Prevention of Mosquitoes (Diptera: Culicidae) and House Flies (Diptera: Muscidae) from Entering Simulated Aircraft with Commercial Air Curtain Units

DAVID A. CARLSON, JEROME A. HOGSETTE, DANIEL L. KLINE, CHRIS D. GEDEN,
AND ROBERT K. VANDERMEER

USDA–ARS, Center for Medical, Agricultural and Veterinary Entomology, 1600 SW 23rd Drive, Gainesville, FL 32608

J. Econ. Entomol. 99(1): 182–193 (2006)

ABSTRACT Commercially available air curtain units were used to create air barriers to prevent mosquitoes and house flies from entering a simulated aircraft doorway together with passengers. Two assemblies of simulated passenger bridge and aircraft were constructed, and airflow measurements were recorded to confirm airflow characteristics for several combinations of commercial units. Three mosquito species were selected for different host-seeking characteristics, and house flies were selected to represent a large, strong-flying insect. Batches of 20 or 200 insects of four species were released into the passenger bridge just before 25 persons passed through the assembly, then insects that entered the aircraft cabin were recovered. Results showed that horizontal plus vertical or vertical-mounted air curtain units with the airflow directed at a 45° angle into the passenger bridge excluded 95–99% of the mosquitoes and 95–100% of the house flies, respectively. Airflows were measured and estimated to be effective if the mean was >4 m/s in the critical area in the center of the converging airflows. The study validates the concept that air barriers can effectively prevent the passage of flying insects into an aircraft.

KEY WORDS airflow, exclusion, biting insects, disease vectors, passenger bridge

INTERNATIONAL AIR TRAFFIC AND the cosmopolitan nature of the world economy present serious challenges and responsibilities for those involved in the transportation of people and cargo. The unintentional introduction of invasive flying insect species via aircraft arriving from abroad is a concern for some countries. Mosquitoes are of particular concern because their blood-feeding requirements make them ideal vectors of many diseases of humans and animals. Because mosquitoes readily track their human hosts unnoticed, they could cryptically follow passengers on board an aircraft in one country where mosquito vectors are infected and disembark with the passengers at an airport in another country.

The house fly, *Musca domestica* L., is known to mechanically transmit several pathogenic organisms to humans, livestock, and poultry (Greenberg 1971). There are many species of flies similar to the house fly in size and flight ability that could cause serious problems with livestock and humans if introduced accidentally into the continental United States. These species include a variety of blow flies (Calliphoridae), *Musca sorbens* (Wiedemann), bush flies, *Musca vetustissima* (Walker), and screwworms *Cochliomyia hominivorax* (Coquerel) and *Chrysomya bezziana* (Villeneuve).

Disease transmission has been demonstrated directly through documented cases of mosquitoes in aircraft and indirectly through confirmed and probable cases of airport malaria (Gratz et al. 2000). Incidents of transmission of malaria in England led to a study of airport malaria cases, collection of mosquitoes from sprayed and unsprayed aircraft, and the effects of aerosol insecticide on caged mosquitoes during commercial intercontinental flights. Mortality of mosquitoes was 100% when the insecticide treatments were applied in recommended amounts, even when caged mosquitoes were located in enclosed spaces such as luggage lockers (Curtis and White 1984).

Some countries, not including the United States, require disinsection of arriving international flights with a pesticide before disembarkation of passengers and crew that involves residual and aerosol spraying before landing (U.S. Department of Transportation 2004, MQS/AQIS 2004). The efficacy of such treatments has been evaluated extensively, and the results vary depending on the insecticide, the insect of interest, method of insect exposure, and the location of the test insects in the aircraft (Brooke and Evans 1971; Sullivan et al. 1972, 1975, 1978; Cawley et al. 1974; Langsford et al. 1976; Bailey 1977; Liljedah et al. 1977; Russell and Paton 1989). In one World Health Organization study (Anonymous 1995), it was noted that some individuals might experience transient discomfort after aircraft disinsection. There are increasing concerns over the effects of chemical disinsection on the health of passengers and especially crew members who are routinely subjected to pesticide exposure

0022-0493/06/0182–0193$04.00/0

during overseas flights (Anonymous 2001, Das et al. 2001, van Netten 2002, Sutton et al. 2003). Thus, the need to protect passengers and aircraft crew from potentially negative effects of insecticide exposure and the need for assurance that an aircraft is free of flying insects represents a significant challenge.

Although the commercial application of air barriers for insect control is not new (Waldron 1958), the first systematic study of air barriers to house flies was reported by Hocking (1960). He suggested that air barriers with an air velocity of 457 m/min from over the doorway would effectively prevent flies from entering a doorway. A subsequent and often-cited USDA directive specified that air barriers were somewhat effective if the air velocity was 488 m/min (≈8 m/s) at 1 m above the floor (Anonymous 1963). Mathis et al. (1970) determined in laboratory experiments that 92% exclusion of house flies could be obtained with an air velocity of 547 m/min (9.1 m/s) at 91 cm from the floor, with the angle of the airstream set at 15° from the vertical into the protected area. These tests were performed in a narrow doorway with a vented space in the floor for air return. In less controlled, but passive (no human activity involved) field conditions, 80% exclusion was obtained. Generally, horizontally mounted air curtain units are assumed to be ≈80% effective at excluding house flies in commercial operations. We expect that passage of people through an air barrier would lead to even less efficacy because insects may cling to or pass through the barriers together with people.

We report herein the results of studies on the efficacy of air barriers generated by commercially available air curtain units at preventing mosquitoes and house flies from entering aircraft through passenger doors via airport passenger bridges. We are aware of no studies where movement of mosquitoes against flowing air in closed rooms with humans was evaluated. The air curtain units used in our studies were mounted horizontally above and vertically alongside the doorway to be protected. This technology offers an alternative to the use of insecticides for aircraft disinsection and therefore obviates the health concerns centered on current disinsection methods.

Materials and Methods

Mosquitoes. The following three mosquito species were selected because each has unique host-seeking behavior that impacts where they will be found in association with human hosts and how they may be affected by air currents. 1) *Aedes aegypti* (L.), an easily disturbed species, is a yellow fever/dengue vector that attacks mainly around the feet and lower part of the body. If an air barrier is not strong enough near the floor, this mosquito should be the most likely to penetrate there. 2) *Anopheles quadrimaculatus* (Say) is a malaria vector that tends to attack the upper torso. It tends not to bite in broad daylight, but once attached to skin or clothing, it may be difficult to dislodge. 3) *Ochlerotatus taeniorhynchus* (Weidemann) is a persistent biting saltmarsh species that attacks mostly from the mid-torso to the head area. It will cling tightly to the body and follow moving hosts very aggressively.

Mosquitoes from colony cages of 4–7 d were separated by sex while immobilized on a cold table (4°C for 5 min) and counted into small cages for transfer to and release in the test facilities. Only females that had never been blood-fed were used for the studies. Mosquitoes were allowed to recover for at least 30 min after exposure to cold temperature and provided with a cotton ball saturated with a 10% sucrose solution until time for release.

