Generic Scenario: Application of Agricultural Pesticides

This generic scenario covers the sector of the agricultural pesticide application industry that applies waterborne pesticides such as insecticides, herbicides, and fungicides for crop maintenance. Agricultural application of pesticides is the largest use of pesticides nationwide. Industry data indicate that $5.16 billion was spent on crop pesticides in 1992. Agricultural crop treatment was 85% of the total U.S. sales of pesticides in 1992 [1, p. 5]. Agricultural pesticide users include 975,500 certified applicators, mainly crop-treating services or individual farmers who apply pesticides to their own fields [2, p. 16].

The largest crop use of herbicide is for treatment of corn fields with the 1993 use of 220×10^6 lb active ingredient. Atrazine, alone or in combination with alachlor, metolachlor, or other herbicides, is the most commonly used material. Corn herbicides typically are applied by boom or aircraft spray for postemergence weed control [3, p. 14]. Corn and cotton are the two heaviest users of insecticides with 27×10^6 and 20×10^6 lb active ingredient, respectively. Chlorpyrifos and terbufos are the insecticides most commonly used on corn. Much of the insecticide used on corn is applied to the soil to control root worm larvae [3, p. 14]. The largest single crop use of fungicides is for protection of peanuts. The 1993 use of fungicides on peanuts was 6.5×10^6 lb active ingredient. The most commonly used fungicide is benomyl [3, p. 20].

The agricultural pesticide application industry must safely and efficiently control a variety of pests in many environments. As a result, the industry has evolved a broad range of formulations and application techniques to serve customer needs.

Chemical pesticides for waterborne spray application may be formulated as emulsifiable concentrates (ECs), wettable powders, water-soluble concentrates, or flowable powders [4, p. E-7]. ECs comprise a water-insoluble pesticide in a solvent along with emulsifiers and other additives. The concentrations of EC formulations typically range from 15 to 60% active ingredient and from 5 to 20% emulsifier, with ~1% suspension agent, <1% antifoam, and the remainder as solvent. Most pesticides do not dissolve in water but, combined with surfactants and dispersants, a solvent and the pesticide will disperse in water. The solvent usually is a volatile organic liquid, but in newer formulations the active ingredient is emulsified in water to form the concentrate [5, 6]. Flowable powders are liquid formulations containing a finely ground solid active ingredient suspended in a liquid carrier. Wettable powders are dry solid formulations where the active ingredient is sorbed onto finely ground dry carrier, usually clay, combined with a wetting agent to ensure the powder will disperse in water. Water-soluble formulations contain pesticides that are easily soluble in water. Water-soluble pesticides are not common.

In addition to the waterborne formulations, some pesticides are available in dust and granular forms. Formulations designed for dry dispersion are not covered by this scenario.

Application Scenario

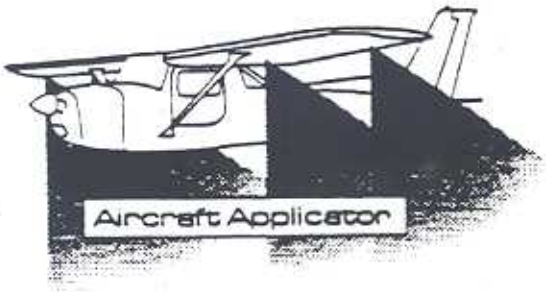
Pesticides usually are obtained as concentrates so the user is responsible for safely (1) storing the material; (2) transferring, mixing, and applying the material; and (3) recycling or disposing of excess concentrate, mixtures, rinsate, and containers. Legal uses, application methods, and required protective clothing for pesticides are specified in the label instructions. Deviation from label instructions is illegal. There are six general steps in agricultural pesticide application by waterborne spray:

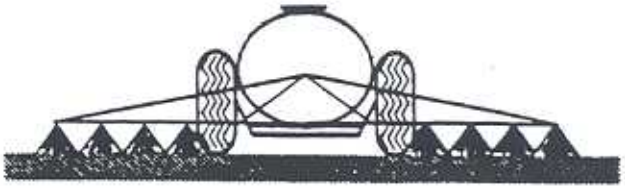
1. Prepare application equipment
2. Mix pesticides
3. Position application equipment
4. Apply the pesticides
5. Return application equipment to the staging area
6. Clean equipment.

