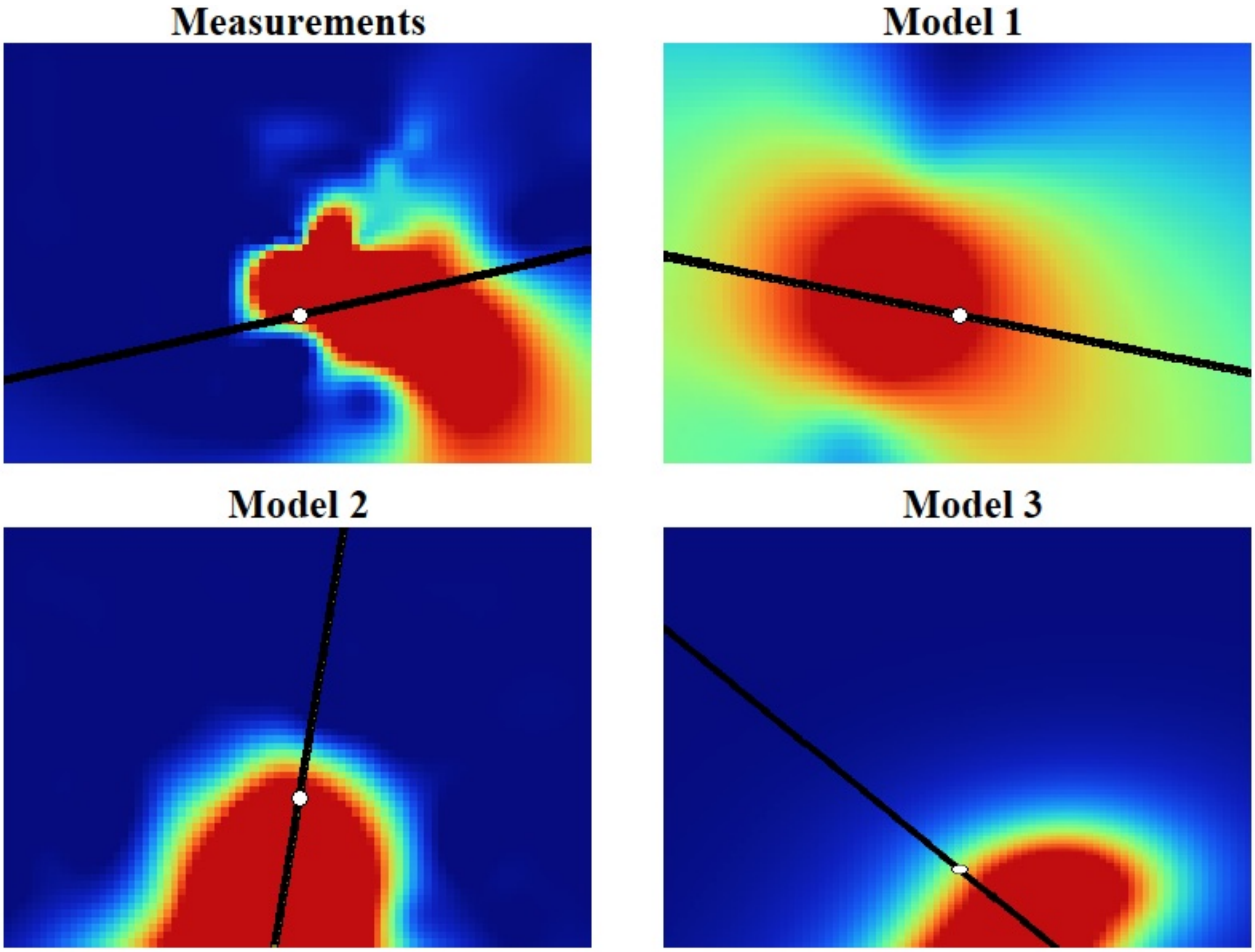

Fig. 2. Cloud axis profiles of the predicted deposition from three models in comparison with the measurements for Test 5. The white dot indicates the dispersion point.