House Flies. The cosmopolitan house fly *M. domestica* was selected as a good example of a robust flying insect in contrast to weaker flying mosquitoes. Laboratory-reared flies of both sexes were immobilized with CO_2 and counted into small cages for transfer to and release in test facilities. Flies were allowed to recover for at least 30 min after exposure to CO_2 and provided with a cotton ball saturated with a 10% sucrose solution until time for release.

Test Facility. The test facility consisted of two pairs of windowless corrugated aluminum sheds, one serving as the simulated aircraft (3.0 by 6.0 m) and the second the simulated passenger boarding bridge (2.4 by 7.3 m). The sheds were placed contiguously in a T-configuration, leaving a screened space of ≈15 cm between the two to simulate the space generally observed between a real aircraft and a passenger boarding bridge. The walls of the sheds were fully insulated and fitted with gypsum wall boards, acoustical tile, or wooden ceilings, and wooden floors. All interior surfaces were painted white to maximize visibility and to assist with the observation and recapture of released insects. During the studies, air within the facility was maintained within a conducive flight activity range of ≈23°C with individual room-type air conditioners. All doors were solid to eliminate outside light. Two overhead banks of standard 1.3-m 40-W white fluorescent tubes provided continuous light.

The passenger boarding bridge was accessed from an exterior door leading into a small entry chamber without lights. A solid wall fitted with a sliding pocket door isolated this chamber from the passenger boarding bridge. A double curtain of fine mesh fabric covered the interior side of the pocket door to prevent exit of insects when the pocket door was opened for insect introduction and movement of simulated passengers. Passage from the boarding bridge into the simulated aircraft was through the contiguous doorways described above, with the simulated aircraft doorway fitted with a solid door that could be closed to isolate the two chambers for recapture of insects. An exit chamber separated the simulated aircraft from its door to the exterior. The wall that separated these two rooms was made of the same fine mesh fabric described above, as were the double curtains hung on the interior and exterior sides of the door frame connecting the two rooms. These curtains retained insects inside the aircraft assembly when passengers walked through the test facility (Fig. 1).

Air Curtain Units. Published data suggested that an airflow of 9.1 m/s measured at 3 feet (91 cm) above the

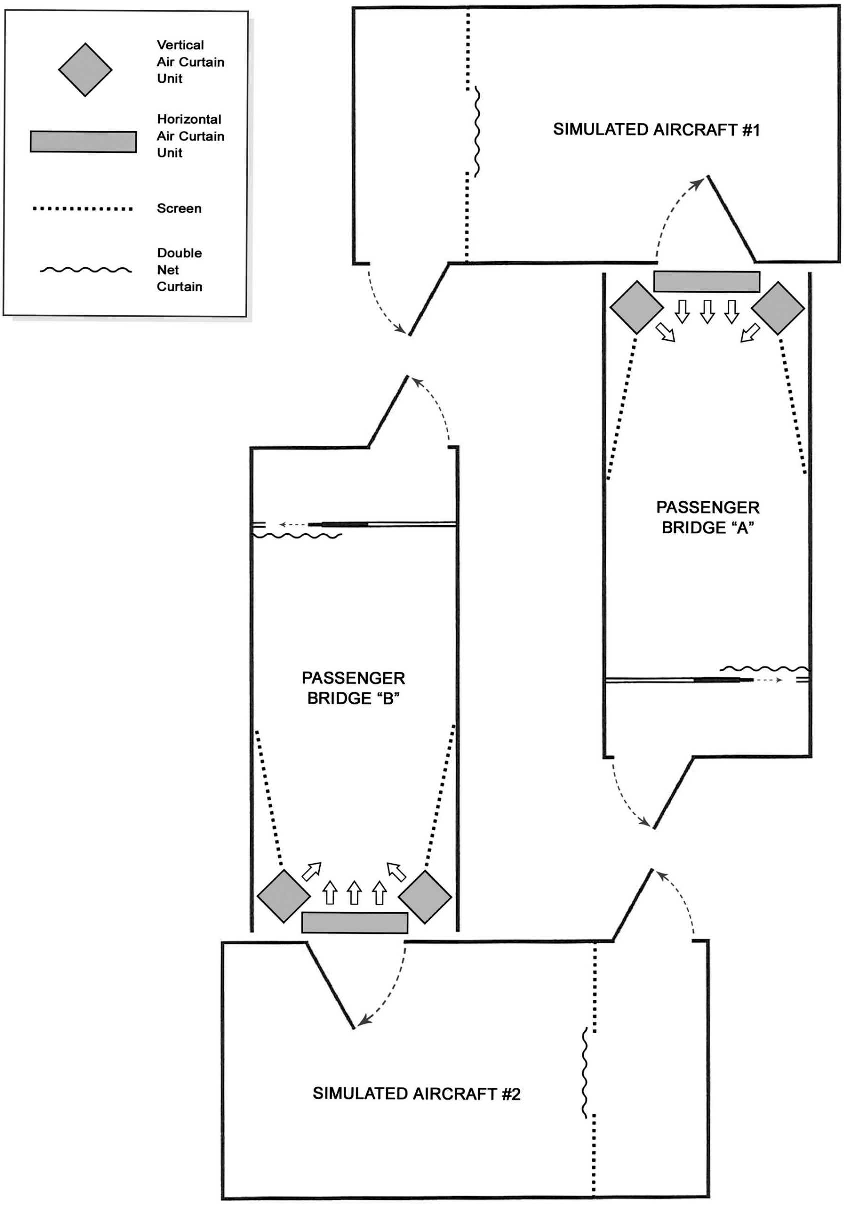

Fig. 1. Top elevation of JW1 and 2, simulated passenger boarding bridge and simulated aircraft.

floor emitted from a horizontal air curtain unit placed overhead (Mathis et al. 1970) gave the best results. For the present experiment, horizontal air curtain units were set up similarly, and then vertical units were added to provide airflows angled into the test subject pathway through the simulated passenger bridge and to protect as much of the doorway as possible.

The motorized air curtain units (hereafter called units) were mounted inside the open doorway of the simulated passenger boarding bridges contiguous with and leading into the simulated aircraft. In one boarding bridge/aircraft assembly (JW1), a single 1.1-m unit (model MKII 1042AA, 0.15 kW, 0.5 horsepower, 110 V, Berner International, New Castle, PA) was mounted horizontally 2 m above the floor of the doorway (Fig. 2) and two 1.83-m units (model FSA 2072AA, 1.12 kW, 2 × 0.5 horsepower, 110 V, Berner, New Castle, PA) were attached vertically to the floor in symmetrical positions on each side of the doorway. In the other assembly (JW2), a single 1.1-m unit (model MKII 1042AA, Berner) was mounted horizontally 2 m above the floor of the doorway as described for JW1 and a pair of 1.83-m units (model Max 1072AA, 0.30 kW, 0.2 horsepower, 110 V, Berner) was attached to the floor vertically on each side of the doorway. In both assemblies, airflow from the horizontally mounted units was directed downward, away from the open doorway and into the interior of the passenger boarding bridge at

