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A CRITICAL REVIEW OF ULTRALOW-VOLUME AEROSOLS OF INSECTICIDE APPLIED WITH VEHICLE-MOUNTED GENERATORS FOR ADULT MOSQUITO CONTROL[1]

GARY A. MOUNT[2]

Center for Medical, Agricultural, and Veterinary Entomology, Agriculture Research Service, U.S. Department of Agriculture, Gainesville, FL 32604

ABSTRACT. This review of ultralow-volume (ULV) ground aerosols for adult mosquito control includes discussion on application volume, aerosol generators, droplet size, meteorology, swath, dispersal speed, assay methods, insecticide efficacy, and nontarget effects. It summarizes the efficacy of ULV insecticidal aerosols against many important pest and disease-bearing species of mosquitoes in a wide range of locations and habitats in the United States and in some countries of Asia and the Americas. Fourteen conclusions were drawn from the review. 1) ULV ground aerosol applications of insecticide are as efficacious against adult mosquitoes as high- or low-volume aerosols. 2) ULV aerosols with an optimum droplet size spectrum can be produced by several types of nozzles including vortex, pneumatic, and rotary. Droplet size of a particular insecticide formulation is dependent primarily on nozzle air pressure or rotation speed and secondarily on insecticide flow rate. 3) Label flow rates of insecticide for ULV aerosol application can be delivered accurately during routine operations with speed-correlated metering systems within a calibrated speed range, usually not exceeding 20 mph. 4) The most economical and convenient method of droplet size determination for ULV aerosols of insecticide is the waved-slide technique. 5) The efficacy of ULV ground aerosols against adult mosquitoes is related to droplet size because it governs air transport and impingement. The optimum droplet size for mosquito adulticiding is 8–15 μm volume median diameter (VMD) on the basis of laboratory wind-tunnel tests and field research with caged mosquitoes. 6) In general, ULV aerosols should be applied following sunset when mosquitoes are active and meteorological conditions are favorable for achieving maximum levels of control. Application can be made during daytime hours when conditions permit, but rates may have to be increased. The critical meteorological factors are wind velocity and direction, temperature, and atmospheric stability and turbulence. 7) Maximum effective swaths are obtained with aerosols in the optimum VMD range during favorable meteorological conditions in open to moderately open terrain. The insecticide dosage must be increased in proportion to increased swath to maintain the same level of mosquito control. 8) Dispersal speed within a range of 2.5–20 mph is not a factor affecting efficacy if insecticide rate and optimum droplet size are maintained. 9) The results of caged mosquito assays are comparable with reductions in free-flying natural populations. 10) The field efficacies of mosquito adulticides applied as ULV ground aerosols are predictable from the results of laboratory wind-tunnel tests. 11) Results of field tests in open to moderately open terrain during favorable meteorological conditions indicated that ULV insecticidal aerosol application rates producing 90% or more control of *Anopheles, Culex,* and *Psorophora* spp. are below or ≈equal to maximum United States Environmental Protection Agency label rates. Against some *Aedes* spp., some pyrethroid insecticides must be synergized to produce 90% control at label rates. 12) Results of field tests in residential areas with moderate to dense vegetation and in citrus groves or other densely wooded areas showed that insecticide rates of ULV ground aerosols must be increased 2–3-fold to obtain 90% or more control of adult mosquitoes. However, the maximum rates on some insecticide labels would have to be increased to allow higher application rates. 13) Applications of ULV ground aerosols of insecticide in accordance with label directions following sunset do not pose a serious threat to humans, nontarget beneficial animals, or automotive paints. 14) Some aerosol generators operated at high RPM levels exceed the OSHA 8-h hearing hazard criteria of 90 dBA and may require hearing protectors for operators.

KEY WORDS Ultralow-volume, ULV, insecticide, adulticide, ground aerosol, mosquito, droplet size

INTRODUCTION

The recent review of ultralow-volume (ULV) aerial sprays of insecticide for mosquito control (Mount et al. 1996) provided a stimulus for a comparable review of ULV ground aerosols. No comprehensive review of ULV ground aerosols has been published previously, although Lofgren (1970, 1972) and Mount (1979, 1985) included ground aerosols in articles on ULV technology. ULV is the application of the minimum effective volume of an undiluted formulation of insecticide in liquid form as received from the manufacturer. The concentration of insecticide in an undiluted formulation may vary from only 2% for some of the pyrethroids to 85% or more for several of the liquid technical formulations of organophosphates. The application volume of an insecticide formulation is dependent on its liquid concentration and intrinsic toxicity to the target mosquito species. However, in cases where the applicator mixes the insecticide formulation with limited quantities of a solvent or carrier for various reasons, the application would be considered low volume (LV) because the minimum volume was not applied.

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[1] This article reports the results of research only. Mention of a proprietary product does not constitute an endorsement or a recommendation for its use by USDA.

[2] Retired collaborator.

Mount et al. (1968) introduced ULV ground aerosols for adult mosquito control following successful ULV aerial spray applications by Knapp and Roberts (1965) and Glancey et al. (1965). For ULV ground aerosol application, Mount et al. (1968) modified a nonthermal aerosol generator (Curtis® 55,000, Curtis Dyna-Fog Ltd., Westfield, IN) that had been developed by the U.S. Army Engineers Research and Development Laboratories, Fort Belvoir, VA (Edmunds et al. 1958). Previously, Mount et al. (1966) indicated that nonthermal aerosols of insecticides diluted in fuel oil or water were comparable in efficacy with high-volume (HV) thermal aerosols of insecticide diluted in fuel oil, the standard atomization method at that time. These results, confirmed by Mount and Lofgren (1967), Taylor and Schoof (1968), and Mount et al. (1969b), demonstrated that diluents and atomization methods were not critical to mosquito control. After initial studies by Mount et al. (1968, 1970b), McNeill and Ludwig (1970), Mount and Pierce (1971), Taylor and Schoof (1971), and Rathburn and Boike (1972a), the ULV ground aerosol method was quickly advanced by the development of commercial ULV generators and the registration of technical and highly concentrated formulations of insecticide for ULV ground aerosol application by the United States Environmental Protection Agency (US-EPA). Within a few years, the ULV ground aerosol method was adopted by many mosquito control organizations throughout the United States and other countries of the world. ULV has been the worldwide standard ground aerosol method of mosquito adulticiding for more than 25 years because of the inherent advantages over HV aerosols. These advantages include lower cost because of the elimination of oil diluents and fuel required for thermal atomization, elimination of the dilution process, an increased effective payload, more rapid and timely application, and increased safety by elimination of dense fogs created by HV thermal atomization.

This review includes references on vehicle-mounted ULV ground aerosol applications of insecticide that were published through 1997 and is presented in chronological order within topical area. Major topics are volume, aerosol generators, droplet size, meteorology, swath, speed, assay methods, efficacy, and nontarget effects. Also, 14 conclusions and 11 summary tables based on the review are provided.

VOLUME

The very essence of the ULV method is minimum application volume. The application of an effective dose of insecticide, undiluted as received from the manufacturer, against target species of mosquitoes is ULV. If the insecticide is diluted by the applicator, then the application is LV or HV. In some cases, manufacturers offer a series of concentrations of the same insecticide, all labeled as ULV formulations. For example, synergized permethrin is labeled and marketed as ULV formulations of 1.5, 3, 3.98, 4, 10, 12, 30, and 31.28%. Only the 30 and 31.28% formulations are ULV, whereas the others are LV or HV. HV applications require HV equipment and are now seldom used by organized mosquito control in the United States. LV applications, where the manufacturer's insecticide formulation is less than maximum concentration or is diluted by the applicator in light mineral oils, refined soybean oil, heavy aromatic naphtha (HAN), or other carriers, are applied with ULV aerosol generators. Are these dilutions needed to maintain or increase the efficacy and swath of various insecticide formulations? The following review shows clearly that diluents and increased volume do not enhance insecticidal efficacy or extend swath. Instead, they show an inverse relationship between dilution and volume. As the percentage of active insecticide in a formulation is decreased, the application volume must be proportionally increased to maintain the same level of mosquito kill. Inert diluents do not kill mosquitoes. Diluents represent only an added cost for purchase and handling. The ULV method was developed to avoid these unnecessary costs.

ULV versus HV: Results by Mount et al. (1968) indicated that the insecticidal efficacy of ground aerosols is unrelated to application volume. In their study, flow rates of 0.36 and 0.26 fl. oz./min of undiluted 95% malathion and 85% naled, respectively, applied at 5 mph provided caged mosquito kills over swaths of 600 ft. that equaled or exceeded kills with a HV rate of 85 fl. oz./min of equal doses of insecticide diluted in fuel oil and dispersed at 5 mph. Furthermore, in tests with natural populations of *Aedes taeniorhynchus* (Wied.) in citrus groves, they obtained better control with 0.51 fl. oz./min of 85% naled than with 85 fl. oz./min of naled diluted in fuel oil dispersed at twice the dose of naled as the ULV application. The initial results with caged mosquitoes by Mount et al. (1968) were confirmed by Mount et al. (1970b) and Rathburn and Boike (1972a), who demonstrated that flow rates of 1.43 and 1.11 fl. oz./min of 95% malathion were equal or better in efficacy over 600-ft. swaths than a HV rate of 85 fl. oz./min of the same doses of malathion diluted in fuel oil.

ULV versus LV: Against *Ae. taeniorhynchus,* Mount et al. (1972) reported equal results with ULV aerosols of 1.37 fl. oz./min of 85% naled and LV aerosols of 13.70 fl. oz./min of 8.5% naled diluted in HAN or soybean oil. However, the HAN formulation had to be atomized at a lower nozzle pressure than the other formulations to achieve an optimum droplet spectrum. Also, Rathburn et al. (1981, 1986) did not increase the efficacy of naled against *Aedes* and *Culex* spp. with formulations of 3–10% Dibrom®$_{14}$ in HAN or various oils applied at 10–21 fl. oz./min compared with results with undiluted Dibrom$_{14}$ (Valent, Walnut Creek, CA). In tests with chlorpyrifos applied at 10 mph over 1,500-ft. swaths against caged adult *Culex pipiens* Linn., Husted et al. (1975) reported slightly higher overall kills with 1.33–1.7 fl. oz./min of a 6-lb. AI/gal ULV formulation than with 7.8–9.0 fl. oz./min of a 1-lb. AI/gal LV formulation. Furthermore, Rathburn and Boike (1981) indicated similar kills of *Culex* spp. with flow rates of 2.1 fl. oz./min of 91% malathion and 3.2–4.3 fl. oz./min of 91% malathion mixed with HAN at a 7:5 ratio. However, Bunner et al. (1987) obtained higher mortalities of *Ae. taeniorhynchus* with a malathion:HAN mixture (1:4) than with undiluted 91% malathion. In their tests, better results with LV aerosols could have resulted from a difference in droplet spectrum rather than increased volume or increased toxicity. Finally, in tests at different times and locations with synergized resmethrin against caged *Anopheles quadrimaculatus* Say, Mount et al. (1974c) and Sandoski et al. (1983) reported results with flow rates of 2.57 and 0.9 fl. oz./min that were similar to those obtained with 12 fl. oz./min of comparable doses of insecticide and synergist diluted 1:8 in various oils (Weathersbee et al. 1991, Groves et al. 1994).

ULV flow rates: Although not designed as studies of application volume, many tests with caged adult mosquitoes have indicated 90% or more kill with flow rates of undiluted insecticide at ≈1 fl. oz./min or less dispersed at 10 mph. These tests include flow rates (fl. oz./min) of 0.84 of 91% malathion (Roberts 1983); 0.95, 0.97, and 0.79 of 93% fenthion (Mount et al. 1970b, 1978a; Mount and Pierce 1971); 1.01 of 85% naled (Mount et al. 1970b); 1.05 of 6 lb. AI/gal of chlorpyrifos (Rathburn and Boike 1975); 0.84 and 0.80 of 40% resmethrin (Rathburn and Boike 1972b, Sandoski et al. 1983); 0.90 of 18% resmethrin plus 54% piperonyl butoxide (Sandoski et al. 1983); and 0.79 of 3.6 lb. AI/gal permethrin (Kline et al. 1986). Moreover, in studies designed to determine minimum effective dose, flow rates of <0.5 fl. oz./min of various insecticides provided 50–90% mosquito kill because of low doses rather than insufficient application volume (Mount and Pierce 1971, 1972b; Mount et al. 1968, 1974c, 1978a). Flow rates of <0.5 fl. oz./min can be metered accurately with most ULV aerosol generators, which eliminates the need for dilution with most insecticide formulations unless specified by the label. Labels that require dilution should be modified to allow ULV application.

AEROSOL GENERATORS

Many improvements in ULV aerosol generators have been made since the modifications of a military nonthermal generator by Mount et al. (1968), who pointed out that other types of equipment could be used to produce ULV aerosols. Mount et al. (1970b) adapted an aerosol nozzle developed by Lowndes Engineering Co., Inc. (Leco®, Valdosta, GA) to a Leco 120 thermal aerosol generator and a Curtis 55,000 nonthermal military generator. Maximum nozzle pressure with the modified Leco 120 was only 3.5 psi, which was adequate for 3 fl. oz./min of 95% malathion volume median diameter [VMD] = 15 μm) but not for 6 fl. oz./min (VMD = 20 μm). McNeill and Ludwig (1970) also used a ULV conversion on a Leco 120 generator for application of 1.065–2.13 fl. oz./min of technical malathion. Anderson and Schulte (1970) described the practical aspects of converting thermal aerosol generators to ULV. Their conversion consisted of removing all parts from a Leco 120 or Tifa® 100E thermal machine (Tifa, Ltd., Millington, NJ) except the engine and blower and then installing an insecticide metering system and a Leco ULV nozzle. The insecticide metering system consisted of a stainless steel tank pressurized by the blower, chemical-resistant tubing, flow meter, needle valve, and solenoid valve for remote operation. With thermal generators modified for ULV application, Anderson and Schulte (1970) reported 2–3 times coverage capability per generator at less than 33% of the cost of previous operations with HV thermal aerosol generators.

In recent years, 6 aerosol generators, including the Leco 1600 (Robinson and Ruff 1990), London Fog® 18–20 ULV (Robinson and Ruff 1991a; London Fog, Inc., Long Lake, MN), Curtis Dyna-Fog® Maxi-Pro 4 ULV (Robinson and Ruff 1991b; Curtis Dyna-Fog, Ltd., Westfield, IN), Conner Engineering Bison® (Robinson and Ruff 1992; Clarke Engineering Technologies, Inc., Roselle, IL), Beecomist® Systems Pro-Mist 25HD ULV (Robinson et al. 1993; Beecomist Systems, Telford, PA), and VecTec® Grizzly (Robinson 1994; Clarke Engineering Technologies, Inc.), have been evaluated at the Pasco County Mosquito Control District, Odessa, FL (Collaborating Center on Testing and Evaluation of Pesticide Application Equipment for the World Health Organization). These comprehensive evaluations provide data on the manufacturer, price, chassis, dimensions, nozzle, blower/compressor, engine, fuel capacity and consumption, instrumentation, remote control, options, gauge accuracy, flow control accuracy, noise levels, and droplet spectrum.