This scenario covers four types of application equipment. Each system is designed for controlled application of waterborne pesticide but has different operating characteristics that affect the possible release quantities, worker exposure, or both. The four application systems are

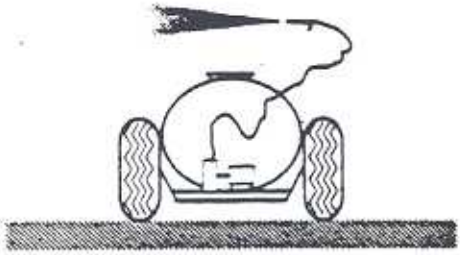
1. Aircraft spray [supply pressure ~100 to 300 kPa (14.5 to 43 psi)]
2. Large tank/boom sprayer [supply pressure ~100 to 300 kPa (14.5 to 43 psi)]
3. Large tank/hand-operated spray gun [supply pressure ~1000 kPa (145 psi)]
4. Large tank/roller or ropewick application (low pressure).

The systems are illustrated below.





Boom Sprayer



Spray Gun Applicator

Ropewick Applicator

Prepare application equipment: In the preparation step the workers first don the appropriate protective clothing, as defined by the label instructions, and then place the necessary spray equipment, pesticides, and water in a staging area.

Pesticides are distributed in a variety of container types. Containers for liquid pesticides in the half-pint to the 2.5-gallon range typically are made of plastic. Larger volume containers (holding 1 to 5 gallons) are metal. Liquid formulations for large-volume use can be supplied in portable, reusable mini-bulk plastic containers. Wettable powders usually are supplied in paper, plastic, or cardstock containers. A survey of farm users in Minnesota showed a strong preference for plastic jugs or bottles, with 56% of pesticide purchases reported in this size. Metal and mini-bulk containers each accounted for about 15% of pesticide container purchases. Plastic bags and paper containers accounted for about 7% and 4%, respectively [7].

Mix pesticides: Once the workers are dressed and the starting materials are obtained, the pesticide is mixed with water. The proportion of pesticide to water and the areal application rate are specified by label instructions. The spray solution typically is prepared by filling the application supply tank with a known quantity of water, adding a measured quantity of pesticide(s), and mixing. For larger tanks an internal mixer is provided. Industrial practice calls for triple rinsing empty containers to allow disposal of the rinsed containers as nonhazardous waste. The rinse solution normally is added to the spray tank, so release of pesticide in container rinsate is minimal.

Position application equipment: After the working solution is mixed in the tank, the equipment is moved from the staging area to the area to be treated. The three large-tank scenarios involve moving the tank containing the working solution of pesticide for some distance. A small amount of working solution may leak from the tank during transport.

Apply the pesticides: Once the application equipment and personnel reach the target area the pesticide working solution is applied. In general a broad-area application is used, but spot treatment is becoming more popular to minimize waste and reduce costs.

The aircraft spray scenario typically involves several workers. One worker will prepare the pesticide working solution. During application a pilot will fly the aircraft and operate the spray system. The aircraft typically travels at a ground speed of 145 to 210 km/hr (90 to 130 mph) with a spray release height of about 3 to 12 m (10 to 40 ft) [8]. Personnel on the ground position flags or balloons to assist the pilot in locating and spraying the required target areas. The large tank/boom scenario typically involves a single worker who drives the prime mover and operates an on/off valve to start and stop working solution flow to the spray boom at the back of the tank. The large tank/spray gun scenario typically involves two workers. One worker drives the prime mover while a second worker manually operates the sprayer. The large tank/roller or wick scenario is similar to the boom scenario. The boom with multiple spray nozzles is replaced by a roller applicator or a boom with dragging wicks.

Pesticide used (not released) is taken as material delivered to the target surface, which varies depending on the type of material and the target pest [9]. Some herbicides are applied to the foliage of weeds, whereas others are applied to the soil to arrest development of seeds. Insecticides and fungicides generally are applied to foliage, but in some cases these pesticides may be targeted to soil.