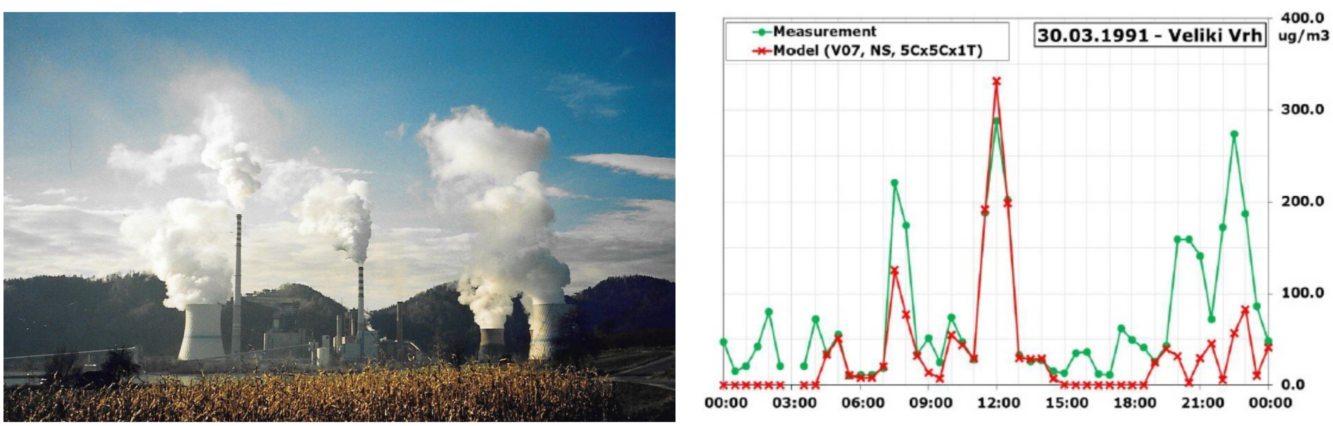

Fig. 3. View of Šoštanj thermal power plant in 1995 (left); comparison of measurements and model predictions for Veliki Vrh monitoring station during 30 March 1991 (right).

III.A.4. Fukushima Scenario (MODARIA)

This modeling exercise is based on measurements made in Japan following the accident at the Fukushima Daiichi Nuclear Power Plant in 2011 and on experiments carried out by Japan Atomic Energy Agency (JAEA).[12] The goal of the modeling exercise is to predict the doses that could be received by reference individuals in the absence of any remediation actions and with specified remediation actions. The exercise starts with a generalized situation approximately three years after the accident; thus the contribution to dose of short-lived radionuclides is not part of the exercise. Earlier remediation efforts are included as part of the history of the situation, but the exercise does not specifically deal with "early" remediation efforts. Input information for the scenario includes information about the radionuclide composition and deposition densities, external dose rates, conditions of the initial deposition event, average meteorological conditions for the area, locations for modeling endpoints, and types of remediation efforts performed or being considered for use. Modeling endpoints for intercomparison among modelers include the deposition at specified outdoor locations, external dose rates at specified locations and times, contributions to external dose rate from relevant surfaces, external and internal doses to specified reference persons, effectiveness of various remediation efforts in reducing dose rates and doses, and estimates of the waste (volume and activity) generated by the remediation efforts. Fig. 4 illustrates some initial modeling results. This exercise was started late in the MODARIA program and will be continued during MODARIA II.

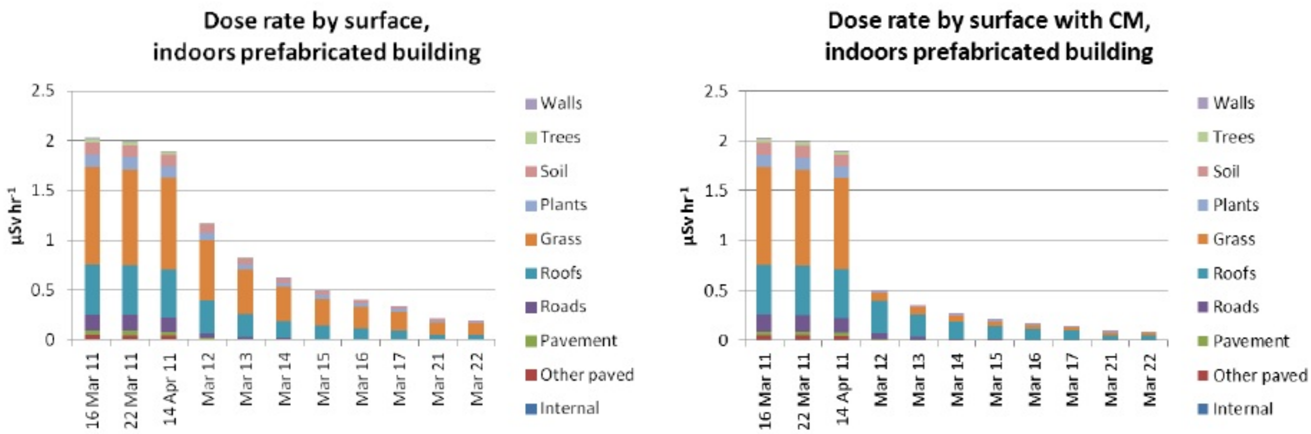

Fig. 4. Example of predicted indoor dose rate without countermeasures (left) and after removal of grass (right). Contributions of various surfaces are indicated.

