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# A REVIEW OF ULTRALOW-VOLUME AERIAL SPRAYS OF INSECTICIDE FOR MOSQUITO CONTROL[1]

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ABSTRACT. This review of research on ultralow-volume (ULV) aerial sprays for mosquito control is a component of an Aerial **SP**ray **EX**pert system (**ASPEX**). Topics include application volume, adulticiding, larviciding, droplet size, and meteorology. The review discusses the efficacy of ULV aerial sprays against many important pest and vector species of mosquitoes in a wide range of locations and habitats in the USA and in some countries of Asia, Africa, and the Americas. Nine conclusions were drawn from this review. 1) ULV applications are as effective for mosquito control as highly-diluted, water-based sprays. 2) More acres can be sprayed per aircraft load with the ULV method than with dilute sprays. 3) High-altitude ULV sprays using wide or stacked swaths could be used in emergencies if wind speed and direction data at appropriate altitudes are available to accurately place the spray. 4) Successful adult mosquito control can be achieved in dense foliage or open housing with ULV aerial sprays, but doses of insecticide must be increased. 5) ULV aerial application of mosquito larvicides can be used successfully in large areas. 6) The optimum droplet size for adult mosquito control is 5–25 μm volume median diameter (VMD). 7) For mosquito adulticiding, near optimum atomization of ULV sprays is achieved with flat-fan nozzles oriented straight down or slightly forward for high-speed aircraft (≥150 mph) or rotary atomizers on slow-speed aircraft (<150 mph). 8) Optimum atomization minimizes paint spotting. 9) Maximum adult mosquito control is achieved just after sunrise and just before sunset with 2–10-mph crosswinds.

## INTRODUCTION

The earliest experiments with undiluted formulations of liquid insecticide for insect control were reported by Messenger (1963, 1964), Skoog et al. (1965), and Wilson et al. (1965). The application concept was subsequently adapted for mosquito control by many investigators. After several years of research and development, the term "ultralow volume" or "ULV" was commonly used to describe the application of undiluted insecticide formulations. In practice, the ULV method involves the application of the minimum effective volume of an undiluted formulation of insecticide (as received from the manufacturer). With the ULV method, the application volume is dependent on the intrinsic toxicity of an insecticide to the target species and its concentration in a liquid formulation. 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 as low-volume because the minimum volume was not applied. During the early development of the ULV method, some applications of technical undiluted insecticide and moderately diluted formulations were referred to as low-volume. For convenience and simplicity in this review, low-volume and ultralow-volume applications will be referred to as ULV.

After development, the ULV aerial spray method of insecticide application for adult mosquito control was quickly adopted in the USA. ULV has been the worldwide standard aerial spray method of mosquito adulticiding for more than 25 years because of inherent advantages over high-volume water- or oil-based sprays. These advantages include an increased effective payload, more rapid and timely application, elimination of the formulation process, less handling of insecticide, reduced pumping requirement, and reduced application costs.

This review is a component of an Aerial **SP**ray **EX**pert system (**ASPEX**) funded by the DoD Legacy Resource Management Program. It includes references published from 1963 to 1995 and unpublished technical reports on operational ULV aerial sprays. ASPEX was developed as a joint project by the USDA-ARS Medical and Veterinary Entomology Research Laboratory and the Aerial Spray Branch, U.S. Air Force Reserve for training and operational use. This expert system also has potential for global use in mosquito control programs. Previous reviews of the ULV application method for mosquito control were made by Lofgren (1970, 1972, 1974) and Lofgren and Mount (1975). In general, this review is presented in chronological order within topical area. Major topics include application volume, adulticiding, larviciding, droplet size, and meteorology. In several studies, we performed probit analysis on efficacy data to estimate rates of insecticide needed for 90% mosquito control. Conclusions and summary tables based on the review are provided.

## RELATIONSHIP BETWEEN APPLICATION VOLUME AND EFFICACY

Despite the rapid and widespread acceptance of the ULV method and numerous tests demonstrating

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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.

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its efficacy, only 2 studies comparing mosquito kills with ULV and water-based aerial sprays were reported. Direct comparison of the effects of naled applied as ULV (1.6–6.4 fl. oz./acre) or water-based aerial sprays (96 fl. oz./acre) against adult salt-marsh mosquitoes, predominantly *Aedes taeniorhynchus* (Wied.), infesting 10–50-acre citrus groves was made by Mount and Lofgren (1967). Their results showed that ULV and dilute sprays of naled were about equal in effectiveness (0.13 and 0.11 lb. active ingredient [AI]/acre, respectively, for 90% control as estimated by profit analysis). Furthermore, Mount and Lofgen (1967) showed that ULV sprays of fenthion were less effective than dilute sprays at 6 h posttreatment but the application methods were about equal at 24 h posttreatment (0.23 and 0.19 lb. AI/acre, respectively, for 90% control as estimated by probit analysis). A second comparison of ULV (3.2 fl. oz./acre of 2 lb. AI/gal formulation) and water-based (64 fl. oz./acre) sprays at equal doses (0.05 lb. AI/acre) of propoxur (Baygon®) was reported by Knapp and Rogers (1968). Their results showed no difference against Ae. sollicitans (Walker) populations in Kentucky with 92 and 88% mean reductions at 1.5–24 h posttreatment for ULV and water-based sprays, respectively.

With aerosols applied by ground equipment, Mount et al. (1968) showed that ULV applications of malathion and naled (0.2–0.5 fl. oz./acre) were equal to or better than higher-volume applications (14 fl. oz./acre) of the same doses of these insecticides against adult salt-marsh mosquitoes (*Aedes* sp.). Also, Husted et al. (1975) reported no difference in the percentage kill of adult *Culex pipiens* Linn. mosquitoes with a 6-fold range in the volume of chlorpyrifos formulations applied at equivalent doses as ground aerosols.

## EFFICACY AGAINST MOSQUITO ADULTS

Efficacy research on ULV aerial sprays for adult mosquito control is divided into small-scale, large-scale, and high-altitude tests. Small-scale tests at normal altitudes (≤200 ft.) were done in relatively small plots (<1 mi.$^2$). The target areas for large-scale tests at normal altitudes were from 4 to more than 700 mi.$^2$ High-altitude tests (>200 ft.) were done to explore the feasibility of wide-swath or stacked-swath applications and were, by necessity, conducted over large areas. Also, several tests of ULV aerial sprays for control of midges are covered here.

*Small-scale tests:* Most of the early trials with ULV aerial sprays against adult mosquitoes were done on a relatively small scale (<1 mi.$^2$) compared to subsequent large-scale testing and most operational applications. The primary purpose of the small-scale tests was to demonstrate the efficacy of ULV aerial sprays of various insecticides against different mosquito species in a variety of locations and habitats. Basic information for small-scale tests against adult mosquitoes is summarized in Table 1. With few exceptions, small-scale tests were done with small, single-engine, fixed-wing aircraft equipped with high-volume spray systems modified to allow ULV applications or with experimental ULV systems. Most applications were made with low capacity, flat-fan nozzles, although some trials were made with various types of rotary atomizers. Obviously, smaller-capacity liquid pumps and transfer pipes were required for ULV flow rates as compared to water-based spray rates. Furthermore, most of these tests were made against natural populations of mosquitoes, though some were done with caged mosquitoes as indicated in Table 1. Crosswind swaths varied from 75 to 200 ft. with release altitudes of 50–175 ft.

The results in Table 1 indicate satisfactory control (89–100%) of various mosquito species with the following rates (fl. oz./acre) of undiluted insecticide: 91–95% malathion, 3.2–8; 50% emulsifiable concentrate (EC) malathion, 13.6; 85% naled, 0.8–1.1; 8 lb. AI/gal fenthion, 0.75–1.8; 93% fenthion, 0.45; 4 lb. AI/gal propoxur, 1.5–1.6. However, tests shown in Table 1 indicate that higher rates of technical malathion (6–8 fl. oz./acre) and 8 lb. AI/gal fenthion (4 fl. oz./acre) were required for satisfactory mosquito control in dense jungle canopy and open houses that offered some protection of adult mosquitoes from the spray droplets. Also, formulations of permethrin diluted in oil provided 81–92% control of *Culex* and *Anopheles* sp. with rates of 0.6–0.9 fl. oz. AI/acre and total application volumes of 40–60 fl. oz./acre (Groves et al. 1994). In other small-scale tests, Patterson et al. (1966) obtained complete control of midges along Florida lake shores with 2 fl. oz./acre of 95% malathion.

*Large-scale, normal-altitude tests:* Although small-scale tests identified effective rates of insecticide for adult mosquitoes, large-scale tests were required to assess the full potential of ULV aerial sprays and establish minimum effective insecticide rates for operational and emergency mosquito control programs. Large-scale target areas accommodate the horizontal transport of small spray droplets and tend to negate short-term mosquito reinfestation from adjacent untreated areas. A summary of large-scale, normal-altitude tests is presented in Table 2. In all but 3 of the large-scale tests, insecticide was dispersed with large, multiengine, fixed-wing aircraft equipped with flat-fan or hollow-cone nozzles oriented straight down or down and 45° forward to the airstream. Ribeiro (1973) and Uribe et al. (1980) used small, single-engine, fixed-wing aircraft equipped with rotary atomizers and Bourg et al. (1978) used a small, single-engine, fixed-wing aircraft with flat-fan nozzles oriented down and 45° forward to the airstream.

With 91.5–95% technical malathion, rates of 2.6–4 fl. oz./acre produced 90–98% control of *Aedes, Anopheles, Culex,* and *Psorophora* sp. in 11 of 13 studies and operational applications (see data and references in Table 2). Also, results from 2 tests in open to wooded habitat demonstrated that 1.5 fl. oz./acre of 95% malathion provided only 57–62% control (Mount et al. 1970a, Meisch and Mount 1978). For control of *Ae. aegypti* (Linn.) in urban areas with open houses, 6–9.3 fl. oz./acre of 95% malathion was required for 89–99% control (Lofgren et al. 1970b, Uribe et al. 1980). In dense vegetation, Eliason et al. (1975) and Taylor et al. (1975) obtained >99% reduction of *Anopheles albimanus* Wied. populations with 6 sequential applications of 95% malathion, all applied at 4.5 fl. oz./acre except for an initial spray at 6 fl. oz./acre. In another test, Mount et al. (1970d) obtained only 33% control of *An. albimanus* populations in the target area with 6 fl. oz./acre of 95% malathion; however, 99% control was observed in an area 0–0.5 mi. downwind of the target area, indicating excessive horizontal transport of the spray.