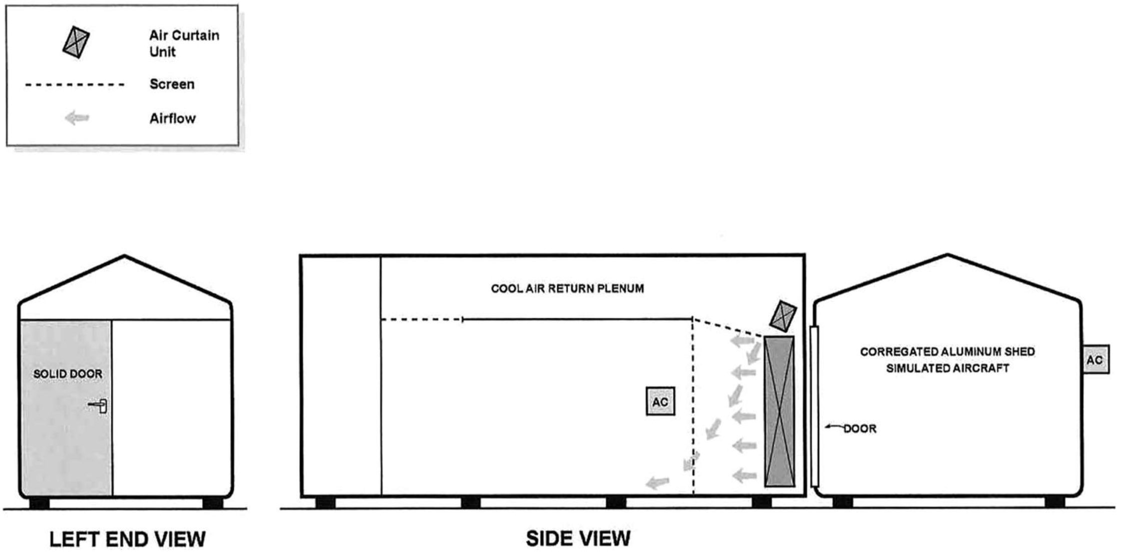

Fig. 2. Side elevation of simulated passenger boarding bridge and simulated aircraft: Horizontal dotted lines in the bridge are screen ceiling vents.

15° from vertical. This air barrier was intended to fill the void between the converging airflows of the vertical units and the open doorway. Air from the vertically mounted units was directed at a 45° angle across the doorway such that the two airflows met at 90° ≈1 m inside the doorway, with the airflow directed into the interior of the passenger boarding bridge. To prevent insects from being sucked into the air curtain units and lost for testing purposes, ceiling vents at the distal end of the passenger bridges were covered with window screen, as were wooden frames (0.4 m in width by 1.30 m in length) that were fitted around air intakes of the vertically mounted units.

Airflow Measurements. The original objective was to achieve an airflow velocity of 9 m/s in the center of the converging airflows at 91 cm. Positive airflow was defined as air movement into the passenger bridge, negative means into the aircraft, ± means variable but measurable direction. Airflow measurements made with the units off were low and variable and are not included here. Sixteen airflow measurements were made at three predetermined positions 33 cm apart in each of five directions (0, 22, 45, 67 and 90° from position 1) in an evenly dispersed array (Fig. 3). A hand-held digital anemometer, model ALMEMD 2290-8 (Ahlborn Mess- und Regelungs Technik GmbH, Holzkirken, Germany) with a strip of attached colored caution tape was used to determine the actual direction of air motion, while rotating the head about the vertical axis only to match direction of airflow. A thin 2-m fiberglass rod with strips of caution tape was used to confirm the direction of airflow, because some measurements showed air entering the aircraft doorway. Airflow was measured with the units positioned as above and with Max and FSA units set at full speed. In addition, the 16 measurements were taken at 0, 45,

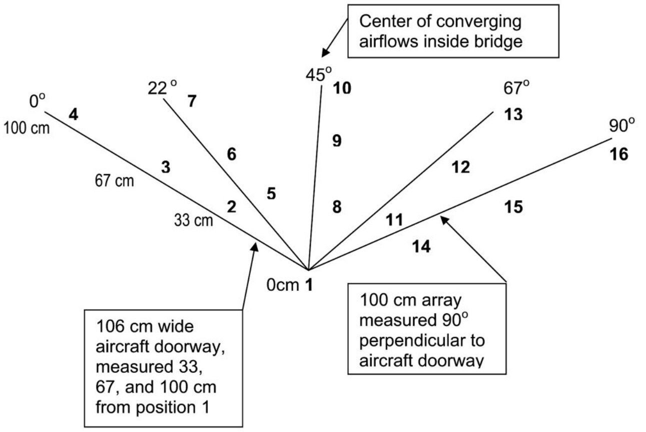

Fig. 3. Template of airflow measurement positions 1–16 placed in an isometric projection viewed from the aircraft looking through the doorway into the passenger boarding bridge. This template applies to each elevation of Figs. 4–9.

Table 1. Mean (± SD) numbers of mosquitoes and house flies recovered from simulated aircraft after passage of 25 passenger equivalents through JW1 equipped with a single horizontal (MK II 1042) and two vertically mounted (one FSA1072AA/side of doorway) air curtain units

Treatment	*Ae. aegypti*	*Oc. taeniorhynchus*	*An. quadrimaculatus*	Total mosquitoes	House flies
All off	9.7 (2.4)a	6.8 (1.5)a	10.3 (3.3)a	26.8 (6.0)a	14.5 (1.5)a
Vertical only	4.2 (0.6)b	3.2 (1.1)ab	2.5 (0.9)b	9.8 (1.8)b	2.8 (0.5)b
Vertical and Horizontal	2.5 (0.6)b	2.0 (1.1)b	1.2 (0.4)b	5.7 (1.2)b	1.5 (0.5)b

Trials with 50 insects of each species released/test ($n = 6$ tests/treatment).
Means within columns followed by the same letter are not significantly different at $P = 0.05$ (Tukey's method).

and 160 cm from the floor. Data were plotted and analyzed to produce surface contour plots of airflow patterns using Surfer (version 8.0, Golden Software, Golden., CO).

Scores for Critical Area Comparison. To evaluate each set of measurements using the array of 16 positions (Fig. 3), the main force of air seemed to flow through positions 7–13. Therefore, these positions were regarded as the Critical Area (CA) in the center of traffic, and the airflows were determined for each elevation A, B, C, and D to obtain a numerical average.

Treatments. The following combinations of air curtain units were used to evaluate the ability of the test insects to pass through the doorway from the simulated passenger boarding bridges into the simulated aircraft: 1) all-units-off (control); 2) vertical-on with horizontal unit off; and 3) all-units-on. For each air curtain combination, two releases of insects were made: five of each mosquito species and five house flies or 20 total insects, or 50 of each mosquito species and 50 house flies or 200 total insects. Before each test, air conditioning units were turned on, the test facility was determined to be insect-free, and air curtain units were set for the selected combination. Insects were released into each passenger boarding bridge under a double mesh curtain inside the pocket door. Insects were allowed to disperse naturally within the room for 5 min, after which any insects that had passed into the aircraft were counted and recorded. Then personnel entered the passenger boarding bridge from the entry chamber, walked through the door with the air curtains into the aircraft and out through the aircraft exit chamber until 25 passenger equivalents were recorded over a period of 8–10 min.

Data Collection and Analysis. After the last person passed into the aircraft unit, the door separating it from the passenger boarding bridge assembly was closed and all insects within the simulated aircraft were captured with a battery-powered vacuum aspirator, frozen, and later counted. Mosquitoes were identified to species.

