# Modeling the Effectiveness of Remediation Efforts in Contaminated Urban Areas: An EMRAS II Urban Areas Working Group Exercise – 15631

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## ABSTRACT

The Urban Areas Working Group was part of the IAEA's EMRAS II (Environmental Modelling for Radiation Safety) Programme during 2009-2011. The Working Group's goal was to test and improve the capabilities of models used in assessment of radioactive contamination in urban settings. The "contaminant transport and countermeasures" exercise was focused on modeling the effectiveness of potential countermeasures or remediation efforts with respect to reduction of human exposures and doses. The exercise was based on a hypothetical situation involving an initial concentration of Co-60 or Pu-239 in air in a specified urban area. Participants were given detailed input information, including descriptions of test locations in two types of urban areas, (1) a business area with buildings and asphalt, and (2) a park area near an apartment town. Several kinds of initial weather conditions (dry, light rain, and heavy rain) were explored. Modeling endpoints included contamination densities, dose rates (from each contributing surface and total), annual and cumulative doses (internal and external) for specified reference individuals, and effectiveness of countermeasures and remediation efforts in terms of dose rate reduction and dose reduction. External doses were emphasized for Co-60 and internal doses for Pu-239. Approaches and model predictions from five models are compared, and explanations for similarities and differences among model predictions are offered. Understanding the effects of different approaches, assumptions, and parameter values is essential to a comparison of results from different models and to understanding both the usefulness and the limitations of any given model.

## INTRODUCTION

The IAEA's EMRAS II (Environmental Modelling for Radiation Safety) Programme, which ran from 2009 to 2011, is one of a series of international model testing and validation programs dating back to the 1980s [1]. The preceding EMRAS program (2003-2007), EMRAS II, and the current MODARIA (Modelling and Data for Radiological Impact Assessments) program have each included a working group focused on modeling radioactive contamination in urban areas, including contamination events, environmental transport of contamination to and within an urban area, and remediation of contamination [1-7]. The Urban Areas Working Group of EMRAS II carried out three modeling exercises, including the "contaminant transport and countermeasures" exercise described here. Each exercise was designed to permit intercomparison of model predictions for a variety of calculation endpoints. Reasons for similarities and discrepancies among model predictions are discussed in terms of the modeling approaches, models, and parameter values used by different assessors. An important objective of each exercise is the identification of areas in which models or selection of parameter values could be improved.

## DESCRIPTION

The contaminant transport and countermeasures exercise provided an opportunity to test model predictions for environmental transport of contaminants and the effects of various countermeasures or remedial measures following a release of radioactivity in an urban area. The scenario was based on a hypothetical deposition of radioactivity in a city from a defined activity concentration in air and made use of detailed geographical information for an actual urban area, part of Seoul, Republic of Korea. Input information for the scenario included information about the radionuclides, the conditions of the initial deposition, meteorological information, locations for modeling endpoints, and descriptions of the countermeasures to be modeled. Modeling endpoints for intercomparison among modelers included the contamination density at specified outdoor locations, external dose rates at specified indoor and outdoor locations at specified times, contributions to external dose rate from relevant surfaces, external and internal doses to specified reference persons, and countermeasure effectiveness. A full description of the scenario, the models, and the results of the test exercise are included in the final report of the Urban Areas Working Group [8].

The exercise started with a defined activity concentration in air at ground level in specified areas. Two radionuclides, Co-60 and Pu-239, were considered separately. Modelers were asked to estimate the partitioning of each radionuclide on various urban surfaces (deposition). The impact of different seasons and weather conditions (summer or winter; dry, light rain, or heavy rain) at the time of the initial deposition was considered; average weather conditions for the region were used for the longer-term estimation of contaminant transport. Two areas of the city were selected for the modeling exercise: a business area (Region 1), and a park area near an apartment town (Region 2). Several locations within each region (indoors and outdoors for Region 1, outdoors for Region 2) were selected as test locations for which model calculations were to be made. Test locations for Region 1 included indoor locations in a tall building and an outdoor location, just outside the same building. Test locations for Region 2 included the center of the park and a location in the parking lot at the edge of the park.

For each combination of season and weather conditions, modelers were asked to assume an initial time-integrated radionuclide concentration in air at ground level of 1 MBq $m^{-3}$ d. For each test location, modelers were asked to calculate the dose rates and radionuclide concentrations first without any countermeasure (no action) and then with each of several specified countermeasures, along with the contributions to external dose rate from the most important surfaces. Participants were also asked to predict annual and cumulative doses (up to 5 years) for each of two reference exposure situations, first without countermeasures and then with each specified countermeasure. For Co-60, external doses and dose rates were requested and internal doses were optional; for Pu-239, internal doses were requested and external doses and dose rates were optional.

Two exposure situations were defined for dose calculations. For Region 1 (the business area), an adult was assumed to spend 40 hours per week indoors at work and 5 hours per week outside in the region. For Region 2 (the park area), an older man was assumed to spend 3 hours per week exercising in the park. For each set of initial conditions, predictions were requested for the initial deposition event and for designated times up to 5 years after the deposition event. Countermeasures to be considered included temporary relocation of the population for 6 weeks, removal of trees or leaves (at day 30), vacuuming or sweeping of the roads (at day 14, assuming no rain), washing or hosing of the roads (at day 14, assuming no rain), washing of roofs and exterior walls (at day 14, assuming no rain), and cutting of grass (at day 7) and removal of soil (5 cm, at day 180) in the park area. Two combinations of countermeasures were also included: a combination of tree removal plus road cleaning, and a combination of relocation plus road cleaning.