This generic scenario assumes that, to have a reasonable probability of reaching the target organism, a surface area must be covered with the active ingredient. The distribution of pesticides in the environment is very complex and is an active research area [4, p. E-2; 10; 11; 12; 13]. Some generalizations can be made from the data collected. The most widely used application method is spray through nozzles carried on a boom sprayer or aircraft. Conventional hydraulic nozzles produce droplets ranging in size from 10 to 1,000 microns. Droplets smaller than 100 microns tend to be carried by air currents until they evaporate. The potential for spray drift declines rapidly for particles larger than about 150 to 200 microns. Results from 80 spray deposit measurements made during periods with an average wind speed of 4.4 meters/sec indicate that the downwind drift averaged 9.2% of the material sprayed. A variety of ground-based equipment and techniques were used in these tests. The measurements indicated that, with reasonable care, the drift could be reduced to 5% or less [14]. Limited data were available on spray drift for aircraft spraying. The data indicate much higher drift losses can be expected for aircraft spray. Test of aircraft spray for postemergence herbicides indicated drift losses of 50% or more [15, p. 222].

The actual use of pesticide in terms of killing a target organism is quite low. The most conservative definition of efficiency is the proportion of the applied dose taken up by the receiving organism (or calculated as required to eliminate a damaging infestation if applied directly to the population). When measured in this very restrictive sense, efficiency is reported to range from about 0.025% for foliar spray of insecticide to 30% for spray application of herbicide [16].

Return application equipment to the staging area: After application of the working solution has been completed, the equipment is moved from the area to be treated back to the staging area.

Clean equipment: At the end of a spray campaign, the spray equipment is rinsed clean with water and protective equipment is cleaned or discarded. Cleaning consists of rinsing out the spray tank and application equipment, and discarding the disposable worker protective clothing. Major wastestreams produced by the cleanup operations are used protective clothing; empty, rinsed pesticide containers; rinsate from cleaning application equipment; rinsate from cleaning reusable protective clothing (particularly boots, gloves, and masks); and surplus working solution.

Pesticide material in the rinse may originate as inaccessible heel or holdup in the concentrate container, inaccessible heel in the application supply tank, excess working solution, or holdup in the applicator lines or equipment [17]. When consistent with label instructions, the rinse water is sprayed onto the treated area. This discharge is assumed to be a release to groundwater and surface water. In some cases, particularly for large-volume applicators, the rinse water is saved reuse in mixing the next batch. Therefore, not all of the pesticide in the rinse water is discharged as waste.

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Waste Generation, Environmental Releases, and Exposure-Level Calculations

A large number of agricultural pesticide users in the United States apply pesticides by many different methods. The main application methods are aircraft spraying or boom spray, but there is no "typical" pesticide application scenario from which per annum calculations can be extrapolated effectively. This scenario will, therefore, calculate environmental releases based on annual consumption of pesticide.

Accurate data are available on the total use of pesticide active ingredient in the United States. Two adjustments are needed to apply the raw pesticide use data for this scenario. Raw pesticide consumption statistics report the amount of active ingredient used. The premanufacturing notice probably will quote the expected-use concentration in the pesticide concentrate (active ingredient, inert vehicle, and additives). The scenario will apply an estimate of the concentration of active ingredient in typical pesticide concentrate to convert from active ingredient use to concentrate use.

The use figures do not differentiate between waterborne, granular, and aerosol application. Adjustment factors are used to estimate the quantity of pesticide use by waterborne spray application by ground equipment.

The environmental releases in the scenario are based on assumptions about the distribution of pesticide as applied. The actual distribution of the pesticide active ingredient, inert vehicle, and additives in the environment is a complex process. The various materials in the formulation distribute to the air, land, and water depending on material and media-specific properties such as soil adsorption, volatility, degradation rates, soil conditions, depth to groundwater, geologic conditions, climate, and irrigation practices (McBride, 1989). No attempts are made to model the complex redistribution of the pesticide after initial application. Pesticide that reaches the target surface is assumed to be used.