Numbers of insects at each release level (five and 50 insects) that passed into the simulated aircraft of each passenger bridge/aircraft assembly were subjected to analysis by General Linear Models (GLM) procedure and means were separated by the method of Tukey (SAS Institute 1992). Unless otherwise stated, $P = 0.05$.

Data from each passenger bridge/aircraft assembly were combined, converted to percentages, subjected to arcsine transformation, and analyzed by GLM using the following model: % Insects in aircraft = air curtain units in operation + vertical air curtain units + insect release levels + all two-way and three-way interaction terms

There were three levels of air curtains units tested (all-units-off, vertical-on, and all-units-on), two levels of vertical-on units (Models FSA 1072AA or Max 1072), and two levels of insect release (five and 50).

Results and Discussion

Insect Recapture Studies. When 50 insects of each species were released in assembly JW1 with all units and attached screens in place, a mean number of 26.8 and 14.5 mosquitoes and flies, respectively, entered the simulated aircraft with all-units-off (Table 1). In contrast, a mean number of 9.8 and 2.8 mosquitoes and flies, respectively, entered with vertical-on, and a mean number of 5.7 and 1.5 mosquitoes and flies, respectively, entered with all-units-on. Mean numbers of insects entering the simulated aircraft during both units-on treatments (vertical-on and all-units-on) were not significantly different, but they were significantly lower than in the all-units-off controls. There were no great numerical differences among individual

Table 2. Mean (± SE) numbers of mosquitoes and house flies recovered from simulated aircraft after passage of 25 passenger equivalents through JW1 equipped with a single horizontal (MK II 1042) and two vertically mounted (1 FSA 1072AA/side of doorway) air curtain units

Treatment	*Ae. aegypti*	*Oc. taeniorhynchus*	*An. quadrimaculatus*	Total mosquitoes	House flies
All off	2.6 (0.8)a	2.0 (0.5)a	1.6 (0.5)a	6.1 (1.2)a	2.1 (0.6)a
Vertical only	0.0 (0.0)b	0.2 (0.2)b	0.2 (0.2)b	0.4 (0.2)b	0.2 (0.2)b
Vertical and Horizontal	0.2 (0.2)b	0.0 (0.0)b	0.2 (0.2)b	0.4 (0.3)b	0.2 (0.2)b

Trials with five insects of each species released/test ($n = 6$ tests/treatment).
Means within columns followed by the same letter are not significantly different at $P = 0.05$ (Tukey's method).

Table 3. Mean (± SE) numbers of mosquitoes and house flies recovered from simulated aircraft after passage of 25 passenger equivalents through JW2 equipped with a single horizontal (MK II 1042) and four vertically mounted (two Max1072/side of doorway) air curtains units

Treatment	*Ae. aegypti*	*Oc. taeniorhynchus*	*An. quadrimaculatus*	Total mosquitoes	House flies
All off	9.0 (1.6)a	7.7 (1.4)a	7.7 (2.8)a	24.3 (5.2)a	14.2 (2.5)a
Vertical only	2.8 (0.7)b	2.5 (0.9)b	2.8 (0.7)b	8.2 (1.9)b	2.0 (0.5)b
Vertical and Horizontal	1.7 (0.3)b	1.0 (0.3)b	0.3 (0.2)c	3.0 (0.4)b	0.6 (0.2)c

Trials with 50 insects of each species released/test ($n = 6$ tests/treatment).
Means within columns followed by the same letter are not significantly different at $P = 0.05$ (Tukey's method).

mosquito species to indicate a differential ability to pass through the air barrier. When five insects of each species were released, a mean number of 6.1 mosquitoes and 2.1 flies entered the simulated aircraft with all-units-off, but a mean number of 0.4 and 0.2 mosquitoes and flies, respectively, entered with vertical-on or all-units-on (Table 2). To summarize Tables 1 and 2, 3 to 4% of the released mosquitoes and flies entered the simulated aircraft with all-units-on compared with 18–42% that entered with all-units-off.

When 50 insects of each species were released in assembly JW2, a mean number of 24.3 and 14.2 mosquitoes and flies, respectively, entered the simulated aircraft with all-units-off (Table 3). In contrast, a mean number of 8.2 and 2.0 mosquitoes and flies, respectively, entered with vertical-on, and a mean number of 3.0 and 0.6 mosquitoes and flies, respectively, entered with all-units-on. Again, mean numbers of insects passing into the simulated aircraft during both vertical-on, and all-units-on were not significantly different, but were significantly lower than in the all-units-off. When only five insects of each species were released, a mean number of 3.9 mosquitoes and 0.7 flies entered the aircraft with all-units-off, but a mean number of 0.8 and 0.3 mosquitoes entered with vertical-on or all-units-on, respectively (Table 4). No house flies entered the simulated aircraft with vertical-on or all-units-on. To summarize Tables 3 and 4, 2% of the released mosquitoes and 0% of the released flies entered the simulated aircraft with all-units-on compared with 16–22% of the mosquitoes and 14–28% of the flies that entered with all-units-off.

Preliminary Trials. For JW1, with only the overhead unit on, a mean of 28% (SD ± 3.1; $n = 3$) of 50 house flies was found in the simulated aircraft after 25 passenger equivalents had moved through the passenger bridge and the aircraft doorway. Then, in JW2 (with only two MK II units operating on either side of the doorway, and with the overhead unit on), a mean of 2.4% (13/550; $n = 5$) of released mosquitoes and 8.5% (17/200; $n = 4$) of released flies was recovered from the aircraft. This level of efficacy was not acceptable as an alternative to insecticide disinsection, and we determined that more air from vertical air curtain units on each side of the doorway would have to be added to achieve the needed protection.

Airflow Measurements. In JW1 with all-units-on (two vertical FSA and one horizontal MK II units, Fig. 4), at 91 cm above the floor an airflow of ≥7 m/s was measured at four of the seven critical positions in the center of the doorway. At 45 cm above the floor, or about knee height, an airflow of ≥7 m/s was measured at positions 8–13 (see red-colored region, Fig. 4 legend). At floor level, an airflow of ≥7 m/s was measured at only three positions, but at positions five and six there was backsplash of −2 and −2.9 m/s, respectively, with the airflow reversed and blowing into the doorway (purple region, Fig. 4).

In JW1 with only the vertical-on (two FSA), at 91 cm above the floor an airflow of ≥7 m/s was measured at two (positions eight and 11) of the seven critical positions in the center of the doorway, however velocities at positions 9, 12, and 13 were almost this high. At 45 cm above the floor, or about knee height, airflows of ≥7 m/s were measured at positions eight and 11; airflow was positive at positions 9 to 10 and 12 to 13 but slightly lower at 5.5–6.5 m/s. At floor level, airflow measurements were similar to those recorded at the 45-cm level above; however, at positions 5 and 6 there was backsplash between −2.5 to −4.9 m/s, with the airflow reversed and blowing into the doorway (Fig. 5).