Five Working Group participants contributed model predictions for the exercise. Four sets of predictions were presented and discussed during the course of the EMRAS II program, and one additional set of predictions was submitted later. Selected information about the models and their use in this exercise is summarized in Table I; full documentation is included in the Working Group report [8]. Three models (METRO-K, CPHR and CHERURB) started with the air concentration as provided in the scenario description; ERMIN and RESRAD-RDD used the deposition calculated by METRO-K. Participants were not required to provide predictions for every endpoint. In particular, two participants (METRO-K and ERMIN) provided predictions for both winter and summer starting conditions, while the other three participants provided predictions only for summer starting conditions. Most participants focused on external doses for Co-60 and internal doses for Pu-239. For internal doses from Pu-239, two participants (CPHR and CHERURB) included only inhalation of the initial plume (no contribution from resuspension), and three (METRO-K, ERMIN, and RESRAD-RDD) included only resuspension (no contribution from the initial plume). Four participants predicted which surfaces contributed most to external dose rates.

## DISCUSSION

Examples of key results from the modeling exercise are discussed below. The emphasis is on the predictions of external dose rates and external doses from Co-60, but internal doses from Pu-239 are also discussed.

### Contamination Densities of Co-60 and Pu-239

Predicted contamination densities of Co-60 under different initial weather conditions are shown (Fig. 1) for Location 4 (outdoors in a paved area next to buildings; Region 1) and Location 5 (on a dirt pathway in an unpaved park area; Region 2). Predicted initial contamination densities for four models are very similar, but the predicted rate of decrease of contamination density varies among models, with METRO-K, ERMIN, and RESRAD-RDD generally having similar shapes.

TABLE I. Comparison of models and parameters used by exercise participants

| **Model (Participant)** | **Deposition** | **Weathering** | **Indoor contamination** | **Trees** |
|---|---|---|---|---|
| METRO-K (Hwang) | Dry deposition by surface; wet deposition from daily rainfall and washout ratio, with retained fraction | Short-term and long-term removal rates by surface | Not included | Deciduous in Region 1, equal proportions of deciduous and coniferous in Region 2; date for leaf fall not specified |
| ERMIN (Charnock) | Deposition on lawn from METRO-K; other surfaces relative to lawn, wet or dry | Surface-specific empirical weathering functions; movement down soil column | Included, from penetration of building; simple empirical retention function for generic indoor surfaces | Deciduous and coniferous; specified date for leaf fall |
| CPHR (Tomás) | Dry deposition velocity; washout coefficient for wet deposition | Half-lives depending on surface | Indoor air but not surfaces; filtration factor | Deciduous, no contamination after first leaf fall |
| RESRAD-RDD (Kamboj, Yu) | Deposition on lawn from METRO-K; other surfaces relative to lawn, wet or dry | Short-term and long-term weathering half-lives; mobile and fixed fractions | Included; indoor floors and walls considered separately; partitioning factors to account for direct and indirect penetration | Not included |
| CHERURB (Chouhan) | Dry deposition velocity by surface; washout ratio with retained fraction for wet deposition | Short-term and long-term removal rates (all surfaces) | Calculated from outdoor air concentration, ventilation rate, filtering fraction, volume of the room, deposition within the room | Deciduous with leaf fall |

The predicted rate of decrease is less for the park area (Location 5) than for the paved area (Location 4), probably reflecting higher loss rates from the paved surfaces (or greater retention in the unpaved area). There was essentially no difference between predicted contamination density for deposition during the summer or during the winter (not shown). A second outdoor location in the paved parking area next to the park (Region 2) gave similar results as Location 4 (not shown).

METRO-K, ERMIN, and RESRAD-RDD all predicted higher contamination densities for Location 5 (the park area) than for Location 4 (in a paved area). The difference in the initial contamination densities between Location 5 and Locations 4 and 6, under dry conditions, was