Nozzles: Three types of nozzle systems have been used to generate ULV aerosols. These are low-air-pressure and high-air-volume vortex, high-air-pressure and low-air-volume pneumatic, and rotary sleeve. In this review, generators equipped with vortex nozzles were the Curtis Dynafog Cyclotronic and Maxi-Pro 4 ULV, Leco HD-ULV and 1600, London Fog 18–20 ULV, Micro-Gen® MS2–15 and LS2–15 (Whitmire Micro-Gen Research Laboratories, Inc., St. Louis, MO), Micro-Mist®, Tifa® 100-E-ULV, and VecTec Grizzly. Those using pneumatic nozzles were the Buffalo Turbine® Sonic, Conner Engineering Bison, and London Aire®

XW. The Beecomist Systems Pro-Mist 25 HD, Cardinal 150, and Whisper-Mist 10 used rotary-sleeve nozzles.

Insecticide metering systems: The widespread conversion from thermal aerosol generators to ULV generators by organized mosquito control stimulated interest in development of improved ULV insecticide metering systems. Metering systems were needed that could deliver accurate flow rates under a wide range of operating conditions. With a needle valve and flowmeter system, Rathburn and Boike (1972a) and Fultz et al. (1972) discovered the need for a temperature-corrected calibration curve for dispersing 95% malathion. Their observations indicated that an adjustment in the flowmeter setting was required with each 2°F variation in temperature. To eliminate the need for temperature correction and to improve flow rate accuracy, manufacturers of aerosol generators used positive displacement pumps with electronic speed control to vary flow rate. Once calibrated for a particular insecticide, positive displacement pumps would deliver constant flow rates, as shown by Fleetwood et al. (1980). By the end of the 1970s, commercial metering systems featuring advanced electronic technology had been developed that provided speed-correlated flow control (Street 1980). Also, a simpler mechanical method involving a speed-monitoring device was developed by James Robinson, Pasco County Mosquito Control District, Odessa, Florida, and described by Street (1980). Speed-correlated flow control systems are now standard technology for ULV aerosol generators and are capable of delivering flow rates within ≈6% of a target label rate during routine operations (Dame and Curtis 1990).

DROPLET SIZE

Prior to 1968, there was limited consideration of aerosol droplet size for mosquito control compared with the current emphasis. With thermal aerosols, a relationship between generator heater temperature, insecticide formulation flow rate, and mosquito kill had been determined by empirical methods. Recently, Brown et al. (1993b) collected droplets of no. 2 fuel dispersed from a Leco 120D thermal aerosol generator on hand-waved Teflon®-coated glass microscope slides (DuPont, Wilmington, DE) for determination of droplet size. Their results indicated VMDs of 15–18 μm for a flow rate of 29 gph and heater temperature of 750°F, which would be comparable with 40 gph and 850°F used by Mount et al. (1968) to generate HV thermal aerosols for comparison with ULV aerosols. Thus, the droplet size estimates by Brown et al. (1993b) suggested that the droplet spectra of thermal aerosols were similar to those for ULV aerosols. The VMD is a droplet diameter where 50% of the aerosol volume is in larger droplets and 50% is in smaller droplets. VMD is used in reference to both volume median diameter and mass median diameter in this review.

Measurement methods: The primary objective of droplet size measurement is to estimate the initial droplet spectrum as dispersed from the aerosol generator. This measurement is necessary to relate the droplet spectrum of the total aerosol volume to mosquito kill efficiency. Droplet size number distribution, by comparison, is relatively unimportant. For example, Mount and Pierce (1972a) reported that 83–94% of malathion droplets dispersed from a Leco HD-ULV generator operated at 4 psi were less than 5 μm in diameter. However, these small droplets represented only 7% of the total volume of malathion dispersed. In operational programs, droplet size measurement is needed to optimize mosquito kill efficiency and to meet label requirements, as emphasized by Walcher (1993). During the development of ULV ground aerosols, Mount et al. (1968) used methods reported by Yeomans (1949) for the initial droplet size estimates of technical malathion aerosols. Rathburn (1970) provided a comprehensive review of methods for assessing the droplet size of insecticidal sprays and aerosols, including Yeomans's method. This method, with modifications, is still in use because it is rapid, convenient, and economical. These modifications include replacement of silicone glass slide coating with Teflon for further reduction in droplet spread (Anderson and Schulte 1971), use of a "direct measurement method" and refinement of the focal-length method to determine droplet spread (Anderson and Schulte 1971, Mount and Pierce 1972a, Dukes et al. 1993), variation in slide-wave technique (Beidler 1975, Peterson et al. 1978, Carroll and Bourg 1979, Brown et al. 1990, Wilhide and Daniel 1995), and computer programs for rapid and convenient calculation of droplet size parameters (West and Cashman 1980, Sofield and Kent 1984, Boobar et al. 1986). Two additional methods of droplet size collection discussed by Rathburn (1970) include settling and impaction. Mount and Pierce (1972a) used these methods to confirm the accuracy of the slide-wave method described by Yeomans (1949).

Haile et al. (1978) developed a method for automatic measurement of the droplet size of insecticidal aerosols with a Coulter Counter® (Beckman Coulter, Inc., Fullerton, CA). Samples of technical malathion aerosols introduced into settlement chambers were collected in a liquid medium placed on the floor of the chamber. Automatic droplet count and size analysis was then accomplished by electronic current path interruption when the liquid containing the droplets passed through a small aperture. Concurrent sampling of droplets of malathion, fenthion, and Klearol® (white mineral oil) aerosols for VMD determination with the Coulter Counter method and standard microscope measurement showed similar results. However, Coulter estimates were less variable than microscope estimates because of the large difference in droplets measured per sample (50,000–100,000 in 90 sec for Coulter versus only 300 in 30 min or more for microscope). The disadvantages of the Coulter method were the high equipment cost and demanding protocol required for collecting, handling, and reading liquid samples. Nevertheless, results from the Coulter study confirmed the accuracy of the standard waved-slide method that is currently used to estimate the VMD of ULV aerosols.

A hot-wire instrument, the Army Insecticide Measuring System (AIMS), has been used operationally (Swartzell 1991) and compared with other methods (Brown et al. 1993c). Brown et al. showed that the hot-wire method produced VMDs that were similar to those obtained from Teflon-coated slides waved through the aerosol cloud or placed in a chamber used for aerosol settlement. However, they also determined that the hot-wire method was sensitive to the aerosol generator air blast and that a preferred sampling distance must be determined for each model of generator to obtain accurate data. Advantages of using AIMS were relative ease of use, large droplet sample (10,000 in 100 sec), and immediate analysis of results in the field.

Phillips and Kutzner (1994) used a Malvern® model 2000 laser droplet analyzer to compare the droplet sizes of malathion and permethrin aerosols dispersed from a Leco HD aerosol generator and a Beecomist Systems Pro-Mist 25 HD rotary atomizer. With a Leco HD dispersing 4.3 fl. oz./min of 95% malathion, their VMD estimate of 11 μm at 4.5 psi nozzle pressure was slightly less than estimates of 13–15 μm reported previously by Beidler (1975), Mount et al. (1975a, 1975b), Mount and Pierce (1976), and Rathburn and Boike (1977). The laser analyzer showed that most of the aerosol volume was in droplets of 5–25 μm diameter, which is comparable with 67–73% in the same range obtained by impaction and settling methods (Mount and Pierce 1972a). The VMD estimate for the same flow rate of 95% malathion dispersed by the Pro-Mist 25 HD generator was 17 μm, with most of the volume in the 5–25-μm-diameter range. The VMD estimates from the laser analyzer for 6 fl. oz./min of 4% permethrin plus 12% piperonyl butoxide were 9 and 20 μm for the Leco HD-ULV (4.5 psi) and the Pro-Mist 25 HD rotary atomizer, respectively. Previously, Mount et al. (1978a) estimated similar VMDs of 8 μm for a 2-lb. AI/gal formulation of permethrin dispersed by a Leco HD-ULV operated at 4 psi (waved-slide and settlement chamber methods).

Optimum droplet size: A critical factor in the successful development of ULV ground aerosols was droplet size. A review of previous research on droplet size (Mount 1970) suggested that the optimum droplet size for outdoor adult mosquito control was 11–20 μm. Thus, Mount et al. (1968, 1970b) varied droplet size by changes in nozzle air pressure and insecticide flow rate with ULV aerosol generators to study the relationship between droplet size and mosquito kill under field conditions (Table 1). Their results with three different dosages of 95% malathion indicated that aerosols of 8–15 μm VMD were consistently more effective against caged adult female *Ae. taeniorhynchus* than those of 15–28 μm VMD.

Table 1. Kill of caged adult female mosquitoes with ultralow-volume aerosols of 95% malathion as influenced by dose, droplet size, and downwind distance (after Mount et al. 1968, 1970b; Haile et al. 1982)

Dose (fl. oz./mi.)[1]	VMD (μm)[2]	Percentage kill at indicated feet downwind			
		150 ft.	300 ft.	600 ft.	Mean
	Aedes taeniorhynchus				
4.3	15–17	34	28	13	25
4.3	8–10	53	38	33	41
12.0	30–39	61	48	24	44
8.5–12.0	16–24	92	74	51	72
8.5–12.0	8–15	92	91	76	86
12.0	5	68	70	57	65
17.0	16–28	93	90	91	91
17.0	10–14	100	100	98	99+
	Anopheles quadrimaculatus				
12.0	30–39	67	48	29	48
12.0	24	95	68	60	74
12.0	8–15	85	73	63	74
12.0	5	87	69	56	71

[1] 1 fl. oz./mi. = 18.5 ml/km.

[2] Volume median diameter (VMD) values in Mount et al. (1968, 1970b) were multiplied by 1.25 to reflect a spread factor of 0.5 instead of 0.4 for silicone-treated slides.

[3] 1 ft. = 0.3048 m.

In a laboratory study, Weidhaas et al. (1970) determined that the minimum lethal dose (LD_{100}) of technical malathion for *Ae. taeniorhynchus* adult female mosquitoes was contained in a 25-μm-diameter droplet. They also extrapolated from malathion to determine that 20- and 17.5-μm-diameter droplets of 85% naled and 93% fenthion, respectively, would also contain LD_{100}s. The results of this study suggested that optimum droplet sizes for aerosols of these insecticides are likely not greater than the size containing the LD_{100} because larger sizes would contain more insecticide than necessary to kill a single mosquito.

In another study, Lofgren et al. (1973) used a scanning electron microscope to observe aerosol droplets impinged on adult mosquitoes. In field tests, caged adult female *Ae. taeniorhynchus* were exposed to ULV aerosols of soybean oil (used to simulate malathion) with a VMD of 19 μm. Results indicated that 100% of the total mass impinged on mosquito wings was in droplets of 2–16 μm diameter. Also, all of 39 droplets observed on the wings of free-flying female *Ae. taeniorhynchus* mosquitoes that had been exposed to ULV aerosols in the field were 1–8 μm diameter. In laboratory experiments, free-flying adult female *Ae. taenio-*

rhynchus were exposed to aerosols of soybean oil with a VMD of 7.7 μm that were produced with a Babington nebulizer (Litt and Swift 1972). Results showed that 99% of the total mass impinged on mosquito wings was in droplets of 2–10 μm diameter.

The results of the initial studies by Mount et al. (1968, 1970b) were confirmed by Haile et al. (1982) in both laboratory and field tests with caged mosquitoes. Analysis of malathion droplets produced from a Berglund-Liu Monodisperse Aerosol Generator in 18 different uniform sizes in a range of 2.8–32.8 μm and dispersed in a wind tunnel against *Ae. taeniorhynchus* indicated that the optimum droplet size range was 10–15 μm diameter. Also, insecticidal efficiency decreased rapidly for sizes smaller than 5 μm diameter and larger than 25 μm diameter. Field tests with 12 fl. oz./mi. of 95% malathion against *Ae. taeniorhynchus* and *An. quadrimaculatus* indicated 82% mosquito kill with 10- and 15-μm VMD aerosols compared with 33, 67, and 72% kill for 39-, 5-, and 24-μm VMD aerosols, respectively. These results are combined with those by Mount et al. (1968, 1970b) in Table 1.

Results by Rathburn and Dukes (1989) suggested that the initial droplet size (≈15 μm VMD) decreased ≈50% with droplets collected at 300 ft. downwind during winds of 2–3 mph (6.8 and 7.5 μm VMD in vegetated and open areas, respectively). A similar study by Brown et al. (1993a) indicated a decrease of ≈33% (27 to 18 μm VMD) in size of droplets collected at 300–400 ft. downwind from a Beecomist Systems Whisper-Mist 10 aerosol generator dispersing 4 fl. oz./min of 91% malathion during unspecified winds. Data from these 2 droplet collection studies suggest that the optimum droplet size for malathion aerosols is less than 15–27 μm VMD because the larger droplets in these applications remained airborne for less than 300 ft.

Recently, Curtis and Beidler (1996) studied the effect of droplet size of ULV permethrin aerosols on caged *Ae. taeniorhynchus* placed at distances of 100–500 ft. downwind in a mature citrus grove consisting of moderately dense vegetation. Their results indicated that, at equal doses, aerosols with a 15-μm VMD produced higher mosquito kills than aerosols with 7- and 26-μm VMDs. The 7-μm VMD aerosols gave consistently lower percentage kills at all distances than the other aerosols. Although the 26-μm VMD aerosols were about equal to the 15-μm VMD aerosols at 100–300 ft., they produced lower kills at 400 and 500 ft.

Droplet size estimates: Estimates of VMD for malathion are shown in Table 2, whereas those for chlorpyrifos, fenthion, naled, permethrin and propoxur are listed in Table 3. Only portions of the total data in two studies with malathion (Mount et al. 1968, Dukes et al. 1990) that included several combinations of nozzle pressures and flow rates are shown in Table 2. Results of the initial studies by Mount et al. (1968, 1970b) showed an inverse relationship between droplet size and nozzle pressure. Estimates of VMD consistently decreased as nozzle pressure increased. For example, at a flow rate of 1.5 fl. oz./min of 95% malathion, VMD decreased 64% (28 to 10 μm) as nozzle pressure increased 375% (1.6 to 6 psi). Their results also indicated a direct relationship between droplet size and insecticide flow rate, although the flow rate effect was less than that of nozzle pressure. At a constant nozzle pressure of 3.5 psi with the Leco ULV nozzle, the VMD increased only 33% (15 to 20 μm) as the flow rate of malathion was increased 400% (1.5 to 6 fl. oz./min). These relationships between droplet size of malathion aerosols and nozzle pressure or flow rate were confirmed by the results of Mount and Pierce (1972b), Peterson et al. (1976), Rathburn and Boike (1977), Haile et al. (1982), and Dukes et al. (1990). These relationships were also demonstrated for chlorpyrifos, naled, and permethrin (Mount and Pierce 1972a, 1972b; Curtis and Beidler 1996).

