Department of Pesticide Regulation

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MEMORANDUM

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SUBJECT: NURSERY STOCK ROOT DIPS: APPLICATOR EXPOSURE ESTIMATES

This memo proposes exposure estimates for workers dipping nursery stock. "Nursery stock" is defined in California law as "any plant for planting, propagation, or ornamentation" (California Food and Agriculture Code, Section 5005). Surrogate data from the Pesticide Handlers Exposure Database (PHED) can be used for mixer/loader exposure estimates, and reentry exposure can be represented by harvesting of ornamentals or other activities. However, no exposure monitoring data are available for applicators dipping plant roots into pesticide solutions. This scenario differs from most pesticide handler scenarios in that workers may immerse hands into a pesticide solution.

It's possible that nursery stock dipping may be similar to pet and livestock dips in which animals are immersed, though a comparison of these activities has not been done. However, exposure monitoring data are also lacking for persons immersing animals into pesticide dips, other than limited biomonitoring (Buchanan *et al.*, 2001), in which individual worker activities were too poorly described to allow an estimate of exposure from amount of pesticide handled.

In the absence of acceptable exposure monitoring data, applicator exposure can be estimated based on models used by U.S. Environmental Protection Agency (U.S. EPA) for other estimating exposure to chemicals dissolved in water. Several models were evaluated to determine the most appropriate approach for dermal and inhalation exposure for this scenario.

Example Active Ingredients

Several active ingredients (AIs) are registered in California for use in dipping nursery stock. Although many AIs have been tested for efficacy as root dips (e.g., Barnard *et al.*, 1995; Klein *et al.*, 2002; Oliver *et al.*, 2004), dipping is not necessarily the most effective treatment method for all pests (Barnard *et al.*, 1995) and it can be considered expensive and time-consuming by growers (Oliver *et al.*, 2004).

Two generic AIs are used as examples in this memo. Example A is less lipophilic than Example B; for convenience, both are assumed to have the same MW. Assumed physical and chemical properties pertinent to exposure assessment are shown in Table 1.

Table 1. Selected Physical and Chemical Properties of Example Active Ingredients [a]

Property	Example A	Example B
Molecular Weight	300	300
Water Solubility	500 mg/L at 25°C	0.50 mg/L at 25°C
Log K_{ow}	1.00 at 25°C	4.00 at 25°C
Vapor Pressure	5.0×10^{-8} mm Hg at 25°C	1.0×10^{-4} mm Hg at 25°C
Henry's Law Constant	1.3×10^{-10} atm-m^3/mole	3.0×10^{-4} atm-m^3/mole

[a] Generic examples.

For convenience, each AI is assumed to be mixed into solution with water at 0.085 lb AI/gallon (10,000 mg AI/L). Although this concentration is far greater than the reported water solubility of either AI, it is a feasible concentration for a pesticide product that contains additives to increase AI solubility in water, and is in the concentration range of dipping solutions prepared according to pesticide product label directions.

Available Information and Assumptions about Root Dipping Practices

Practically no information is available about specific activities involved in root dips with pesticide solutions. Limited information was found about root dipping of seedlings done by nurseries to protect roots from desiccation prior to transplanting (MDNR, 2003; VDF, 2004). Seedlings are "lifted" (carefully removed by hand or machine to separate roots from soil) from nursery beds when temperatures are cool and quickly transported to a packing shed to be sorted and bundled before shipment or storage. Roots may be trimmed to a standard length by hand or machine; dipping is done at this point. Figure 1A shows seedlings that have been dipped in a clay slurry just before packaging (VDF, 2004); the forearm of a worker dipping seedlings can be seen in the upper left corner of the picture. Figure 1B shows a worker dipping seedling bundles.

Because details about pesticide root dipping are lacking, exposure estimates for this scenario are based on the assumption that root dips with pesticides are similar to root dips done to protect roots from desiccation, except that pesticidal root dips require workers to wear clothing and PPE specified on pesticide product labels. Workers are assumed to immerse seedling roots into a container such as a bucket or vat while holding seedlings above roots, and that hands are immersed in the pesticide solution.

Most of the exposure is anticipated to be to hands. However, inspection of Figure 1B suggests that workers may also be exposed by splashes or drips on the forearms, torso, and legs. Although this exposure is not immersion in the same way as hands, in the absence of a better approach these exposed body surfaces are included with hands when calculating dermal exposure estimates.

Figure 1. Seedling roots are dipped in kaolin clay at two state nurseries [a]. Dipping operations shown are to protect roots against drying out, and no pesticide use is mentioned in either case.

A) Note raincoat-covered sleeve of worker dipping seedlings in upper left corner; after dipping, bundled seedlings are placed in packing paper on conveyor belt.

B) Note clay residue on forearms, torso, and legs.

[a] A from VDF (2004). B from MDNR (2003).