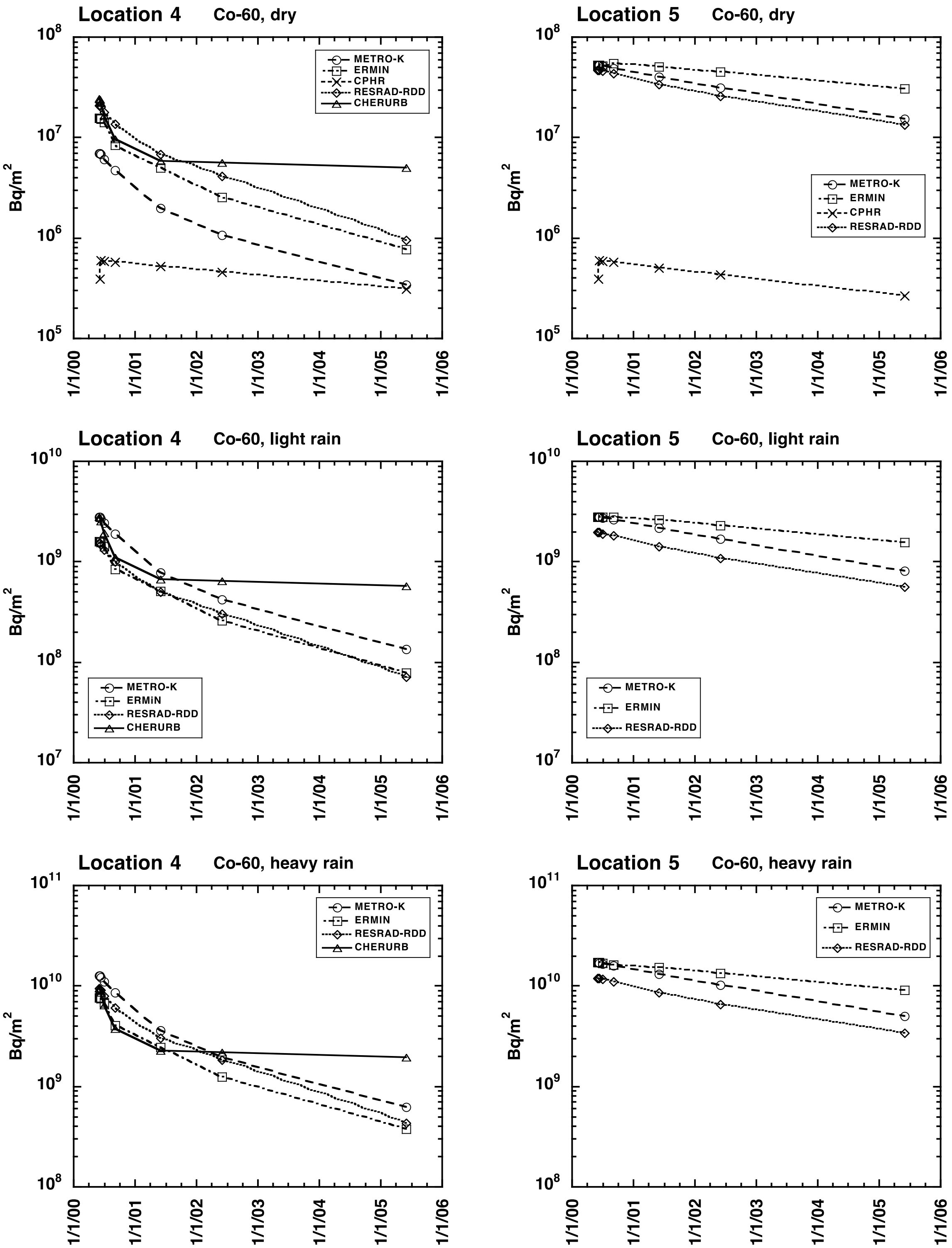

Fig. 1. Predicted contamination density (Bq $m^{-2}$) of Co-60 at Location 4 (left; outdoors in a business area) and Location 5 (right; outdoors in a park area). Predictions are shown for initial conditions in summer of dry weather (top), light rain (center), and heavy rain (bottom).

about a factor of 8 for METRO-K and somewhat less for ERMIN and RESRAD-RDD. This difference decreased for wet conditions, with similar initial depositions at all three locations for a given model.

For a given model, the predicted initial contamination densities for Co-60 (Fig. 1) and Pu-239 (Fig. 2) were not greatly different. However, the predicted values over time varied between Co-60 and Pu-239, with Pu-239 generally having a slightly lower loss rate (shallower slope) than Co-60, especially for Location 5 (the park area). Loss rates were similar for METRO-K, ERMIN, and RESRAD-RDD (Figs. 1-2), especially for wet initial conditions. CHERURB showed a slower long-term loss rate on paved surfaces (Location 4), while ERMIN and CPHR showed the slowest loss rates for the park area (Location 5).

For dry conditions, predicted initial contamination density from four of the models (METRO-K, ERMIN, RESRAD-RDD, and CHERURB) was around $10^7$ Bq $m^{-2}$ (with a range of $7 \times 10^6$ to $3 \times 10^7$) for either radionuclide at Location 4 and about $5 \times 10^7$ Bq $m^{-2}$ at Location 5 (Figs. 1-2). For light rain and heavy rain, the differences were very small. Predicted initial contamination densities at all locations were about 2-3 $\times 10^9$ Bq $m^{-2}$ for light rain and about $10^{10}$ Bq $m^{-2}$ for heavy rain. These predictions clearly show the importance of initial weather conditions in determining the initial deposition of a contaminant.

## External Dose Rates for Co-60

Predicted external dose rates from Co-60 for dry initial conditions in summer are shown by model for an indoor location (ground floor of a large building) and the two outdoor locations (Fig. 3, left). The predictions for external dose rates at the outdoor locations reflect the results for contamination densities at those locations. For wet deposition (light rain or heavy rain conditions), initial values from METRO-K, ERMIN, and RESRAD-RDD were similar for both outdoor locations (around 10-30 mGy $h^{-1}$ for light rain and 100 mGy $h^{-1}$ for heavy rain; not shown), but as with contamination densities, loss rates for the paved location were greater (steeper slopes) than for the dirt location. The difference between the paved and dirt locations was greater for dry conditions (initial values around 0.1-0.2 mGy $h^{-1}$ for Location 4 and 0.4-0.5 mGy $h^{-1}$ for Location 5). For METRO-K and ERMIN, differences between a summer release and a winter release were small.

Both CHERURB (especially for dry conditions) and CPHR showed an initial steep slope followed by a much slower loss rate (small slope) at later times. For dry conditions at Locations 4 and 5, CPHR predictions for the initial time period were within the range of the predictions from the other four models; however, after the initial time period, CPHR predictions were substantially below those of the other models. CHERUB predictions were generally above those of the other models for Location 4 for later time periods.