In JW2 with all-units-on (four Max/1 MK II), at 91 cm above the floor an airflow of ≥7 m/s was not measured at any of the seven critical positions. At 45 cm above the floor, an airflow of ≥7 m/s was measured

Table 4. Mean (± SE) numbers of mosquitoes and house flies recovered from simulated aircraft after passage of 25 passenger equivalents through JW2 equipped with a single horizontal (MK II 1042) and four vertically mounted (2 Max1072/side of doorway) air curtain units

Treatment	*Ae. aegypti*	*Oc. taeniorhynchus*	*An. quadrimaculatus*	Total mosquitoes	House flies
All off	1.4 (0.4)a	1.0 (0.3)a	1.4 (0.6)a	3.9 (0.8)	0.7 (0.3)
Vertical only	0.3 (0.2)b	0.2 (0.2a	0.3 (0.2)ab	0.8 (0.4)	0.0 (0.0)
Vertical and Horizontal	0.0 (0.0)b	0.3 (0.2)a	0.0 (0.0)b	0.3 (0.2)	0.0 (0.0)

Trials with five insects of each species released/test ($n = 6$ tests/treatment).
Means within columns followed by the same letter are not significantly different at $P = 0.05$ (Tukey's method).

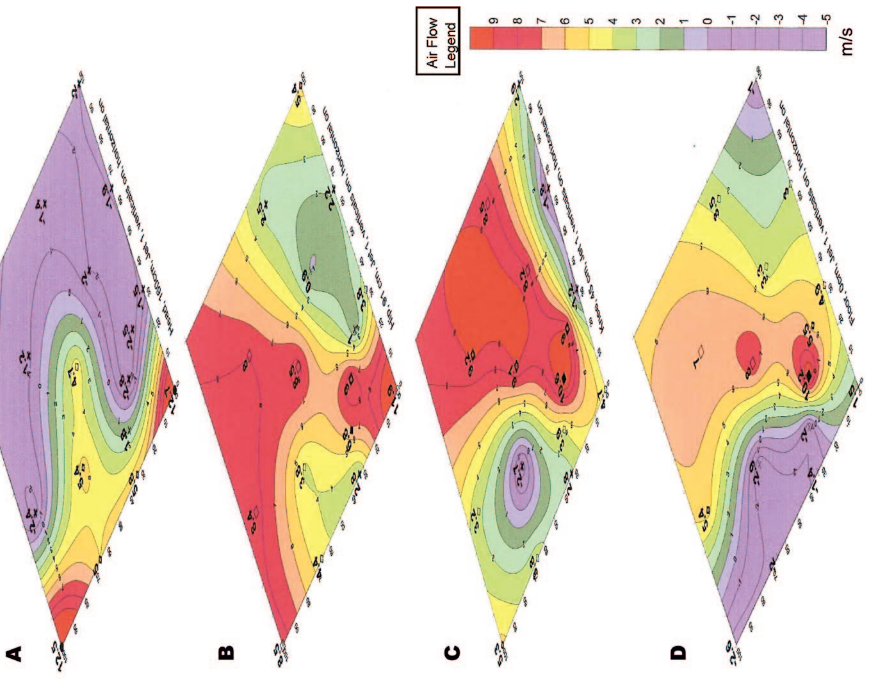

Fig. 4. Airflow measured in arrays at 16 positions and four elevations above the floor. (A) 160 cm. (B) 91 cm. (C) 45 cm, (D) Floor (JW1, two FSA/horizontal MK II, all-units-on). Red to purple scale is meters per second.

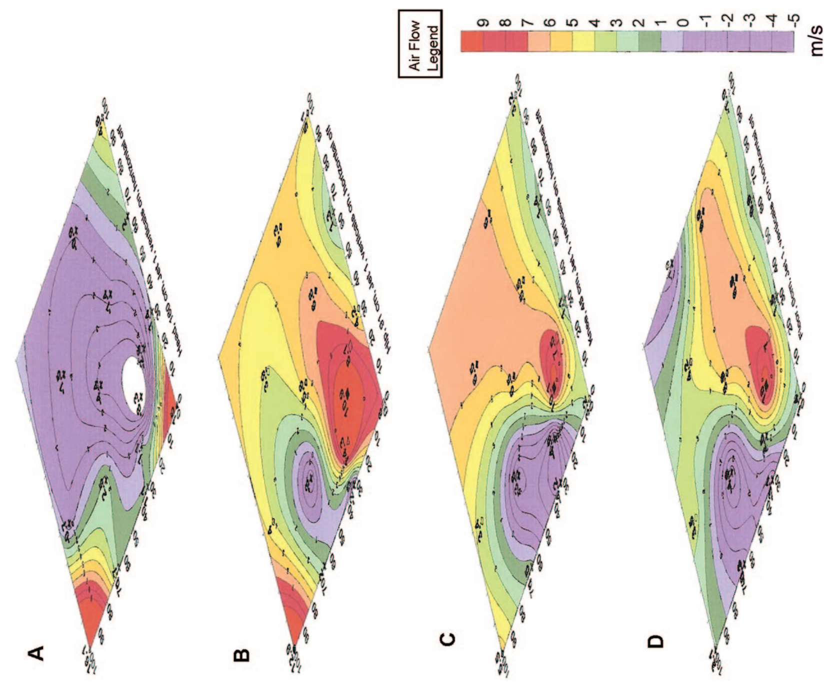

Fig. 5. Airflow measured in arrays at 16 positions and four levels above or at the floor. (A) 160 cm. (B) 91 cm. (C) 45 cm. (D) Floor (JW1, two FSA vertical-on). Red to purple scale is meters per second.

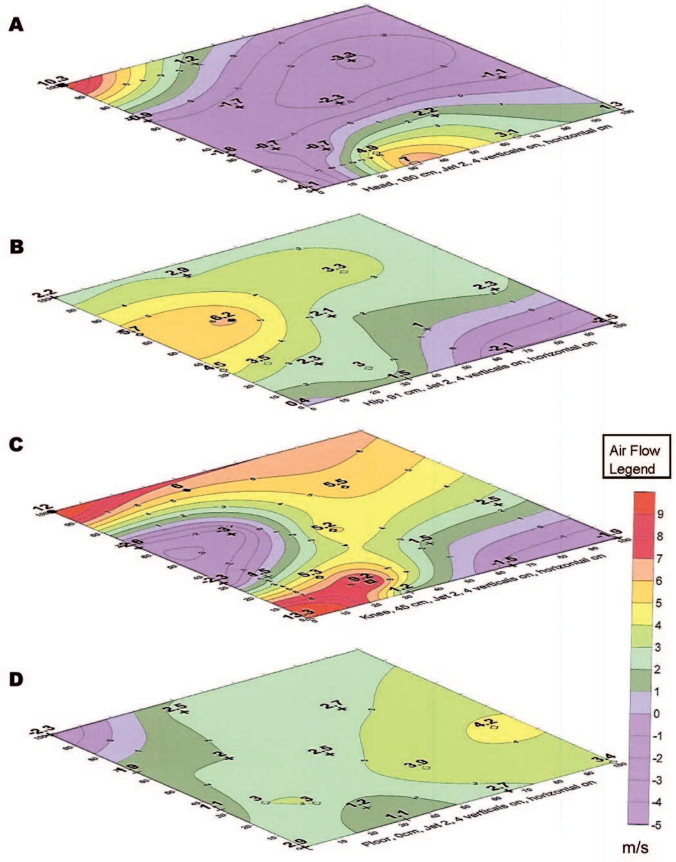

Fig. 6. Airflow measured in arrays at 16 positions and four levels above or at the floor. (A) 160 cm. (B) 91 cm. (C) 45 cm. (D) Floor (JW2, four MAX/ horizontal MK II, all-units-on). Red to purple scale is meters per second.