1. Environmental Releases

Variables/Assumptions:

PMN :	weight fraction of PMN material in pesticide concentrate formulation; given by manufacturere
AC :	annual consumption of pesticide active ingredient (a.i.) in agricultural applications; estimated use in 1991: herbicides, 495×10^6 pounds a.i.; insecticides, 175×10^6 pounds a.i.; fungicides, 75×10^6 pounds a.i.; other, 72×10^6 pounds a.i.; total, 817×10^6 pounds a.i. (U.S. EPA, 1991, p. 10)
FORM :	concentration of active ingredient (weight of a.i. per weight of total concentrate formulation); 0.33 as typical value with a range of 0.15 to 0.6 (estimate)
AQU :	percent of total concentrate applied as waterborne spray in general crop maintenance; assume (0.90 estimate)
CH :	fraction of concentrate not removed from container; 0.005 (Ozkan and Heimlich, no date)
CRR :	fraction of container rinsate not placed into the application tank at the time of mixing; 0.10 (estimate)
ML :	fraction of concentrate spilled in preparing application mix; 0.005 (estimate)
PL :	fraction of concentrate spilled during equipment movement; 0.001 of liquid concentrate (estimate)
SL :	fraction of concentrate applied but lost from target area as particle or vapor drift; 0.1 for boom or handgun spray application or 0.05 for roller or carpet wick (Bode, no date); 0.5 for aircraft application (Kirk et al., 1989, p. 222)

RL : fraction of concentrate applied in target area but not reaching the target surface; 0.25 for herbicide or soil insecticide application with ground equipment, 0.75 for insecticide or fungicide application to foliage with ground equipment; 0.4 for aircraft application (estimate)

UN : fraction of concentrate remaining in the spray tank after application, 0.05 (estimate)

CL : fraction of concentrate remaining on surfaces of application equipment and protective clothing, 0.01 (estimate)

FIELD: fraction of equipment rinsate sprayed onto application area, 0.7 (estimate).

Gross Calculations:

Total quantity of PMN chemical used: USE

General: USE = PMN*[(AC/FORM)*AQU]
Example: Insecticide spray for 1991
USE = PMN*[175×10^6 lb/yr 0.33)*0.85] = 477×10^6 PMN lb/yr

Total quantity of PMN chemical applied in target area: SPRAYED

General: SPRAYED = USE*[1 − CH*CRR − (ML + PL) − (UN + CL)]
Example: Insecticide spray for 1991
SPRAYED = 477×10^6 PMN*[1 − 0.005*0.1 − (0.005 + 0.001) − (0.05 + 0.01)] = 445×10^6 PMN lb/yr

Solid Waste: Assume all containers are triple-rinsed so that a negligible amount of pesticide concentrate remains in the discarded container. The only source of concentrate in solid waste is traces of material in disposable protective clothing. The quantity is assumed to be small. Solid waste also is generated by disposal of outdated or canceled pesticides. No data were available to quantify this potential solid waste source.

Air Emissions: The assumed path of air emissions is droplet evaporation or drift during the spraying operations.

General: Air Emission = SPRAYED*SL
Example: Insecticide spray for 1991 based on the conservative loss rate estimate assuming all material is applied by aircraft
Air Emission = 445×10^6 *PMN*0.5 = 223×10^6 *PMN lb/yr

Water Emissions: The assumed path for water emissions are spills and leaks, working solution sprayed in the target area but not remaining on the target surface, and rinse solutions sprayed onto the target area.

General: Water Emission = USE*{(ML + PL) + [(UN + CL) + (CH*CRR)]*FIELD} + SPRAYED*RL
Example: Insecticide spray for 1991 based on the conservative loss rate estimate assuming all material is applied by aircraft
Water Emission = 477×10^6 *PMN*{(0.005 + 0.001) + [(0.05 + 0.01) + (0.005*0.1)]*0.7} + 445×10^6 *PMN*0.4 = 198×10^6 *PMN lb/yr

2. User Exposure:

This generic scenario covers the application of agricultural pesticides for crop maintenance using waterborne pesticides. Human exposure to a PMN chemical contained in such a pesticide can include both occupational (farm) worker exposure and nonapplication (or nonoccupational) exposure. Of these two types of human exposure, farm worker exposure can be expected to be much more significant than nonapplication exposure due to farm workers' involvement in direct pesticide application activities.