Satisfactory levels of control (88–99%) were obtained in 9 of 10 studies at 0.5–1 fl. oz./acre of 85% naled applied for control of *Aedes, Anopheles, Culex,* and *Psorophora* sp. in large-scale tests and operational applications (see data and references in Table 2). In one test, Bourg et al. (1978) obtained only 71% control of *Ae. sollicitans* with 1 fl. oz./acre of 85% naled, apparently because of mosquito reinfestation of the 3 mi.$^2$ target area. In an operational program, Biery (1987; footnote 7, Table 2) observed 68–99% kill of caged *Ae. aegypti* exposed to sprays of 1 fl. oz./acre of 85% naled with the level of kill dependent on weather conditions.

The effectiveness of ULV aerial application of 95% fenitrothion at 6.1 fl. oz./acre against adult *Cx. tritaeniorhynchus* Giles was shown by Self et al. (1973). The target area (6.25 mi.$^2$) consisted of rice fields, small villages, and occasional marshes with reeds. Based on animal bait and animal shelter collections, fenitrothion provided an average of 71–81% reduction in the population of adult female mosquitoes.

*High-altitude tests:* The feasibility of dispersing ULV insecticides from wide swaths at a constant high altitude (>200 ft.) or from multiple swaths over the same flight path at increasingly higher altitudes (stacked swaths) was explored by various investigators. These application methods utilize the range in horizontal transport potential of the ULV aerial spray droplet spectrum. One advantage for both methods is increased swath width. A second advantage for the stacked swath method is that an urban area can be treated without actually flying spray aircraft over the target area. Twin-engine, fixed-wing aircraft were used in all high-altitude tests except 2 reported by Akesson et al. (1969). All insecticides were atomized with flat-fan or hollow-cone nozzles oriented straight down or down and 45° forward to the airstream. Basic data and references for 6 tests on high-altitude dispersal of ULV aerial sprays are presented in Table 3.

In 2 California tests (not shown in Table 3), chlorpyrifos (Dursban®) was dispersed at high altitudes in stacked swaths at Bakersville and naled (Dibrom® 14) was similarly dispersed at Colusa (Akesson et al. 1969). Based on insecticide deposits, both tests revealed that droplets were air transported 4,000–14,000 ft. downwind from release at 500–2,000 ft. of altitude. These investigators observed that droplet size decreased with increased downwind distance and that droplets <50 μm diameter apparently did not fall out because airborne droplets of 10–30 μm diameter were collected with cascade impactors at various distances downwind of the flight path.

In high-altitude, wide-swath tests, Machado et al. (1969b) applied 85% naled from an altitude of 1,000 ft. to 2 large tracts of land (11–12.5 mi.$^2$) in Louisiana for control of *Ae. sollicitans* populations (Table 3). Naled was applied at 0.5–1 fl. oz./acre in 1,000-ft. swaths at a speed of approximately 150 mph. The aircraft and spray system was described by Machado et al. (1969a). For the first 3 tests, because the investigators were concerned about excessive horizontal transport, the nozzles were oriented in a trailing position to the slipstream to minimize shearing action, thus maximizing droplet size. In these tests, 59–86% control was achieved, depending on the amount of vegetation in the treated area. In the fourth test (1 fl. oz./acre), the investigators decided to take advantage of the potential horizontal transport of spray droplets and oriented the nozzles down and 45° forward in relation to the slipstream. Also, the dispersal altitude was reduced to 500 ft. because of surface winds of 8–10 mph. In the fourth test, 94% control was achieved in an urban area and 76% control was achieved in a densely wooded area with heavy underbrush.

High-altitude nighttime ULV applications of 0.55–0.8 fl. oz./acre of 85% naled for control of adult mosquitoes were tested in Florida by Taylor and Rathburn (1970) (Table 3). Pre- and posttreatment light trap collections in the target areas indicated 14–100% control of *Aedes, Culex,* and *Psorophora* sp. Also, caged mosquito kills and deposits on cards indicated that the naled spray drifted 0.5–3 mi. downwind from the upwind edge of the target area when surface wind velocities were <2 mph.

Mount et al. (1970a) investigated high-altitude, wide-swath applications of 95% malathion over a 20 mi.$^2$ target area in Florida (Table 3). Maximum kills of caged *Ae. taeniorhynchus* mosquitoes occurred 0.5–3 mi. downwind at 150 ft. of spray altitude and 1–5 mi. downwind at 500- and 1,000-ft.

Table 1. ULV aerial sprays of insecticides at altitudes of $\leq$200 ft. against adult mosquitoes in small target areas ($<$1 mi.$^2$).

| Species | Location | Habitat |
|---|---|---|
| Malathion, 95% | | |
| *Aedes sollicitans* (Walker) | Kentucky | Open to wooded |
| *Ae. taeniorhynchus* (Wied.) | Florida | Citrus groves |
| *Glyptotendipes paripes* | Florida | Lake shore |
| Edwards (midges) | Florida | Lake shore |
| *Anopheles albimanus* Wied., | Panama | Dense jungle |
| *An. triannulatus* (Neiva and Pinto) | Panama | Dense jungle |
| *Ae. taeniorhynchus* | Florida | Open to wooded |
| *Culex nigripalpus* Theobald | Florida | Open to wooded |
| *Ae. aegypti* (Linn.) | Thailand | Open houses |
| | Thailand | Open houses |
| *Cx. quinquefasciatus* Say | Thailand | Open houses |
| | Thailand | Open houses |
| *Ae. simpsoni* (Theobald) | Ethiopia | False banana |
| | Ethiopia | False banana |
| Malathion, 50% EC | | |
| *Ae. aegypti, Ae. africanus* Neveu-Lemaire, *Ae. luteocephalus* (Newstead) | Nigeria | Open houses |
| Naled, 85% (14 lb. AI/gal) | | |
| *Ae. taeniorhynchus* | Florida | Citrus groves |
| *Ae. sollicitans* | Kentucky | Open to wooded |
| *Ae. taeniorhynchus* | Kentucky | Open to wooded |
| Fenthion, 8 lb. AI/gal (Baytex®) | | |
| *Ae. sollicitans* | Kentucky | Open to wooded |
| | Kentucky | Open to wooded |
| *Ae. taeniorhynchus* | Florida | Citrus groves |
| *Ae. stimulans* (Walker) | Michigan | Wooded |
| | Michigan | Wooded |
| *An. albimanus,* | Panama | Dense jungle |
| *An triannulatus* | Panama | Dense jungle |
| | Panama | Dense jungle |
| *Cx. quinquefasciatus* | Florida | Open field |
| *Ae. stimulans* | Michigan | Wooded |
| | Michigan | Wooded |
| *Ae. sollicitans* | Kentucky | Open to wooded |
| Fenthion, 93% (Baytex®) | | |
| *Cx. quinquefasciatus* | Florida | Open field |
| Propoxur, 4 lb, AI/gal (Baygon®) | | |
| *Ae. stimulans* | Michigan | Wooded |
| | Michigan | Wooded |
| *Ae. sollicitans* | Kentucky | Open to wooded |
| Permethrin + piperonyl butoxide[3] | | |
| *Cx. quinquefasciatus* | Louisiana | Open field |
| *An. quadrimaculatus* Say | Arkansas | Open field |

[1] Reduction of the natural population (n) or kill of caged mosquitoes (c) within 48 h posttreatment.

[2] Volume for 90% reduction estimated by probit analysis of combined data from indicated references.

[3] Biomist® 30:30 or 31:66 diluted 1:19 with Envirotech® oil and applied at 0.9 fl. oz. AI/acre or 0.6–0.67 fl. oz. AI/acre, respectively.

spray altitudes. With 3,000 ft. of spray altitude, little or no mosquito kill occurred within 5 mi. downwind. In general, wind velocity increased with each increase in altitude (5, 10, 12, and 15 mph at altitudes of 150, 500, 1,000, and 3,000 ft., respectively) in a series of 11 tests.

Mount et al. (1970d) used knowledge gained from the Florida tests and results from previous

Table 1. Extended.

| Volume (fl. oz./acre) | Percentage control | Reference(s) |
|---|---|---|
| Malathion, 95% | | |
| 3.8 | 90[2] n | Knapp and Roberts (1965), Knapp and Pass (1966), Knapp and Gayle (1967) |
| 5.1 | 90[2] n | Glancey et al. (1965, 1966); Mount and Lofgren (1967); Mount et al. (1970b, 1970e, 1970f, 1971) |
| 2.0 | 100 n | Patterson et al. (1966) |
| 4.0 | 100 n | Patterson et al. (1966) |
| 3.0 | 62 n | Lofgren et al. (1968) |
| 8.0 | 90 n | Lofgren et al. (1968) |
| 3.2 | 54–97 c | Rathburn et al. (1969) |
| 3.2 | 16–87 c | Rathburn et al. (1969) |
| 3.0 | 64 c | Kilpatrick et al. (1970b) |
| 6.0 | 100 c | Kilpatrick et al. (1970b) |
| 3.0 | 64 c | Kilpatrick et al. (1970b) |
| 6.0 | 99 c | Kilpatrick et al. (1970b) |
| 6.0 | 76–89 n | Brooks et al. (1970) |
| 20.2 | 93–100 n | Brooks et al. (1970) |
| Malathion 50% EC | | |
| 13.6 | 99 n | Knudsen et al. (1980) |
| Naled, 85% (14 lb, AI/gal) | | |
| 1.1 | 90[2] n | Glancey et al. (1966), Mount and Lofgren (1967) |
| 0.8 | 90[2] n | Knapp and Gayle (1967), Knapp and Rogers (1968) |
| 1.0 | 61 c | Rathburn et al. (1969) |
| Fenthion, 8 lb. AI/gal (Baytex®) | | |
| 0.8 | 93 n | Knapp and Pass (1966) |
| 1.6 | 100 n | Knapp and Pass (1966) |
| 1.8 | 90[2] n | Glancey et al. (1966); Mount and Lofgren (1967); Mount et al. (1970b 1970e, 1970f, 1971) |
| 0.75 | 93 n | Stevens and Stroud (1966) |
| 1.5 | 96 n | Stevens and Stroud (1966) |
| 1.6 | 62 n | Lofgren et al. (1968) |
| 4.0 | 90 n | Lofgren et al. (1968) |
| 4.8 | 95 n | Lofgren et al. (1968) |
| 0.45 | 90[2] c | Mount et al. (1970b) |
| 1.6 | 100 n | Stevens and Stroud (1967) |
| 2.4 | 100 n | Stevens and Stroud (1967) |
| 1.5 | 90[2] n | Knapp and Gayle (1967) |
| Fenthion, 93% (Baytex®) | | |
| 0.45 | 90[2] c | Mount et al. (1970b) |
| Propoxur, 4 lb, AI/gal (Baygon®) | | |
| 1.6 | 100 n | Stevens and Stroud (1967) |
| 2.4 | 100 n | Stevens and Stroud (1967) |
| 1.5 | 90[2] n | Knapp and Gayle (1967) |
| Permethrin + piperonyl butoxide[3] | | |
| 60 | 87 c | Groves et al. (1994) |
| 40–45 | 81–92 c | Groves et al. (1994) |

work (Lofgren et al. 1968) to investigate the practicality of high-altitude, wide-swath sprays of malathion and fenthion for control of anopheline mosquito populations in Panama (Table 3). Spray altitudes were based on the desired swath interval and the altitude of the lowest wind current, as surface conditions were calm during all spray applications. In the target area, control of the natural population with 6 fl. oz./acre of 95% malathion averaged 87% at 24 h posttreatment while 14 h kill of adult female