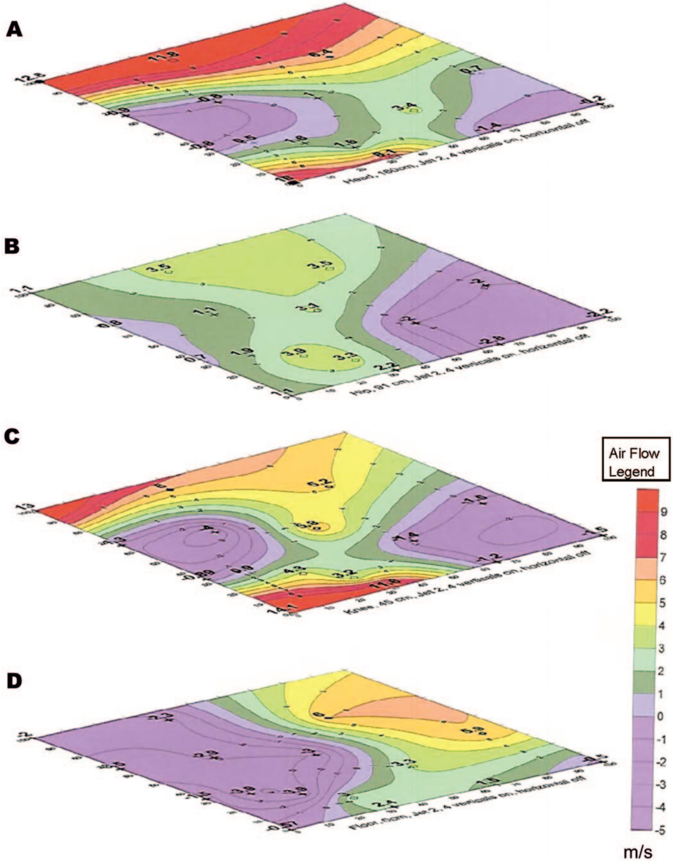

Fig. 7. Airflow measured in arrays at 16 positions and four levels above or at the floor. (A) 160 cm. (B) 91 cm. (C) 45 cm. (D) Floor (JW2, four MAX vertical-on). Red to purple scale is meters per second.

only at position 11; however, an airflow of ≥5.2 m/s was measured at positions 7–10. At floor level, an airflow of ≥7 m/s was not measured at any position, but airflow at positions 4–16 was positive with no backsplash (Fig. 6). In JW2 with only the vertical-units-on (four Max), an airflow of ≥7 m/s was not measured at any critical position at 91 or 45 cm above the floor. At 45 cm above the floor, airflow at positions 8–10 was measured at only 4.2–5.8 m/s. At floor level, airflow at positions 5–9 was strongly negative, with relatively high levels of backsplash (Fig. 7).

Scores for CA Comparison. For JW1 with all-units-on, the sum of airflow scores was CA 126.4 ($\bar{x}$ airflow = 4.5 m/s) (Fig. 4) but was CA 139.5 with vertical-on ($\bar{x}$ airflow = 5.0 m/s) (Fig. 5). In JW2 with all-units-on, the sum of airflow scores was CA 56.8 ($\bar{x}$ airflow = 2.0 m/s) (Fig. 6), but scored higher at CA 70.5 with four vertical-on ($\bar{x}$ airflow = 2.5 m/s) (Fig. 7).

However, in the preliminary configuration of JW2 with 3 U on (two vertical-units-on and the horizontal unit on), only one ≥7 m/s airflow was seen, at 45 cm. The sum of airflow scores was CA 29.3 ($\bar{x}$ airflow = 1.0 m/s) (Fig. 8). Even so, the bioassay results for this configuration were still better than the original results of Mathis et al. (1970). In JW2 with two vertical units on, the sum of airflow scores was CA 62.0 ($\bar{x}$ airflow = 2.2 m/s) (Fig. 9): These measurements indicate that the conclusion from preliminary bioassays in JW2 was correct for this configuration, showing that higher average air flows were necessary.

In trying to establish an appropriate target airflow velocity, examination of airflows showed ≥7 m/s airflow in JW1 at 13 (red only) of 28 critical positions with all-units-on (Fig. 4), but only six of 28 with vertical-on only (Fig. 5). Tests showed ≥7 m/s in JW2 with all-units-on at just one of 28 critical positions (Fig. 6) and just one with all four vertical-on (Fig. 7). Because there was no statistical difference between these results, 7 m/s airflow is too high.

We considered that tests showed ≥3.9-m/s airflow (green to red) in JW1 at 16 of 28 critical positions with all-units-on (Fig. 4) and 19 of 28 critical positions with vertical units only (Fig. 5). Also, airflow tests showed ≥3.9 m/s in JW2 with all-units-on at eight of 28 critical positions (Fig. 6) and seven of 28 critical positions with all four vertical units on (Fig. 7).

There were significant differences in the mean numbers of insects passing through the doorway in the JW1 and JW2 systems when all units were either off or in operation, respectively, either at the high or the low rates of insect release (Tables 1–4). When airflows in these trials were compared with mean numbers of mosquitoes and flies caught in the simulated aircraft, data indicated that velocities averaging two or more meters per second were effective for maintaining the insects inside the simulated bridge. There were no significant differences in the mean numbers of insects passing through the doorway in the JW1 and JW2 systems when all units were in operation or when only the vertical units were in operation, respectively (Tables 1–4), except at the high rate of insect release when significantly higher mean numbers of *An. quadrimaculatus* and house flies passed through the doorway with only vertical-on operation (Table 3). However on a numerical basis, nearly twice as many insects at the high release rate were prevented from passing through the doorway during all-units-on operation (Tables 1 and 3). This is important from a practical aspect.

Therefore, as found by Mathis et al. (1970), an airflow of 8 m/s measured at 91 cm that is produced by a single overhead air curtain unit may be necessary for 80% exclusion of house flies. With an air barrier generated from vertical units such as those described here, a target 4 m/s airflow for a sufficient number of locations in the air barrier may be adequate. Thus there may not be just one critical measurement, but an effective air barrier should have a sufficient pattern of positive airflows above ≈4 m/s; efficacy is likely to be lost if the mean airflows are uniformly below 2 m/s.

In preliminary trials with unscreened air curtain units, we noticed dramatic losses of released insects that were destroyed by passage through the units. After movement of about a third of the passengers, it seemed that half of the insects had disappeared. It was necessary to prevent this interesting but unexpected leakage by installing screens to obtain realistic recovery of test insects for the purpose of these trials. Whereas determination of the loss rates of insects into the units was not attempted, it is reasonable to conclude that such losses would be considerable and would be a helpful factor toward the desired end. While examining these losses and installing screens, we found that mosquitoes could not escape from a screen laid directly on the intake of the most powerful vertical FSA units but that house flies could crawl off this surface with difficulty and escape.