Estimates of VMD shown in Tables 2 and 3 indicated that all of the aerosol generators included in this review can, with appropriate nozzle pressure or rotational speed and flow rate combinations, atomize malathion and other insecticides to meet label requirements and achieve maximum or near maximum efficiency in killing adult mosquitoes. Although VMD estimates in Table 2 indicated that excessive atomization is not likely to occur with technical malathion at flow rates of 3 fl. oz./min or more, studies with less viscous or more volatile insecticide formulations indicated that overatomization is a possibility. For example, Mount and Pierce (1972b) estimated a 5-μm VMD and obtained unsatisfactory mosquito kill with naled diluted in heavy aromatic naphtha.

METEOROLOGY

For ULV ground aerosols of insecticide against adult mosquitoes, the critical meteorological parameters are wind velocity and direction, temperature, and atmospheric stability and turbulence. Although most of the research reviewed in this paper does not directly relate meteorology to mosquito control, general guidelines can be interpreted. Also, the results from one comprehensive study (Schatmeyer and Urone 1973) correlating meteorological parameters with mosquito kill are discussed. These investigators used a portable meteorological station that consisted of a trailer-mounted tower and electronic instrumentation housed in a van-type vehicle. The tower design was patterned after a similar unit used by Rathburn and Miserocchi (1969). The electronic equipment was arranged to continuously record meteorological measurements for 6 entire evenings of 3–4 aerosol runs per evening in a residential area of Gainesville, FL.

Wind velocity and direction: Some horizontal wind velocity is required to drift an insecticidal

Table 2. Volume median diameters (VMD) of ultralow-volume (ULV) ground aerosols of 91–96% malathion (Cythion®, Fyfanon®).

Aerosol generator[1]	Nozzle (psi)[2]	Fl. oz./min[3]	Sizing method[4]	VMD (μm)[5]	Reference
Curtis® 55,000[6]	1.6, 2.6, 4, 6	1.5	WS	28, 18, 14, 10[7]	Mount et al. (1968)
Leco® ULV	3.5	1.5, 3, 6	WS	15, 16, 20[7]	Mount et al. (1970b)
Leco HD-ULV	4	3.0	WS, SC, CI	18, 16, 17	Mount and Pierce (1972a)
Leco HD-ULV	2.5, 4, 5	3.0	WS	21, 18, 14	Mount and Pierce (1972b)
BTS, M-MS, L-HD	110, 4, 4	3.0	WS	25, 16, 15	Mount et al. (1975a)
M-LS, L-HD	6, 6	4.3	WS	12, 11	Mount et al. (1975c)
Leco HD-ULV	4.5	4.3	WS	14–15	Beidler (1975)
LA-XW,-L-HD	90, 4	4.3	WS	14, 15	Mount and Pierce (1976)
Leco HD-ULV	4.5, 5, 6	4.0	WS	17, 16, 14	Peterson et al. (1976)
BTS, LA-XW, M-LS	100, 90, 4.5	4.3	WS	14, 11, 12	Rathburn and Boike (1977)
MM, T-100, L-HD	65, 4, 4	4.3	WS	14, 17, 14	Rathburn and Boike (1977)
Leco HD-ULV	4	4.3	WS, Coulter Counter®	17–22, 17–27	Haile et al. (1978)
Leco HD-ULV	4	4.3	WS	11–18	Peterson et al. (1978)
Leco HD-ULV	3.5	4.0	WS, SC	21–25, 19–26	Carroll and Bourg (1979)
Leco HD-ULV	1, 3, 5, 7.5	1.0	Coulter Counter	30, 15, 10, 8	Haile et al. (1982)
London Aire® XW	90	1.0	Coulter Counter	5	Haile et al. (1982)
CDC, L-HD, L-HD-2	6	4.3	WS	13, 15, 14	Dukes et al. (1990)
CDC, L-HD, L-HD-2	7	8.6	WS	14, 16, 16	Dukes et al. (1990)
Leco 1600	6	4.3, 8.6	WS	15, 17	Robinson and Ruff (1990)
London Aire 18-20	6	4.3, 8.6	WS	16, 18	Robinson and Ruff (1991a)
Dyna-Fog® Maxi-Pro 4	6	4.3, 8.6	WS	15, 17	Robinson and Ruff (1991b)
Leco MD-ULV	8	6.0	WS	14–24	Perich et al. (1992)
Conners Engr. Bison®	90	4.3, 6.5	WS	16, 19	Robinson and Ruff (1992)
Leco HD-ULV	5	8.6	WS, AIMS	16, 16	Brown et al. (1993c)
Pro-Mist® 25HD ULV	—[8]	4.3, 6.5, 8.6	WS	15, 17, 18	Robinson et al. (1993)
L-HD, PM-25	4.5, —[8]	4.3	Laser analyzer	11, 17	Phillips and Kutzner (1994)
VecTec® Grizzly ULV	7.3–7.4	4.3, 8.6	WS	16, 17	Robinson (1994)

[1] L-HD = Leco® HD-ULV; L-HD-2 = Leco HD-ULV with 2 MD nozzles; BTS = Buffalo Turbine® Sonic; M-MS = Micro-Gen® MS2-15; M-LS = Micro-Gen® LS2-15; LA-XW = London Aire® XW; MM = Micro Mist®; T-100 = Tifa® 100-E-ULV; CDC = Curtis Dynafog® Cyclotronic; PM-25 = Beecomist® Systems Pro-Mist 25.

[2] Nozzle pressures for respective aerosol generators (1 psi = 6.894757 kPa).

[3] Flow rates for respective nozzle pressures and aerosol generators (1 fl. oz./min = 29.7 ml/min).

[4] Sizing methods for respective flow rates, nozzle pressures and aerosol generators. WS = waved slide; SC = settlement chamber; CI = cascade impactor; AIMS = Army Insecticide Measuring System.

[5] VMDs for respective sizing methods, flow rates, nozzle pressures, and aerosol generators.

[6] Modified for ULV.

[7] VMD values in references were multiplied by 1.25 to reflect a spread factor of 0.5 instead of 0.4 for silicone-coated slides.

[8] Not applicable because atomization was achieved by rotation (30,000+ RMP) instead of pressure.

Table 3. Volume median diameters (VMD) of ultralow-volume (ULV) ground aerosols of chlorpyrifos, fenthion, naled, permethrin, and propoxur.

Aerosol generator	Nozzle (psi)[1]	Fl. oz./min[2]	Sizing method	VMD (µm)[3]	Reference
			Chlorpyrifos, 6 lb. AI/gal (Dursban®)		
Leco® HD-ULV	1.5, 4	3.2	Waved slide	17, 10	Mount and Pierce (1972a)
Leco HD-ULV	1.5, 4	3.2	Settlement chamber	18, 10	Mount and Pierce (1972a)
Leco HD-ULV	1.5, 4	1.6	Waved slide	15, 9	Mount and Pierce (1972b)
Leco HD-ULV	1.5, 4	3.2	Waved slide	17, 10	Mount and Pierce (1972b)
Military generator[4]	3.5	1.3	Settlement chamber	9	Husted et al. (1975)
Leco HD-ULV	4	1.6	Waved slide	9	Mount et al. (1975c)
			Fenthion, 93% (Baytex®)		
Leco HD-ULV	4	2	Waved slide	10	Mount et al. (1975c)
Leco HD-ULV	4	1	Waved slide, Coulter Counter®	13, 13	Haile et al. (1978)
			Naled, 8.5% in heavy aromatic naphtha (Dibrom®)		
Leco HD-ULV	1.5, 4	7	Waved slide	15, 5	Mount and Pierce (1972b)
			Permethrin, 2 lb. AI/gal		
Leco HD-ULV	4	2	Waved slide, settlement chamber	8, 8	Mount et al. (1978a)
			Permethrin plus piperonyl butoxide, 4% + 12%		
Leco HD-ULV	4.5	6	Lazer analyzer	9	Phillips and Kutzner (1994)
Pro-Mist® 25	—[5]	6	Laser analyzer	20	Phillips and Kutzner (1994)
			Permethrin, 57% (Punt®)		
Dynafog® Cyclotronic	4.5, 3, 0.5	0.8	Waved slide	7, 15, 26	Curtis and Beidler (1996)
			Permethrin plus piperonyl butoxide, 31% + 66% (Permanone®)		
Leco 1600	3.2	9.4	Waved slide	16	Meisch et al. (1997)
			Propoxur, 1 lb. AI/gal (Baygon®)		
Leco HD-ULV	4	11.5	Waved slide	14	Mount et al. (1975c)
			Propoxur, 1.67 lb. AI/gal (Baygon®)		
Leco HD-ULV	4	9	Waved slide, settlement chamber	9, 9	Mount et al. (1978a)

[1] 1 psi = 6.894757 kPa.

[2] 1 fl. oz./min = 29.7 ml/min.

[3] VMDs for respective sizing methods, flow rates, and nozzle pressures.

[4] Modified for ULV.

[5] Not applicable because atomization was achieved by rotation (30,000+ rpm) instead of pressure.

aerosol cloud across the target area, typically 1 or 2 city blocks in width. The wind velocities indicated for all but 1 of the field efficacy studies summarized herein were <1–11 mph with an overall mean of ≈3.5 mph. Thus, wind velocities of 1–7 mph, with gusts not exceeding 11 mph, are likely the most suitable for aerosol applications against adult mosquitoes. Against caged *Ae. taeniorhynchus* and *Culex nigripalpus* Theobald, Rathburn and Boike (1972b) obtained slightly higher kill during wind velocities of 6–11 mph (78%) than 1–6 mph (68%) when mosquitoes were exposed to aerosols of 95% malathion and 3.3 lb. AI/gal resmethrin. From 21 separate aerosol runs during 6 evenings, Schatmeyer and Urone (1973) constructed a statistical linear model that indicated that mosquito kill was directly related to wind velocity. Even though their study included wind velocities of only 0.4–2.5 mph, the model predicted improved mosquito kill with increased wind velocity to ≈4 mph. Schatmeyer and Urone also speculated that wind velocities greater than 4 mph might be used to assist aerosol penetration into vegetated areas but only at short range. Because of a limited wind velocity range (<1–7 mph), Curtis and Mason (1988) were unable to demonstrate any statistically significant relationship between wind velocity and kill of caged adult female *Ae. taeniorhynchus* in a Florida citrus grove.

Wind direction data predict the direction of aerosol cloud drift. In experimental applications, wind direction should be parallel with rows of caged mosquito or observation stations and perpendicular to the aerosol generator line of travel. Floore et al. (1991) stated that their tests were not done when wind direction varied >45° from perpendicular to swath direction. Although not stated by other investigators, this procedure has been followed in most ULV ground aerosol studies. Other techniques that have been used to account for deviations in wind direction include calculation of actual downwind distance (Schatmeyer and Urone 1973) and statistical correction in mosquito kill for increased exposure distance (Curtis and Mason 1988, Curtis and Beidler 1996). For operational applications in large urban and suburban areas with extensive road networks, complete coverage can be obtained regardless of wind direction unless wind direction changes frequently during application. Frequent wind direction shifts during an application can cause incomplete coverage and require retreatment.

Temperature: Ambient temperature is important because it influences mosquito activity, but it may or may not influence the efficacy of some insecticides. Also, the vertical temperature gradient is 1 factor that determines atmospheric stability, which is discussed in the next section. Ambient temperatures reported for field efficacy studies included herein were 63–89°F with a mean of ≈79°F. Low temperatures can reduce the effectiveness of insecticides, as indicated by Stevens and Stroud (1967), who reported possible recovery of adult *Aedes stimulans* (Walker) in 12 h following an application of propoxur spray at ≈60°F in Michigan. However, Mount et al. (1969a) obtained satisfactory control of *Aedes* spp. with aerial sprays of malathion during ambient temperatures of <60°F in subarctic Alaska, where mosquitoes are apparently adapted to host-seeking activity during relatively low temperatures as compared with mosquito species in temperate and tropical climates. In Michigan, Knepper (1988) showed no correlation between temperature over a wide range (54–90°F) and percentage kill of *Cx. pipiens* and *Culex restuans* Theobald with a mixture of malathion, resmethrin and HAN. Furthermore, Curtis and Mason (1988) showed no temperature effect within a range of 74–89°F with applications of naled against caged *Ae. taeniorhynchus* in a Florida citrus grove.

Atmospheric stability and turbulence: Atmospheric stability and turbulence are important factors that influence aerosol cloud diffusion across the target swath. Factors that determine atmospheric stability are wind velocity, temperature gradient, and time of day. The relatively stable air associated with evening (≈6–11 p.m.) is generally considered the most suitable for aerosol applications. Of the field efficacy studies in this review that indicated application times, 85 and 15% were accomplished with evening and morning applications, respectively. Aerosol applications in the evening are usually more efficacious than those made in the morning because of more favorable meteorological conditions. For example, with aerosols of 95% malathion against *Ae. taeniorhynchus,* Mount and Pierce (1976) obtained a 90% effective rate of 0.162 lb. AI/acre with morning applications, whereas previous evening applications indicated 90% effective rates of 0.025–0.076 lb. AI/acre (Mount and Pierce 1971, 1972b; Mount et al. 1974c, 1975b, 1975c). Nevertheless, Mount and Pierce (1974) obtained more satisfactory daytime control of *Ae. taeniorhynchus* in small residential areas in the Florida Keys with morning aerosol applications of naled than with evening applications because of rapid and heavy mosquito reinfestation.

Stability ratios have been used as a measure of suitable meteorological conditions for wide-swath (660–5,280 ft.) aerosol applications against mosquitoes in California pastures. Womeldorf and Mount (1977), Miller et al. (1982) and Townzen et al. (1987) calculated stability ratios from a formula adapted from Haugen et al. (1961) as follows:

$$\text{Stability ratio} = \frac{t_2 - t_1 \times 10^5}{\bar{u}^2}$$

where

t_2 = temperature (°C at 10 m)

t_1 = temperature (°C at 3 m)

$\bar{u}$ = average wind velocity (cm/sec).

Table 4. Kill of caged adult female *Aedes taeniorhynchus* with ground aerosols of 18 fl. oz./mi. of 95% malathion as influenced by wind velocity, stability ratio, distance, and elevation, Gainesville, FL (after Schatmeyer and Urone 1973).

			Percentage 18-h kill at indicated feet downwind and (feet) elevation					
Evening[1]	Wind velocity[2] (mph)	Stability ratio[3] (3–98 ft.)	150 ft.	300 ft.			500 ft.	Mean
			(3 ft.)	(3 ft.)	(30 ft.)	(50–100 ft.)	(3 ft.)	(3 ft.)
1	1.4	0.5	44	23	32	—	7	25
2	1.2	−2.9	56	45	59	—	28	43
3	2.0	0.9	58	58	81	—	20	45
4	1.5	4.1	42	34	85	89	20	32
5	0.6	177.0	89	76	71	3	59	75
6	2.0	−1.1	81	47	92	84	57	62

[1] Each evening consisted of 3–4 runs of 3 fl. oz./min of 95% malathion dispersed with a Leco HD-ULV aerosol generator operated at 4 psi and 10 mph (aerosol applications by G. A. Mount) (1 fl. oz./acre = 29.7 ml/min; 1 psi = 6.894757 kPa).

[2] Mean value calculated as aerosol cloud drift velocity (1 mph = 1.609 km/h).