Exposure from pesticide application activities will be primarily through inhalation and dermal routes. Nonapplication exposure may be from a combination of inhalation, ingestion, and dermal routes, although exposure through inhalation is likely to dominate the total exposure for most chemicals. Ideally, measurement studies would be the best approach to estimate exposure to the PMN chemical in the pesticide formulation. These studies could be conducted using existing methods for estimating dermal and inhalation exposure from pesticide applications (e.g., Lavy et al., 1982; Nigg et al., 1988; NOPES, 1990). If measurement studies cannot be conducted to estimate human exposure from PMN-pesticide application activities, literature-reported measurements of worker and nonoccupational exposure to pesticides may need to be used. However, inferring exposure to a PMN chemical based on measured exposure to pesticides would be subject to a great deal of uncertainty. Nevertheless, such an approach may be the only one feasible for a particular PMN evaluation and is developed further in this generic scenario.

A number of studies have been conducted in recent years to estimate occupational and nonoccupational exposure to pesticides. These studies have included measurements of airborne concentrations of pesticides during application activities, and measurements of indoor-outdoor air unrelated to application activities. Dermal exposure during pesticide application activities also has been studied. Lavy et al. (1982; and other references contained therein) studied occupational exposure from pesticide application for specific operators, such as pesticide mixers, tractor (or boom) sprayers, and aerial sprayers. Nigg et al. (1988) studied pesticide exposure of Florida greenhouse applicators; data were collected from handgunners (tank-type) using a variety of sprays, tractor drivers pulling boom or span sprayers, a drencher, and assisting personnel. Pesticide applications during the study were conducted in both enclosed and open-air environments. Yeary and Leonard (1993) recently measured pesticide breathing zone air concentrations during application to lawns, shrubs, and trees. The ongoing NCI-EPA NEFOES (NEFOES, 1993) study of farm occupational exposure also provides information on occupational or direct-application-related pesticide exposure.

EPA's recent Nonoccupational Pesticide Exposure Study (NOPES, 1990) investigated nonoccupational exposure to common pesticides. In that study, airborne concentrations of 32 different pesticides were measured both indoors and outdoors; during residential application events, dermal exposure of a small number of subjects also was monitored. The study was conducted in two separate geographic areas of the country, Jacksonville, Florida and Springfield-Chicopee, Massachusetts. Jacksonville was selected as representative of a high-pesticide-use area, whereas Springfield-Chicopee was believed to represent a low- to moderate-pesticide-use region. EPA's NEFOES study (NEFOES, 1993) also measured indoor-outdoor air concentrations in farm communities in close proximity to agricultural pesticide applications.

There are many difficulties associated with applying the exposure data reported in the above pesticide studies for estimating potential human exposure to a PMN chemical as required for this generic scenario. The PMN chemical's physical and chemical characteristics, such as vapor pressure and solubility, and its pesticide application parameters, such as application concentration, spray rate, and work procedures, will affect the extent of dermal and inhalation exposure from pesticide application. These characteristics must be adequately considered to extrapolate the literature-reported exposures for specific pesticides to provide estimates of potential exposure to a PMN chemical. One approach for this purpose is discussed below; the approach will require modification and refinement on a case-by-case basis depending on the nature of the PMN chemical.

(i) Inhalation Exposure:

Application-Related Exposure (Farm Worker):

Pesticide concentrations during application events have been measured in a number of studies. Typically, data from these studies consist of the breathing zone air concentration during the application event; the spray rate of active ingredient (a.i.); and the mode of spraying, e.g., tractor-driven boom spray, tank-based handgunner, backpack sprayer, etc. If one of the pesticides monitored in these studies has physico-chemical properties (vapor pressure, solubility, etc.) similar to those of the PMN chemical, then the measured breathing zone air concentration can be used to allow an estimate of the potential PMN air concentration, as:

$C_{Pesticide}$ * Pesticide (a.i.) Spray Rate / PMN Spray Rate = C_{PMN} (rough estimate).