We also observed interesting details of insect flight behavior relevant to the findings but beyond the scope of the current study, specifically, how insects got through the air barrier, as follows.

1. When only the overhead horizontal unit was operating, a strong airflow swept the length of the floor of the bridge and carried most mosquitoes and some flies to the back wall of the bridge. Many mosquitoes remained high on the walls or on the ceiling's screened air return and were thus unlikely to follow moving passengers as they had been carried away from the aircraft doorway. This factor favors the desired result of preventing insects from entering the aircraft.
2. When all units were screened and operating normally, an even stronger circular airflow was established that flowed like a very wide horizontal figure 8). Many insects would be carried away and remain out of the airflow as much as possible in the rear of the bridge, but others were carried back to the intake screens over the FSA units. Some of these insects remained unmoving and high up on the intake screens for the duration of each trial, but they would have been destroyed by unscreened units.

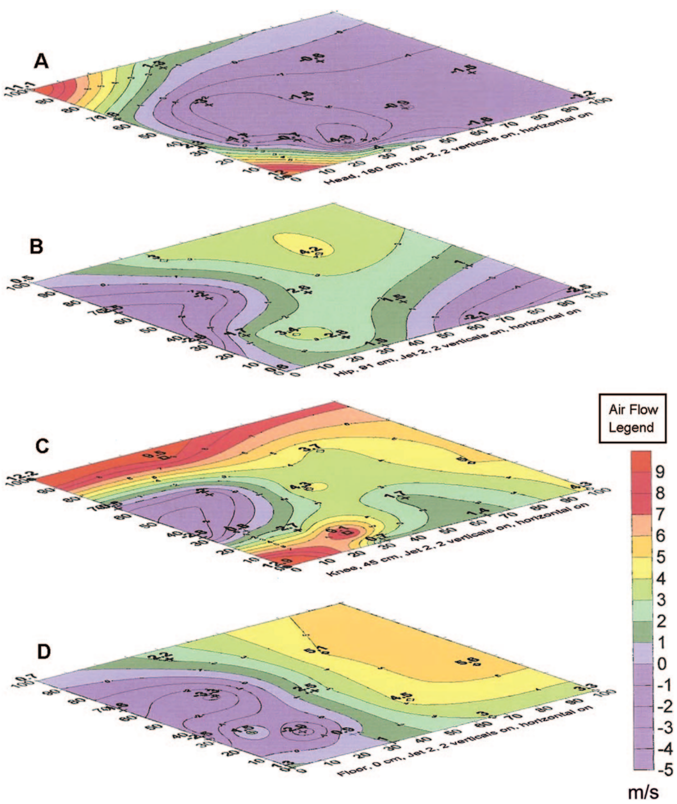

Fig. 8. Airflow measured in arrays at 16 positions and four levels above or at the floor. (A) 160 cm. (B) 91 cm. (C) 45 cm. (D) Floor (JW2, two MAX/ horizontal MK II all-units-on). Red to purple scale is meters per second.

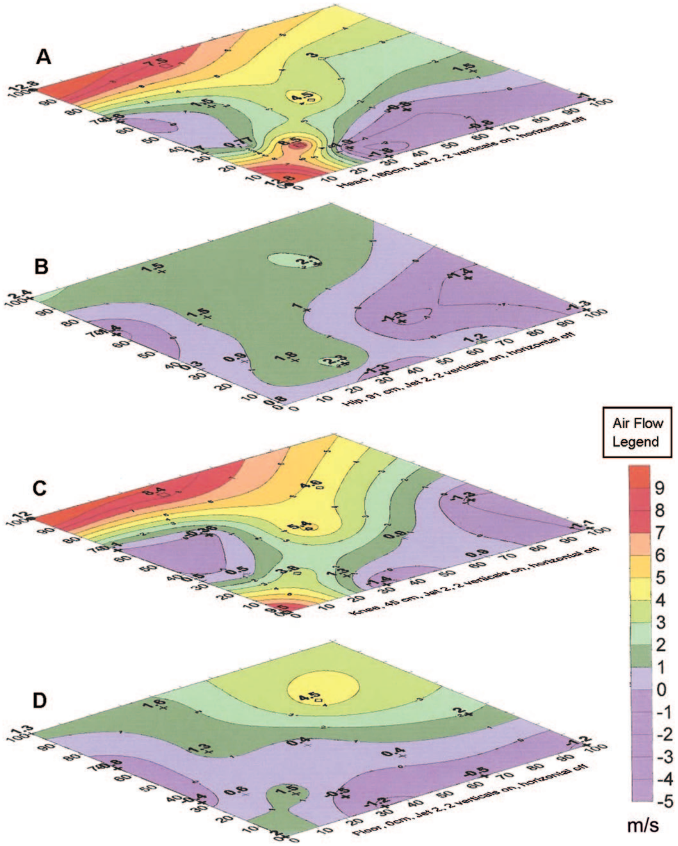

Fig. 9. Airflow measured in arrays at 16 positions and four levels above or at the floor. (A) 160 cm. (B) 91 cm. (C) 45 cm. (D) Floor (JW2, two MAX vertical-on). Red to purple scale is meters per second.

3. With all-units-on or just vertical-on, a few mosquitoes were trapped in standing circular eddies adjacent to the base of each screen, close to the feet of the simulated passengers moving by. Some of these flying mosquitoes could have been kicked or otherwise carried into the air currents by air splashing off the passengers to be then carried into the aircraft on this backsplash. However, this was a situation created by the design of our experimental units that would not occur in a commercial situation without protective screens.
4. Air backsplash also was observed to carry weakly flying mosquitoes in front of the passenger's face or body through the air barrier and through the aircraft doorway. This factor seemed to be at least as common as mosquitoes seen clinging to clothing on the backs of walking passengers who wore light-colored clothing. Both circumstances are unavoidable.
5. Newly released house flies that quickly flew the length of the bridge toward the protected doorway and passed through the air barrier were observed to be displaced laterally by a few centimeters, but would often continue straight onward through the doorway. Similarly, with all-units-on and normal operation, low-flying flies were displaced even lower but were then carried by the backsplash off the floor through the doorway. Flies were rarely "knocked sideways" and thereby deterred from entry. We could observe this behavior only with house flies as mosquitoes were too small.
6. As a consequence of their design, the cylindrical fans are not continuous, resulting in asymmetry and variation in emitted airflow that is unfavorable to the desired result. For example, each 183-cm-tall vertical FSA unit has cylindrical fans of only 82-cm length, the rest being taken up by internal spaces and fan motors. Thus, the airflow is reduced near these gaps, despite fitting of internal metal plates that divert some air into these gaps. These gaps were more noticeable in airflow measurements at 45 cm above the floor, but not as much at 55 cm above the floor (data not shown). The consequence is nonuniformity and asymmetry in airflow.