Predicted external dose rates at indoor locations were typically at least an order of magnitude lower than the external dose rates predicted for outdoor locations. In general, most models showed highest values for the top (24th) floor of a tall building, then for the ground floor, and then for an intermediate (10th) floor (not shown). For heavy rain, METRO-K gave much higher

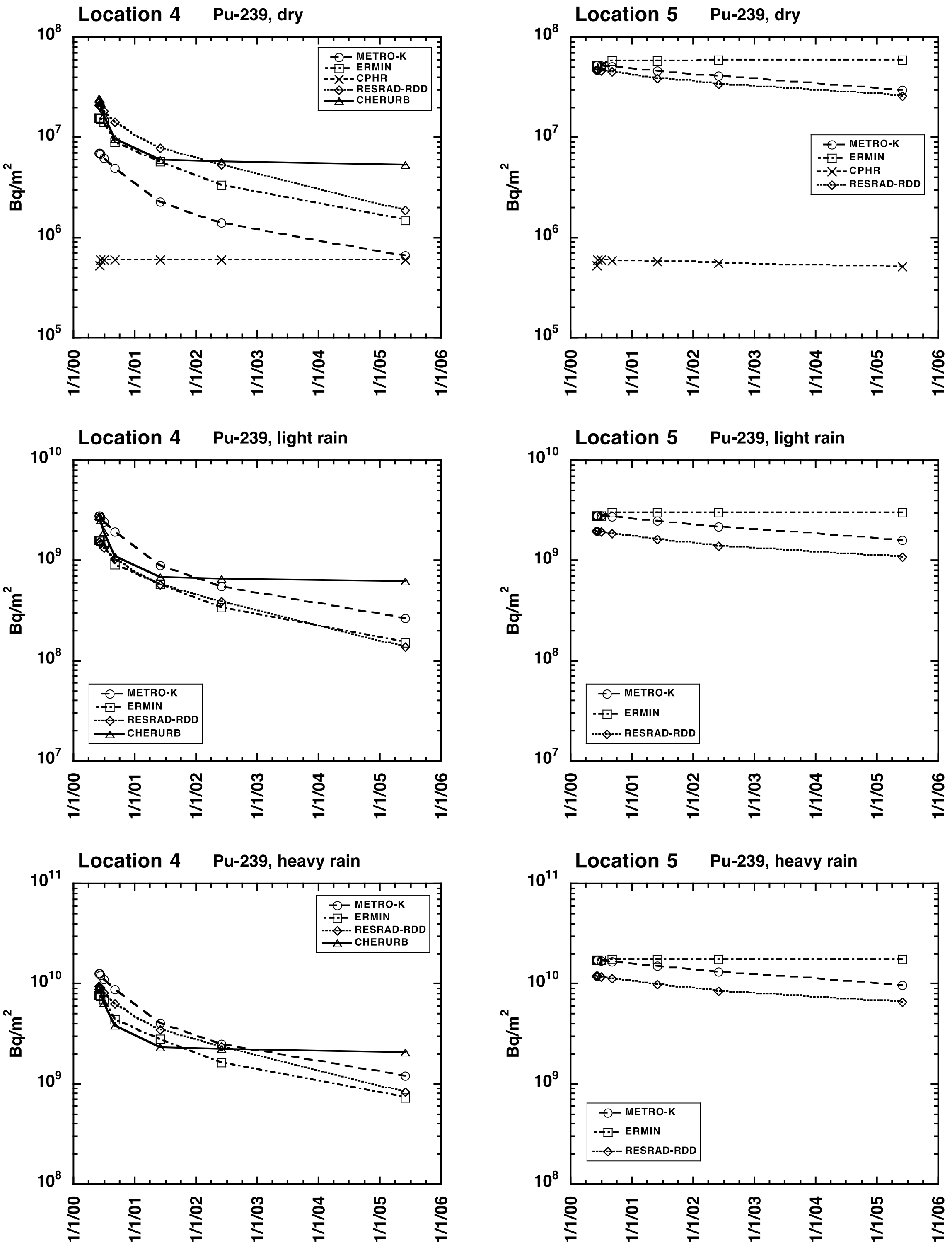

Fig. 2. Predicted contamination density (Bq m$^{-2}$) of Pu-239 at Location 4 (left; outdoors in a business area) and Location 5 (right; outdoors in a park area). Predictions are shown for initial conditions in summer of dry weather (top), light rain (center), and heavy rain (bottom).