Attempts to learn about pesticide dips, and about how many seedlings per day are handled by each worker in California are ongoing. At present, the following information is available about how many seedlings are handled by nurseries in the U.S.:

- Forest nurseries in southern U.S. states typically bundle and ship "up to several hundred thousand seedlings per day" (Wilhoit *et al*., 1993).
- Most seedlings (~80%) in the U.S. come from the South, which ships more than 1.2 billion seedlings annually (Frankel *et al*., 1999).
- In 2002, a total of 1,807 nurseries in California grew a total of 33,380 acres (13,508 hectares, or ha) of nursery stock (NASS, 2004). This compares to the U.S. total of 24,975 nurseries growing a total of 467,941 acres (189,369 ha), and the South total of 8,447 nurseries growing a total of 134,781 acres (54,544 ha). From these figures, the average size of a California nursery is 18.4 acres, compared to U.S. and South averages of 18.7 (7.57 ha) and 16.0 (6.47 ha) acres/nursery, respectively. This suggests that the South is able to grow more seedlings because more nurseries are located there, not because the average nursery is larger than in California, and it is possible that California nurseries can also process several hundred thousand seedlings daily, like those in the southern U.S.

More than one worker would be expected to process seedlings in large nurseries (i.e., one worker is not expected to process several hundred thousand seedlings daily). In addition, it's possible that use of pesticide dips would slow down the process, allowing fewer seedlings to be processed if workers are more careful with pesticides than with clay slurries. However, no information is available to determine how many seedlings are dipped by each worker.

Applicator Dermal Exposure Estimate

As mentioned above, in the nursery stock dipping scenario workers are assumed to immerse hands in the pesticide solution; forearms and front of torso and legs are also likely to be exposed by splashes or drips. U.S. EPA has used two basic approaches in models that estimate dermal exposure for skin immersed in liquids, based either on the amount of chemical in a thin film clinging to skin after immersion, or on diffusion of chemicals through skin during immersion. These approaches are summarized in Table 2.

Table 2. Summary of Approaches Investigated for Estimating Dermal Exposure of Workers Dipping Nursery Stock into Pesticide Solution

Model Approach	Key Parameter	Comments
Thin Film		
E-FAST [a]	Film thickness on skin (Q)	Default Q value based on a 1984 Versar interim report: study of chemicals in water solutions, bath oil, cooking oil, and mineral oil remaining on hands after dipping (U.S. EPA, 2000). Includes water-based solution data, but these data were omitted from a later Versar report finalized in 1992.
ChemSTEER [b]	Film thickness on skin (Qu)	Default Qu value based on 1992 Versar final report in which experiments were repeated: study of chemicals in bath oil, cooking oil, and mineral oil remaining on hands after dipping (U.S. EPA, 2000). Water-based solutions were omitted from this model due to uncertainties in the data.
Skin Diffusion		
SWIMODEL [c]	Skin permeability coefficient (K_p)	Based on correlation of Potts and Guy (1992), which includes human and animal *in vitro* and animal *in vivo* data (U.S. EPA, 1992). Steady-state equations used to estimate exposure.
RAGS-E [d]	Skin permeability coefficient (K_p)	Adapted from correlation of Potts and Guy (1992); only human *in vitro* data are used (U.S. EPA, 2004c). Complex equations address non-steady-state exposure (Cleek and Bunge, 1993).

[a] Exposure and Fate Assessment Screening Tool, Beta Version (Versar, 1999). Hand laundering with liquid laundry detergent scenario in Consumer Exposure Module was considered closest to nursery stock dipping.
[b] Chemical Screening Tool for Exposures and Environmental Releases, Beta Version (U.S. EPA, 2004a).
[c] Swimmer Exposure Assessment Model Version 3.0 (U.S. EPA, 2003).
[d] Risk Assessment Guidance for Superfund (RAGS), Part E, Supplemental Guidance for Dermal Risk Assessment (U.S. EPA, 2004c).

Thin-film models

Thin-film models assume that exposure is due to a thin layer of the chemical on a defined skin surface area. Two such models were investigated, the Exposure and Fate Assessment Screening Tool (E-FAST) and the Chemical Screening Tool for Exposures and Environmental Releases (ChemSTEER). Both models are available for downloading from U.S. EPA websites (U.S. EPA, 2004a; 2004b). ChemSTEER was developed by U.S. EPA's Chemical Engineering Branch to provide screening-level estimates of environmental releases and worker exposures to chemicals manufactured and used in industrial and commercial workplaces (U.S. EPA, 2004a), and E-FAST was developed for U.S. EPA to provide screening-level exposure estimates for environmental and general population risk assessment of new chemicals under the Toxic Substances Control Act (Versar, 1999).

Because few data exist on the actual thickness of films of various liquids on human skin, dermal exposure estimates in both models rely on default values that are based on laboratory experiments conducted by Versar in which subjects immersed hands in containers of various liquids and allowed the liquids to drip off the hands back into the container; the decreased weight of liquid in container was assumed to equal the amount remaining on skin (U.S. EPA, 1991).

E-FAST

A Consumer Exposure Module (CEM) within E-FAST allows screening-level assessment of inhalation and dermal exposures to chemicals in certain types of consumer products. One of the scenarios in CEM is hand-washing with liquid laundry detergent, which includes immersion of both hands. E-FAST combines several models used by U.S. EPA for exposure assessment; dermal exposure estimates in the CEM use the same approach and equations as the DERMAL Exposure Model (Versar, 1999). Additional information about this model is given in the U.S. EPA Residential Exposure Assessment SOPs (REAWG, 1997) and is also described in U.S. EPA's Chemical Engineering Branch documents (U.S. EPA, 1991; 2000). REAWG (1997) recommends that, "Although the other model inputs may be changed by the user, it is recommended that users accept all model defaults unless product or chemical-specific data are available for the scenario."