Our results demonstrated the potential effectiveness of air curtain units in preventing flying insects from entering an aircraft. Presumably, an air barrier that was turned inward toward an aircraft doorway could prevent insects on board from leaving with disembarking passengers. It is difficult to compare our results with the air curtain units with insecticide disinsection studies. A substantial difference was our use of free-flying insects, whereas insecticide evaluation trials invariably use caged insects placed strategically throughout the aircraft (Curtis and White 1984). We demonstrated the difficulty of using free-flying insects in disinsection evaluations in commercial aircraft by conducting two release-recapture trials with 40 mosquitoes and 20 house flies in a 130-seat, single-aisle Boeing 727 passenger aircraft. After 3 h of searching during the two trials by experienced scientists, less than one-third of the released insects could be recaptured. The aircraft offered numerous refuges where the released free-flying insects could not only hide but also escape exposure to pesticides used for disinsection. Dark carpets and upholstery typically found on commercial aircraft further hampered insect recovery by making them very difficult to spot when resting. Thus, disinsection evaluations might only be performed on a practical basis with caged insects, but the results tend to be artificial because cage placement does not necessarily coincide with preferred insect resting sites. Cages also tend to increase mortality by preventing insects from avoiding the applied pesticides.

Interestingly, a recent schedule of aircraft disinsection procedures issued by New Zealand and Australia quarantine services states that for evaluation of aircraft residual treatments, cages of house flies attached near the overhead (ceiling) receive a pass if 30% or more of the flies are affected and cages placed in all other locations receive a pass if 70% or more of the flies are affected. In other words, 100% effectiveness is not required. Our results indicate that air barriers can provide a useful alternative to insecticide disinsection of aircraft.

In summary, we prevented >97% of released mosquitoes and 98–100% of released flies, respectively, from passing through a simulated aircraft doorway using only strategically placed air curtain units. These percentages are much lower if compared with numbers of insects passing through when all units were off. An effective airflow was found to be 4 m/s or higher for at least 25% of the measurements made in the critical area of converging airflows in the simulated aircraft boarding bridge. This technique could be adapted to use in the commercial airline industry and the military to reduce the dependence on chemical insecticides for disinsection of aircraft. The present results also show that air curtain units could be placed to blow into an aircraft doorway to prevent insects from leaving the aircraft with the passengers, that is, if labels in our experiment for the simulated "aircraft" and "passenger bridge" were reversed. However, an exit point for the large volume of air (≈6000–8000 feet^3/min) would have to be provided, as by opening another door protected by a mosquito net at the other end of the aircraft fuselage.

Acknowledgments

We thank M. Falkner, S. Dilling, A. Lloyd, J. Urban, and A. Nalli for technical assistance. We thank Miranda Berner and Berner International for loaning the air curtain units. We thank Major Richard Cipriano and Deputy Bill Hill III (Hillsborough County Sheriffs Office) for permission to use its aircraft training facility. We thank A. Konheim (U.S. Department of Transportation) for partial support of this effort.

References Cited

Anonymous. 1963. Facilities and equipment fact sheet, Meat Inspection Division. Agricultural Research Service, United States Department of Agriculture, MID-FE-1.

Anonymous. 1995. Report of the informal consultation on aircraft disinsection. World Health Organization, 6–10 November 1995.

Anonymous. 2001. The airliner cabin environment and the health of passengers and crew. National Academy Press, Washington, DC.

Bailey, J. 1977. Guide to hygiene and sanitation in aviation. World Health Organization, Geneva, Switzerland.

Brooke, J. P., and M. Evans. 1971. Disinsection of aircraft with pressure packs containing the pyrethroids, resmethrin and bioresmethrin. Pestic. Sci. 2: 133–137.

Cawley, B. M., W. N. Sullivan, M. S. Schechter, and J. U. McGuire. 1974. Desirability of three synthetic pyrethroid aerosols for aircraft disinsection. Bull. World Health Organ. 51: 537–540.

Curtis, C. F., and G. B. White. 1984. *Plasmodium falciparum* transmission in England: entomological and epidemiological data relative to cases in 1983. J. Trop. Med. Hygiene 87: 101–114.

Das, R., J. Cone, and P. Sutton. 2001. Aircraft disinsection. Bull. World Health Organ. 79: 900–901.

Gratz, N. G., R. Steffen, and W. Cocksedge. 2000. Why aircraft disinsection? Bull. World Health Organ. 78: 995–1004.

Greenberg, B. 1971. Flies and disease, volume 1. Ecology, classification and biotic associations. Princeton University Press, Princeton, NJ.

Hocking, R. 1960. An insect proof doorway. Bull. World Health Organ. 51: 135–44.

Langsford, W. A., N. Rajapaksa, and R. C. Russell. 1976. A trial to assess the efficacy of in-flight disinsection of a Boeing-747 aircraft on the Singapore/Sydney sector. Pyrethrum Post 13: 137–142.

Liljedah, L. A., H. J. Retzer, W. M. Sullivan, M. S. Schechter, B. M. Cawley, N. O. Morgan, C. M. Amyx, B. A. Schiefer, and E. J. Gerberg. 1977. Aircraft disinsection; the physical and insecticidal characteristics of dextro phenothrin applied by aerosol at blocks away. Bull. World Health Organ. 54: 391–396.

Mathis, W., E. A. Smith, and H. F. Schoof. 1970. Use of air barriers to prevent entrance of house flies. J. Econ. Entomol. 63: 29–31.

[MQS/AQIS] Ministry of Quarantine Services/Australian Quarantine Inspection Service. 2004. Schedule of aircraft disinsection procedures. http://www.affa.gov.au/corporate_docs/publications/pdf/quarantine/airports/mqs_aqis_disinsection_procedures.pdf (accessed 14 January 2004).

Russell, R. C., and Paton, R. 1989. In-flight disinsection as an efficacious procedure for preventing international transport of insects of public health importance. Bull. World Health Organ. 67: 543–547.

SAS Institute. 1992. User's guide: statistics. SAS Institute, Cary, NC.

Sullivan, W. N., R. Pal, J. W. Wright, J. C. Azurin, R. Okamoto, J. U. McGuire, and R. M. Waters. 1972. Worldwide studies on aircraft disinsection at "blocks away". Bull. World Health Organ. 46: 485–491.

Sullivan, W. N., A. N. Hewing, M. S. Schechter, J. U. McGuire, R. M. Waters, and E. S. Fields. 1975. Further studies of aircraft disinsection and odor characteristics of aerosols containing resmethrin and d-trans-resmethrin. Botyu-Kagaku 40: 5–13.

Sullivan, W. N., B. M. Cawley, M. S. Schechter, D. K. Hayes, K. Staker, and R. Pal. 1978. A comparison of Freon based and water based insecticidal aerosols for aircraft disinsection. Bull. World Health Organ. 56: 129–132.

Sutton, P., X. Vergara, J. Beckman, and R. Das. 2003. Occupational illness among flight attendants due to aircraft disinsection. Report published by the Occupational Health Branch, California Department of Health Services, Sacramento, CA.

U.S. Department of Transportation. 2004. Aircraft disinsection requirements. http://ostpxweb.dot.gov/policy/Safety%20Energy%20Env/disinsection.htm (accessed 7 July 2004).

van Netten, C. 2002. Analysis and implications of aircraft disinfectants. Sci. Total Environ. 293: 257–262.

Waldron, W. G. 1958. A study of the effectiveness of mechanical fans used as fly control measures in public eating-places. M.S. thesis, Public Health and Preventive Medicine, University of California, Los Angeles, CA.

Received 20 January 2005; accepted 20 July 2005.