Table 2. ULV aerial sprays of insecticides at altitudes of ≤200 ft. against adult mosquitoes in large target areas (>1 mi.[2]).

| Species | Location | Habitat | Aircraft |
|---|---|---|---|
| Malathion, 95% | | | |
| *Culex quinquefasciatus* | Texas | Urban to wooded | C-123 |
| *Aedes* sp. | Alaska | Open to wooded | C-123 |
| *Cx. tarsalis* Coquillett, *Ae. vexans* (Meigen), *Ae. nigromaculis* (Ludlow), *Psorophora signipennis* (Coquillett) | Texas | Urban to wooded | C-123 |
| *Ae. taeniorhynchus* | Florida | Open to wooded | C-47 |
| | Florida | Open to wooded | C-47 |
| | Florida | Open to wooded | C-47 |
| *Ae. aegypti* | Florida | Open to wooded | C-47 |
| | Thailand | Open houses | C-47 |
| | Thailand | Open houses | C-47 |
| *Anopheles albimanus* | Panama | Dense jungle | C-47 |
| *Ae. sollicitans, Psorophora* sp. | Texas | Urban to wooded | C-123, C-47 |
| *Ae. aegypti* | Angola | Urban to wooded | Piper Pawnee |
| *An. albimanus* | Haiti | Sugarcane, banana | Beechcraft D-18 |
| *Ae. dorsalis* (Meigen), *Ae. melanimon* Dyar | Wyoming | Pasture | Beechcraft C-45 |
| *Ps. columbiae* (Dyar and Knab), | Arkansas | Urban, rice fields | Beechcraft 18 |
| *An quadrimaculatus* | Arkansas | Urban, rice fields | Beechcraft 18 |
| *Ae. aegypti* | Colombia | Open houses | Cessna 188 |
| | Colombia | Open houses | Cessna 188 |
| *Ae. taeniorhynchus* | Florida | Open field | C-130 |
| Malathion, 91.5% | | | |
| *Cx. tarsalis* | Minnesota | Open to wooded | C-123 |
| Naled, 85% (14 lb, AI/gal) | | | |
| *Ae. sollicitans, Psorophora* sp. | Texas | Urban to wooded | C-123, C-47 |
| *Ae. sollicitans* | Louisiana | Urban to wooded | Grumman Ag-Cat. |
| *Cx. salinarius* Coquillett | Louisiana | Urban to wooded | Grumman Ag-Cat |
| *Ps. columbiae, An. quadrimaculatus* | Arkansas | Urban, rice fields | DC-3 |
| *Ae. taeniorhynchus* | Florida | Open field | C-123 |
| | Florida | Open field | C-123 |
| | Florida | Open field | C-123 |
| *Culicoides* sp. (biting midges) | South Carolina | Salt-marsh | C-123 |
| *Ae. aegypti* | Puerto Rico | Urban | C-130 |
| *Ae. taeniorhynchus* | Florida | Open field | C-130 |
| *Psorophora* sp., *Ae. vexans, Ae. sollicitans, Ae. atlanticus* Dyar and Knab, *Ae. tormentor* Dyar and Knab, *Anopheles* sp. | South Carolina | Open to wooded | C-130 |
| *Ae. taeniorhynchus* | Florida | Open to wooded | C-130 |
| Fenitrothion, 95% (Accothion®) | | | |
| *Cx. tritaeniorhynchus* Giles | Korea | Rice fields, villages | C-46 |

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[1] Reduction of the natural population (n) or kill of caged mosquitoes (c), usually within 48 h posttreatment.

[2] Exact size not indicated in reference.

[3] Higher level of control achieved downwind of target area.

[4] Haile, D. G. and D. L. Kline. 1989. Evaluation of C-130 modular aerial spray system (MASS) for ultra-low-volume application (ULV) of insecticides for adult mosquito control. Unpublished USDA-ARS Report, p. 61.

[5] Biery, T. L. 1983. Public health emergency in Minnesota. Unpublished U.S. Air Force Report, p. 21.

[6] Volume for Dibrom® 14 only which was diluted in heavy aromatic naphtha (1:5).

[7] Biery, T. L. 1987. Aerial spray mission for dengue control in San Juan, P.R. Unpublished U.S. Air Force Report, p. 8.

[8] Biery, T. L. 1989. 1989 USAFR emergency mosquito aerial spray operation as part of FEMA Hugo relief effort. Unpublished U.S. Air Force Report, p. 35.

[9] Biery, T. L. 1993. 1992 USAFR emergency mosquito aerial spray operations as part of the FEMA Hurricane Andrew relief effort in Florida. Unpublished U.S. Air Force Report, p. 27.

Table 2. Extended.

| Swath (ft.) | Area (mi.²) | Volume (fl. oz./acre) | Percentage control[1] | Reference(s) |
|---|---|---|---|---|
| Malathion, 95% | | | | |
| 500 | 742 | 3.0 | >90 n | Kilpatrick and Adams (1967) |
| 500 | 24 | 3.0 | 96 n | Mount et al. (1969) |
| 500 | 25 | 3.0 | 64 n | Mitchell et al. (1969, 1970) |
| 2,112 | 25 | 1.5 | 62 c | Mount et al. (1970a) |
| 1,056 | 25 | 3.0 | 96 c | Mount et al. (1970a) |
| 500 | 1 | 3.0 | 59–97 c | Glancey et al. (1970) |
| 500 | 1 | 3.0 | 97 c | Glancey et al. (1970) |
| 500 | >1[2] | 3.0 | 82 n | Lofgren et al. (1970a) |
| 500 | 7 | 6.0 | 91 n | Lofgren et al. (1970b) |
| 1,056 | 6 | 6.0 | 33[3] n | Mount et al. (1970d) |
| 1,000 | 4,684 | 2.6 | 94–98 n | Pinkovsky (1972) |
| Unlisted | >1[2] | 6.8 | 84–96 n | Ribeiro (1973) |
| 300 | 31 | 4.5–6.0 | >99 n | Eliason et al. (1975), Taylor et al. (1975) |
| 300 | 6–7 | 4.0 | 86–91 n | Forcum (1976) |
| 350 | 16 | 1.5 | 57 n | Meisch and Mount (1978) |
| 350 | 16 | 3.0 | 97 n | Meisch and Mount (1978) |
| 165 | >2 | 3.9 | 58–75 n | Uribe et al. (1980) |
| 165 | >2 | 9.3 | 89–94 n | Uribe et al. (1980) |
| 1,000–3,000 | >1[2] | 3.0 | >90 c | Haile and Kline (1989)[4] |
| Malathion, 91.5% | | | | |
| 2,000 | 820 | 3.0 | 94 n | Biery (1983)[5] |
| Naled, 85% (14 lb. AI/gal) | | | | |
| 1,000 | 916 | 0.75 | 94–98 n | Pinkovksy (1972) |
| 328 | 3 | 1.0 | 71 n | Bourg et al. (1978) |
| 328 | 3 | 1.0 | 88 n | Bourg et al. (1978) |
| 350 | 16 | 1.0 | 92 n | Meisch and Mount (1978) |
| 2,112 | 6 | 0.25[6] | 82 c | Haile et al. (1982b) |
| 2,112 | 6 | 0.25 | 83 c | Haile et al. (1982b) |
| 2,112 | 6 | 0.75 | 93 c | Haile et al. (1982b) |
| 1,000 | >12 | 1.0 | >99 n | Haile et al. (1984) |
| 1,000 | 277 | 1.0 | 68–99 c | Biery (1987)[7] |
| 1,000–3,000 | >1[2] | 0.75 | >90 c | Haile and Kline (1989)[4] |
| 1,250–2,500 | 1,337 | 0.5 | 90–95 n | Biery (1989)[8] |
| 2,500 | 436 | 1.0 | 93–99 n | Biery (1993)[9] |
| Fenitrothion, 95% (Accothion®) | | | | |
| 500 | >6 | 6.1 | 71–81 n | Self et al. (1973) |

*An. albimanus* averaged 100 and 87% in screen cages placed on a road shoulder and under jungle canopy, respectively. Also, some mosquito control was achieved with malathion for 1 mi. downwind of the target area with 16% control of the natural population at 24 h posttreatment as well as 100 and 52% kill of caged mosquitoes along a road and under jungle canopy. With 1.2 fl. oz./acre of 8 lb. AI/gal fenthion, control of the natural population in the target area averaged 51% while kill of caged mosquitoes on a road and under jungle canopy averaged 92 and 88%, respectively. Fenthion provided mosquito control downwind for 1 mi. of the target area with 61% reduction of the natural pop-

Table 3. ULV aerial sprays of insecticides at altitudes of >200 ft. against adult mosquitoes in large target areas (>1 mi.$^2$).

| Species | Location | Habitat | Aircraft |
|---|---|---|---|
| | Malathion, 95% | | |
| *Aedes taeniorhynchus* | Florida | Open to wooded | C-47 |
| | Florida | Open to wooded | C-47 |
| | Florida | Open to wooded | C-47 |
| | Florida | Open to wooded | C-47 |
| *Anopheles albimanus* | Panama | Dense jungle | C-47 |
| | Naled, 85% (14 lb, AI/gal) | | |
| *Ae. solicitans* | Louisiana | Urban to wooded | DC-3 |
| *Psorophora columbiae* | Florida | Urban to wooded | C-47 |
| *Culex nigripalpus* | Florida | Urban to wooded | C-47 |
| *Ps. ciliata* (Fabr.) | Florida | Urban to wooded | C-47 |
| *Ae. infirmatus* Dyar and Knab | Florida | Urban to wooded | C-47 |
| *Ae. taeniorhynchus* | Florida | Open to wooded | C-123 |
| | Florida | Open to wooded | C-123 |
| | Naled, 80% | | |
| *An. quadrimaculatus* | Arkansas | Urban, rice | Piper Aztec |
| *Ps. columbiae* | Arkansas | Urban, rice | Piper Aztec |
| | Fenthion, 8 lb, AI/gal (Baytex®) | | |
| *An. albimanus* | Panama | Dense jungle | C-47 |
| | Panama | Dense jungle | C-47 |
| | Fenthion, 93% (Baytex®) | | |
| *An. albimanus, An. triannulatus* | Panama | Dense jungle | C-123 |

[1] Reduction of the natural population (n) or kill of caged mosquitoes (c), usually within 48 h posttreatment.