[3] Mean value calculated after Haugen et al. (1961) (1 ft. = 0.3048 m).

All but 2 of the stability ratios reported by these investigators were positive, thus indicating ground-based inversions with warmer air at the higher elevation.

Schatmeyer and Urone (1973) studied the influence of wind velocity, stability ratio, downwind distance, and caged mosquito elevation on kill of adult female *Ae. taeniorhynchus,* and a summary of their results is presented in Table 4. Of 6 evenings, each consisting of 3–4 runs, the highest mean mosquito kill (75%) obtained at 3 ft. elevation was during a strong ground-based inversion. This inversion occurred during evening 5, which produced the highest mean stability ratio of any evening. Mean mosquito kill at 3 ft. of elevation for the other evenings ranged from 25 to 62% even though stability ratios were negative for evenings 2 and 6. Runs during evening 5 also produced only 3% mosquito kill at 50–100 ft. of elevation compared with 84–89% kills at these elevations during evenings 4 and 6. Thus, these results showed that the strong inversion during evening 5 retarded vertical movement of the aerosol cloud beyond 30 ft. of elevation. A low level of turbulence also restricted aerosol elevation during evening 5. Measures of turbulence for evenings 1–4 and 6 were about equal but were much greater than those for evening 5 (Schatmeyer and Urone 1973). In contrast to evening 5, mosquito kills at 50–100 ft. of elevation were about equal to kills at 3 ft. of elevation during evenings 4 and 6 at 300 ft. downwind (Table 4). Schatmeyer and Urone concluded from their model that mosquito kill was inversely related to the vertical atmospheric turbulence and spreading effects produced by vertical differences in horizontal wind velocity.

SWATH

The effective swath of ULV ground aerosol applications is determined by droplet size, insecticide rate, meteorology, and target environment. Most aerosols are applied in urban and suburban areas where a network of streets allows coverage of a target area large enough to provide several days of mosquito control before retreatment is required because of mosquito reinfestation. In small target areas of less than 1 mi.^{2}, application may have to be made more frequently to provide satisfactory control. With most applications, insecticide flow rates are usually set to provide an effective swath of 1 or 2 city blocks. Thus, most of the studies reviewed herein included observations of caged mosquitoes or counts of natural mosquito populations over swaths of 300–600 ft. However, several investigators have used swaths >600 ft. against mosquitoes in California pastures.

Droplet size: Results by Mount et al. (1968, 1970b) and Haile et al. (1982) shown in Table 1 show that the effective swath of an aerosol application is related to droplet size. Against caged adult female *Ae. taeniorhynchus,* a VMD range of 8–15 μm provided an effective swath (92% mean kill) of 300 ft. at a dose of 8.5–12 fl. oz./mi. of 95% malathion, whereas a VMD range of 16–24 μm was effective (92% mean kill) for only 150 ft.

Insecticide rate: Numerous investigators have demonstrated the effect of an insecticide rate on the effective swath. Mount et al. (1968, 1970b) showed that a dose of 4.3 fl. oz./mi. of 95% malathion did not produce an effective swath at any downwind distance, whereas 17 fl. oz./mi. was effective for 600 ft. even when the VMD was above the optimum range. Mount et al. (1968, 1970b) also reported 85–100% mean kill or reduction for 300-ft. swaths with 6–12 fl. oz./mi. of 85% naled against caged and natural populations of *Ae. taeniorhynchus* in an open field and citrus grove, respectively, but no effective swath with only 3 fl. oz./mi. of 85% naled.

Stains et al. (1969) demonstrated the effect of an increased insecticide dose by dispersing massive rates of 396 and 446 fl. oz./mi. of 85% naled and 6 lb. AI/gal chlorpyrifos, respectively, to achieve effective swaths of 1–2 mi. against caged adult *Culex tarsalis* Coquillett at Skaggs Island, Sonoma County, California, with flat, open terrain and 6–8-mph winds. Also at Skaggs Island, Husted et al. (1975) obtained 87% mean kill of caged *Cx. pipiens* at 150–1,000 ft. downwind with 8–10 fl. oz./mi. of 6-lb. AI/gal chlorpyrifos.

Against caged adult *Culex quinquefasciatus* Say in Arkansas, Thompson and Meisch (1977) showed that 6–12 fl. oz./mi. of 2-lb. AI/gal permethrin provided effective swaths (93–100% kill) of 300 ft., whereas 4 fl. oz./mi. was effective for only 100 ft. In another Arkansas study, Sandosky et al. (1983) reported data indicating that 10.8 fl. oz./mi. of 1.5-lb. AI/gal resmethrin plus 4.5 lb. AI/gal piperonyl butoxide had an effective swath (90–99.9% kill of caged *An. quadrimaculatus*) of 300 ft., whereas 5.4 fl. oz./mi. did not produce 90% kill at any distance.

Womeldorf and Mount (1977) obtained effective swaths of 1,320 ft. with 60 and 118 fl. oz./mi. of 5% pyrethrins plus 25% piperonyl butoxide and 25% resmethrin, respectively, against natural populations of *Aedes nigromaculis* (Ludlow) in California pastures. Also, rates of 24–36 fl. oz./mi. of 26% bendiocarb produced 800–1,125-ft. swaths in California pastures (Miller et al. 1982, Townzen et al. 1987).

Against caged *Ae. taeniorhynchus* exposed in a moderate to heavily vegetated Florida citrus grove, Curtis and Mason (1988) showed that 21.6 fl. oz./mi. of 85% naled provided an effective swath (88–100% kill) of 500 ft., whereas 7.2 fl. oz./mi. was effective (94% mean kill) for only 100 ft. These results suggest that an insecticide rate higher than the label rate is required for 90% or more adult mosquito control in moderate to heavily vegetated target areas.

Meteorology: The results by Schatmeyer and Urone (1973) shown in Table 4 indicated that a strong ground-based inversion (evening no. 5) characterized by stable air and reduced turbulence greatly enhanced mosquito kill over downwind distances of 100–500 ft. Although Curtis and Mason (1988) associated downwind distance with mosquito kill, they were unable to show a correlation between wind velocity and mosquito kill. Some of the variation in mosquito kill in their tests may have been caused by other meteorological factors, such as low-level atmospheric stability and turbulence, that were not measured.

Vegetation and other obstacles: Moderate to dense vegetation and other obstacles, such as homes and solid walls or fences, will limit the effective swath of an aerosol application. Mount et al. (1968) used 12 fl. oz./mi. of 85% naled to reduce a natural population of *Ae. taeniorhynchus* >90% in moderately dense citrus groves over a 300-ft. swath, whereas only 6 fl. oz./mi. was needed to kill >90% of caged adult female *Ae. taeniorhynchus* exposed in an open field. Taylor and Schoof (1971) also obtained twice the level of kill of 3 species of mosquitoes exposed to 95% malathion aerosols over 600-ft. swaths in an open area as those exposed in a moderately dense wooded area. Caged *Psorophora columbiae* (Dyar and Knab) mosquitoes exposed to 93% fenitrothion aerosols in the center of a wide privet hedge were killed at only half the rate of those exposed in the open (Walker et al. 1981). Curtis and Mason (1988) obtained >90% kill of caged adult female *Ae. taeniorhynchus* over 500-ft. swaths in a moderately to densely vegetated citrus grove with 21.6 fl. oz./mi. of 85% naled, whereas the labeled rate of 7.2 fl. oz./mi. provided only 34–58% kill. Rathburn and Dukes (1989) observed 2.5 times more droplets with >3 times greater volume when 91% malathion aerosols were sampled in an open residential area compared with a densely vegetated residential area. Floore et al. (1991) showed that aerosols of technical malathion and 18% resmethrin plus 54% piperonyl butoxide were more efficacious against caged adult *Ae. taeniorhynchus* and *Cx. quinquefasciatus* exposed in an open residential area than in a moderately vegetated residential area. Also, Linley and Jordan (1992) obtained higher percentage kills of caged *Cx. quinquefasciatus* exposed to aerosols of malathion, naled, and resmethrin plus piperonyl butoxide in open than in vegetated terrain.

Droplet collection studies by Rathburn and Dukes (1989) and Brown et al. (1993a) indicated that, although droplet density was greatly reduced by vegetation, the droplet size of malathion aerosols was only slightly smaller when collected in vegetation than in the open. Thus, the application of insecticidal aerosols with a smaller droplet size than 8–15 μm VMD would not likely reduce the limiting effect of vegetation on swath and overall mosquito kill.

Dense housing can also limit the swath of ULV aerosols. In Thailand, Pant et al. (1971) used swaths of only ≈150 ft. for indoor application to kill adult *Aedes aegypti* (Linn.) They obtained 1-day, 3-day, and 5-day posttreatment reductions of 82–99%, 74–89%, and 56–63%, respectively, in numbers of adult female mosquitoes collected on humans with aerosol applications of 95% malathion. A portion of the malathion aerosol was blown indoors by moving a vehicle-mounted ULV generator as close as possible past the open doors and windows of the houses and commercial buildings in target villages. The aerosol generator was moved at a speed of ≈3 mph with the nozzle discharge to the side facing the open windows and doors. Flow rates of technical malathion were 3.5–4.4 fl. oz./min, which produced a dose of 70–80 fl. oz./mi., a rate near that required for effective ULV aerial sprays of malathion against *Ae. aegypti* in Thailand (Lofgren et al. 1970a, 1970b) and >4 times greater than the rate required for 90% kill of caged adult mosquitoes exposed in open terrain.

SPEED

When an effective insecticide dose (fl. oz./mi.) and appropriate atomization are maintained for a designated swath, dispersal speed is not a factor affecting efficacy. Results by Mount et al. (1970b) indicated no difference in the effectiveness of 95% malathion aerosols dispersed at 10 and 20 mph with equivalent doses. Moreover, many investigators, including Mount and Pierce (1971, 1972b, 1976), Mount et al. (1974c, 1975a, 1975b), Rathburn and Boike (1975), Fultz and Carter (1980), and Dukes et al. (1990), have used dispersal speeds of 2.5–20 mph to vary the dose of various insecticides being evaluated for efficacy against adult mosquitoes. Factors that determine the appropriate speed for ground aerosol application are driving conditions in the target area, atomization capacity of the aerosol generator, and insecticide label specifications. The primary reason for higher speeds is, of course, greater coverage capability with each application unit. With speed-correlated insecticide metering systems on ULV aerosol generators, vehicle speed can be varied within calibrated limits (for example, 5–20 mph) and still maintain a constant insecticide dose without any adjustment by the operator. However, with automated operation, droplet size will vary somewhat with change in flow rate as discussed previously. Thus, the droplet sizes of maximum and minimum flow rates within a designated speed range must be determined to ensure atomization within the optimum range and compliance with insecticide labels. Devices for automatic adjustment of nozzle air pressure or rotational speed to maintain constant droplet size output with variation in vehicle speed and insecticide flow rate are technically feasible, but their use on aerosol generators has not been reported.

ASSAY METHODS

The principal method of evaluating the efficacy of insecticidal aerosols has been with caged adult female mosquitoes. There are several advantages in using caged mosquitoes to determine the efficacy of ground aerosols instead of using natural, free-flying mosquito populations. The caged mosquito method provides rapid, economical, and standardized evaluation, whereas assays of natural populations of mosquitoes require additional resources. Also, results with natural population assays can be less certain because of mosquito reinfestation following aerosol application, especially in small target areas of less than 1 mi.^{2}

Comparison of results with caged and free-flying mosquitoes: Results from direct comparisons of caged mosquito and free-flying population methods of assay justify the use of caged mosquitoes. Against *Ae. taeniorhynchus* in Florida, Mount et al. (1966) obtained similar kills of caged wild female adult mosquitoes (70–76%) and reductions in free-flying natural populations (62–75%) simultaneously exposed to HV aerosols (both thermal and nonthermal) of 15 fl. oz./mi. of 85% naled in densely vegetated citrus groves. Also, Pant et al. (1971) obtained 91% kill of caged adult *Cx. quinquefasciatus* (cited as *Culex fatigans*) placed inside houses and exposed simultaneously to the malathion aerosols that reduced the natural population of *Ae. aegypti* by 90%. Against *Ps. columbiae* (cited as *Psorophora confinnis* Lynch Arribalzaga) in Lonoke, AR, a town of ≈1.6 mi.^{2} of typical residential area with moderately dense vegetation, Mount et al. (1972) dispersed 18 fl. oz./mi. of 95% malathion and obtained similar results with caged wild mosquitoes (96% kill) and free-flying natural populations of mosquitoes (91–94% reduction) exposed simultaneously to the aerosol applications. Also, in California pastures, Womeldorf and Mount (1977) observed kills (58–100%) of caged *Cx. quinquefasciatus* that were similar to reductions (69–96%) of natural *Ae. nigromaculis* populations from simultaneous exposure to aerosols of synergized pyrethrins and resmethrin. Finally, against *Ae. taeniorhynchus* in a 50-acre residential beach community in Crescent Beach, FL, Mount et al. (1978b) showed that kills (59–70%) of caged adult females and 45-min posttreatment reductions (56–72%) of a natural population were essentially the same from simultaneous exposure to propoxur aerosols applied at 57–114 fl. oz./mi. of a 1-lb. AI/gal formulation. With aerosol applications of 7.2 fl. oz./mi. of 85% naled in the same community, the percentage kill of caged mosquitoes was somewhat less than the percentage reduction of the natural population (65 versus 85%).

Cage materials: Various cage materials have been tested for insecticide droplet penetration and mosquito kill efficiency. Mount et al. (1966) described a double compartment cage separated by a plastic slide mechanism that was used successfully for many years to evaluate ULV ground aerosols of insecticide. One side of the cage consisted of a 1.75-in. × 5.5-in. cylindrical plastic tube lined with clean paper and covered with a plastic screen on 1 end, whereas the opposite side consisted of an equal size cylindrical tube of 16-mesh galvanized screen wire. During aerosol exposure, all mosquitoes were confined to the screen portion of the cage with the slide in the closed position and the screen end of the plastic tube covered with masking tape to prevent contamination. After aerosol exposure, the tape was removed, the slide was opened to blow mosquitoes into the uncontaminated plastic tube for posttreatment kill observations, and then the slide was closed. Breeland (1970) used a variety of metal, plastic, and nylon screens in ULV aerial spray droplet penetration tests and observed that nylon and galvanized screen were almost equal to unscreened controls. In another ULV aerial spray study, Mount et al. (1970c) observed higher kill (91%) of mosquitoes exposed in 16-mesh galvanized screen wire cages than kill (6–37%) in 32- or 60-mesh galvanized screen wire cages or kill (6–66%) in various fabric cages including nylon. Townzen and Natvig (1973) used 18-mesh nylon net for construction of disposable cages routinely used in field assays with adult mosquitoes. Rathburn et al. (1989) obtained essentially the same percentage kill of adult female *Ae. taeniorhynchus* and *Cx. quinquefasciatus* exposed to ULV ground aerosols in the Townzen and Natvig disposable cages of cardboard and 18-mesh nylon net and their standard metal cages with 14- × 18-mesh bronze screen wire. However, Rathburn et al. used CO_2 anesthesia to transfer all mosquitoes to clean holding cages for observation following aerosol exposure, whereas Townzen and Natvig left mosquitoes in the exposure cages for observation of kill. Boobar et al. (1988) reported that aerosol droplet penetration of sentinel cages was directly related to the percentage of open area in the screen materials. With ULV aerosols of fenitrothion and bendiocarb, Bunner et al. (1989a) showed that kill of adult female *Ae. aegypti* was slightly less (68–75%) when mosquitoes were transferred to clean cages following exposure than when left in the contaminated exposure cages (72–87%).