where $C_{Pesticide}$ is the reported breathing zone air concentration of the pesticide ($\mu g/m^3$), the pesticide (a.i.) and PMN spray rates are in kg/hr, and C_{PMN} is the estimate of the breathing zone PMN concentration. For this approach to yield an appropriate estimate, the pesticide concentration must have been measured in a spray operation similar to that in question for the PMN chemical. For example, Nigg et al. (1988) measured a mean chlorpyrifos air concentration of 27 ± 6 $\mu g/m^3$ for a tractor driver using a boom sprayer. The pesticide (a.i.) spray rate was 0.962 ± 0.044 kg/hr in the applications and the applications were conducted in an outdoor (open-air) environment. Using these values, an estimate of the air concentration of potential exposure to a PMN chemical with similar characteristics as chlorpyrifos could be estimated for tractor-driven boom-spray application of the pesticide. Air concentrations for a number of other pesticides measured during a variety of spraying operations are presented by Nigg et al. (1988) and by Lavy et al. (1982).

Inhalation exposure during the spray operation is then estimated from the air concentration as:

$$C_{PMN}\ (\mu g/m^3) * 1.75\ m^3/hr * H\ (hr) = ??\ (\mu g),$$

where 1.75 m^3/hr is the inhalation rate (medium-duty work) and H is the duration of the application operation.

Nonapplication-Related Exposure:

Nonapplication-related exposure to the PMN chemical in the farm environment is much more difficult to estimate than application-related inhalation exposure. The air concentration of the PMN chemical will depend on its characteristics such as volatility, atmospheric reactivity, and lifetime, as well as the methods used for spray application of the pesticide formulation containing the PMN. An approach similar to that discussed above for the breathing zone PMN air concentration during pesticide application could be extended to estimate indoor/outdoor PMN concentrations in the farm environment. Again, monitoring data (from studies such as NEFOES) for a pesticide with physico-chemical and spray application characteristics similar to those of the PMN chemical would have to be available. Annual average indoor and outdoor air concentrations of the pesticide could be combined with information on pesticide and PMN annual application rates to provide a speculative estimate of the potential air concentration of the PMN chemical as a result of application operations. Differences in atmospheric reactivity between the PMN chemical and the monitored pesticide also must be considered.

(ii) Dermal Exposure:

Dermal exposure is expected to be significant only in application-related human exposure. Dermal exposure during pesticide application can be estimated using an approach similar to that discussed above for inhalation exposure. Nigg et al. (1988) derived Estimated Total Body Accumulation Rates (ETBAR) in mg deposited/kg of pesticide (a.i.) sprayed for a variety of pesticides and a number of pesticide spraying operators, such as handgunners (fine spray, coarse spray, and pulse fog), tractor drivers (span and boom spray), drenchers, and assisting personnel. The ETBARs were derived using results from dermal exposure pads placed at various places on the subjects' bodies, above any clothing or protective gear. The ETBARs thus provide an estimate of the pesticide accumulation rate on the body of an applicator unprotected by clothing of any kind, and can be appropriately scaled depending on the types of protective clothing used.

To estimate dermal exposure to a PMN chemical, an ETBAR derived for a pesticide with similar physico-chemical characteristics and spray application method can be used along with a scaling factor to account for the spray rate,

$$ETBAR_{Pesticide}\ (mg/kg) * \text{PMN Spray Rate}\ (kg/hr) * H = \text{Unprotected Dermal Exposure}_{PMN}\ (mg),$$

where $ETBAR_{Pesticide}$ is the measured accumulation rate for the pesticide similar to the PMN chemical, the PMN spray rate is in kg/hr, and H is the number of hours of application operation. The unprotected dermal exposure calculated can be reduced to account for protective clothing worn by the applicators. Nigg et al. (1988) derived penetration factors for a number of pesticides and a variety of protective clothing. Generally,

penetration rates varied from 0 to 23%, depending on the amount of pesticide to be transmitted and the compound itself. CEB (1991) provides guidance for use in estimating the efficacy of dermal protective clothing.

Exposure from mixing the pesticide formulation prior to application, and from cleaning the equipment at the end of spraying operations, also leads to dermal exposure. Assuming that mixing and cleaning operations are conducted with a frequency, FT (number/day), and using estimates of the typical dermal exposure from these types of routine contact operations (CEB, 1991), the dermal exposure to a PMN chemical in the pesticide formulation is:

$$(1{,}300\text{-}3{,}900)\ \text{mg} * \text{FT} * \%\text{PMN}/100 = ??\ \text{mg/day}$$

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