[2] Apparently most of the insecticide was transported beyond the target area.

[3] Volume for Dibrom® 14 only, which was diluted in heavy aromatic naphtha (1:5).

[4] Higher level of control achieved downwind of target area.

ulation plus 91 and 82% kill of caged adult mosquitoes on a road and under jungle canopy, respectively.

Lofgren et al. (1972) followed up the previous ULV aerial spray studies in Panama (Lofgren et al. 1968, Mount et al. 1970d) by treating a 20 mi.$^2$ plot of jungle terrain with 2 aerial sprays of fenthion, an effective mosquito adulticide and larvicide (Table 3). The second application to the same plot was made 9 days following the initial spray to kill new larvae before pupation and new adults before oviposition. The predominant anopheline species in the test were *An. albimanus* and *An. triannulatus* Neiva and Pinto. A rate of 1 fl. oz./acre of 93% fenthion was dispersed at 350-ft. altitude during the first application and 150–200 ft. altitude for the second spray. Based on man-biting collections and collections from horse-baited traps, these sprays provided successful control (initial reduction of 95 and >81% overall) of the adult anopheline mosquito population for 31 days following the second application.

Haile et al. (1982b) obtained only 55% kill of caged *Ae. taeniorhynchus* with either 0.125 or 0.25 fl. oz./acre of naled (85% naled diluted 1:5 in heavy aromatic naphtha and undiluted 85% naled, respectively) dispersed at altitudes of 240 and 270 ft., respectively. However, these unsatisfactory results are likely due more to insufficient dose than to excessive horizontal transport caused by high-altitude dispersal.

In a high-altitude nighttime test, Weathersbee et al. (1986) applied 80% naled to ricefields of 4 mi.$^2$ surrounding Stuttgart, Arkansas for adult mosquito control (Table 3). A rate of 0.72 fl. oz./acre of 80% naled applied at 200–300-ft. altitude produced reductions of 48 and 68% of *An. quadrimaculatus* and *Psorophora columbiae* (Dyar and Knab) populations, respectively, at 24 h posttreatment. Because of high application altitudes and surface wind velocities of 5–10 mph during application, some of the naled was likely transported downwind of the target area. Furthermore, the 24-h reductions may reflect some reinfestation of the target area.

## EFFICACY AGAINST MOSQUITO LARVAE

The advantages of the ULV aerial spray method for mosquito adulticiding cannot universally be applied to mosquito larviciding. The ULV method is well suited to large-scale operations whereas most mosquito larviciding is done on a relatively small scale. Nevertheless, knowledge of ULV aerial

Table 3. Extended.

| Altitude (ft.) | Swath (ft.) | Area (mi.$^2$) | Volume (fl. oz./acre) | Percentage control[1] | Reference(s) |
|---|---|---|---|---|---|
| Malathion, 95% | | | | | |
| 500 | 2,112 | 25 | 1.5 | 74 c | Mount et al. (1970a) |
| 500 | 1,056 | 25 | 3.0 | 100 c | Mount et al. (1970a) |
| 1,000 | 1,056 | 25 | 3.0 | 97 c | Mount et al. (1970a) |
| 3,000 | 1,056 | 25 | 3.0 | 33[2] c | Mount et al. (1970a) |
| 300 | 1,056 | 6 | 6.0 | 87 n | Mount et al. (1970d) |
| Naled, 85% (14 lb. AI/gal) | | | | | |
| 500 | 1,000 | >12 | 1.0 | 85 n | Machado et al. (1969b) |
| 600–1,000 | 500 | 4–28 | 0.55–0.80 | 87–100 n | Taylor and Rathburn (1970) |
| 600–1,000 | 500 | 4–28 | 0.55–0.80 | 14–80 n | Taylor and Rathburn (1970) |
| 600 | 500 | 28 | 0.55 | 72 n | Taylor and Rathburn (1970) |
| 600 | 500 | >4 | 0.80 | 95 n | Taylor and Rathburn (1970) |
| 240 | 2,112 | 6 | 0.125[3] | 55 c | Haile et al. (1982b) |
| 270 | 2,112 | 6 | 0.25 | 55 c | Haile et al. (1982b) |
| Naled, 80% | | | | | |
| 200–300 | Unlisted | 4 | 0.72 | 48[2] n | Weathersbee et al. (1986) |
| 200–300 | Unlisted | 4 | 0.72 | 68[2] n | Weathersbee et al. (1986) |
| Fenthion, 8 lb. AI/gal (Baytex®) | | | | | |
| 300 | 2,112 | 6 | 1.2 | 45[4] n | Mount et al. (1970d) |
| 500 | 4,224 | 6 | 1.2 | 57[4] n | Mount et al. (1970d) |
| Fenthion, 93% (Baytex®) | | | | | |
| 150–350 | 2,112 | 20 | 1.0 | 95 n | Lofgren et al. (1972) |

sprays of insecticides was needed to predict their effect on larval populations. Thus, bioassays with mosquito larvae were included in some tests designed primarily for adulticiding. In California, where larviciding has been a mainstay of mosquito control operations, ULV aerial sprays of insecticides were tested against mosquito larvae in pastures and rice fields. However, insecticide formulations were somewhat diluted with various oils in most of the California trials. Furthermore, several investigators tested the ULV aerial spray method for large-scale larvicide applications against *Ae. aegypti* during the previous eradication effort in the USA during the 1960s. All larvicide tests were done with small, single-engine, fixed-wing or rotary-wing aircraft except those by Eliason et al. (1970), Lofgren et al. (1972), and Mount et al. (1970d), which were done with relatively large, twin-engine, fixed-wing aircraft. Most insecticides were dispersed with flat-fan or hollow-cone nozzles. However, a few tests were done by applying insecticides with rotary atomizers. Tests of ULV aerial sprays of insecticides against mosquito larvae are summarized in Table 4.

Although the test results against mosquito larvae shown in Table 4 are not comprehensive enough to determine minimum effective larvicide rates, they indicate expected larval mortality at normal adulticide rates. Results from 8 studies with 95% malathion at 2–3 and 6–6.8 fl. oz./acre indicated 38–100% ($\bar{x} = 71\%$) and 67–100% ($\bar{x} = 85\%$) control of *Aedes* and *Culex* sp. larvae, respectively. Also, 13.6 fl. oz./acre of 50% malathion killed 97% of *Ae. aegypti* larvae in open glass beakers (Knudsen et al. 1980). In tests with midge larvae, *Chironomus fulvipilus* Rempel, Patterson et al. (1966) obtained 95% mortality with 2 fl. oz./acre of 95% malathion. In 5 different studies including *Aedes, Anopheles,* and *Culex* larvae, 93–100% control was obtained with doses of 0.047–0.12 lb. AI/acre of fenthion which is equivalent to 0.6–1.6 fl. oz./acre of 93% fenthion. A wide dose range of chlorpyrifos (0.011–0.125 lb. AI/acre = 0.35–3.8 fl. oz./acre of 4 lb. AI/gal formulation) was used to obtain 74–100% control of *Aedes, Anopheles,* and *Culex* larvae in 4 different studies. Temephos, which is not used as an adulticide, produced 79–100% control of *Ae. aegypti* larvae at a dose of 0.0625 lb. AI/acre of temephos (= 2.33 fl. oz./acre of 4 lb. AI/gal formulation) (Kilpatrick et al. 1970a, Eliason et al. 1970). Finally, Mount et al. (1970e) obtained 86–100% control of *Cx. quinquefasciatus* Say larvae with 0.75–1.5 fl. oz./acre of 8.34 lb. AI/gal fenitrothion.

## DROPLET SIZE

Droplet size is an important factor affecting the efficacy of insecticides applied aerially for mosquito control. The size of droplets governs their air transport as well as subsequent impingement and coverage on target insects and their habitat. For

Table 4. ULV aerial sprays of insecticides against mosquito larvae.

| Species | Location | Habitat |
|---|---|---|
| | Malathion, 95% | |
| *Aedes nigromaculis* | California | Pasture |
| *Culex tarsalis* | California | Pasture |
| *Cx. quinquefasciatus* | Florida | Open pans |
| *Chironomus fulvipilus* Rempel (midges) | Florida | Open pans |
| *Cx. quinquefasciatus* | Florida | Open cups |
| *Ae. aegypti* | Florida | Urban |
| | Thailand | Open cups |
| | Thailand | Open cups |
| *Cx. quinquefasciatus* | Thailand | Open cups |
| | Thailand | Open cups |
| *Ae. aegypti* | Thailand | Open cups |
| | Thailand | Open cups |
| *Cx. quinquefasciatus* | Thailand | Open cups |
| | Angola | Open dishes |
| | Malathion, 50% | |
| *Ae. aegypti* | Nigeria | Open glass beakers |
| | Fenthion, diluted (Baytex®) | |
| *Ae. nigromaculis* | California | Pasture |
| | Fenthion, 8 lb. AI/gal (Baytex®) | |
| *Ae. stimulans* | Michigan | Open cartons |
| *Cx. quinquefasciatus* | Florida | Open cups |
| | Florida | Open cups |
| *An. albimanus* | Panama | Open cups |
| | Fenthion, 93% (Baytex®) | |
| *An. albimanus, An. triannulatus* | Panama | Aquatic |
| | Chlorpyrifos, diluted (Dursban®) | |
| *Anopheles* sp. *Culex* sp. | California | Rice field |
| *An. freeborni* Aitken, *Cx. tarsalis* | California | Rice field |
| | Chlorpyrifos, 4 lb. AI/gal (Dursban®) | |
| *Cx. quinquefasciatus* | Florida | Open cups |
| *Ae. aegypti* | Florida | Open metal cans |
| | Temephos, 4 lb. AI/gal (Abate®) | |
| | Florida | Open metal cans |
| | Florida | Urban |
| | Fenitrothion, 8.34 lb AI/gal (Accothion®) | |
| *Cx. quinquefasciatus* | Florida | Open cups |
| | Florida | Open cups |

[1] Reduction of the natural population or kill of containerized mosquito larvae as indicated in "Habitat" column within 48 h posttreatment.

economical and rapid application, ULV aerial sprays for adult mosquito control rely on air transport of droplets by crosswinds to obtain wide swaths. Important aspects of spray droplet size include measurement methods, optimum size, factors affecting atomization, and effect of droplet size on paint.