Cage configuration, orientation, and placement: In addition to cage materials, the cage design, orientation to the prevailing wind, and placement height can influence mosquito assay results. Rathburn et al. (1969) demonstrated the effect of cage orientation and placement on results with ULV aerial sprays of insecticide. With a flat cage design, they obtained higher kills with vertical (34 and 87%) than horizontal (16 and 23%) cages at both ground level and 6 ft. above the ground, respectively. Rathburn et al. also indicated no difference in results with flat and cylindrical cages. With applications of ULV ground aerosols of synergized pyrethrins and resmethrin against caged *Cx. quinquefasciatus* in California pastures, Womeldorf and Mount (1977) obtained higher kill of mosquitoes in cages placed at 3 ft. above the ground (92%) than at 0.5 ft. above the ground (73%). Similarly, Tapley et al. (1980) obtained 91 and 77% kill of caged mosquitoes of 8 different species at heights of 5.3 and 1.3 ft., respectively, that were exposed to aerosols of 25% bendiocarb. On the basis of wind tunnel tests, Bunner et al. (1989b) suggested that a cylinder, screened on all sides, with the longitudinal axis perpendicular to the ground would provide a consistent cage profile to the wind, regardless of wind direction.

INSECTICIDE EFFICACY

The efficacy of potential mosquito adulticides is determined initially in laboratory wind-tunnel tests. New insecticides are compared against a standard adulticide, usually malathion. Those insecticides with a toxicity equal to or greater than the standard are considered for field trials. Other factors for consideration prior to field testing include mammalian toxicity, potential nontarget effects, and commercial availability.

Laboratory wind-tunnel tests: A summary of the relative toxicities of nonthermal aerosols of mosquito adulticides tested in laboratory wind tunnels is presented in Table 5. Because of the variation in methods, materials, and measures of toxicity in various reports, results are given as the reciprocal ratio of each insecticide to malathion and are listed in order of decreasing toxicity. The most toxic mosquito adulticides were synergized pyrethrins and the pyrethroids, deltamethrin, permethrin, fluvalinate, resmethrin, and phenothrin. Note that the toxicities of permethrin and resmethrin were increased by ≈4-fold when synergized with piperonyl butoxide. Against *Ae. taeniorhynchus,* Mount et al. (1974a) showed that the maximum toxicity of pyrethrins was achieved with a 1:5 ratio of insecticide to piperonyl butoxide, whereas the toxicity of resmethrin was enhanced with each ratio increase from 1:1 to 1:25 of resmethrin to piperonyl butoxide. With pyrethrins and the pyrethroids, toxicities varied considerably among genera with *Anopheles* spp. having the highest reciprocal ratios to malathion. The 2 carbamates, bendiocarb and propoxur, were intermediate in toxicity, and the 5 organophosphates, fenitrothion, fenthion, chlorpyrifos, naled, and malathion, were the least toxic. Reciprocal ratios to malathion among genera did not vary more than 2.6-fold with any of the carbamate or organophosphate adulticides.

Effective rates in field tests: In all insecticide efficacy field studies including 3 or more discriminating doses, probit analysis (Raymond 1985) was used to estimate rates of insecticide needed for 90% mosquito control. With 2 doses, probit paper was used to estimate the 90% effective rate. Thus, effective doses for 90% control indicated in this summary may differ slightly from those shown in some of the original reports. When only 1 dose was tested that produced 90% or more control, that dose is included in the tables. For convenience and comparability, data from all studies were converted, when necessary, to indicate application speed in mph, flow rate in fl. oz./min, and rate in lb. AI/acre. Although much of the insecticide is not deposited because aerosols are space treatments, the quantity of insecticide per unit area is a convenient and comparable term for indicating the rate needed for satisfactory control. Insecticide flow rates in units of time or distance are also commonly used to indicate the insecticide rate; however, flow rates must be associated with a swath to be meaningful. Effective rates are based on insecticide concentration, flow rate, vehicle speed, and kill of caged or reduction of natural populations of adult mosquitoes, usually within 24 h, over a 300-ft. swath, unless otherwise indicated in the tables.

Results of successful tests: The rates of ULV

Table 5. Summary of relative toxicities of nonthermal aerosols of insecticides to adult mosquitoes in laboratory wind-tunnel tests (after Mount et al. 1970a, 1971, 1974b; Mount and Pierce 1973, 1975; Pierce et al. 1973; Coombes et al. 1977; Zboray and Mount 1977; Rathburn et al. 1982; Magnuson et al. 1985; Floore et al. 1992).

	Reciprocal ratio to malathion				
Insecticide	*Aedes* spp.[1]	*Anopheles* spp.[2]	*Culex* spp.[3]	*Psorophora* sp.[4]	Mean
Deltamethrin	77.5	—	—	18.0	47.8
Permethrin + PBO, 1:5	—	42.8	—	—	42.8
Resmethrin + PBO, 1:5	13.5	52.0	18.5	7.4	22.9
Permethrin	9.4	13.0	—	9.7	10.7
Pyrethrins + PBO, 1:5	9.4	15.5	5.2	5.8	9.0
Fluvalinate	0.6	—	16.7	—	8.7
Resmethrin	3.2	16.5	3.7	—	7.8
Phenothrin	1.2	—	14.2	—	7.7
Bendiocarb	4.7	—	3.1	—	3.9
Propoxur	2.9	5.0	—	3.2	3.7
Fenitrothion	2.9	—	4.6	2.6	3.4
Fenthion	4.7	2.9	1.8	2.6	3.0
Chlorpyrifos	3.1	2.8	2.9	2.0	2.7
Naled	2.2	2.1	2.4	1.8	2.1
Malathion[5]	1.0	1.0	1.0	1.0	1.0

[1] *Aedes aegypti* (Linn.), *Ae. nigromaculis* (Ludlow), and *Ae. taeniorhynchus* (Wied.).

[2] *Anopheles albimanus* Wied. and *An. quadrimaculatus* Say.

[3] *Culex nigripalpus* Theobald and *Cx. quinquefasciatus* Say.

[4] *Psorophora columbiae* (Dyar and Knab).

[5] In tests using the same methods and materials, concentrations of malathion were 428, 364, 388, and 140 ppm for 90% kill of *Aedes, Anopheles, Culex,* and *Psorophora* spp., respectively, in 12–24 h posttreatment.

ground aerosols of insecticide observed to provide 90% or more kill of caged mosquitoes or, in a few cases, reduction of natural mosquito populations are presented in Tables 6–10 and are summarized in Table 11. With 3 exceptions, Table 11 summarizes all of the results presented in Tables 6–10. These exceptions were with malathion and included the indoor applications by Pant et al. (1971) and Perich et al. (1990) and the morning tests with marginal meteorological conditions reported by Mount and Pierce (1976). Also, 3 exceptions to 90% or more control (72–85%) are footnoted in Tables 6–9. The flow rates in Tables 6–11 reflect only the undiluted insecticide formulations as indicated and do not include any diluents although some investigators used diluents in their tests, especially with pyrethroid insecticides.

Insecticides summarized in Table 11 are listed in order of decreasing efficacy. Results show that 5 pyrethroids, including cyfluthrin, deltamethrin, lambda cyhalothrin, cypermethrin, and synergized phenothrin, were the most effective insecticides tested as ULV ground aerosols against adult mosquitoes. Other highly effective pyrethroids were fenvalerate and fluvalinate. Highly efficacious pyrethroids that have US-EPA registration include synergized phenothrin, synergized permethrin, synergized pyrethrins, permethrin, synergized resmethrin, phenothrin, and resmethrin. One highly effective carbamate, bendiocarb, is US-EPA registered for use. Organophosphate adulticides requiring higher doses than the pyrethroids include fenthion, chlorpyrifos, naled, and malathion. These insecticides have been registered by US-EPA for >25 years as ULV ground aerosols to control adult mosquitoes.

With most of the adulticides, the US-EPA maximum label rate equals or exceeds the effective rate shown for each mosquito genus in Table 11. The maximum label rate for synergized pyrethrins and unsynergized or synergized permethrin, phenothrin, and resmethrin is 0.007 lb. AI/acre, which equals or exceeds the effective rate for each of these adulticides tested against *Anopheles* and *Culex* spp. However, against *Aedes* spp., unsynergized phenothrin and resmethrin had effective rates above the maximum label rate of 0.007 lb. AI/acre. The effective rate of 0.0079 lb. AI/acre for synergized resmethrin against *Aedes* spp. was only slightly more than the label rate, whereas no data for synergized phenothrin against *Aedes* spp. have been reported. With bendiocarb, the effective rate (0.006 lb. AI/acre) for *Aedes, Anopheles,* and *Culex* spp. was only ≈one-half the maximum label rate of 0.011 lb. AI/acre. The maximum label rate of 0.03 lb. AI/acre for fenthion exceeds the effective rates for *Aedes, Anopheles,* and *Culex* spp. by almost 3-fold, which allows the application of rates that may be effective even when meteorological conditions are marginal or when aerosols are applied in moderately dense vegetation. The maximum label rate of 0.02 lb. AI/acre for naled is essentially the same as the effective rate for each genus. With malathion, effective rates for each genus were less than the maximum label rate of 0.054 lb. AI/acre.

Results of unsuccessful tests: Not all trials with ground ULV aerosols of insecticide have been highly successful in controlling adult mosquitoes.

Table 6. Rates of ultralow-volume (ULV) ground aerosols of 91–96% malathion (Cythion®, Fyfanon®) for 90% or more control of adult mosquitoes.

Species	Location	Habitat	Aerosol generator	Speed[1] (mph)	Flow rate[2] (fl. oz./min)	Rate[3] (lb. AI/acre)	Reference
Aedes taeniorhynchus (Wied.)	Florida	Open field	Curtis 55,000[4]	5	0.63	0.061 c	Mount et al. (1968)
Ae. taeniorhynchus	Florida	Open field	Leco ULV	10	6.02	0.076 c	Mount et al. (1970b)
Culex quinquefasciatus Say	Texas	Open field	Leco ULV	10	1.58	0.020 c	McNeill and Ludwig (1970)
Ae. taeniorhynchus	Florida	Open field	Leco ULV	10	2.00	0.025 c	Mount and Pierce (1971)
Aedes aegypti (Linn.)	Thailand	Indoors	Leco ULV	3	4.00	0.326 n[5]	Pant et al. (1971)
Ae. taeniorhynchus	Georgia	Residential	Leco ULV	10	3.77	0.048 c	Taylor and Schoof (1971)
Anopheles albimanus (Wied.)	Georgia	Residential	Leco ULV	10	2.37	0.030 c	Taylor and Schoof (1971)
Cx. quinquefasciatus	Georgia	Residential	Leco ULV	10	4.69	0.059 c	Taylor and Schoof (1971)
Ae. taeniorhynchus	Florida	Residential	Leco ULV	5	1.35	0.034 c	Rathburn and Boike (1972a)
Culex nigripalpus Theobald	Florida	Residential	Leco ULV	5	3.01	0.076 c	Rathburn and Boike (1972a)
Ae. taeniorhynchus	Florida	Open field	Leco HD-ULV	10	5.63	0.071 c	Mount and Pierce (1972b)
Psorophora columbiae (Dyar and Knab)	Arkansas	Residential	Leco HD-ULV	10	3.00	0.038 c,n	Mount et al. (1972)
Ae. taeniorhynchus	Florida	Open field	Leco HD-ULV	10	4.76	0.060 c	Mount et al. (1974c)
Ae. taeniorhynchus, Aedes sollicitans (Walker)	N. Carolina	Residential	Leco HD-ULV	10	4.30	0.054 n	Axtell and Dukes (1974)
Ae. taeniorhynchus	Florida	Open field	Leco HD-ULV	10	4.93	0.062 c	Mount et al. (1975b)
Anopheles quadrimaculatus Say	Florida	Open field	Leco HD-ULV	10	4.22	0.053 c	Mount et al. (1975b)
Ae. taeniorhynchus	Florida	Open field	Leco HD-ULV	10	4.07	0.051 c	Mount et al. (1975c)
Ae. taeniorhynchus	Florida	Open field	Micro-Gen MS	10	4.65	0.059 c	Mount et al. (1975c)
An. quadrimaculatus	Florida	Open field	Leco HD-ULV	10	2.40	0.030 c	Mount et al. (1975c)
An. quadrimaculatus	Florida	Open field	Micro-Gen MS	10	3.80	0.048 c	Mount et al. (1975c)
Ae. taeniorhynchus	Florida	Open field	Leco HD-ULV	10	12.85	0.162 c	Mount and Pierce (1976)
Ae. taeniorhynchus	Florida	Open field	Lond. Aire XW	10	15.15	0.191 c	Mount and Pierce (1976)
An. quadrimaculatus	Florida	Open field	Leco HD-ULV	10	9.30	0.117 c	Mount and Pierce (1976)
An. quadrimaculatus	Florida	Open field	Lond. Aire XW	10	9.83	0.124 c	Mount and Pierce (1976)
Ae. taeniorhynchus	Florida	Residential	Various[6]	10	2.13	0.027 c	Rathburn and Boike (1977)
Cx. nigripalpus	Florida	Residential	Various[6]	10	2.13	0.027 c	Rathburn and Boike (1977)
Ae. taeniorhynchus	Florida	Residential	Leco HD-ULV	10	1.40	0.017 c	Rathburn and Boike (1981)
Cx. quinquefasciatus	Florida	Residential	Leco HD-ULV	10	2.10	0.025 c	Rathburn and Boike (1981)
Ae. taeniorhynchus	Florida	Open field	Leco HD-ULV	10	2.00	0.024 c	Roberts (1982)
An. quadrimaculatus	Florida	Open field	Leco HD-ULV	10	2.00	0.024 c	Roberts (1982)
An. quadrimaculatus	Arkansas	Open field	Leco HD-ULV	10	3.00	0.036 c	Walker and Meisch (1982)
Ae. taeniorhynchus	Florida	Open field	Leco HD-ULV	10	1.24	0.015 c	Roberts (1983)
An. quadrimaculatus	Florida	Open field	Leco HD-ULV	10	0.84	0.010 c	Roberts (1983)
Ae. aegypti	Dom. Rep.	Indoors	Leco HD-ULV	5	9.00	0.218 c[7]	Perich et al. (1990)
Ae. taeniorhynchus	Florida	Residential	Leco HD-ULV	10	2.10	0.025 c	Floore et al. (1991)
Cx. quinquefasciatus	Florida	Residential	Leco HD-ULV	10	2.10	0.025 c	Floore et al. (1991)
Ae. aegypti	Malaysia	Residential	Leco HD-ULV	5	3.01	0.076 c[8]	Vythilingam and Panart (1991)

[1] A speed of 10 mph is indicated when a range of speeds (2.5–20 mph) was used to vary insecticide dose (1 mph = 1.609 km/h).