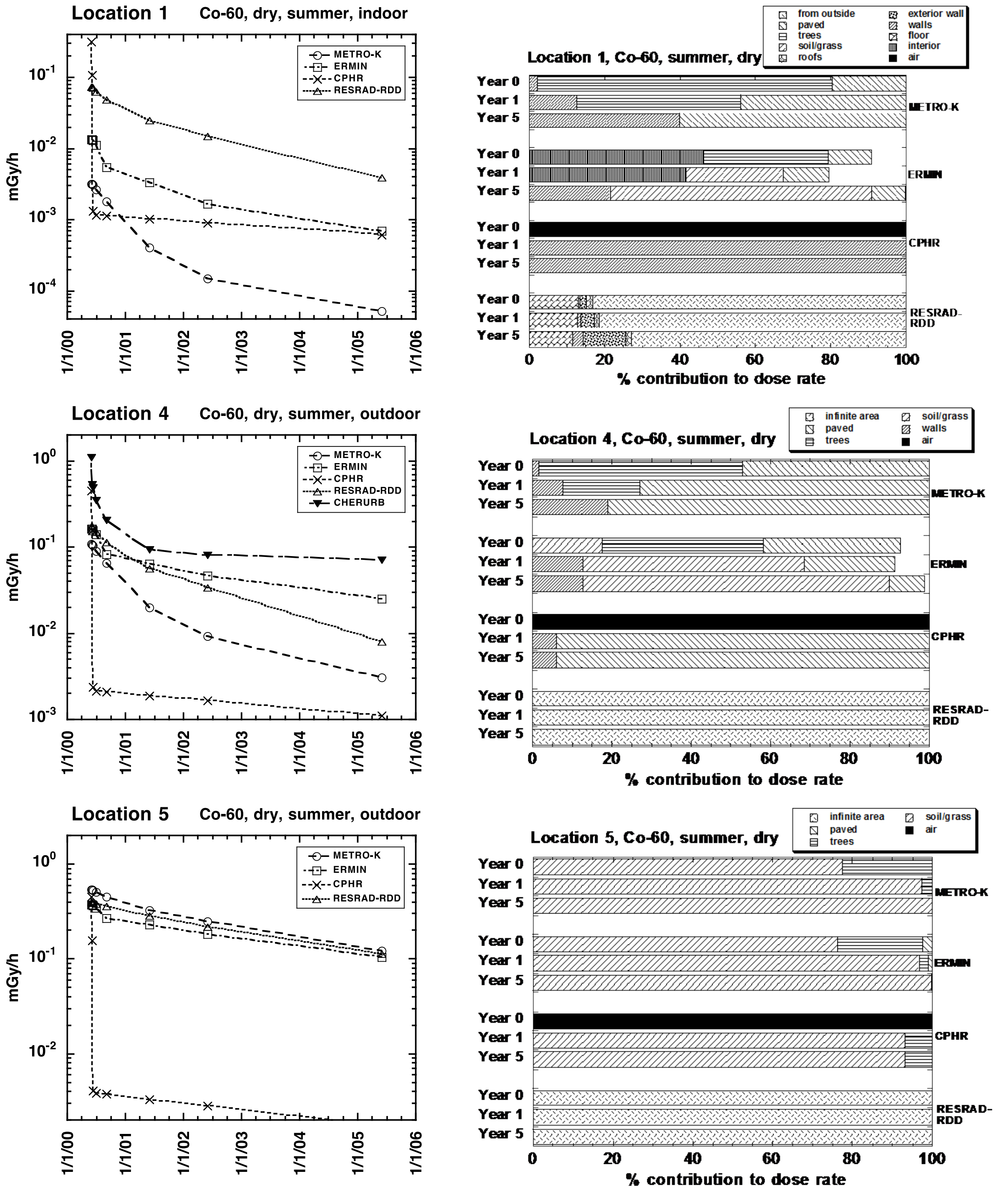

Fig. 3. Predicted external dose rate (mGy $h^{-1}$) from Co-60 (left) and most important surfaces contributing to dose rate (right) at Location 1 (top; ground floor indoors in a business area), Location 4 (center; outdoors in a business area), and Location 5 (bottom; outdoors in a park area). Predictions are shown for initial conditions of dry weather in summer.

values for the ground floor than for higher floors. For any given set of initial weather conditions, RESRAD-RDD gave similar initial values for all three indoor locations, with different loss rates for later time periods. In general, RESRAD-RDD produced the highest predictions for all three indoor locations and all three sets of initial weather conditions. For dry conditions, CPHR had the highest initial predicted values, but also had a very steep early loss rate and generally low values over later time periods. As for outdoor locations, the differences between summer and winter deposition events were very small (METRO-K and ERMIN only).

## Surfaces Contributing to External Dose Rates

Four modelers included the percentage contributions to their predicted external dose rates from specified surfaces (Fig. 3, right). Understanding the surfaces included by various models is important to understanding the model predictions of external dose rates and doses, especially how the predicted dose rates vary over time, with different release conditions, by location, by isotope, or among models.

For indoor locations, the contributing surfaces were dependent on the location within the building. For the ground floor location (Fig. 3, top), most models included contributions from outdoor surfaces (e.g., trees and pavement for METRO-K and ERMIN, grass for ERMIN, and exterior walls and "from outside" for RESRAD-RDD). Contributions from indoor surfaces were variously considered in terms of walls (all four models), "interior" (ERMIN), and floors (RESRAD-RDD). CPHR included the contribution from "air" during the initial period after the release. For the 10th floor, RESRAD-RDD showed a major contribution "from outside," while most models had the major contribution to dose rate coming from walls or interior surfaces. For the 24th (top) floor), a major contribution from roofs was evident for all models; RESRAD-RDD still had a significant contribution "from outside."

For Co-60, for the ground floor location, both METRO-K and ERMIN showed an important contribution to dose rate from trees. For METRO-K, trees were the dominant surface initially (Year 0), less so at Year 1, and not important at Year 5, while walls and paved surfaces became increasingly important over time. For ERMIN, trees were important only for Year 0; however grass became increasingly important over time. ERMIN also showed a decrease over time in the importance of interior surfaces and a corresponding increase in the importance of walls for all indoor locations, especially the 10th floor location. For the top floor, roofs were much more important than walls or interior surfaces for ERMIN and RESRAD-RDD, with increasing importance over time. For METRO-K, walls were the primary contributor to dose at the 10th floor location for all time points, and similarly roofs for the top floor. In general, surfaces that act as "sinks" (grass, walls, roofs) tended to contribute a greater percentage of the dose rate at later time points than those surfaces presumed to have net losses of contamination over time (e.g., trees, interior surfaces).

Results for the paved outdoor location (Location 4, next to buildings) tended to be similar for any given model (Fig. 3, center). The results for three models (METRO-K, ERMIN, CPHR for Years 1 and 5) included a significant contribution to external dose rate from paved surfaces, with a lesser contribution from walls. METRO-K and ERMIN both included a contribution from trees, which decreased over time. For METRO-K, the contributions from walls and pavement increased over time. For ERMIN, the results showed a decrease in contribution over time from pavement and an increase over time from grass. For Location 5 (the center of a park area), the main contributors to external dose rate for these three models were grass and trees (Fig. 3, bottom). CPHR included the contribution from "air" during the initial period after the release for all outdoor locations. The fourth model (RESRAD-RDD) calculated the external dose rate for all outdoor locations in terms of an "infinite area" and did not distinguish among individual surfaces.