*Measurement methods:* Generally, measurements are made to estimate the initial droplet spectrum as dispersed from the spray system instead of droplets that impinge on mosquitoes or their habitat. Determination of the initial droplet spectrum is difficult to achieve because droplet collection is usually some distance removed from the flight path of the aircraft. With most methods of droplet sampling, size parameters can be biased by the collection method or placement of collection devices. The volume median diameter (VMD) is the most commonly used parameter to describe a droplet spectrum. The VMD is the droplet diameter where 50% of the spray volume is in larger drops and 50% is in smaller drops. Several methods are available for droplet size determination of insecticidal sprays, including microscopic reading of droplets on slides and optical or laser measurement systems. However, all of these methods involve one or more

Table 4. Extended.

| Volume (fl. oz./acre) | Dose (lb. AI/acre) | Percentage control[1] | Reference(s) |
|---|---|---|---|
| | | Malathion, 95% | |
| 6.0 | 0.485 | 67 | Mulhern et al. (1965) |
| 6.0 | 0.485 | 60 | Mulhern et al. (1965) |
| 2.0 | 0.162 | 100 | Patterson et al. (1966) |
| 2.0 | 0.162 | 95 | Patterson et al. (1966) |
| 2.6 | 0.20 | 63 | Mount et al. (1970e) |
| 3.0 | 0.243 | 94 | Eliason et al. (1970) |
| 3.0 | 0.243 | 38 | Kilpatrick et al. (1970b) |
| 6.0 | 0.485 | 100 | Kilpatrick et al. (1970b) |
| 3.0 | 0.243 | 61 | Kilpatrick et al. (1970b) |
| 6.0 | 0.485 | 100 | Kilpatrick et al. (1970b) |
| 3.0 | 0.243 | 69 | Lofgren et al. (1970a) |
| 6.0 | 0.485 | 76 | Lofgren et al. (1970b) |
| 6.0 | 0.485 | 89 | Lofgren et al. (1970b) |
| 6.8 | 0.550 | 100 | Ribeiro (1973) |
| | | Malathion, 50% | |
| 13.6 | 0.549 | 97 | Knudsen et al. (1980) |
| | | Fenthion, diluted (Baytex®) | |
| 6.4–11.0 | 0.07–0.12 | 80–100 | Mulhern et al. (1965) |
| | | Fenthion, 8 lb. AI/gal (Baytex®) | |
| 0.75 | 0.047 | 100 | Stevens and Stroud (1966) |
| 0.65 | 0.05 | 93 | Mount et al. (1970e) |
| 1.3 | 0.10 | 100 | Mount et al. (1970e) |
| 1.2 | 0.094 | 100 | Mount et al. (1970d) |
| | | Fenthion, 93% (Baytex®) | |
| 1.0 | 0.076 | >99 | Lofgren et al. (1972) |
| | | Chlorpyrifos, diluted (Dursban®) | |
| 5.0–8.0 | 0.013–0.050 | 74–100 | Burgoyne et al. (1968) |
| 1.4–1.6 | 0.011–0.025 | 97–100 | Womeldorf and Whitesell (1972) |
| | | Chlorpyrifos, 4 lb, AI/gal (Dursban®) | |
| 3.2 | 0.10 | 100 | Mount et al. (1970e) |
| Unlisted | 0.125 | 98 | Kilpatrick et al. (1970a) |
| | | Temephos, 4 lb. AI/gal (Abate®) | |
| Unlisted | 0.0625 | 100 | Kilpatrick et al. (1970a) |
| 2.33 | 0.0625 | 79 | Eliason et al. (1970) |
| | | Fenitrothion, 8.34 lb. AI/gal (Accothion®) | |
| 0.75 | 0.05 | 100 | Mount et al. (1970e) |
| 1.5 | 0.10 | 86 | Mount et al. (1970e) |

problems in sampling, measurement, cost, or convenience. A comprehensive review of droplet sampling and size determination methodology was provided by Rathburn (1970).

A low-altitude method was designed by Mount et al. (1970b) to minimize bias in collecting droplets on microscope slides. This method uses multiple passes of the spray aircraft at the minimum safe altitude (usually 25–50 ft., depending on the aircraft) over a level, open area during relatively calm weather. Teflon-coated glass microscope slides attached to electrically driven spinners placed under the flight line were used to collect spray droplets. A spread factor is required to relate the diameter of droplets on slides to the actual droplet diameter. A method developed by Yeomans (1949) that compensates for the higher critical impingement velocities of smaller droplets was used to calculate the VMD. The accuracy of Yeomans' hand wave method for estimating the VMD of ground-applied aerosols was verified by Mount and Pierce (1972), Haile et al. (1978), and Carroll and Bourg (1979). Their studies showed equivalent estimates of VMD with settling, impaction, and Coulter Counter® methods. However, the accuracy of Yeomans' method for aircraft application of somewhat larger droplet spectra has not been fully verified. Thus, Yeomans' method may somewhat underestimate the actual VMD when applied to ULV aerial sprays. Also, a simulated method employed by

Mount et al. (1970c) used the airstream of a high-velocity mist blower for droplet size collection. VMD estimates from this simulated method were 20–30% smaller than those obtained from actual aircraft applications (Mount et al. 1970b). Bouse and Carlton (1983) and Yates et al. (1983) also used laser droplet imaging systems to measure droplet size of aerial sprays.

*Optimum droplet size spectrum:* The optimum size spectrum for the most efficient mosquito control is dependent on type of application (adulticide or larvicide), impingement efficiency, and transport requirement. Decreasing the droplet size to below the optimum spectrum increases air transport and reduces impingement on adult mosquitoes and their associated habitats. Conversely, increasing the droplet size to above the optimum spectrum decreases swath intervals and increases impingement on nontarget surfaces such as canopy above the mosquito habitat.

*Adulticiding:* The literature on optimum droplet size for adult mosquito control with sprays or aerosols was reviewed previously by Mount (1970). Four separate laboratory studies provide knowledge on the optimum droplet size of insecticidal aerosols for mosquito adulticiding. Based on wind tunnel test results, Weidhaas et al. (1970) calculated that the minimum lethal dose ($LD_{100}$) of undiluted technical grade formulations of malathion, naled, and fenthion for adult female *Ae. taeniorhynchus* is contained in droplets of 25, 20, and 17.5 μm diameter, respectively. These results suggest that larger droplets of these insecticides applied as ULV aerosols could be wasteful because of overdosing. Also, in a settlement chamber study with still air, Lofgren et al. (1973) used a scanning electron microscope to observe that 2–16-μm-diameter droplets of soybean oil (used to simulate technical insecticides) impinged more efficiently on mosquito wings than smaller or larger droplets. Furthermore, in a wind tunnel study, Haile et al. (1982a) defined the relationship between adult mosquito mortality and droplet size with exposure of *Ae. taeniorhynchus* to uniform size droplets of malathion insecticide transported at 2.3 mph. Their results indicated that the optimum droplet size range for kill of adult mosquitoes is 10–15 μm diameter. An extension of the optimum size range to 4–26 μm diameter resulted in only a ≤1.7-fold reduced kill efficiency compared to the more narrow range. These results are consistent with those reported previously by Latta et al. (1947), who demonstrated that the most effective droplet size range for adult mosquitoes exposed to DDT in a wind tunnel was 12–20 μm diameter. Haile et al. (1982a) also demonstrated that ground-applied aerosols with VMDs of 5–24 μm provided greater percentage kill of adult mosquitoes than an aerosol with a VMD of 39 μm.

In studies with aircraft applications at 95 mph, Mount et al. (1970e, 1971) showed that adult mosquito kill efficiency could be increased about 2-fold by applying ULV insecticides with rotary atomizers (mean VMD = 31 μm) instead of flat-fan nozzles (mean VMD = 43 μm). This difference in efficiency was consistent with 2 species of mosquitoes, caged adult female *Ae. taeniorhynchus* and *Cx. quinquefasciatus,* as well as natural populations of salt-marsh mosquitoes, predominantly *Ae. taeniorhynchus,* in citrus groves with dense foliage. The increased efficiency was attributed to the smaller and more uniform droplets emitted from the rotary atomizers. The rotary atomizers emitted 83% ($\bar{x}$ of all droplet size estimates) of the spray volume in droplets of <5–50 μm diameter and only 0.1% of the volume in droplets of >100 μm diameter. Comparatively, 61% of the spray volume from flat-fan nozzles was in droplets of <5–50 μm diameter with 18% of the volume in droplets of >100 μm diameter. These tests indicate that the optimum size for aerial sprays is close to that reported for ground and laboratory tests. However, comparative tests with aerial sprays using smaller droplets have not been done because increased atomization is difficult to achieve. Depending on atmospheric conditions, the optimum size for aerial sprays may be somewhat larger than for ground aerosols because sprays must move downward from release altitude to mosquito habitats near the ground.

Mount et al. (1970d) tested ULV spray droplet penetration in the dense jungle canopy of Panama. This test was done when surface winds were calm to minimize loss of droplets by horizontal transport. Droplets collected in the open on a road and under the dense jungle canopy were compared by "flooding" a small target area with 5 swaths of technical malathion at 50-ft. intervals and at 75–100 ft. altitude. Droplets were collected on silicone-treated glass microscope slides rotated in a vertical plane with a battery-operated spinning device at a velocity of 5 mph to enhance impingement of the malathion droplets. Approximately 50% of the total spray volume penetrated the jungle canopy. The VMD of the initial spray was 52 μm, as sampled on the open road, while the VMD of the spray that was collected under the canopy was only 32 μm. The maximum droplet size that penetrated the jungle canopy was 68 μm diameter. Taylor et al. (1975) obtained similar results with ULV aerial sprays of technical malathion in Haiti with average VMDs of 46 μm and 28 μm for open and protected sites, respectively. Moreover, Perich et al. (1992) showed that droplet size (VMD) of ULV aerial sprays of a resmethrin formulated in mineral oil was ≈10–20 μm smaller inside than outside of houses in the Dominican Republic.