[2] Flow rate of technical or concentrated insecticide formulation as received from the manufacturer without diluent added by investigator (1 fl. oz./min = 29.7 ml/min).

[3] Rate based on insecticide concentration, flow rate, vehicle speed, and kill of caged (c) or reduction of natural (n) populations of adult mosquitoes, usually within 24 h, over a 300-ft. swath unless otherwise indicated (1 lb. AI/acre = 1.12 kg AI/ha).

[4] Modified for ULV application.

[5] Based on a 150-ft. swath.

[6] Includes Leco® HD-ULV, Micro-Gen® LS2-15, London Aire® XW, Buffalo Turbine® Sonic, Micro Mist®, and Tifa® 100-E-ULV.

[7] Mosquito kills of 100 and 44% outside and inside of houses, respectively.

[8] Mosquito kills of 92 and 39% outside and inside of houses, respectively.

Table 7. Rates of ultralow-volume (ULV) ground aerosols of chlorpyrifos, fenitrothion, fenthion, and naled for 90% or more control of adult mosquitoes.

Species	Location	Habitat	Aerosol generator	Speed[1] (mph)	Flow rate[2] (fl. oz./min)	Rate[3] (lb. AI/acre)	Reference
		Chlorpyrifos, 6 lb. AI/gal (Dursban®, Mosquitomist®)					
Culex quinquefasciatus	Texas	Open field	Leco ULV	10	1.25	0.005 c	McNeill and Ludwig (1970)
Aedes taeniorhynchus	Florida	Open field	Leco ULV	10	1.81	0.014 c	Mount and Pierce (1971)
Ae. taeniorhynchus	Florida	Open field	Leco HD-ULV	10	2.56	0.020 c	Mount and Pierce (1972b)
Psorophora columbiae	Arkansas	Residential	Leco HD-ULV	15	3.20	0.017 n	Mount et al. (1972)
Ae. taeniorhynchus	Florida	Residential	Leco HD-ULV	10	1.05	0.008 c	Rathburn and Boike (1975)
Culex nigripalpus	Florida	Residential	Leco HD-ULV	10	1.66	0.013 c	Rathburn and Boike (1975)
Cx. quinquefasciatus	California	Open field	Military[4]	10	1.33	0.010 c	Husted et al. (1975)
Ae. taeniorhynchus	Florida	Residential	Leco HD-ULV	10	1.34	0.010 c	Rathburn et al. (1981)
Cx. nigripalpus	Florida	Residential	Leco HD-ULV	10	2.13	0.017 c	Rathburn et al. (1981)
Cx. quinquefasciatus	California	Open field	Custom built	6	2.00	0.008 c[5]	Townzen et al. (1987)
			Chlorpyrifos, 12%				
Aedes aegypti	Mexico	Open field	Leco 500	10	6.50	0.008 c	Velazquez-Quintana et al. (1995)
Cx. quinquefasciatus	Mexico	Open field	Leco 500	10	6.50	0.008 c	Velazquez-Quintana et al. (1995)
Ae. taeniorhynchus	Florida	Open field	Leco ULV	10	1.49	0.019 c	Mount and Pierce (1971)
Anopheles quadrimaculatus	Arkansas	Open field	Leco HD-ULV	10	2.22	0.029 c	Walker et al. (1981)
Ps. columbiae	Arkansas	Open field	Leco HD-ULV	10	2.22	0.029 c	Walker et al. (1981)
		Fenitrothion, 95% (Sumithion®, Accothion®)					
Ae. taeniorhynchus	Florida	Residential	Leco HD-ULV	10	2.13	0.028 c	Rathburn et al. (1981)
Cx. nigripalpus	Florida	Residential	Leco HD-ULV	10	2.13	0.028 c	Rathburn et al. (1981)
			Fenthion, 93% (Baytex®)				
Ae. taeniorhynchus	Florida	Open field	Leco ULV	15	0.95	0.008 c	Mount et al. (1970b)
Ae. taeniorhynchus	Florida	Open field	Leco ULV	10	0.97	0.012 c	Mount and Pierce (1971)
Ae. taeniorhynchus	Florida	Residential	Leco HD-ULV	10	1.07	0.013 c	Rathburn and Boike (1975)
Cx. nigripalpus	Florida	Residential	Leco HD-ULV	10	1.07	0.013 c	Rathburn and Boike (1975)
Ae. taeniorhynchus	Florida	Open field	Leco HD-ULV	10	1.45	0.018 c	Mount et al. (1978a)
An. quadrimaculatus	Florida	Open field	Leco HD-ULV	10	0.79	0.010 c	Mount et al. (1987a)
		Naled, 85%, 14 lb. AI/gal (Dibrom®)					
Ae. taeniorhynchus	Florida	Open field	Curtis 55,000[4]	5	0.39	0.014 c	Mount et al. (1968)
Ae. taeniorhynchus	Florida	Wooded	Curtix 55,000[4]	5	0.65	0.024 n	Mount et al. (1968)
Ae. taeniorhynchus	Florida	Open field	Leco ULV	15	1.01	0.012 c	Mount et al. (1970b)
Ae. taeniorhynchus	Florida	Open field	Leco HD-ULV	10	1.37	0.025 c	Mount and Pierce (1972b)
Ae. taeniorhynchus	Florida	Open field	Leco HD-ULV	10	1.37	0.025 c	Mount and Pierce (1972b)
Ps. columbiae	Arkansas	Residential	Leco HD-ULV	10	1.20	0.020 n	Mount et al. (1972)
Ae. taeniorhynchus	Florida	Residential	Leco HD-ULV	10	1.81	0.033 n	Mount and Pierce (1974)

Table 7. Continued.

Species	Location	Habitat	Aerosol generator	Speed[1] (mph)	Flow rate[2] (fl. oz./min)	Rate[3] (lb. AI/acre)	Reference
			Naled, 85%, 14 lb. AI/gal (Dibrom®)				
Ae. taeniorhynchus	Florida	Residential	Leco HD-ULV	5	0.60	0.020 n[6]	Mount et al. (1978b)
Ae. taeniorhynchus	Florida	Residential	Leco HD-ULV	10	0.75	0.012 c	Rathburn et al. (1981)
Cx. nigripalpus	Florida	Residential	Leco HD-ULV	10	0.75	0.012 c	Rathburn et al. (1981)
Ae. taeniorhynchus	Florida	Residential	Leco HD-ULV	10	1.00	0.018 c	Rathburn et al. (1986)
Cx. quinquefasciatus	Florida	Residential	Leco HD-ULV	10	1.00	0.018 c	Rathburn et al. (1986)
Cx. nigripalpus	Florida	Residential	Leco HD-ULV	10	1.00	0.018 c	Rathburn et al. (1986)

[1] A speed of 10 mph is indicated when a range of speeds (2.5–20 mph) was used to vary insecticide dose (1 mph = 1.609 km/h).

[2] Flow rate of technical or concentrated insecticide formulation as received from the manufacturer without diluent added by investigator (1 fl. oz./min = 29.7 ml/min).

[3] Rate based on insecticide concentration, flow rate, vehicle speed, and kill of caged (c) or reduction of natural (n) populations of adult mosquitoes, usually within 24 h, over a 300-ft. swath unless otherwise indicated (1 lb. AI/acre = 1.12 kg AI/ha).

[4] Modified for ULV application.

[5] Based on 1,000-ft. swath.

[6] Forty-five-minute posttreatment reduction of 85%.

Possible reasons for mediocre results or control failure include 1) inadequate insecticide dose, 2) mosquito resistance to the insecticide used, 3) unfavorable meteorological conditions, 4) inadequate coverage of the target area because of dense vegetation and other obstacles or an incomplete road network, and 5) rapid mosquito reinfestation of the target area.

Turner (1977) reported that ULV ground aerosols of 96% malathion had limited practicability for control of *Anopheles farauti* Laveran, the principal vector of malaria on the island of Guadalcanal in the Solomon Islands. He applied 0.036 lb. AI/acre (17 fl. oz./mi.) to 102 villages at 10-day intervals with a Leco HD-ULV aerosol generator and obtained a mean reduction in man-biting collections of 72% at 1-day posttreatment compared with the mean 1–3-day pretreatment collections. Collections returned to pretreatment levels at 2–6 days posttreatment, which indicated rapid reinfestation of the villages. Unfavorable weather, including heavy rains, strong winds, and wrong wind direction, during some of the aerosol applications also contributed to the inadequate levels of mosquito control.

Strickman (1979) was only moderately successful in reducing oviposition rates of *Cx. pipiens* and *Cx. restuans* at 2 target sites of ≈0.14 and 0.23 mi.^{2} in Decatur, IL, with 3 ground aerosol applications of 52.7 fl. oz./mi. of 91% malathion at 2–3-wk intervals. Strickman's results indicated mean reductions of 52, 47, and 31% in numbers of egg rafts deposited in pails of water treated with alfalfa pellets on 0, 1, and 2 nights posttreatment. Possible reasons for mediocre results include small treatment sites, long intervals between aerosol applications, a high rate of mosquito reinfestation, and tolerance of *Culex* spp. to malathion.

Fox (1980), Fox and Specht (1988), and Chadee (1985) observed the lack of effectiveness of ULV ground aerosols of 4.3 fl. oz./min of 95–96% malathion dispersed from Leco HD-ULV aerosol generators against populations of *Ae. aegypti* in San Juan, Puerto Rico, and St. Joseph, Trinidad, West Indies. At a dispersal speed of 10 mph and swath of 300 ft. (not stated), the application rate would have been 0.054 lb. AI/acre. Possible reasons for ineffectiveness include malathion resistance (Fox and Bayona 1972), inadequate insecticide rate, and mosquito protection from aerosols by dense vegetation, solid fencing, and housing. A rate of 0.326 lb. AI/acre was used by Pant et al. (1971) for successful control of *Ae. aegypti* in Thailand, a rate 6-fold greater than the 0.054 lb. AI/acre rate used in Puerto Rico and Trinidad. Also, in Trinidad, applications were begun at 5 p.m. when, no doubt, unstable air and turbulence would diffuse much of the aerosol upward and above mosquito habitat.

Parsons (1982) reported that weekly applications of 7.2–12 fl. oz./mi. of 85% naled were ineffective in controlling natural populations of mosquitoes (species not indicated) in Fort Meade, FL. Actually,

Table 8. Rates of ultralow-volume (ULV) ground aerosols of bendiocarb and propoxur for 90% or more control of adult mosquitoes.

Species	Location	Habitat	Aerosol generator	Speed[1] (mph)	Flow rate[2] (fl. oz./min)	Rate[3] (lb. AI/acre)	Reference
		Bendiocarb, 25%, 1.67 lb. AI/gal (Ficam®)					
Aedes taeniorhynchus	Louisiana	Open field	Micro-Gen ED	10	2.50	0.006 c	Tapley et al. (1980)
Aedes sollicitans (Walker)	Louisiana	Open field	Micro-Gen ED	10	2.50	0.006 c	Tapley et al. (1980)
Aedes aegypti	Louisiana	Open field	Micro-Gen ED	10	2.50	0.006 c	Tapley et al. (1980)
Anopheles albimanus	Louisiana	Open field	Micro-Gen ED	10	2.50	0.006 c	Tapley et al. (1980)
Culex pipiens	Louisiana	Open field	Micro-Gen ED	10	2.50	0.006 c	Tapley et al. (1980)
Culex quinquefasciatus	Louisiana	Open field	Micro-Gen ED	10	3.60	0.008 c	Tapley et al. (1980)
Aedes nigromaculis (Ludlow)	California	Pasture	Leco HD-ULV	5	2.50	0.003 n[4]	Miller et al. (1982)
Anopheles freeborni Aitken	California	Pasture	Leco HD-ULV	5	2.50	0.003 c[4]	Miller et al. (1982)
Cx. quinquefasciatus	California	Pasture	Leco HD-ULV	5	2.00	0.003 c[4]	Miller et al. (1982)
Culex tarsalis Coquillett	California	Pasture	Leco HD-ULV	5	2.00	0.003 c[4]	Miller et al. (1982)
Ae. taeniorhynchus	Florida	Open field	Leco HD-ULV	10	4.62	0.010 c	Roberts (1984)
Anopheles quadrimaculatus	Florida	Open field	Leco HD-ULV	10	3.85	0.008 c	Roberts (1984)
Ae. nigromaculis	California	Pasture	Micro-Gen[5]	5	4.00	0.005 n[4]	Townzen et al. (1987)
Cx. quinquefasciatus	California	Pasture	Micro-Gen[5]	5	4.00	0.010 c[4]	Townzen et al. (1987)
		Propoxur, 1–2 lb. AI/gal (Baygon®)					
Ae. taeniorhynchus	Florida	Open field	Leco ULV	10	12.96	0.034 c	Mount and Pierce (1971)
Ae. taeniorhynchus	Florida	Open field	Leco HD-ULV	10	18.88	0.025 c	Mount et al. (1975b)
An. quadrimaculatus	Florida	Open field	Leco HD-ULV	10	12.78	0.017 c	Mount et al. (1975b)
Ae. taeniorhynchus	Florida	Open field	Leco HD-ULV	10	4.01	0.009 c	Mount et al. (1978a)
An. quadrimaculatus	Florida	Open field	Leco HD-ULV	10	2.91	0.006 c	Mount et al. (1978a)
Ae. taeniorhynchus	Florida	Residential	Leco HD-ULV	5	9.50	0.024 n[6]	Mount et al. (1978b)
An. quadrimaculatus	Arkansas	Open field	Leco HD-ULV	5	9.12	0.024 c	Walker et al. (1981)
Psorophora columbiae	Arkansas	Open field	Leco HD-ULV	5	5.79	0.018 c	Walker et al. (1981)
An. quadrimaculatus	Arkansas	Wooded	Leco HD-ULV	5	7.00	0.021 c	Walker et al. (1981)
Ae. taeniorhynchus	Florida	Residential	Leco HD-ULV	10	8.52	0.011 c	Rathburn et al. (1981)
Culex nigropalpus	Florida	Residential	Leco HD-ULV	10	8.52	0.011 c	Rathburn et al. (1981)

[1] A speed of 10 mph is indicated when a range of speeds (2.5–20 mph) was used to vary insecticide dose (1 mph = 1.609 km/h).

[2] Flow rate of technical or concentrated insecticide formulation as received from the manufacturer without diluent added by investigator (1 fl. oz./min = 29.7 ml/min).

[3] Rate based on insecticide concentration, flow rate, vehicle speed, and kill of caged (c) or reduction of natural (n) populations of adult mosquitoes, usually within 24 h, over a 300-ft. swath unless otherwise indicated (1 lb. AI/acre = 1.12 kg AI/ha).

[4] Based on 300–2,200-ft. swaths.

[5] Model not specified.

[6] Forty-five-minute reduction of 72%.

Table 9. Rates of ultralow-volume (ULV) ground aerosols of pyrethrins and resmethrin for 90% or more control of adult mosquitoes.