For METRO-K and ERMIN, trees were much more important for a summer release than for a winter release, and for dry conditions vs. wet conditions. In all cases in which trees were a major contributor to external dose rate (all three locations in Fig. 3), the importance decreased over time, with corresponding increases in the percent contributions from walls, grass, or paved surfaces. For the other two indoor locations (10th and top floors), no significant seasonal or weather-related differences in contributing surfaces were apparent. For the outdoor locations for ERMIN, the importance of grass surfaces increased over time, while the predicted contribution from paved surfaces decreased.

## External Doses from Co-60

Predicted cumulative external doses from Co-60 after 1 year and 5 years post-deposition are shown (Fig. 4) for different initial weather conditions. Consistent with the predictions for contamination densities and external dose rates, predicted doses were higher for wet deposition than for dry deposition (heavy rain > light rain >> dry). The first year of exposure contributed most of the 5-year cumulative dose for all models. Predicted doses for Region 2 (the park area) were very similar among four models, reflecting similar predicted behavior for Location 5. For predicted doses for Region 1, there was more variability among models, reflecting the contribution from time spent indoors as well as outdoors. In general, predicted external dose rates for indoor locations varied more widely among models than did those for outdoor locations (Fig. 3). For RESRAD-RDD, CPHR, and CHERURB, predicted doses were higher for Region 1 than for Region 2, while for METRO-K and ERMIN, predicted doses were higher for Region 2 than for Region 1.

## Internal Doses from Pu-239

Predicted cumulative internal doses from Pu-239 (Fig. 5) reflected the contribution from either the initial plume (CPHR and CHERURB) or resuspension (METRO-K, ERMIN, and RESRAD-RDD). Thus for CPHR and CHERURB, the entire internal dose was received early on, and the cumulative doses after 1 year or 5 years were identical. For the other three models, most of the dose was received during the first year, with only small additional contributions to the dose after 5 years. For both CPHR and CHERURB, the predicted dose for Region 1 was higher than that for Region 2, substantially so for CPHR. For internal doses from resuspended materials, both ERMIN and RESRAD-RDD predicted higher doses in Region 1 than in Region 2. METRO-K predicted substantially higher doses in Region 2 than Region 1 for dry initial conditions, but only slightly higher for initial conditions of light or heavy rain.