III.B. Modeling Exercises Based on Hypothetical Situations

III.B.1. Short-range Atmospheric Dispersion and Countermeasures Exercise, Hypothetical Release Event (EMRAS)

This modeling exercise was based on a hypothetical dispersal of radioactivity in an urban area from a short-term, single release to the atmosphere.[4,7] Reference surface contamination at selected sites was used as the input information for the modelers. Modeling endpoints for the exercise included radionuclide concentrations and external dose rates at specified locations, contributions to the dose rates from individual surfaces, and annual and cumulative external doses to specified reference individuals. Model predictions were requested for a "no action" situation (no remedial measures) and for selected countermeasures (cutting and removal of grass, removal of trees and leaves, removal of soil, washing of roads, washing of roofs and exterior walls, indoor cleaning). The predicted effectiveness of various countermeasures was compared with respect to short-term and long-term effects on predicted doses to the reference individuals (Fig. 5).

III.B.2. Mid-range Atmospheric Dispersion Exercise, Hypothetical NPP Accident (EMRAS II)

This modeling exercise was based on a hypothetical accident in a nuclear power plant in central Spain, releasing Cs-137 and I-131 during a one-hour period.[9,10] Participants in the exercise were supplied with meteorological conditions and radionuclide release rates and asked to predict time-integrated concentrations of radionuclides in air at specific locations and the arrival times of the plumes at those locations. Modelers were also asked to provide maps of the predicted deposition. Different plume behavior was observed for different atmospheric conditions (neutral stability vs. stable conditions; Fig. 6). The predicted arrival times of the plume were less variable among participants than the predicted deposition and air concentrations.

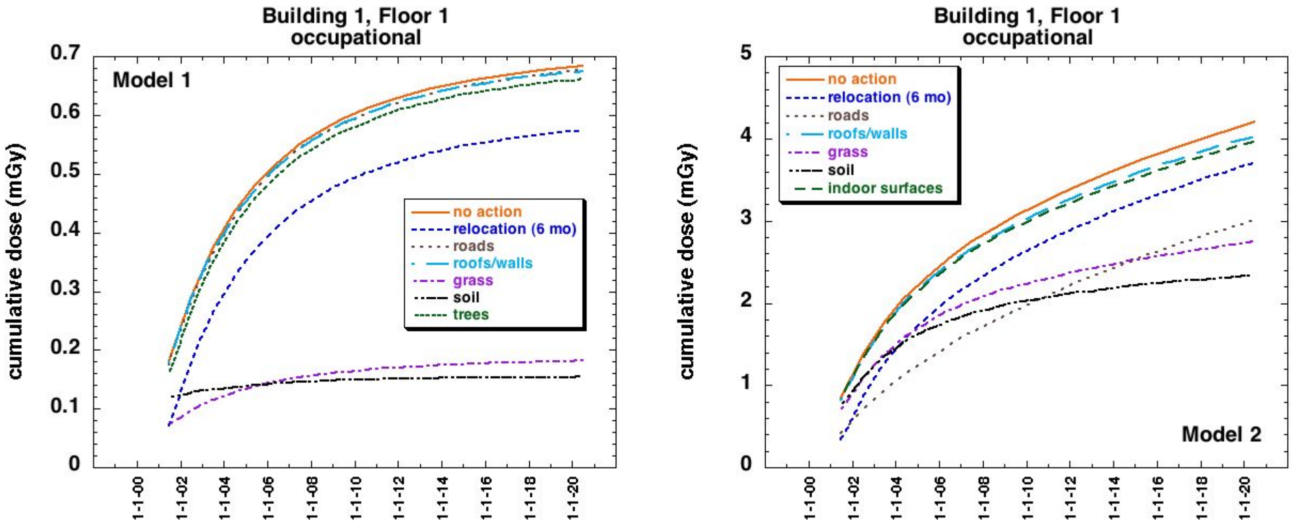

Fig. 5. Predicted cumulative doses (mGy) from two models, showing the predicted effects of several different countermeasures. Results are shown for occupational exposure on the ground floor of an office building.