Species	Location	Habitat	Aerosol generator	Speed[1] (mph)	Flow rate[2] (fl. oz./min)	Rate[3] (lb. AI/acre)	Reference
Pyrethrins, 4–12% plus piperonyl butoxide, 12–60% (Pyrenone®, Synerol®)							
Aedes taeniorhynchus	Florida	Open field	Leco HD-ULV	10	8.89	0.0086 c	Mount and Pierce (1972b)
Ae. taeniorhynchus, Aedes sollicitans	NC	Residential	Leco HD-ULV	10	4.00	0.0019	Axtell and Dukes (1974)
Anopheles albimanus	El Salvador	Residential	Leco HD-ULV	5	2.50	0.0024 n	Hobbs (1976)
Ae. taeniorhynchus	Florida	Residential	Leco HD-ULV	10	5.60	0.0027 c	Rathburn and Boike (1975)
Culex nigripalpus	Florida	Residential	Leco HD-ULV	10	3.30	0.0016 c	Rathburn and Boike (1975)
Aedes nigromaculis	California	Pasture	Leco HD-ULV	5	10.24	0.0057 n[4,5]	Womeldorf and Mount (1977)
Culex quinquefasciatus	California	Pasture	Leco HD-ULV	5	5.51–10.24	0.0057 c[4]	Womeldorf and Mount (1977)
Anopheles quadrimaculatus	Arkansas	Open field	Leco HD-ULV	10	3.00	0.0016 c	Walker and Meisch (1982)
Culex tarsalis	California	Pasture	Custom built	10	15.70	0.0015 c[4]	Townzen et al. (1988)
Resmethrin, 2–3.34 lb. AI/gal (SBP-1382®)							
Ae. taeniorhynchus	Florida	Open field	Leco ULV	10	10.30	0.0268 c	Mount and Pierce (1971)
Cx. nigripalpus	Florida	Residential	Leco HD-ULV	5	0.84	0.0073 c	Rathburn and Boike (1972b)
Ae. taeniorhynchus	Florida	Open field	Leco HD-ULV	10	16.32	0.0710 c	Mount and Pierce (1972b)
Ae. nigromaculis	California	Pasture	Leco HD-ULV	5	9.83	0.0058 n[4]	Womeldorf and Mount (1977)
Cx. quinquefasciatus	California	Pasture	Leco HD-ULV	5	9.83	0.0058 c[4]	Womeldorf and Mount (1977)
Aedes vexans (Meigen)	Minnesota	Wooded	Custom built	10	1.61	0.0070 n	Sjogren and Frank (1979)
Cx. nigripalpus	Florida	Residential	Leco HD-ULV	10	1.38	0.0036 c	Rathburn et al. (1981)
An. quadrimaculatus	Arkansas	Open field	Leco HD-ULV	5	0.80	0.0070 c	Sandoski et al. (1983)
Psorophora columbiae	Arkansas	Open field	Leco HD-ULV	10	0.80	0.0070 c	Stark et al. (1985)
Resmethrin, 0.9–1.5 lb. AI/gal plus piperonyl butoxide, 4.5 lb. AI/gal (Scourge®, Oblique®)							
Ae. taeniorhynchus	Florida	Open field	Leco HD-ULV	10	8.56	0.0100 c	Mount et al. (1974c)
An. quadrimaculatus	Florida	Open field	Leco HD-ULV	10	2.57	0.0030 c	Mount et al. (1974c)
Cx. quinquefasciatus	California	Pasture	Leco HD-ULV	5	8.89	0.0024 c[4]	Womeldorf and Mount (1977)
An. quadrimaculatus	Arkansas	Open field	Leco HD-ULV	5	0.90	0.0035 c	Sandoski et al. (1983)
Ps. columbiae	Arkansas	Open field	Leco HD-ULV	10	0.92	0.0018 c	Stark et al. (1985)
Aedes melaniman	California	Residential	Custom built	5	2.00	0.078 c	Townzen et al. (1987)
Cx. quinquefasciatus	California	Pasture	Custom built	5	4.00	0.0035 c[4]	Townzen et al. (1987)
Ae. taeniorhynchus	Florida	Residential	Leco HD-ULV	10	3.00	0.0059 c	Floore et al. (1991)
Cx. quinquefasciatus	Florida	Residential	Leco HD-ULV	10	3.00	0.0059 c	Floore et al. (1991)
An. quadrimaculatus	Arkansas	Open field	Leco HD-ULV	15	1.35	0.0020 c	Weathersbee et al. (1991)
An. quadrimaculatus	Arkansas	Open field	Leco HD-ULV	15	0.68	0.0010 c	Groves et al. (1994)

[1] A speed of 10 mph is indicated when a range of speeds (2.5–20 mph) was used to vary insecticide dose (1 mph = 1.609 km/h).

[2] Flow rate of technical or concentrated insecticide formulation as received from the manufacturer without diluent added by investigator (1 fl. oz./min = 29.7 ml/min).

[3] Rate based on insecticide concentration, flow rate, vehicle speed, and kill of caged (c) or reduction of natural (n) populations of adult mosquitoes, usually within 24 h, over a 300-ft. swath unless otherwise indicated (1 lb. AI/acre = 1.12 kg AI/ha).

[4] Dose based on 660–2,640-ft. swaths.

[5] Landing rate reductions were 75–76%.

Table 10. Rates of ultralow-volume (ULV) ground aerosols of pyrethroid insecticides for 90% or more control of adult mosquitoes.

Species	Location	Habitat	Aerosol generator	Speed[1] (mph)	Flow rate[2] (fl. oz./min)	Rate[3] (lb. AI/acre)	Reference
Bioresmethrin, 15% plus piperonyl butoxide, 15%							
Aedes taeniorhynchus	G. Cayman	Swamp	Mod. Tifa	10	3.20	0.0027 n[4]	Brooke et al. (1974)
Cyfluthrin, 3.2 lb. AI/gal							
Ae. taeniorhynchus	Florida	Open field	Leco HD-ULV	10	0.02	0.0001 c	Roberts (1985)
Anopheles quadrimaculatus	Florida	Open field	Leco HD-ULV	10	0.04	0.0002 c	Roberts (1985)
Cypermethrin, 2.48 lb. AI/gal							
Ae. taeniorhynchus	Florida	Open field	Leco HD-ULV	10	0.44	0.0014 c	Roberts (1983)
An. quadrimaculatus	Florida	Open field	Leco HD-ULV	10	0.06	0.0002 c	Roberts (1983)
Deltamethrin, 2%, 0.167 lb. AI/gal							
Ae. taeniorhynchus	Florida	Open field	Leco HD-ULV	10	2.26	0.0005 c	Roberts (1982)
An. quadrimaculatus	Florida	Open field	Leco HD-ULV	10	0.09	0.00002 c	Roberts (1982)
Fenvalerate, 2.4 lb. AI/gal							
Ae. taeniorhynchus	Florida	Open field	Leco HD-ULV	10	1.36	0.0042 c	Roberts (1982)
An. quadrimaculatus	Florida	Open field	Leco HD-ULV	10	0.34	0.0010 c	Roberts (1982)
Fluvalinate, 2 lb. AI/gal							
Ae. taeniorhynchus	Florida	Open field	Leco HD-ULV	10	4.50	0.0117 c	Kline et al. (1986)
An. quadrimaculatus	Florida	Open field	Leco HD-ULV	10	0.38	0.0010 c	Kline et al. (1986)
Lambda cyhalothrin, 2%							
Culex tarsalis	California	Open desert	Micro-Gen G-9HD	5	1.13	0.0003 c[4]	Schaefer et al. (1990)
An. quadrimaculatus	Arkansas	Open field	Leco HD-ULV	15	1.55	0.0003 c	Weathersbee et al. (1991)
Permethrin, 2–5 lb. AI/gal (Punt®)							
Culex quinquefasciatus	Arkansas	Open field	Leco HD-ULV	10	1.21	0.0030 c	Thompson and Meisch (1977)
Ae. taeniorhynchus	Florida	Open field	Leco HD-ULV	10	2.91	0.0076 c	Mount et al. (1978a)
An. quadrimaculatus	Florida	Open field	Leco HD-ULV	10	0.36	0.0009 c	Mount et al. (1978a)
An. quadrimaculatus	Arkansas	Open field	Leco HD-ULV	10	0.50	0.0013 c	Walker and Meisch (1982)
Ae. taeniorhynchus	Florida	Open field	Leco HD-ULV	10	0.79	0.0037 c	Kline et al. (1986)
An. quadrimaculatus	Florida	Open field	Leco HD-ULV	10	0.21	0.0010 c	Kline et al. (1986)
Cx. quinquefasciatus	California	Pasture	Custom built	7	4.25	0.0045 c[4]	Townzen et al. (1987)
Cx. tarsalis	California	Pasture	Custom built	7	4.25	0.0045 c[4]	Townzen et al. (1987)
Permethrin, 12–31% plus piperonyl butoxide, 20–66% (Permanone®, Biomist®, Flak®)							
Aedes sollicitans	New Jersey	Open field	Beecomist HD	5	0.50	0.0033 c	McNelly and Benzon (1995)
An. quadrimaculatus	Arkansas	Open field	Leco 1600	15	0.80	0.0007 c	Groves et al. (1994)
An. quadrimaculatus	Arkansas	Open field	Leco 1600	15	0.80	0.0017 c	Groves et al. (1994)
An. quadrimaculatus	Arkansas	Open field	Leco 1600	10	0.53	0.0035 c	Meisch et al. (1997)

Table 10. Continued.

Species	Location	Habitat	Aerosol generator	Speed[1] (mph)	Flow rate[2] (fl. oz./min)	Rate[3] (lb. AI/acre)	Reference
		Phenothrin, 40%, 3.04 lb. AI/gal (Sumithrin®, Solo® 40-OS)					
Ae. taeniorhynchus	Florida	Open field	Leco HD-ULV	10	4.74	0.0206 c	Roberts (1981)
An. quadrimaculatus	Florida	Open field	Leco HD-ULV	10	0.36	0.0014 c	Roberts (1981)
		Phenothrin, 20% (Sumithrin®, Solo® 40-OS) plus piperonyl butoxide, 50%					
An. quadrimaculatus	Arkansas	Open field	VecTec Grizzly	15	0.93	0.0012 c	Groves et al. (1994)
Psorophora columbiae	Arkansas	Open field	VecTec Grizzly	15	0.93	0.0012 c	Groves et al. (1994)

[1] Ten miles per hour is indicated when a range of speeds (2.5–20 mph) was used to vary insecticide dose (1 mph = 1.609 km/h).

[2] Flow rate of technical or concentrated insecticide formulation as received from the manufacturer without diluent added by investigator (1 fl. oz./min = 29.7 ml/min).

[3] Rate based on insecticide concentration, flow rate, vehicle speed, and kill of caged (c) or reduction of natural (n) populations of adult mosquitoes, usually within 24 h, over a 300-ft. swath unless otherwise indicated (1 lb. AI/acre = 1.12 kg AI/ha).

[4] Dose based on 600–>2,640-ft. swath.

Parsons showed that a mean reduction in CDC light trap and truck trap collections of 50% was achieved during the nights of treatment. However, essentially the same levels of reduction were consistently observed at 2 untreated sites. Because the untreated sites were only ≈2,000–3,000 ft. from the large target treatment area of ≈3 mi.^{2}, these untreated sites may have also been treated with the naled aerosol. Nevertheless, the results of Parson's tests suggest that a higher rate of naled may be required for highly effective mosquito control in Fort Meade and comparable communities.

In New Orleans, LA, Focks et al. (1987) observed 73 and 75% reduction in mean adult captures and oviposition rates, respectively, of *Ae. aegypti* populations subjected to 11 sequential aerosol applications of 24 fl. oz./mi. of 91% malathion at 12-h intervals over a 5.5-day period. The authors suggested that overcrowded housing and dense vegetation hampered aerosol drift and effectiveness. Another possible reason for mediocre results could have been unfavorable meteorological conditions because aerosol applications were made during the morning (6:00–7:15 a.m.) when conditions are usually calm and late afternoon (5:30–6:45 p.m.) when unstable air would diffuse much of the aerosol above mosquito habitat. Furthermore, the 0.048 lb. AI/acre rate of malathion used in this study would have to be increased 2- or 3-fold to provide a high degree of mosquito kill in dense vegetation.

Against caged wild *An. quadrimaculatus* in Arkansas, Weathersbee et al. (1989) obtained 75% control with 0.0012 lb. AI/acre of synergized resmethrin (Scourge®, Clarke Engineering Technologies Inc.) and only 49% control with 0.012 lb. AI/acre of fenthion. However, subsequent results with synergized resmethrin showed adequate control (90% or more) of *An. quadrimaculatus* in Arkansas at rates of 0.001–0.002 lb. AI/acre (Weathersbee et al. 1991, Groves et al. 1994). Poor results with fenthion are likely a result of mosquito resistance to this insecticide because previous tests with fenthion against caged mosquitoes from a laboratory colony indicated satisfactory results at 0.01 lb. AI/acre (Mount et al. 1978a).

Efird et al. (1991) reported only 42% kill of caged wild *An. quadrimaculatus* in Arkansas with a rate of 0.05 lb. AI/acre of malathion. They indicated the possibility of resistance of this species to malathion as suggested by unpublished results of laboratory topical application studies. Also, in the same field studies, they obtained only 77% mosquito kill with 0.0015 lb. AI/acre of synergized permethrin, whereas Groves et al. (1994) showed ≈90% kill of caged wild *An. quadrimaculatus* in Arkansas with synergized permethrin at 0.0007–0.0017 lb. AI/acre (Table 10). Thus, meteorological conditions may have been less favorable in the 1991 tests than in the 1994 tests.

Groves et al. (1997) reported 45–75% control of caged wild mosquitoes of 3 different species and

Table 11. Summary of rates for ultralow-volume (ULV) ground aerosols of undiluted insecticide for 90% or more control of adult mosquitoes in open to moderately open terrain with favorable meteorological conditions.