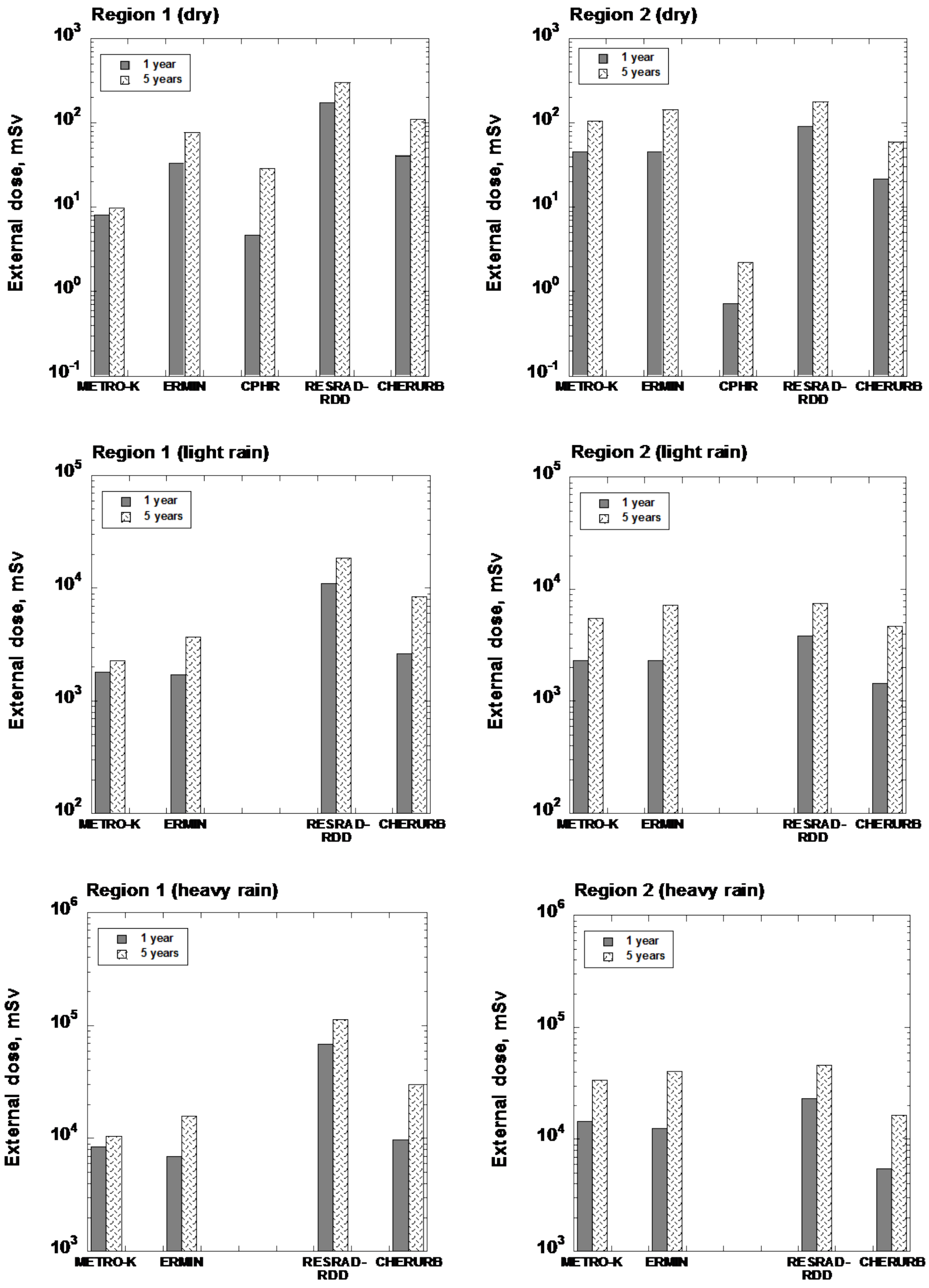

Fig. 4. Predicted external doses (mSv) from Co-60 after 1 year and 5 years in Region 1 (left; business area) and Region 2 (right; park area). Predictions are shown for initial conditions in summer of dry weather (top), light rain (center), and heavy rain (bottom).

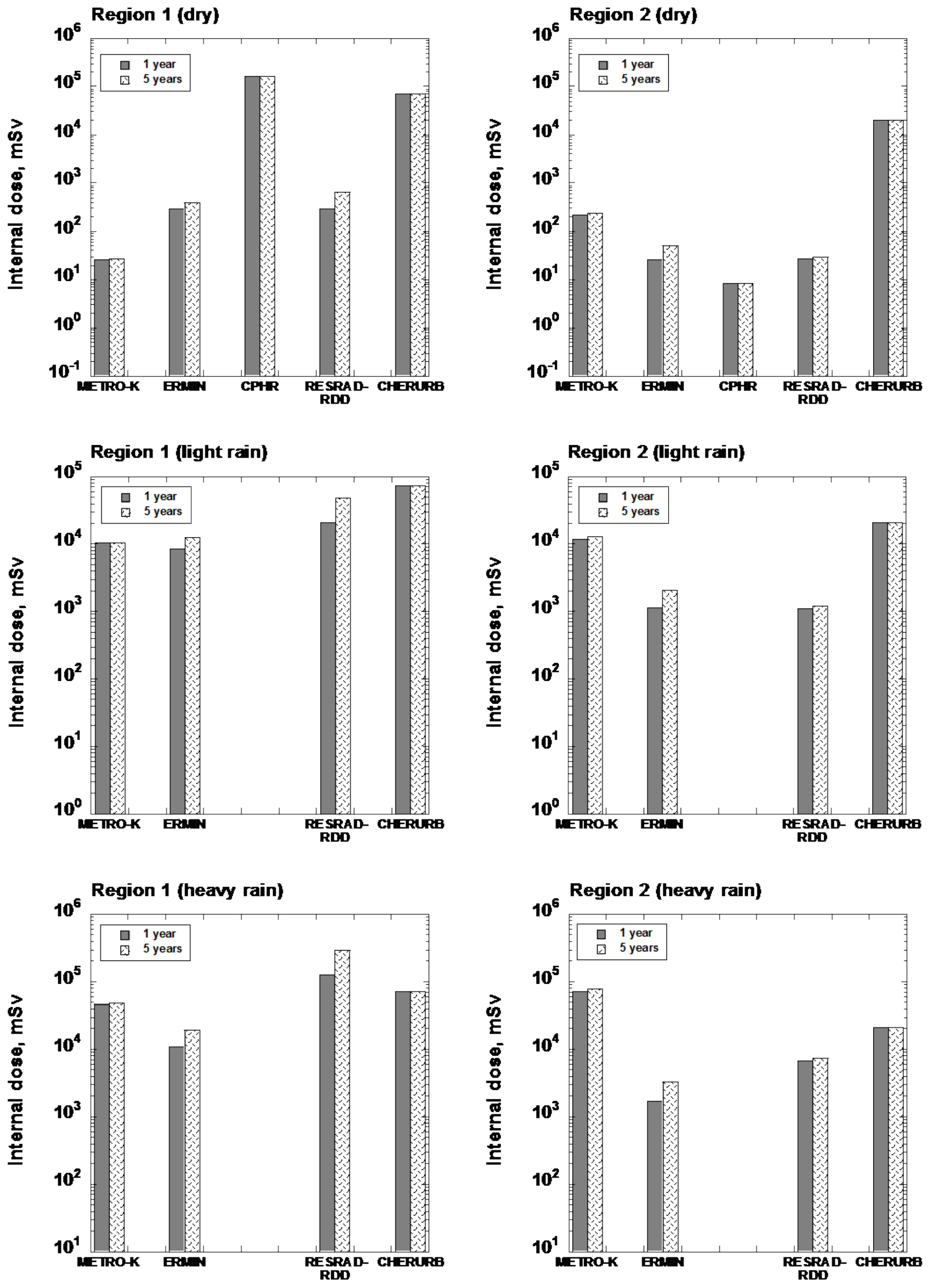

Fig. 5. Predicted internal doses (mSv) from Pu-239 after 1 year and 5 years in Region 1 (left; business area) and Region 2 (right; park area). Predictions are shown for initial conditions in summer of dry weather (top), light rain (center), and heavy rain (bottom).