*Larviciding:* No definitive studies on optimum droplet size for mosquito larviciding have been reported in the literature. Logically, factors such as drift, foliage penetration, and coverage that influence the optimum size range for adulticiding also influence the droplet size needed for effective and efficient larviciding. Larviciding is usually done in small target areas. Thus, relatively large droplets must be used to avoid excessive air transport. If target areas are also covered by dense vegetation, relatively small droplets are required to penetrate the vegetation and reach the larval habitat. An exception to small droplets for penetration would be the use of large droplets in a high-volume, water-based spray that would create runoff. The contradiction in droplet size requirements for little or no horizontal transport and foliage penetration argues against using ULV aerial sprays for larviciding of small target areas covered by dense vegetation. However, ULV sprays have been used successfully to larvicide small areas with dense vegetation (Burgoyne et al. 1968) and large areas with heavy vegetation where horizontal transport can be tolerated and is even desirable for foliage penetration and wide swath coverage (Lofgren et al. 1972, Womeldorf and Whitesell 1972).

*Factors affecting atomization:* A wide variety of factors affect the atomization of liquid insecticide formulations dispersed as aerial sprays. These factors include the type of nozzle, orientation of nozzles to the airstream, shearing force created by the airstream during flight, physical characteristics of the insecticide formulation, and flow rate. An understanding of the relationship between these factors and droplet size will influence the choice of aircraft and application equipment for an operational program.

Mount et al. (1970e, 1971) showed that droplet sizes (VMD) of malathion and fenthion sprays were 28% less with rotary atomizers than with flat-fan nozzles when dispersed in an air-blast velocity of 95 mph. Moreover, the percentage of volume atomized into droplets within the <5–50 μm range was much greater with rotary atomizers ($\bar{x}$ = 88) than with flat-fan nozzles ($\bar{x}$ = 51) (Mount et al. 1971).

Various investigators have demonstrated that orientation to the airstream affects the atomization characteristics of flat-fan nozzles. At an air speed of 95 mph, Mount et al. (1970c) showed that a nozzle orientation down and 45° forward provided maximum atomization of technical malathion while positions of straight down and down and 45° back produced VMDs that were 17 and 50% larger, respectively, than the former. Similarly, Bouse and Carlton (1983) and Yates et al. (1983) reported average decreases of 16 and 21% for vegetable oil and water-based sprays, respectively, dispersed at 90–118 mph by nozzles oriented down and 30–45° forward compared to nozzles oriented straight down.

The effect of airstream velocity on atomization of liquids dispersed by flat-fan nozzles was studied by several investigators. Mount et al. (1970c) showed that a relatively slow airstream velocity of only 50 mph produced a VMD 25% larger than the VMD produced by a velocity of 95 mph. Also, Mount et al. (1970b) demonstrated that the VMDs of aerial sprays of naled dispersed at 110 mph were 63% larger than those dispersed at 150 mph. Moreover, Yates et al. (1983) and Bouse and Carlton (1983) showed that even small differences in airstream velocity, such as 90 versus 110 mph and 100 versus 118 mph, produced VMDs 15 and 6% larger at the slower velocities with aqueous and oil sprays, respectively.

Important physical characteristics of ULV insecticide formulations that affect atomization are density, viscosity, and surface tension. These characteristics are inherent with technical or highly concentrated formulations and, without dilution, cannot be altered to change droplet size. Data from Mount et al. (1970e, 1971) indicated that VMDs for 93% fenthion were 31% larger than VMDs for 95% malathion when atomized with the same type of nozzles and about equal flow rates. Also, Mount et al. (1970b) showed that the VMD for 85% naled was 53% greater than for 95% malathion dispersed from the same flat-fan nozzles at equal pressure and aircraft speed. However, the lower flow rate requirements for fenthion and naled, because of higher toxicities than malathion, tend to offset their physical characteristics that resist atomization.

In general, an increasing flat-fan nozzle flow capacity resulted in an increase in VMD. With simulated aerial sprays, Mount et al. (1970c) showed that the VMD increased 47% from a rated capacity (water at 40 psi) of 0.023 gal/min to 1 gal/min. Greater differences in droplet size due to nozzle capacity were shown with an Air Force C-123 aircraft flown at 150 mph. Mount et al. (1970b) indicated 32 and 43% decreases in VMD when flat-fan nozzle capacities were decreased 2- and 3-fold with applications of 95% malathion and 85% naled, respectively. With rotary atomizers, Mount et al. (1970e, 1971) showed −3 to 14% ($\bar{x}$ = 9%) increases in VMD related to 30–100% ($\bar{x}$ = 55%) increases in flow rate of 95% malathion and 93% fenthion.

*Effect on paint:* A potential side effect of ULV aerial spraying over urban areas is spotting of painted surfaces, particularly automotive paint. However, this effect can be avoided or minimized by dispersing aerial sprays in the optimum or near optimum size range. In tests with aerial sprays, Kilpatrick et al. (1970a) indicated that technical malathion at rates >4 fl. oz./acre and sprays >75 μm VMD would cause damage to painted surfaces. In tests with ground-applied aerosols, Rathburn and Boike (1977) demonstrated no visible damage on automotive paint panels under 3× magnification or by unaided eye from exposure to ground-applied aerosols of technical malathion with VMDs of 11–17 μm. Furthermore, Tietze et al. (1992) indicated a positive correlation between malathion droplet VMD and damage spot size on automotive paints.

Tietze et al. (1992) reported size thresholds of droplets too small to cause visible damage of 8 and 11 μm VMD for 2 different types of automotive paint.

Another strategy for avoiding or minimizing the effect of ULV aerial sprays on paint is to decrease swath width over urban areas. With wide swaths, insecticide flow rate must be increased to maintain insecticide dose. Increased flow rate, in turn, increases the potential for deposition of greater numbers of relatively large droplets at a specific site. This is especially the case when prevailing winds decrease in velocity substantially and unexpectedly during an application.

## METEOROLOGY

With ULV aerial sprays against adult mosquitoes, the critical meteorological parameters are wind velocity and direction, temperature, and atmospheric stability. In contrast to highly diluted water-based sprays, relative humidity as it relates to droplet evaporation is not critical with ULV sprays because the undiluted insecticide formulations are essentially nonvolatile. Although research reviewed in this paper does not directly relate meteorology to mosquito control, some general guidelines can be interpreted.

*Wind velocity and direction:* Wind velocity data are required prior to spray operations to determine whether or not the average velocity at ground level exceeds a maximum threshold, usually ≈10 mph. The wind velocity ranges at ground level reported in small-scale (Table 1), large-scale (Table 2), and high-altitude (Table 3) tests were <1–10, <1–17, and <1–10 mph, respectively. As noted by Mount et al. (1970a), wind velocity generally increases with an increase in altitude. Thus, winds exceeding ≈10 mph at ground level may cause excessive displacement of swaths when spray is released at altitudes of >200 ft. An example is the 9–15-mph wind velocity reported by Weathersbee et al. (1986) (Table 3) that likely caused excessive air transport of naled sprays released at 200–300 ft. altitude during nighttime applications. However, when sprays are released at ≤200 ft. altitude, turbulence created by the aircraft vortices can force insecticide droplets down. In this case, wind velocities somewhat in excess of 10 mph can be used to disperse the spray over wide swaths. Swaths of 2,000–2,500 ft. were used by Biery (1989; footnote 8, Table 2) and Haile and Kline (1989; footnote 4, Table 2) for good mosquito control with relatively high crosswinds using malathion and naled sprays released at 150 ft. altitude from C-130 aircraft. Conversely, calm conditions may require the use of narrower swaths for thorough coverage of the target area. Also, release altitude can be increased to a level where wind currents are present to disperse the spray over a wider swath. For example, Mount et al. (1970a) and Lofgren et al. (1972) used high release altitudes (175–350 ft.) to disperse malathion and fenthion sprays during calm ground level conditions in dense jungle habitat in Panama (Table 3).

Regardless of wind velocity and release altitude, wind direction data are needed to establish crosswind swath direction for aerial sprays. If high-altitude sprays are planned, wind direction data are required for both ground level and release altitude.

*Temperature:* Ambient temperature is important because it influences mosquito activity and the efficacy of insecticides. Ambient temperatures reported for mosquito adulticide trials listed in Tables 1–3 were 57–88°F. Nevertheless, low temperatures can reduce the effectiveness of insecticides, as indicated by Stevens and Stroud (1967). They reported possible recovery of adult *Ae. stimulans* (Walker) 12 h following an application of propoxur spray at ≈60°F in Michigan. In contrast, Mount et al. (1969) obtained satisfactory control of *Aedes* sp. with malathion sprays during ambient temperatures of <60°F in subarctic Alaska where mosquitoes are apparently adapted to host-seeking activity during relatively low temperatures as compared to mosquito species in temperate and tropical climates.

*Atmospheric stability:* Atmospheric stability is an important factor that influences transport of droplets from release altitude to ground level. Many factors determine air stability, such as wind velocity, temperature gradient, and time of day. In general, the stable or slightly unstable air associated with early morning or evening are considered most suitable for aerial sprays. Of the small-scale studies listed in Table 1 that indicated application times, 73 and 27% were accomplished with early morning and evening sprays, respectively. Most of the morning sprays were applied during 6:00–8:40 a.m. However, a few sprays were applied as early as 5:30 a.m. or as late as 10:30 a.m. with satisfactory results. In Tables 2 and 3, 67, 20, and 13% of the large-scale studies were done with evening, early morning, and night sprays, respectively. With one exception, the evening and early morning sprays were applied during 5:45–10:00 p.m. and 6:00–8:30 a.m. respectively. Biery (1993; footnote 9, Table 2) reported emergency spray applications during 3:46–8:20 p.m. following Hurricane Andrew. The night applications were made during 3:58–5:20 a.m. (Taylor and Rathburn 1970) and 10:00 p.m.–1:00 a.m. (Weathersbee et al. 1986).