The equation is as follows (Versar, 1999):

$$\text{Dose (mg/kg)} = [Q * SA/BW * WF * (1000 \text{ mg/g})$$

where:

Q = Amount retained on the skin (default: 1.13×10^{-5} g/cm^2 per event);
SA/BW = Surface area to body weight ratio (default: 15.6 cm^2/kg); and
WF = Weight fraction of product (unitless).

ChemSTEER

Among the dermal exposure scenarios available in ChemSTEER is one called, "2-Hand Immersion in Liquids." This scenario is intended to apply to "miscellaneous activities related to liquid processing," as well as spray coating scenarios in automobile manufacturing. This model uses the following equation (U.S. EPA, 2004a):

$$D_{exp} = S * Qu * Y_{derm} * FT$$

where:

D_{exp} = Dermal exposure (mg/day)
S = Surface area of contact (model default: 840 cm^2 for two hands);
Qu = Quantity retained on the skin (default between 1.3 and 10.3 mg/cm^2-event);
Y_{derm} = Weight fraction of chemical in the liquid (product-specific, no default); and
FT = Frequency of use (events/worker-day, default: 1).

Using Thin-Film Models

There are two problems with using the thin-film models for estimating exposure for workers dipping nursery stock. These are the thin-film assumption itself and the data on which the models are based:

1) The basic assumption underlying thin-film models is difficult to reconcile with dermal exposure to chemicals by hands being immersed in water. The dermal exposure estimates provided by E-FAST and ChemSTEER are based on an assumption that exposure is through a thin film on the skin. As was argued by U.S. EPA (1992):

> For water or vapor scenarios, it is not practical to apply this concept of percent absorbed because of the difficulty in estimating the contact rate. Attempts have been made to apply dermal absorption models that consider the thickness of a thin film of chemical and water on the skin (EPA, 1983; Wester *et al.*, 1987; Wester and Maibach, 1989b). However, for exposure scenarios of interest in environmental settings, this thickness is difficult to establish. There is essentially an infinite thickness of material available, and the contaminant will be continuously replaced, thereby increasing the amount of available material by some large, but unknown, amount.

If workers put their hands into solution just once during the seedling root dipping operation, the thin-film model would be an acceptable approximation, assuming it is based on appropriate data. But because workers put their hands into the dipping solution repeatedly, and there is no information about the extent to which the thin film is replaced with a new one, this model seems likely to underestimate exposure.

2) The data sets underlying the thin-film models are either not based at all on aqueous solutions (ChemSTEER) or are partly based on aqueous solution data that were later omitted from the revised study report because of uncertainties in the data (E-FAST). Both models are based on data from studies done by Versar. In 1984, Versar provided U.S. EPA with an interim report containing data from chemicals dissolved in several water- and oil-based liquids. In 1992, Versar provided a final report containing oil-based liquid data from new experiments and in which the water-based liquid data were omitted (U.S. EPA, 2000). These data are not appropriate for estimating exposure to workers immersing hands in aqueous solutions of pesticides. For these reasons, exposure estimates for the nursery stock dipping scenario were not based on thin-film models.

Skin diffusion models

Two models were considered; both relate dermal exposure to a skin permeability coefficient (K_p). The Swimmer Exposure Assessment Model (SWIMODEL), developed by EPA (2003) for estimating human exposures to chemicals found in swimming pool or spa waters, calculates K_p using Equation 5.8 in U.S. EPA (1992), from the correlation of Potts and Guy (1992). This correlation is based on the data reported by Flynn (1990), which includes human and animal *in vitro* and animal *in vivo* data. The Risk Assessment Guidance for Superfund, Part E (RAGS-E), provides a modification of the equation to calculate K_p as part of the Supplemental Guidance for Dermal Risk Assessment (U.S. EPA, 2004c). The modified equation relies on the human *in vitro* data only from the Flynn (1990) data set; all non-human data were excluded (U.S. EPA, 2000).

The models also differ in the equations used to estimate exposure from K_p. SWIMODEL uses a steady-state equation, which does not consider uptake in the pre-steady-state interval. Cleek and Bunge (1993) suggested that uptake is more rapid before steady-state is achieved, and that exposures are underestimated by using steady-state equations. To correct for this, a series of estimated parameters was introduced to cover both this lag-time before steady state is reached, and to address differences in permeability between the stratum corneum and the viable epidermis. These parameters are included in the RAGS-E model.

SWIMODEL

The equation for calculating the chemical-specific permeability coefficient in SWIMODEL is as follows (U.S. EPA, 1992):

$$\log K_p = -2.72 + 0.71 \log K_{ow} - 0.0061\ MW$$

Using data summarized in Table 1, the K_p values are 0.0000144 cm/hr and 0.0195 cm/hr for chemicals A and B, respectively (Table 3).