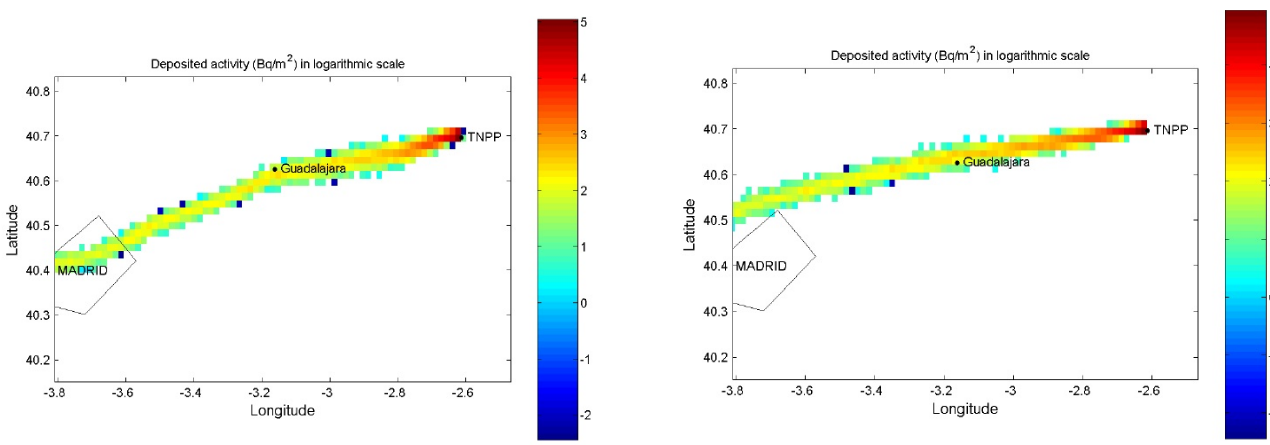

Fig. 6. Contour maps showing model predictions for Cs-137 deposition assuming stable (left) or neutral (right) conditions.

III.B.3. Contaminant Transport and Countermeasures Exercise (EMRAS II)

This modeling exercise was based on a hypothetical situation starting with a unit concentration of Co-60 or Pu-239 in air in an urban area from an undefined release event.[9,11] Two types of urban areas were considered, a business area with buildings and pavement, and a park area near apartment buildings. The exercise considered the importance of initial weather conditions (dry, light rain, or heavy rain at the time of deposition). Modeling endpoints included contamination densities, dose rates from individual surfaces and all surfaces combined, annual and cumulative doses (internal for Pu-239 and external for Co-60) for specified reference individuals, and the effectiveness of countermeasures and remediation efforts in terms of dose rate reduction and dose reduction. Model results depended in part on the surfaces included within each model, with respect both to the contributions to dose rate from various surfaces and to the effects of individual countermeasures (Fig. 7).

III.C. Model Reviews

III.C.1. Review of Urban Models and Countermeasure Information (EMRAS)

Computer models are often used to assess urban contamination situations (real or hypothetical) and potential remedial options. Among other things, the models are useful in planning and preparedness efforts (e.g., evaluation of "what if?" situations; comparison of various remediation strategies with respect to decision-making). The EMRAS Urban Working Group summarized the available modeling approaches, approaches for modeling countermeasure effectiveness, and sources of information on parameters related to countermeasure effectiveness.[4,5] Much of the available information comes from the Chernobyl accident and might not be generally applicable for other situations.

III.C.2. Review of Atmospheric Dispersion Models (MODARIA)

The goal of this activity was to provide a review and comparison of models (computer codes) for predicting transport of radioactive contaminants to urban environments, especially atmospheric dispersion, deposition and environmental transport for situations such as an accident at a nuclear power plant. Although the review is not exhaustive, it includes key models in use today in various countries (including several used in the MODARIA program) and some historic models still named in national regulations. The review summarizes the models' capabilities and requirements (computational and in terms of necessary input data), intended uses and other important features. The intent was not to provide an evaluation of which model is "best", but to provide information that can help someone become familiar with key model features and assist in selection of the most appropriate model for a given situation. The review was assembled in an Excel® workbook format with a separate page (worksheet) for each model and a table comparing major features or attributes of all the included models. The latest version of the workbook (2016) contains information on 26 models.[12]