The early morning and evening time frames tend to optimize spray efficacy because of increased mosquito activity and probability of adequate atmospheric stability for effective spray dispersion into mosquito habitat with adequate crosswinds. A stable atmosphere is normally characterized by warmer air on top of colder air and usually occurs when insolation intensity is reduced or absent. Conversely, an unstable atmosphere is characterized by colder air on top of warmer air and usually occurs during the middle of the day when insolation intensity is highest. Thermals, which are rising air currents caused by incoming solar radiation falling on the earth, usually occur during an unstable atmosphere. A strong inversion may actually resist the downward air transport of sprays. For example, Biery (1987; footnote 7, Table 2) reported that an inversion layer caused spray to hang in the atmosphere and cause contamination of a C-130 aircraft in a spray mission for dengue control in San Juan, Puerto Rico. However, an inversion can only be detected prior to spray operations by measurement of temperature rise with increasing altitude.

## CONCLUSIONS

1. ULV applications of insecticide are as efficacious against adult mosquitoes as water-based, highly-diluted sprays. 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 diluents such as water and petroleum-based products do not kill mosquitoes and only add cost and inconvenience to aerial spray operations.
2. The increased number of acres that can be sprayed per aircraft load with the ULV method offers a great advantage over highly diluted sprays for large-scale control of adult mosquitoes. Moreover, this advantage is further enhanced by normal-altitude (≤200 ft.), wide-swath applications that benefit from undiluted insecticide droplets that maintain their integrity during air transport to target mosquitoes and associated habitats.
3. High-altitude (>200 ft.) applications of ULV sprays using wide or stacked swaths could be used for mosquito adulticiding in emergencies or unusual situations if wind velocity and direction data at appropriate altitudes are available to accurately predict placement of the insecticide. However, high-altitude methods are not suitable for most adulticiding programs because detailed wind data are usually unavailable.
4. Successful mosquito control in dense foliage or open housing can be achieved with ULV aerial sprays. However, because of the filtration effect of dense foliage or domicile structure, insecticide doses must be increased ≈2-fold compared to normal doses to achieve satisfactory mosquito control. A caveat here is that, in some cases, a 2-fold dose increase may be above the labeled rate.
5. The ULV aerial application method is suitable for mosquito larviciding over large target areas, especially when concurrent adulticiding is required. However, ULV sprays do not offer a substantial advantage over highly diluted sprays for most mosquito larviciding programs because target areas are relatively small, thus reducing the benefit of increased effective payloads. Furthermore, there is the added problem of accurate insecticide placement into small target areas with ULV applications. This placement problem can be overcome more readily with highly diluted sprays than with ULV sprays by increasing droplet size to reduce horizontal transport and by increasing volume to create runoff when foliage penetration is required. Granular formulations of larvicides can also be used instead of ULV sprays to maximize placement and foliage penetration.
6. The efficacy of ULV aerial sprays against adult mosquitoes is directly related to droplet size because it governs air transport and impingement. The optimum size range for mosquito adulticiding is 5–25 μm VMD based on laboratory wind tunnel and ground aerosol research. However, this size range has been only partially confirmed by research with ULV aerial sprays.
7. For mosquito adulticiding, near optimum atomization of ULV aerial sprays is achieved by using flat-flan nozzles on high-speed aircraft (≥150 mph) or rotary atomizers on slow-speed aircraft (<150 mph). Flat-fan nozzles should be oriented straight down or down and 30–45° forward to the airstream for maximum atomization of the insecticide. Also, flat-fan nozzles with the lowest flow rate capacity that does not create plugging problems should be used to minimize droplet size for maximum foliage or domicile penetration and mosquito kill. Rotary atomizers should be operated at maximum recommended rotational speed and low flow rates to achieve near optimum droplet size.
8. Near optimum atomization of ULV aerial sprays is required not only for maximum biological efficacy, but also to avoid or minimize spotting automotive paint in urban and suburban areas.
9. In general, ULV aerial sprays should be applied during the crepuscular periods following sunrise or preceding sunset when mosquitoes are active and atmospheric stability is favorable to achieve maximum levels of adult mosquito control. Prevailing crosswinds of 2–10 mph are also necessary for successful wide-swath applications.

## REFERENCES CITED

Akesson, N. B., W. E. Burgoyne, W. E. Yates and K. Aref. 1969. Aerial spray applications of low volatility and fine atomization for mosquito control. Proc. Calif. Mosq. Control Assoc. 37:44–52.

Bourg, J. A., M. K. Carroll and A. J. Blake. 1978. Agcat ULV spray system development, calibration, and field tests using naled. Mosq. News 38:36–38.

Bouse, L. F. and J. B. Carlton. 1983. Factors affecting size distribution of vegetable oil spray droplets. ASAE paper no. AA-83-006, p. 17. ASAE, St. Joseph, MI.

Brooks, G. D., P. Neri, N. G. Gratz and D. B. Weathers. 1970. Preliminary studies on the use of ultra-low-volume applications of malathion for control of *Aedes simpsoni.* Bull. W.H.O. 42:37–54.

Burgoyne, W. E. and N. B. Akesson. 1968. Aircraft operations in the Colusa project. Down to Earth 24:7–10.

Burgoyne, W. E., K. G. Whitesell and N. B. Akesson.

1968. Entomological evaluation within the Colusa project. Down to Earth 24:13–15.

Carroll, M. K. and J. A. Bourg. 1979. Methods of ULV droplet sampling and analysis: effects on the size and spectrum of the droplets collected. Mosq. News 39: 645–655.

Eliason, D. A., V. R. Joseph and J. Karam. 1975. A prospective study of the effects of ultralow volume (ULV) aerial application of malathion on epidemic *Plasmodium falciparum* malaria I. study design and perspective. Am. J. Trop. Med. Hyg. 24:183–187.

Eliason, D. A., J. W. Kilpatrick and M. F. Babbitt. 1970. Evaluation of the effectiveness of the ultra low volume aerial application of insecticides against *Aedes aegypti* (L.) in Florida. Mosq. News 30:430–436.

Forcum, D. L. 1976. Aerial control of adult *Aedes* mosquitoes over irrigated Wyoming pastures. Mosq. News 36:137–141.

Glancey, B. M., H. R. Ford and C. S. Lofgren. 1970. Evaluation of a fuselage-mounted spray boom for ultralow volume application of insecticides for mosquito control. Mosq. News 30:174–180.

Glancey, B. M., C. S. Lofgren, J. Salmela and A. N. Davis. 1965. Low volume aerial spraying of malathion for control of adult salt-marsh mosquitoes. Mosq. News 25:135–137.

Glancey, B. M., A. C. White, C. N. Husman and J. Salmela. 1966. Low volume applications of insecticides for the control of adult mosquitoes. Mosq. News 26: 356–359.

Groves, R. L., J. C. McAllistar, C. L. Meek and M. V. Meisch. 1994. Evaluation of aerial and ground-applied adulticides against mosquito species in Arkansas and Louisiana. J. Am. Mosq. Control Assoc. 10:407–412.

Haile, D. G., G. A. Mount and N. W. Pierce. 1978. Automatic measurement of droplet size of insecticide aerosols with a Coulter Counter®. Mosq. News 38:1–9.

Haile, D. G., G. A. Mount and N. W. Pierce. 1982a. Effect of droplet size of malathion aerosols on kill of caged adult mosquitoes. Mosq. News 42:576–583.

Haile, D. G., D. L. Kline, J. F. Reinert and T. L. Biery. 1984. Effects of aerial applications of naled on *Culicoides* biting midges, mosquitoes and tabanids on Parris Island, South Carolina. Mosq. News 44:178–183.

Haile, D. G., T. L. Biery, J. F. Reinert and N. W. Pierce. 1982b. Aerial applications of naled diluted in HAN with UC-123-K aircraft for adult mosquito control. Mosq. News 42:41–48.

Husted, S. R., J. A. Mulrennan, R. M. Frederick, D. A. Blair and H. J. U'ren. 1975. Volume as a factor in ULV dispersal of equal dosages of chlorpyrifos for adult mosquito control. Mosq. News 35:286–288.

Kilpatrick, J. W. and C. T. Adams. 1967. Emergency measures employed in the control of St. Louis encephalitis epidemics in Dallas and Corpus Christi, Texas, 1966. Proc. 35 Annu. Conf. Calif. Mosq. Control Assoc. p. 53.

Kilpatrick, J. W., D. A. Eliason and M. F. Babbitt. 1970a. Studies of the potential effectiveness of ultra low volume aerial applications of insecticides against *Aedes aegypti* (L.) larvae. Mosq. News 30:250–258.

Kilpatrick, J. W., R. J. Tonn and S. Jatanasen. 1970b. Evaluation of ultra-low-volume insecticide dispensing systems for use in single-engined aircraft and their effectiveness against *Ae. aegypti* populations in south-east Asia. Bull. W.H.O. 42:1–14.

Knapp, F. W. and C. H. Gayle. 1967. ULV aerial insecticide application for adult mosquito control in Kentucky. Mosq. News 27:478–482.

Knapp, F. W. and B. C. Pass. 1966. Low-volume aerial sprays for mosquito control. Mosq. News 26:22–25.

Knapp, F. W. and W. W. Roberts. 1965. Low volume aerial application of technical malathion for adult mosquito control. Mosq. News 25:46–47.

Knapp, F. W. and C. E. Rogers. 1968. Low volume aerial insecticide application for the control of *Aedes sollicitans* Walker. Mosq. News 28:535–540.

Knudsen, A. B., Y. H. Bang, D. N. Bown and V. Ezike. 1980. Aerial application of 50% malathion for the control of sylvatic vectors of yellow fever in a rural wooded community near Enugu, Nigeria. Mosq. News 40: 551–559.

Latta, R., L. D. Anderson, E. E. Rogers, V. K. LaMer, S. Hochberg, H. Lauterbach and I. Johnson. 1947. The effect of particle size and velocity of movement of DDT aerosols in a wind tunnel on the mortality of mosquitoes. J. Wash. Acad. Sci. 37:397–407.

Lofgren, C. S. 1970. Ultra-low volume applications of concentrated insecticides in medical and veterinary entomology. Annu. Rev. Entomol. 15:321–342.

Lofgren, C. S. 1972. Ultralow volume (ULV) application of insecticides. Am. J. Trop. Med. Hyg. 21:819–824.

Lofgren, C. S. 1974. Recent developments in methods of mosquito control. Bull. W.H.O. 50:323–328.