Table 3. Dermal Exposure Estimates Calculated for Example Active Ingredients with Estimated Values of Permeability Coefficients from SWIMODEL [a]

Parameter	Example A	Example B
Kp (cm/hr) [b]	0.000144	0.0195
Hands		
AD_{Derm} (mg per day) [c]	10.5	1,410
Hand ADD (mg/kg/day) [d]	0.149	2.01
Non-Hand Dermal		
AD_{Derm} (mg per day) [e]	84.5	11,400
Dermal ADD (mg/kg/day) [f]	0.603	81.4
Total		
Total Dermal ADD (mg/kg/day) [g]	0.618	83.4

[a] Solution concentration (C_w) is assumed to be 10,000 mg AI/L for both active ingredients. Physical and chemical properties used in calculations are in Table 1.
[b] Skin permeability coefficient (K_p) calculated from Equation 5.8 in U.S. EPA (1992).
[c] Estimated hand exposure per day. Calculated from SWIMODEL equation. SA = 904 cm^2 (surface area of both hands; combined male and female medians from EPA, 1997). ET = 8 hours.
[d] Hand ADD is absorbed daily dose via hands. To calculate, AD_{Derm} multiplied by 0.1 for use of gloves with default protection factor of 90% (Aprea *et al*., 1994); divided by 70 kg default body weight (Thongsinthusak *et al*., 1993).
[e] Estimated dermal exposure per day. Calculated from SWIMODEL equation. SA = 7,306 cm^2 (surface area of chest/stomach, forearms, front of thighs and lower legs; combined male and female medians from EPA, 1997). ET = 8 hours.
[f] Dermal ADD is absorbed daily dose. To calculate, AD_{Derm} multiplied by 0.5 for one layer of clothing with default protection factor of 50% (Thongsinthusak *et al*., 1993); divided by 70 kg default body weight (Thongsinthusak *et al*., 1993).
[g] Total Dermal ADD is the sum of Hand ADD and Dermal ADD.

These permeability coefficients are used to calculate dermal exposure. SWIMODEL calculates the dermal dose rate in mg per event (AD_{Derm}) using the steady-state equation below:

$$AD_{Derm} = C_w * SA * K_p * ET * (0.001 L/cm^3)$$

where

C_w (mg/L) is the concentration of the pesticide in water;
SA (cm^2) is surface area of exposed skin;
K_p (cm/hr) is the chemical-specific permeability coefficient; and
ET (hrs/event) is exposure time.

Table 3 gives the absorbed dose per event calculated with equations from SWIMODEL. Workers handling pesticides are generally required to wear chemical-resistant gloves. Because such gloves are assumed to have a 90% protection factor (Aprea *et al*., 1994), the estimated dermal exposure via hands is multiplied by 0.1. The default protection factor for a single layer

of clothing is 50% (Thongsinthusak *et al.*, 1993). The absorbed daily dose (ADD) is calculated by dividing the exposure by the default body weight of 70 kg (Thongsinthusak *et al*., 1993).

RAGS-E

The equation for calculating the chemical-specific permeability coefficient in RAGS-E, which relies solely on human *in vitro* data, is as follows (U.S. EPA, 2004c):

$$\log K_p = -2.80 + 0.66 \log K_{ow} - 0.0056\ MW$$

Using data summarized in Table 1, the K_p values are 0.000151 cm/hr and 0.0145 cm/hr for Example A and Example B, respectively (Table 4). The equation for dermal exposure per event in RAGS-E is as follows (modified from Equation 3.3 in U.S. EPA (2004c), surface area term added to get result in mg/event rather than mg/cm^2):

$$DA_{event} = FA * K_p * SA * Cw * (0.001L/cm^3) * [t/(1+B) + 2\tau((1+3B+3B^2)/(1+B)^2)]$$

where

DA_{event} is the absorbed dose per event (mg per event);
FA is the fraction absorbed water (dimensionless, default = 1);
SA (cm^2) is surface area of exposed skin;
C_w (mg/L) is the concentration of the pesticide in water;
t is the event duration (hours);
τ is the lag time per event (hours); and
B is the dimensionless ratio of the permeability coefficient of a compound through the stratum corneum relative to its permeability across the epidermis.

Table 4 gives the absorbed dose per event calculated with the above equations. The same protection factors apply as were used in exposure estimates from SWIMODEL calculations.

Best Estimate of Dermal Exposure (Exposure Appraisal and Conclusion)

The major difference between SWIMODEL and the RAGS-E model is the inclusion of parameters in the latter model for non-steady-state exposure. This approach, based on the submitted manuscript of Cleek and Bunge (1993), was recommended by U.S. EPA (1992) for estimating exposure to organic compounds in water. Bunge *et al*. (1995) compared dermal absorption of chemicals estimated by steady-state and their model with non-steady-state terms, and found that the steady-state equations consistently underestimated dermal absorption. The differences between steady-state and non-steady-state exposure estimates were greater for compounds with a fairly high Log K_{ow} (> 6) than for compounds with low Log K_{ow} (< 2), though Bunge *et al.* (1995) did not test compounds with Log K_{ow} in an intermediate range.