TABLE II. Examples of predicted countermeasure effectiveness for external doses from Co-60 (dry initial conditions in summer)

| Model | Time period | Dose (mSv) no action | Countermeasure or remedial measure, % reduction | | | | |
|---|---|---|---|---|---|---|---|
| | | | Relocation (6 weeks) | Tree removal | Soil and grass removal | Road cleaning | Washing roofs |
| Region 1 | | | | | | | |
| METRO-K | 1 year | 8.2 | 34 | 28 | 0 | 38 | 4 |
| | 5 years | 9.9 | 28 | 23 | 0 | 40 | 9 |
| ERMIN | 1 year | 33 | 19 | 10 | 0.04 | 17 | 9 |
| | 5 years | 78 | 8 | 6 | 0.02 | 11 | 13 |
| CPHR | 1 year | 4.7 | 47 | 0 | - | 8 | 38 |
| | 5 years | 29 | 16 | 0 | - | 39 | 27 |
| RESRAD-RDD | 1 year | 174 | 11 | -[a] | 0 | 44 | 13 |
| | 5 years | 299 | 6 | - | 0 | 37 | 6 |
| CHERURB | 1 year | 40.8 | 28 | 3 | - | 10 | 3 |
| | 5 years | 111 | 10 | 5 | - | 14 | 5 |
| Region 2 | | | | | | | |
| METRO-K | 1 year | 46 | 16 | 4 | 72 | 0 | 0 |
| | 5 years | 106 | 7 | 2 | 77 | 0 | 0 |
| ERMIN | 1 year | 45 | 16 | 5 | 50 | 2 | 1 |
| | 5 years | 143 | 5 | 2 | 74 | 1 | 0 |
| CPHR | 1 year | 0.73 | 33 | 5 | - | 0 | 0 |
| | 5 years | 2.2 | 11 | 6 | - | 0 | 0 |
| RESRAD-RDD | 1 year | 91 | 8 | - | 87 | 0 | 0 |
| | 5 years | 180 | 4 | - | 92 | 0 | 0 |
| CHERURB | 1 year | 21.8 | 28 | 3 | 46 | 11 | 1 |
| | 5 years | 59.9 | 10 | 5 | 56 | 15 | 3 |

[a] Endpoint not included by participant.

## Effectiveness of Countermeasures or Remedial Actions

Examples of predicted countermeasure effectiveness for external doses from Co-60 are shown in Table II for dry starting conditions in summer. All models predicted an effect on cumulative dose from relocation of the population for the first 6 weeks following a deposition event. For Region 1, with contributions to dose from indoor and outdoor surfaces, the predicted effectiveness of relocation (in terms of percent reduction of the dose) ranged from 11% to 47% for the first year and from 6% to 28% for five years. For Region 2, with only outdoor surfaces contributing, the predicted effectiveness of relocation ranged from 8% to 33% for the first year and from 4% to 11% for five years. For the other remedial measures included in Table II, the effectiveness depended greatly on the predicted contribution of the surface (prior to remediation) to the external dose. Thus for Region 1, with little or no expected contribution to dose from soil or grass surfaces, removal of soil and grass had no effect on predicted external dose. However, for Region 2, with primarily unpaved surfaces contributing to dose, removal of soil and grass was predicted to reduce the external dose by 46-87% over 1 year and 56-92% over 5 years. The reverse situation is seen for cleaning of roads and washing of roofs; a reduction in dose of as much as 40% was predicted for Region 1, but little no effect for Region 2. The predicted effect of removing trees varied among models, depending on the expected contribution of trees to the external dose; for example, METRO-K predicted a 20-30% reduction in dose in Region 1 from removal of trees.

For internal doses from Pu-239 (not shown), the effectiveness of countermeasures depended on the components of the dose calculation. Thus for CPHR and CHERUB, which considered only the dose from the initial plume, relocation for 6 weeks entirely eliminated the internal dose. For the models that considered only resuspension (METRO-K, ERMIN, and RESRAD-RDD), measures that reduced the contamination available for resuspension were effective in reducing the predicted doses. Thus for Region 1, cleaning the roads had a modest (RESRAD-RDD) or significant (METRO-K) effect in terms of dose reduction. For ERMIN, washing roofs was slightly more important than cleaning the roads, and both were modestly effective primarily for conditions of wet initial deposition. For Region 2, removal of grass and soil (METRO-K, ERMIN, and RESRAD-RDD) or trees (ERMIN) were predicted to reduce internal dose significantly.

## CONCLUSIONS

The contaminant transport and countermeasures exercise provided participants in the Urban Areas Working Group with an opportunity to compare model predictions and discuss reasons for similarities and differences in the predictions. In this exercise, predicted contamination densities and subsequent endpoints were greatly dependent on weather conditions at the time of deposition (especially wet vs. dry conditions), but not greatly dependent on seasonality. Important differences in surfaces contributing to external dose rates were seen between the business area (Region 1) and the park area (Region 2). In general, the 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. Thus remediation of paved surfaces was important in Region 1, while remediation of grass and soil surfaces was important in Region 2. For internal dose, models considering only an initial plume (and not resuspension) predicted a dose reduction only from relocation, not from other remedial measures, while models considering resuspension did predict dose reductions from remedial measures such as cleaning roads or removing soil.

A general conclusion from this international model testing exercise is that models should match the assessment situation for which they are to be used. In the context of this exercise, models can evaluate the effectiveness of remediating a surface only if that surface is included in the model. Similarly, if a particular exposure pathway is likely to be important, then it should be included in the model. Participants received the same starting information but for many endpoints produced different results. This reflects differences in model capabilities, interpretation of input information, 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. Models such as the ones used in this exercise can facilitate comparison of various remediation strategies in the aftermath of an actual contamination event.

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