Insecticide[1]	Lb. AI/gal	% AI	Lb. AI/acre (fl. oz./min at 10 mph for 300-ft. swath)[2]				
			Aedes spp.	*Anopheles* spp.	*Culex* spp.	*Psorophora* spp.	Mean
Cyfluthrin	3.2	—	0.0001 (0.02)	0.0002 (0.04)	—	—	0.00015 (0.03)
Lambda cyhalothrin	—	2%	—	0.0003 (1.55)	0.0003 (1.55)	—	0.00030 (1.55)
Deltamethrin	—	2%	0.0005 (2.26)	0.00002 (0.09)	—	—	0.00035 (1.38)
Cypermethrin	2.48	—	0.0014 (0.44)	0.0002 (0.06)	—	—	0.0008 (0.25)
Phenothrin + PBO[3]	1.52 + 4.4	20 + 50%	—	0.0012 (0.93)	—	0.0012 (0.93)	0.0012 (0.93)
Fenvalerate	2.4	—	0.0042 (1.36)	0.0010 (0.34)	—	—	0.0026 (0.84)
Bioresmethrin + PBO	—	15 + 15%	0.0027 (0.32)	—	—	—	0.0027 (0.32)
Permethrin + PBO	2.89 + 6.09	31 + 66%	0.0036 (0.95)	0.0020 (0.53)	—	—	0.0028 (0.74)
Pyrethrins + PBO	—	12 + 60%	0.0047 (3.62)	0.0020 (1.54)	0.0029 (2.23)	—	0.0032 (2.46)
Permethrin	3.60	—	0.0057 (1.22)	0.0011 (0.24)	0.004 (0.85)	—	0.0036 (0.77)
Resmethrin + PBO	1.5 + 4.5	18 + 54%	0.0079 (4.05)	0.0024 (1.23)	0.0039 (2.00)	0.0018 (0.92)	0.0040 (2.05)
Bendiocarb	1.67	—	0.006 (2.73)	0.006 (2.73)	0.006 (2.73)	—	0.0060 (2.73)
Fluvalinate	2.0	—	0.0117 (4.50)	0.0010 (0.38)	—	—	0.0064 (2.46)
Phenothrin	3.04	40%	0.021 (5.20)	0.0014 (0.35)	—	—	0.011 (2.75)
Fenthion	9.67	93%	0.013 (1.03)	0.010 (0.79)	0.013 (1.03)	—	0.012 (0.95)
Resmethrin	3.34	40%	0.028 (6.44)	0.0070 (1.61)	0.0056 (1.29)	0.007 (1.61)	0.012 (2.76)
Chlorpyrifos	6.00	—	0.012 (1.54)	—	0.010 (1.28)	0.017 (2.18)	0.013 (1.67)
Propoxur	1.00	—	0.021 (16.16)	0.017 (13.08)	0.011 (8.46)	0.018 (13.85)	0.017 (13.08)
Naled	14.00	85%	0.020 (1.20)	—	0.016 (0.96)	0.020 (1.20)	0.019 (1.14)
Fenitrothion	9.67	93%	0.024 (1.90)	0.029 (2.30)	0.028 (2.22)	0.029 (2.36)	0.028 (2.22)
Malathion	9.70	95%	0.042 (3.32)	0.033 (2.62)	0.039 (3.10)	0.038 (3.00)	0.038 (3.00)

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[1] Insecticide formulations listed here are maximum or near maximum concentrations currently registered by US-EPA for ULV ground aerosol application. Other ULV formulations of the same insecticide with similar concentrations may also be registered for use and even more concentrated formulations of some insecticides may be available in the future. However, substantially lower concentrations of some insecticides are also registered, but would represent low-volume (LV) or high-volume (HV) application even though labels indicate ULV application. Dilution of the insecticide formulations listed in this table by the applicator would also represent LV or HV applications rather than ULV application. Common names of insecticides are used in this table. See preceding tables for trade names of insecticides.

[2] 1 lb. AI/acre = 1.12 kg AI/ha; 1 fl. oz./min = 29.7 ml/min; 1 mph = 1.609 km/h; 1 ft. = 0.3048 m.

[3] PBO = piperonyl butoxide.

genera with rates of 0.00175 lb. AI/acre of synergized permethrin (Permanone®, Fairfield American Corp., Frenchtown, NJ) and resmethrin (Scourge) and 0.001 lb. AI/acre of synergized prallethrin (Responde®). The likely explanation for these unsatisfactory results is insufficient insecticide rate. The 0.00175 rate for both synergized permethrin and resmethrin is substantially less than effective rates (averages of 0.0025 and 0.0047 lb. AI/acre, respectively) reported previously for these insecticides (see Tables 9–11).

NONTARGET EFFECTS

One factor that limits the potential nontarget effects of ULV ground aerosols is that effective insecticide rates for adult mosquitoes are relatively low compared with rates used for other types of insect control. A 2nd factor is that aerosols consisting of small droplets are space treatments, and only a small portion of the insecticide is deposited on the ground or vegetation in the target area. Tucker et al. (1987) reported that only 1.4–2.0% of fenthion and 16–17% of malathion aerosols were deposited on filter papers placed 25 ft. downwind at ground level. Also, Moore et al. (1993) showed that only 1–17% of malathion aerosols was deposited on filter papers placed at 50–300 ft. downwind at ground level. The potential nontarget effects of ULV ground aerosols of insecticide that have been studied include those on human targets, beneficial animals, automotive paint, and noise level of aerosol generators.

Human targets: Moore et al. (1993) demonstrated that quantities of ULV malathion aerosols deposited on humans were inconsequential. Stationary and moving human subjects were exposed to a rate of 4.3 fl. oz./min of 91% malathion dispersed at 10 mph at downwind distances of 5–50 ft. Their results indicated that estimated levels of malathion dermal exposure were less than the acute lethal dose for human subjects by 4 orders of magnitude or more.

Nontarget animals: In tests with mammals and birds, Joseph et al. (1972) observed no mortality or red cell cholinesterase inhibition of caged bobwhite quail, *Colinus virginianus,* white laboratory mice, and containerized goldfish exposed to 18 and 180 (10 times the labeled rate) fl. oz./mi. of 95% malathion aerosols. Also, Mallack et al. (1975) demonstrated that 95% malathion aerosols rates that were 5–20 times the labeled rate (130–520 fl. oz./mi.) did not inhibit brain acetycholinesterase levels in mature chickens and New Zealand rabbits.

Several studies on fish, shrimp, crabs, and other marine organisms have been reported. Tagatz et al. (1974) reported no kill of confined blue crabs, *Callinectes sapidus*; grass shrimps, *Palaemonetes vulgaris* and *Palaemonetes pugio*; pink shrimp, *Penaeus duorarum*; or sheepshead minnows, *Cyprinodon variegatus,* exposed to 26 fl. oz/mi. of 95% malathion aerosols. Furthermore, brain acetylcholinesterase activity was not reduced in sheepshead minnows exposed to the aerosols. In a series of studies with ULV ground aerosol applications of fenthion at 6 fl. oz./mi., Clark et al. (1985) reported mean kills of 79 and 83% of caged *Ae. taeniorhynchus* and *Cx. quinquefasciatus* mosquitoes at downwind distances of 50–300 ft. Deaths of grass shrimp, *P. pugio,* and pink shrimp were attributed to low salinity and dissolved oxygen rather than to exposure to fenthion aerosols (Borthwick and Stanley 1985). Also, Tagatz and Plaia (1985) observed no difference in average numbers of individuals and species, primarily annelids and arthropods, in estuarine benthic communities located in fenthion-treated and untreated sites. Moore et al. (1985) demonstrated that fenthion from the aerosol applications did not accumulate to a detectable level (0.010 μg/g) in tissues of caged shrimp or fish. In tests with caged mysids, *Mysidopsis bahia,* McKenney et al. (1985) obtained mean kills of 32 and 50% in control and exposed sites, respectively, following 3 fenthion aerosol applications on different dates. They suggested that the insecticide reduced growth of the mysids by 24% on the basis of dry weight measurements 180 days posttreatment. Furthermore, Tucker et al. (1987) observed no kill of common snook juveniles, *Centropomus undecimalis*; tarpon snook juveniles, *Centropomus pectinatus*; sheepshead minnow juveniles, *Cyprinodon variegatus,* or adult calanoid copepods, *Acartia tonsa,* exposed to aerosol applications of 24 fl. oz./mi. of 91% malathion, 6 fl. oz./mi. of 93% fenthion, or 8 fl. oz./mi. of 85% naled.

In studies on nontarget insects, Washino et al. (1977) used pretreatment and 24-h posttreatment deZulueta 24-ft.^{2} net collections to measure 31–81% reduction in 3 different test sites and a 78% increase in a 4th test site of natural populations of Cicadellidae exposed to ULV aerosols of 0.006 lb. AI/acre of synergized pyrethrins or 0.003–0.006 lb. AI/acre of synergized resmethrin. With aerosol applications against caged honeybees, Caron (1979) reported 39–68% kill at 50–100 ft. with 95% malathion, 14–33% kill at 50–200 ft. with 10% naled, and essentially no kill at any exposure distance with 5% pyrethrins. However, he observed that routine night applications of these insecticides had no discernible effect on honeybee colonies.

Automotive paint: Rathburn and Boike (1972a) reported no visible damage to paint on panels furnished by General Motors Corporation that were exposed at only 10 ft. from the line of travel of an aerosol generator dispersing 26 fl. oz./mi. of 95% malathion. Also, Mount et al. (1978a) observed no visible damage to automotive paints exposed to aerosols of 6 fl. oz./mi. of 2 lb. AI/gal of permethrin or 54 fl. oz./mi. of 1.67 lb. AI/gal propoxur. From results of a laboratory study, Tietze et al. (1992) indicated a positive correlation between malathion droplet size and paint damage spot size. Laboratory settling chamber tests revealed that size thresholds of malathion droplets too small to cause visible damage averaged 8 and 11 μm diameter on washed 1K (basecoat: 872-AB921; clearcoat: RK7103) and 2K (basecoat: 872-AB921; clearcoat: RK7100) black paint standards supplied by E. I. DuPont De Nemours and Company (Troy, MI). In field tests, they observed no visible damage to 1K and 2K paints, but microscopic damage was found on paint panels placed on the hood, trunk, and doors of an automobile when parked parallel or perpendicular to the course of the aerosol generator and when driven through the aerosol cloud from a stationary generator.

Aerosol generator noise: Most ULV aerosol generators produce considerable noise and some may exceed the United States Occupational Safety and Health Administration (US-OSHA) 8-h hearing hazard criteria of 90 dBA when engines are operated at a high RPM. Nelson et al. (1975) measured the noise levels at the operator's ear from several generators mounted on a ¾-ton truck. Noise levels were 87–105 dBA for 2 generators equipped with vortex nozzles (Micro-Gen MS2–15 and Leco HD-ULV), 83–105 dBA for a generator with a pneumatic nozzle (Buffalo Turbine Sonic), and 72 dBA for a generator equipped with a rotary nozzle (Beecomist Systems Cardinal 150 ULV). In another study, noise produced by Leco HD-ULV and Micro-Gen ED2–20A aerosol generators was measured at 70–78 dBA when the generators passed by a microphone at 10 mph (Morton 1980). Robinson and Ruff (1991a, 1991b) and Robinson (1994) reported that 3 generators with vortex nozzles and rotary air compressors (London Fog 18–20 ULV, Curtis Dyna-Fog Maxi-Pro 4 ULV, and VecTec Grizzly ULV) produced ≥91 dBA when operated at high engine RPM (≥2,200 for London Fog, ≥1,800 for Curtis Dyna-Fog, and ≥1,950 for VecTec). A generator with a pneumatic nozzle and piston air compressor (Conner Engineering Bison ULV) was shown to be relatively quiet with only 83 dBA at 3,000 engine RPM, the highest level tested (Robinson and Ruff 1992). However, the quietest unit was a rotary nozzle generator (Beecomist Systems Pro-Mist 25HD ULV), with only 63 dBA at a maximum nozzle RPM of 33,500 (Robinson et al. 1993).

CONCLUSIONS

1. ULV ground aerosol applications of insecticide are as efficacious against adult mosquitoes as HV or LV aerosols. The degree of adult mosquito kill obtained with any insecticide application is related to the dose of active ingredient and many other application and environmental factors but not to application volume. Inert ingredients such as water or oil diluents do not kill mosquitoes and only add cost and inconvenience to ground aerosol operations. Dilution of an insecticide formulation would be required only if the flow rate of the undiluted formulation is substantially less than 0.5 fl. oz./min. Some insecticide labels that require dilution should be modified to allow ULV application of the undiluted formulation. ULV technology offers an increased insecticide payload for more rapid application and increased safety by elimination of dense fogs created by HV thermal atomization.

2. ULV aerosols with an optimum droplet size spectrum can be produced by several types of nozzles including vortex, pneumatic, and rotary. Droplet size is dependent primarily on nozzle air pressure or nozzle rotation speed and secondarily on insecticide flow rate.

3. Label flow rates of insecticide for ULV aerosol application can be delivered accurately (within ≈6%) during routine operations with speed-correlated metering systems within a calibrated speed range, usually not exceeding 20 mph.

4. The most economical and convenient method of droplet size determination for ULV aerosols of insecticide is the waved-slide technique. This simple technique uses Teflon-covered glass microscope slides, a micrometer disc in an ocular objective on a compound microscope for measurement of size, and calculation of VMD based on droplet diameter because droplet impingement is a function of diameter. Other techniques that have been used successfully for droplet size determination are settlement chamber, cascade impactor, Coulter Counter, hot wire, and laser.

5. The efficacy of ULV ground aerosols against adult mosquitoes is related to droplet size because it governs air transport and impingement. The optimum droplet size for mosquito adulticiding is 8–15 μm VMD on the basis of laboratory wind-tunnel tests and field research with caged mosquitoes.

6. In general, ULV aerosols should be applied following sunset when mosquitoes are active and meteorological conditions are favorable for achieving maximum levels of mosquito control. However, with favorable or even marginal meteorological conditions, application can be made successfully during daytime hours when nighttime application is impractical. During marginal meteorological conditions, application rates may have to be increased to achieve satisfactory results. The critical meteorological factors are wind velocity and direction, temperature, and atmospheric stabililty and turbulence. Wind velocities of 1–7 mph, with gusts not exceeding 11 mph, are the most suitable for aerosol drift across target swaths. A ground-based inversion with a low level of turbulence will optimize aerosol cloud diffusion across the target swath. However, successful mosquito kill can be achieved even during slightly unstable conditions if a prevailing wind exists.

7. Maximum effective swaths are obtained with aerosols in the optimum VMD range during favorable meteorology in open to moderately open terrain. In general, the insecticide rate must be in-

creased in direct proportion to an increase in swath to maintain the same level of mosquito control.

8. Dispersal speed within a range of 2.5–20 mph is not a factor affecting efficacy if insecticide rate and optimum atomization are maintained.

9. Percentage kills with caged mosquito assays are comparable with reductions in free-flying natural populations. For the most consistent results with the caged method, mosquitoes should be exposed in 14–18-mesh cylindrical cages, screened on all sides, with the longitudinal axis perpendicular to the ground and at a height 2–6 ft. above the ground.

10. The field efficacies of mosquito adulticides applied as ULV ground aerosols are predictable from the results of laboratory wind-tunnel tests.

11. Results of field tests in open to moderately open terrain during favorable meteorological conditions indicated that ULV insecticidal aerosol application rates producing 90% or more control of *Anopheles, Culex,* and *Psorophora* spp. are below or ≈equal to maximum US-EPA label rates. Against some *Aedes* spp., some pyrethroid insecticides must be synergized to be 90% or more effective at label rates.

12. Results of field tests in residential areas with moderate to dense vegetation and in citrus groves or other densely wooded areas showed that insecticide rates of ULV ground aerosols must be increased 2–3-fold to obtain 90% or more control of adult mosquitoes. However, the maximum rates on some insecticide labels would have to be increased to allow higher application rates.

13. Applications of ULV ground aerosols of insecticide in accordance with label directions following sunset do not pose a serious threat to humans, nontarget beneficial animals, or automotive paints.

14. Some aerosol generators operated at high RPM levels exceed the US-OSHA 8-h hearing hazard criteria of 90 dBA and may require hearing protectors for operators.

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