Table 4. Dermal Exposure Estimates Calculated for Example Pesticides with Estimated Values of Permeability Coefficients and Non-Steady-State Terms from RAGS-E [a]

Parameter	Example A	Example B
Kp (cm/hr) [b]	0.000151	0.0145
τ (hours) [c]	5.03	5.03
B [d]	0.00092	0.153
Hands		
DA_{event} (mg per day) [e]	24.6	2,400
Hand ADD (mg/kg/day) [f]	0.0351	3.42
Non-Hand Dermal		
DA_{event} (mg per day) [g]	199	19,400
Dermal ADD (mg/kg/day) [h]	1.42	138
Total Dermal		
Total Dermal ADD (mg/kg/day) [i]	1.46	141

[a] Solution concentration (C_w) is assumed to be 10,000 mg AI/L for both active ingredients. Physical and chemical properties used in calculations are in Table 1.
[b] Skin permeability coefficient (K_p) calculated from Equation 3.8 in U.S. EPA (2004c).
[c] Time-lag to reach steady-state (τ) calculated from Equation A.4 in U.S. EPA (2004c).
[d] Calculated from Equation A.1 in U.S. EPA (2004c); Method 4 in Bunge and Cleek (1995).
[e] Estimated hand exposure per day. Calculated from Equation 3.3 in U.S. EPA (2004c), SA = 904 cm^2 (surface area both hands; combined male and female medians from EPA, 1997). ET = 8 hours.
[f] Hand ADD is absorbed daily dose via hands. To calculate, DA_{event} multiplied by 0.1 for use of gloves with default protection factor of 90% (Aprea *et al*., 1994); divided by 70 kg default body weight (Thongsinthusak *et al*., 1993).
[g] Estimated dermal exposure per day. Calculated from Equation 3.3 in U.S. EPA (2004c), SA = 7,306 cm^2 (surface area of chest/stomach, forearms, front of thighs and lower legs; combined male and female medians from EPA, 1997). ET = 8 hours.
[h] Dermal ADD is absorbed daily dose. To calculate, AD_{Derm} multiplied by 0.5 for one layer of clothing with default protection factor of 50% (Thongsinthusak *et al*., 1993); divided by 70 kg default body weight (Thongsinthusak *et al*., 1993).
[i] Total Dermal ADD is the sum of Hand ADD and Dermal ADD.

There are many assumptions and uncertainties with both models. AI-specific K_p values are estimated in both models, based on equations derived from a data set of about 200 organic compounds in aqueous solutions. The calculated K_p values for specific AIs may be either over- or underestimated; there are not enough data available to be sure. Both example AIs are well within the range of MW and Log K_{ow} in which K_p estimates are considered valid, based on Equations 3.9 and 3.10 in U.S. EPA (2004c).

However, use of K_p with solutions of formulated pesticide products may result in overestimates, as the formulations contain additives to increase water solubility of AIs. K_p values, which are based on data from solutions without such additives, might overestimate the flux of AIs into skin. Alternately, flux into the skin could be increased by the additives, as suggested by recent studies (Brand and Mueller, 2002; Williams and Barry, 2004). Exposure estimates could be improved if skin permeability measures were made using solutions of formulated products in concentrations that are pertinent to typical product use.

Another uncertainty from the use of K_p in estimating dermal exposure is that skin permeabilities are almost always estimated from *in vitro* rather than *in vivo* data. The use of *in vitro* data to determine dermal absorption is problematic because the extent of compound solubility in receptor solutions may affect results (Wester and Maibach, 2000). Also, relationships between *in vivo* and *in vitro* test results have not been reliably established for many classes of compounds, and have been shown to vary for compounds that have been tested (Wester and Maibach, 2000; Zendzian and Dellarco, 2003). Nevertheless, these models rely on the assumption that *in vitro* dermal penetration is approximately the same as *in vivo*.

Other assumptions common to both models are that the chemical concentration of water in contact with skin (C_w) is constant; and that absorbed dose is a function of solution concentration, skin permeability, and amount of exposed skin surface. These are reasonable assumptions, but have not been tested for solutions of pesticide products.

Because the dermal exposure models relate exposure to surface area, and because the hands have a smaller surface area (904 cm^2) than the rest of the body considered (7,306 cm^2), an unintended result occurs in dermal exposure estimates: the hands, which are immersed in solution, contribute less to total dermal exposure than the rest of the body (chest/stomach, forearms, front of thighs and lower legs), which is not immersed. Including non-immersed parts of the body is anticipated to result in an overestimate of exposure, unless clothing that is contaminated by splashes or drips allows enough pesticide solution in contact with skin to provide sufficient AI for a constant C_w throughout the workday (because both models assume a constant C_w). There is no information available on the amount of solution likely to be splashed or dripped onto a worker's clothing; furthermore, this is likely to vary by worker. If such data were available, then a "splash/drip" factor could be incorporated into the model, and the estimated dermal exposure decreased accordingly.

Additional uncertainty exists in the RAGS-E model, in the parameters τ and B. Calculations for these parameters rely on many assumptions and limited, surrogate data. The RAGS-E model has undergone some validation, but not with these AIs in formulated products (additives in the pesticide formulations may affect τ and B, as well as K_p).

There is a substantial difference between the exposure estimates obtained from the steady-state SWIMODEL and the RAGS-E model, which incorporates a non-steady-state term. Because the estimated time to reach steady-state (5 hours; see Table 4) is a substantial portion of the assumed 8-hour workday, and because available data suggest that steady-state equations underestimate absorption when this is true (Bunge *et al*., 1995; McDougal and Jurgens-Whitehead, 2001), the best estimate of dermal exposure is considered to be obtained from the RAGS-E model.