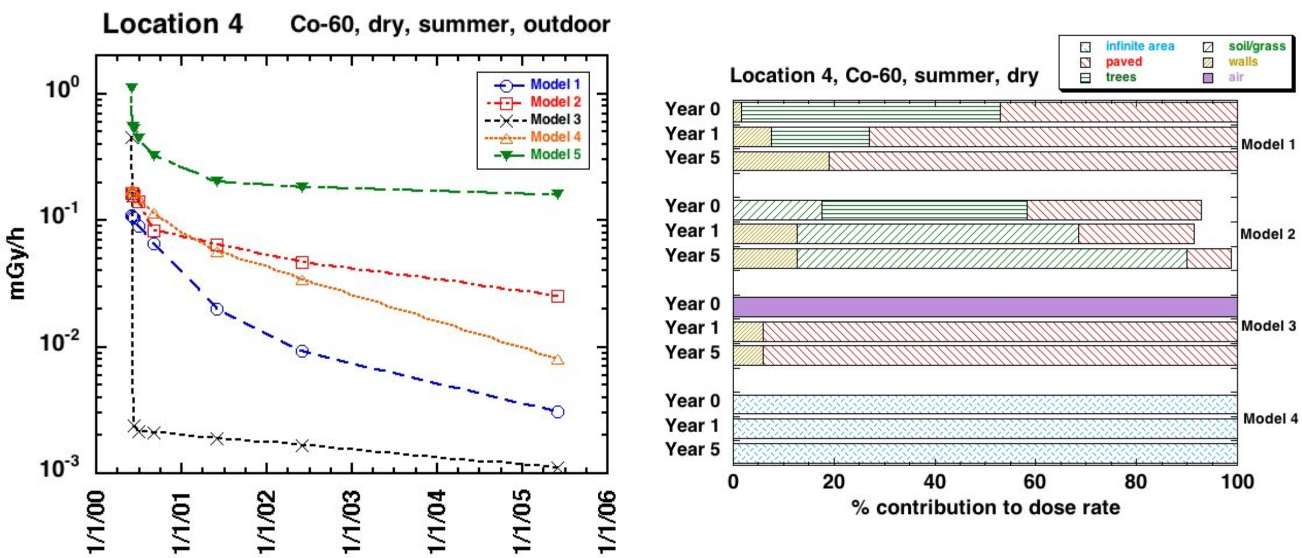

Fig. 7. Predicted external dose rate (mGy/h) from Co-60 (left) and most important surfaces contributing to dose rate (right) at an outdoor location in a business area. Predictions are shown for initial conditions of dry weather in summer.

IV. CONCLUSIONS

The modeling exercises carried out by the "Urban" Working Groups in recent IAEA model testing programs have provided participants with opportunities to compare model predictions among participants, and in some cases with measurements, for several types of assessment situations. Participants in each exercise received the same starting information, but often produced different results. This reflects differences in model capabilities, interpretation of input information, choice of assumptions and parameter values, and interests of assessors. Comparing and discussing predictions from several models provides an opportunity to better understand the model results and to reduce errors in the modeling.

In the atmospheric dispersion exercises, models have varied in their computational type (e.g., Gaussian vs. Lagrangian), handling of source terms and meteorological information (e.g., time-dependent vs. average data), and in the selection of parameter values (e.g., for deposition velocity or atmospheric stability class). In exercises involving contaminant deposition and potential countermeasures, the predicted effectiveness of remediation of a given surface, in terms of external dose reduction, depends on the expected contribution of that surface to external dose rate and dose.

Several of the models used in these exercises are intended to support real-time decision making in the event of an accidental release or other emergency situation. Other models are intended to facilitate comparison of various remediation strategies in the aftermath of an actual contamination event. In general, all of these models are potentially useful in planning and preparedness efforts, for evaluating various "what if?" situations. Because of the importance of these models in efforts to protect human health, it is important to continue to improve modeling capabilities for urban contamination situations, including situations not addressed in the exercises thus far. Building on the efforts of the Urban Working Groups in the EMRAS, EMRAS II, and MODARIA programs, a new "Urban" Working Group in the upcoming MODARIA II program will seek to provide additional opportunities for improvement of assessment capabilities for urban modeling.

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