Lofgren, C. S. and G. A. Mount. 1975. ULV aerial sprays for adult mosquito control. Fifth Int. Agric. Aviation Cong., Warwickshire, United Kingdom, p. 109–115.

Lofgren, C. S., D. W. Anthony and G. A. Mount. 1973. Size of aerosol droplets impinging on mosquitoes as determined with a scanning electron microscope. J. Econ. Entomol. 66:1085–1088.

Lofgren, C. S., R. M. Altman and B. M. Glancey. 1968. Control of anopheline species in the Canal Zone with ultra-low volume sprays of malathion and fenthion. Mosq. News 28:353–355.

Lofgren, C. S., H. R. Ford, R. J. Tonn and S. Jatanasen. 1970a. The effectiveness of ultra-low-volume applications of malathion at a rate of 6 US fluid ounces per acre in controlling *Aedes aegypti* in a large-scale test at Nakhon Sawan, Thailand. Bull. W.H.O. 42:15–25.

Lofgren, C. S., H. R. Ford, R. J. Tonn, Y. H. Bang and P. Siribodhi. 1970b. The effectiveness of ultra-low-volume applications of malathion at a rate of 3 fluid ounces per acre in controlling *Aedes aegypti* in Thailand. Bull. W.H.O. 42:27–35.

Lofgren, C. S., D. A. Dame, L. Johnston, C. T. Adams, N. W. Pierce and K. F. Baldwin. 1972. Control of anophelines in Canal Zone jungles with ULV aerial applications of fenthion. Mosq. News 32:566–573.

Machado, W. C., A. J. Blake, E. S. Bordes, Jr. and G. T. Carmichael. 1969a. Evaluation of a multi-engine aircraft in the ULV application of Dibrom. Mosq. News 29:47–52.

Machado, W. C., E. S. Bordes, Jr., A. J. Blake and G. T. Carmichael. 1969b. A technique for ULV insecticide application from high altitudes. Mosq. News 29:353–360.

Meisch, M. V. and G. A. Mount. 1978. Ultralow volume aerial applications of insecticides for mosquito control in Arkansas riceland communities. Mosq. News 38: 343–346.

Messenger, K. 1963. Low volume aerial spraying will be boon to applicator. Agric. Chem. 18:63–66.

Messenger, K. 1964. Low volume aerial spraying. Agric. Chem. 19:61–64.

Mitchell, C. J., J. W. Kilpatrick, R. O. Hayes and H. W. Curry. 1970. Effects of ultra-low volume applications of malathion in Hale county, Texas. II. Mosquito populations in treated and untreated areas. J. Med. Entomol. 7:85–91.

Mitchell, C. J., R. O. Hayes, P. Holden, H. R. Hill and T. B. Hughes, Jr. 1969. Effects of ultra-low volume applications of malathion in Hale county, Texas. I. Western encephalitis virus activity in treated and untreated towns. J. Med. Entomol. 6:155–162.

Mount, G. A. 1970. Optimum droplet size for adult mosquito control with sprays or aerosols of insecticides. Mosq. News 30:70–75.

Mount, G. A. and C. S. Lofgren. 1967. Ultra-low volume and conventional aerial sprays for control of adult salt-marsh mosquitoes, *Aedes sollicitans* (Walker) and *Aedes taeniorhynchus* (Wiedemann), in Florida. Mosq. News 27:473–477.

Mount, G. A. and N. W. Pierce. 1972. Droplet size of ultralow volume ground aerosols as determined by three collection methods. Mosq. News 32:586–589.

Mount, G. A., J. G. McWilliams and C. T. Adams. 1969. Control of adult mosquitoes in Alaska with malathion. Mosq. News 29:84–86.

Mount, G. A., C. T. Adams, C. S. Lofgren and D. E. Weidhaas. 1970a. Altitude and drift of ultralow volume aerial sprays of technical malathion for mosquito control. Mosq. News 30:580–584.

Mount, G. A., C. S. Lofgren, K. F. Baldwin and N. W. Pierce. 1970b. Droplet size and mosquito kill with ultralow volume aerial sprays dispersed from a rotary-disc nozzle. Mosq. News 30:331–334.

Mount, G. A., C. S. Lofgren, N. W. Pierce and K. F. Baldwin. 1970c. Effect of various factors on droplet size of simulated ultra-low volume aerial sprays of technical malathion. Mosq. News 30:48–51.

Mount, G. A., C. S. Lofgren, N. W. Pierce and C. N. Husman. 1968. Ultra-low volume nonthermal aerosols of malathion and naled for adult mosquito control. Mosq. News 28:99–103.

Mount, G. A., N. W. Pierce, C. S. Lofgren and J. Salmela. 1971. Droplet size and kill of adult mosquitoes with ultralow volume aerial sprays dispersed from a rotary-cylinder atomizer. Mosq. News 31:326–330.

Mount, G. A., C. T. Adams, W. G. Pearson, C. S. Lofgren and D. E. Weidhaas. 1970d. Ultralow volume aerial sprays of malathion and fenthion for anopheline mosquito control in Panama Canal Zone jungle. Mosq. News 30:604–610.

Mount, G. A., R. E. Lowe, K. F. Baldwin, N. W. Pierce and K. E. Savage. 1970e. Ultra-low volume aerial sprays of promising insecticides for mosquito control. Mosq. News 30:342–346.

Mount, G. A., C. S. Lofgren, N. W. Pierce, K. F. Baldwin, H. R. Ford and C. T. Adams. 1970f. Droplet size, density, distribution, and effectiveness in ultra-low volume aerial sprays dispersed with TeeJet® nozzles. Mosq. News 30:589–599.

Mulhern, T. D., C. M. Gjullin, O. V. Lopp, D. Ramke, R. F. Frolli, D. E. Reed and W. D. Murray. 1965. Low volume airplane sprays for the control of mosquito larvae. Mosq. News 25:442–447.

Patterson, R. S., D. L. von Windeguth, B. M. Glancey and F. L. Wilson. 1966. Control of the midge *Glyptotendipes paripes* with low-volume aerial sprays of malathion. J. Econ. Entomol. 59:864–866.

Perich, M. J., B. L. Bunner, M. A. Tidwell, D. C. Williams, C. D. Mara and T. Carvalhe. 1992. Penetration of ultra-low volume applied insecticide into dwellings for dengue vector control. J. Am. Mosq. Control Assoc. 8:137–142.

Pinkovsky, D. D. 1972. United States Air Force aerial spray activities in Operation Combat VEE. Mosq. News 32:332–334.

Rathburn, C. B., Jr. 1970. Methods of assessing droplet size of insecticidal sprays and fogs. Mosq. News 30: 501–513.

Rathburn, C. B., Jr. and A. H. Boike, Jr. 1977. Bioassay and droplet size determinations of six ULV aerosol generators. Mosq. News 37:31–34.

Rathburn, C. B., Jr. and A. J. Rogers, A. H. Boike, Jr. and R. M. Lee. 1969. Evaluation of the ultra-low volume aerial spray technique by use of caged adult mosquitoes. Mosq. News 29:376–381.

Ribeiro, H. 1973. The control of *Aedes aegypti* during the yellow fever epidemic in Luanda, Angola, in 1971. Bull. W.H.O. 48:504–505.

Self, L. S., H. I. Ree, C. S. Lofgren, J. C. Shim, C. Y. Chow, H. K. Shin and K. H. Kim. 1973. Aerial applications of ultra-low-volume insecticides to control the vector of Japanese encephalitis in Korea. Bull. W.H.O. 49:353–357.

Skoog, F. E., F. T. Cowan and K. Messenger. 1965. Ultra-low volume aerial spraying of dieldrin and malathion for rangeland grasshopper control. J. Econ. Entomol. 58:559–565.

Stevens, L. F. and R. F. Stroud. 1966. Control of mosquito adults and larvae with ultra-low volume aerial applications of Baytex and Baytex-Baygon mixture. Mosq. News 26:124–128.

Stevens, L. F. and R. F. Stroud. 1967. Control of mosquito adults and larvae with ultra-low-volume aerial applications of Baygon® and Baygon-Baytex® mixture. Mosq. News 27:482–485.

Taylor, D. J. and C. B. Rathburn, Jr. 1970. Large area tests of ultra low volume naled for control of adult mosquitoes. Mosq. News 30:383–387.

Taylor, R. T., M. Solis, D. B. Weathers and J. W. Taylor. 1975. A prospective study of the effects of ultralow volume (ULV) aerial application of malathion on epidemic *Plasmodium falciparum* malaria. II. entomological and operational aspects. Am. J. Trop. Med. Hyg. 24:188–192.

Tietze, N. S., J. P. Ruff, C. F. Hallmon, P. G. Hester and K. R. Shaffer. 1992. Effect of ULV malathion on automotive paint finishes. J. Am. Mosq. Control Assoc. 8:241–246.

Uribe, L. J., G. C. Garrido, M. Nelson, M. E. Tinker and J. Moquillaza. 1980. Aerial ULV application trial of malathion against *Aedes aegypti* in a city of Colombia. World Health Organization, Vector Biology and Control Series 80:768.

Weathersbee, A. A., III, M. V. Meisch, C. A. Sandoski, M. F. Finch, D. A. Dame, J. K. Olson and A. Inman. 1986. Combination ground and aerial adulticide applications against mosquitoes in an Arkansas riceland community. J. Am. Mosq. Control Assoc. 2:456–460.

Weidhaas, D. E., M. C. Bowman, G. A. Mount, C. S. Lofgren and H. R. Ford. 1970. Relationship of minimum lethal dose to the optimum size of droplets of insecticides for mosquito control. Mosq. News 30:195–200.

Wilson, C. M., R. F. Ruppel and R. E. Treese. 1965. Low-volume concentrate sprays applied by aircraft for control of the cereal leaf beetle. J. Econ. Entomol. 58:11–14.

Womeldorf, D. J. and K. G. Whitesell. 1972. Rice field mosquito control studies with low volume Dursban® sprays in Colusa County, California. I. Introduction. Mosq. News 32:364–368.

Yates, W. E., R. E. Cowden and N. B. Akesson. 1983. Nozzle orientation, air speed and spray formulation affects on drop size spectrums. Trans. ASAE (Am. Soc. Agric. Eng.) 26:1638–1643.

Yeomans, A. H. 1949. Directions for determining particle size of aerosols and fine sprays. U.S. Dept. Agric. Bur. Plant Quarant. ET 267.