Inhalation Exposure Approaches

As with dermal exposure, no inhalation exposure monitoring data are available for workers dipping nursery stock. Inhalation exposure is anticipated to occur, based on the assumption that dipping tanks have a free liquid surface from which chemicals can volatilize into the air. Several models have been proposed to estimate inhalation exposure resulting from volatilization of chemicals from aqueous solutions; three models used by U.S. EPA address evaporation from containers or pools of liquid. All three are mass balance models which obtain the air concentration of evaporated chemical from various estimates of volatilization. The models are summarized in Table 5.

Table 5. Summary of Approaches Investigated for Estimating Inhalation Exposure of Workers Dipping Nursery Stock into Pesticide Solution

Model Approach	Key Parameter	Comments
Two-Zone Mass Balance		
E-FAST [a]	Emission rate (ER)	ER based on time for 90% of a pure chemical film to evaporate, the molecular weight and vapor pressure.
Volatilization Mass Balance		
SWIMODEL [b]	Pesticide concentration in air (C_{vp})	C_{vp} based on calculation of unitless Henry's Law constant from water solubility, molecular weight and vapor pressure.
ChemSTEER [c]	Vapor generation rate (G)	G based on evaporation rate of a volatile liquid into a flowing air stream (Hummel *et al.*, 1996)

[a] Exposure and Fate Assessment Screening Tool, Beta 1.1 Version (Versar, 1999).
[b] Swimmer Exposure Assessment Model Version 3.0 (U.S. EPA, 2003).
[c] Chemical Screening Tool for Exposures and Environmental Releases, Beta Version (U.S. EPA, 2004a).

Two-Compartment Mass-Balance Models

Several single-and multiple-compartment mass-balance models have been developed or used by U.S. EPA, including the Multi-Chamber Concentration and Exposure Model (MCCEM). U.S. EPA relies on this model, in combination with the Screening Consumer Inhalation Exposure

Software (SCIES), for residential inhalation exposure estimates (REAWG, 1997). Both models have been incorporated into E-FAST.

E-FAST

To estimate inhalation exposure for a person hand-washing with liquid laundry detergent, E-FAST calculates indoor air concentration in a home using a two-zone model, in which the first zone is the room where the product is used and the second zone is the remainder of the home. The model does not consider sinks. To estimate inhalation exposure for a person hand-washing with liquid laundry detergent, E-FAST begins with an estimate of "Chinn release emission rate" of evaporation of a hypothetical thin film, calculated according to the following equation:

$$ER = Mass/d$$

where:

ER is the emission rate (mg/hour); and
d is the Chinn evaporation time (hours). This is calculated by:

$$d = 145 / (MW * VP)^{0.9546}$$

where:

MW is the molecular weight (g/mole); and
VP is the vapor pressure (mm Hg).

Airborne exposure concentration is then calculated by dividing the emission rate by room size and multiplying by event duration. Because of its dependence on room size (for which defaults are available that apply to homes, but not for greenhouses or nurseries), this model was not used to estimate exposure of workers dipping nursery stock.

Volatilization from Open Surface Models

Models that consider only volatilization from open surface, rather than room size, can be used to estimate inhalation exposure without assumptions about room size. Both SWIMODEL and ChemSTEER estimate chemical vapor concentration from volatilization equations.

SWIMODEL

SWIMODEL estimates ambient vapor concentration of a chemical from its air-water partitioning estimated with a unitless Henry's Law constant, which is calculated based on the Henry's Law constant in units of atm-m^3/mole using the following equation:

$$H' = H / (R * T)$$

where

H' is the unitless Henry's Law constant;
H is the aqueous Henry's Law constant (atm-m^3/mole);
R is the gas constant (8.19×10^{-5} atm-m^3/mole-K); and
T is the ambient air temperature (degrees Kelvin, or 273 added to degrees Celsius).

The unitless Henry's Law constant and solution concentration of the pesticide are used to estimate the pesticide's concentration in air as follows:

$$C_{vp} = H' * C_w * (1{,}000\ L/m^3)$$

where

C_{vp} ($\mu g/m^3$) is the concentration of the pesticide in air;
H' is the unitless Henry's Law constant; and
C_w is the concentration of chemical in water ($\mu g/L$).

SWIMODEL calculates the potential dose rate in mg per event ($AD_{Inhalation}$) as:

$$AD_{Inhalation} = C_{vp} * ET * IR * (1\ mg/1{,}000\ \mu g)$$

where

C_{vp} ($\mu g/m^3$) is the concentration of the pesticide in air;
ET (hrs/event) is exposure time; and
IR (m^3/hr) is inhalation rate.

Table 6 shows results of vapor concentration calculations for the example AIs. For Example A, with a Henry's Law constant of 1.3×10^{-10} atm-m^3/mole, C_{vp} was calculated to be 54 $\mu g/m^3$. For Example B, with a Henry's Law constant of 3.0×10^{-4} atm-m^3/mole, C_{vp} was calculated to be 1.25×10^8 $\mu g/m^3$.

However, as mentioned above in the dermal exposure section, pesticide products may contain additives to increase water solubility. Because of this, the vapor concentrations estimated using the SWIMODEL equation can be greater than realistic vapor concentrations. To check this, the equation used to estimate vapor pressure by the gas saturation method (U.S. EPA, 1996) can be re-arranged to provide an estimate of saturated vapor concentration based on reported vapor pressure. The equation is given below.

$$C_{sat} = [(VP/760) * MW * (1{,}000\ mg/g)(1{,}000\ L/m^3)] / [R * T]$$

where

C_{sat} ($\mu g/m^3$) is the saturated concentration of the pesticide in air;
MW is the molecular weight;
R is the gas constant (8.19×10^{-5} atm-m^3/mole-K); and
T is the ambient air temperature (degrees Kelvin, or 273 added to degrees Celsius).

Estimates of C_{sat} are given in Table 6. These values are considerably lower than the estimated C_{vp}, suggesting that C_{vp} values are indeed higher than concentrations that would be expected to occur. Therefore, C_{sat} was used in calculating inhalation exposure for each AI.

A default value of 20 m^3/day was used for IR (Andrews and Patterson, 2000); this value assumes moderate to heavy activity during an 8 hour workday. Because IR is given for the workday rather than on an hourly basis, ET is set to 1 day in the exposure calculation. The inhalation contribution to the ADD is calculated by multiplying the inhalation exposure estimate by 0.1 for use of a respirator (NIOSH, 1987), and dividing by the default body weight of 70 kg (Thongsinthusak *et al.*, 1993). Exposure estimates are given in Table 6.

Table 6. Inhalation Exposure Estimates Calculated Based on SWIMODEL Equations [a]

Parameter	Example A	Example B
H' [b]	5.42×10^{-9}	0.0125
C_{vp} [c]	54.2	1.25×10^{8}
C_{sat} [d]	4.13	8,265
$AD_{Inhalation}$ (mg per day) [e]	0.0827	165
Inhalation ADD (mg/kg/day) [f]	0.000118	0.236

[a] Cw = 10,000 mg/L for both active ingredients. Physical and chemical properties used in calculations are in Table 1.
[c] Unitless Henry's Law constant. See text for equation.
[d] Calculated concentration of pesticide in air. See text for equation.
[e] Saturated vapor concentration. See text for equation.
[f] Estimated inhalation exposure per day. See text for equation. C_{sat} used for C_{vp}, IR = 20 m^3/day, ET = 1 day.
[g] ADD is absorbed daily dose. To calculate, $AD_{inhalation}$ was multiplied by 0.1 for use of a respirator (NIOSH, 1987); divided by 70 kg default body weight to obtain dose (Thongsinthusak *et al.*, 1993).

ChemSTEER

As with dermal exposure, ChemSTEER uses various approaches to estimate inhalation exposure depending on specifics of the exposure scenarios. Two of the approaches involve volatilization of chemicals from an open liquid surface, depending on speed of air moving across the surface;

the penetration model is recommended for air currents up to 100 feet/minute (U.S. EPA, 2004a), and was the one considered for inhalation exposure estimates for workers dipping nursery stock.

The penetration model is based on an equation for diffusion of an evaporating liquid into a flowing gas, developed from Fick's second law of diffusion by Hummel *et al.* (1996). The version of this equation used by ChemSTEER is as follows:

$$G = [8.24 \times 10^{-8} * MW^{0.835} * X * VP * (1/29 + 1/MW)^{0.25} * vz^{0.5} * A] / [T^{0.05} * d^{0.5} * P^{0.5}]$$

where

G is the vapor generation rate (g/sec);
MW is the molecular weight;
X is the vapor pressure correction factor (unitless, default 1);
VP is the vapor pressure of the pure chemical (mm Hg);
vz is the air speed at the liquid surface (default 100 ft/min);
A is the surface area of the static liquid ($\pi * d^2/4$ cm^2);
T is the ambient air temperature (default 298 ºK);
d is the diameter of the static liquid pool (default 92 cm); and
P is the atmospheric pressure (1 atm).

The chemical concentration to which a worker is exposed is calculated with the following equation (defaults are provided by ChemSTEER, listed in the user documentation provided with the software):

$$C_m = [170{,}000 * T * G] / [Q * k * V_m]$$

where

C_m is the concentration of chemical in air (mg/m^3);
T is the ambient air temperature (default 298 ºK);
G is the vapor generation rate (g/sec);
VP is the vapor pressure of the pure chemical (mm Hg);
Q is the ventilation rate (indoor worst-case default is 500 ft^3/min);
k is the mixing factor (unitless, indoor worst-case default is 0.1); and
V_m is the molar volume (default 24.45 L/mole).

Inhalation exposure (I) is calculated from C_m by multiplying it by the inhalation rate (IR). Estimates of C_m and I are given in Table 7. A default value of 20 m^3/day was used for IR (Andrews and Patterson, 2000); this value assumes moderate to heavy activity during an 8-hour workday. The inhalation contribution to the ADD is calculated by multiplying the inhalation exposure estimate (I) by 0.1 for use of a respirator (NIOSH, 1987), and dividing the inhalation exposure estimate by the default body weight of 70 kg (Thongsinthusak *et al.*, 1993). Exposure estimates are given in Table 7.

Table 7. Inhalation Exposure Estimates Calculated Based on ChemSTEER Penetration Model Equations [a]

Parameter	Example A	Example B
G [b]	1.11×10^{-9}	2.22×10^{-6}
C_m (mg/m^3) [c]	4.59×10^{-5}	9.19×10^{-2}
$AD_{Inhalation}$ (mg per day) [d]	9.19×10^{-4}	1.84
Inhalation ADD (mg/kg/day) [e]	1.31×10^{-6}	2.62×10^{-3}

[a] Cw = 10,000 mg/L for both active ingredients. Physical and chemical properties used in calculations are in Table 1.
[b] Vapor generation rate based on Penetration Model. See text for equation.
[c] Calculated concentration of pesticide in air. See text for equation.
[d] Estimated inhalation exposure per day. See text for equation. C_{sat} used for C_{vp}, IR = 20 m^3/day, ET = 1 day.
[e] ADD is absorbed daily dose. To calculate, $AD_{inhalation}$ was by 0.1 for use of a respirator (NIOSH, 1987); divided by 70 kg default body weight to obtain dose (Thongsinthusak *et al*., 1993).

Best Estimate of Inhalation Exposure (Exposure Appraisal and Conclusion)

Both SWIMODEL and ChemSTEER estimate pesticides concentrations in air based on conditions that may not be met in the nursery stock dipping scenario. In fact, substantial deviations from the assumptions on which the models are based occur with both models (also true of the two-compartment model used by E-FAST).

SWIMODEL relies on water-air partitioning to determine concentration of a chemical in air, using the Henry's Law constant for the chemical. However, Henry's Law constant applies to dilute, single-chemical aqueous solutions only. Staudinger and Roberts (2001) give 10,000 mg/L as an upper boundary defining a "dilute" solution under Henry's Law. This concentration is reached in both examples provided. Furthermore, other chemicals present in the pesticide formulations can interact with the pesticide molecules, potentially affecting the partitioning of the AI into air (Staudinger and Robert, 2001). Because the calculated concentrations of AI in air were higher than anticipated at saturation, the estimated saturation concentrations were used instead in exposure calculations; in other words, it was assumed that the AIs are present at air-saturating concentrations. Because of this assumption, inhalation exposure is anticipated to be overestimated when calculated using SWIMODEL equations.

ChemSTEER was developed to predict the rate of volatilization of pure chemicals, not aqueous solutions; it also was validated using pure chemicals. Assumptions in the model include equilibrium (steady-state) conditions; evaporation and air flow occur in one direction only (parallel to the surface of the pool); air flow is a linear function of the distance above the liquid; there is essentially no mixing in the area above the liquid surface where the greatest portion of the concentration gradient exists; there is no significant difference in temperature between the liquid and air above it; and at atmospheric pressure, the chemical VP $\leq$ 35 mm Hg (Hummel *et*

al., 1996). Of these assumptions, only the last one is met with assurance with the examples presented here (see Table 1 for vapor pressures). Because this model estimates chemical movement into air from solution, any deviation from the steady-state assumption would give lower chemical concentration in air than estimated; thus, the model is anticipated to overestimate exposure, rather than underestimate it.

For both models, deviations from model assumptions are expected to result in overestimates for inhalation exposure of workers dipping nursery stock in pesticide solutions. No reason is apparent to prefer one model above the other, except that the most health-protective estimate is given by SWIMODEL. However, both models give inhalation exposure estimates that are orders of magnitude below the dermal exposure estimates for both AIs. Thus, the inhalation contribution to total exposure is considered negligible under both models.

Conclusion

In the absence of exposure monitoring data, several models were evaluated for their potential to estimate exposures of workers dipping nursery stock in pesticide solutions. Models were evaluated by determining the data and assumptions needed to use them, and results were calculated for models where appropriate.

For dermal exposure, two thin-film models were evaluated (E-FAST and ChemSTEER). The thin-film models were rejected because the thin-film assumption is considered inappropriate for this scenario (repeated immersion of hands in pesticide solution) and because neither model was based on acceptable data from aqueous solutions. Two skin diffusion models were evaluated (SWIMODEL and RAGS-E). Both models develop estimates of a skin permeability coefficient (K_p), and combine that with surface area of exposed skin and chemical concentration in solution to estimate absorbed dose. The RAGS-E model was anticipated to provide a better estimate because it includes non-steady state terms (see Table 4 and associated equations).

For inhalation exposure, a two-compartment model used by E-FAST was rejected as it required information about room size. Two volatilization mass balance models (SWIMODEL and ChemSTEER) were used to estimate inhalation exposure. The vapor concentration in air estimated by SWIMODEL was higher than the anticipated saturated vapor concentration (C_{sat}); for exposure estimates, C_{sat} was used to estimate inhalation exposure. Both SWIMODEL and ChemSTEER rely on numerous assumptions, and no reason was found to prefer one above the other besides the health-protectiveness of the larger exposure estimate that was obtained by SWIMODEL (see Table 6 and associated equations). In the examples given, inhalation exposure estimates were substantially below dermal exposure estimates, and inhalation exposure was determined to have a negligible contribution to total exposure. This result might not occur with all pesticide solutions.

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