ARTICLES

PERFORMANCE OF AERIAL SPRAY EQUIPMENT USED TO DISPERSE DDT AT ORLANDO, FLORIDA—SUMMARY *

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The dispersion of DDT oil solutions and water emulsions from airplanes created greater and more widespread interest than any of the other war time entomological problems investigated for the armed forces. The development of sprays and methods of aerial dispersal for the control of mosquitoes and other insects was an important contribution to the war effort. Potts (1939) and Whitten (1941) had previously employed airplanes for the application of sprays, but until the development of DDT this means of application was impractical for mosquito control.

Studies were made at the Orlando, Fla., laboratory of this Bureau, from 1942 to 1945, which involved the development of suitable equipment for dispersing DDT sprays, the proper concentrations for solutions, droplet-size range, rates of distribution, and effectiveness of sprays against various species. This paper presents a summary of the physical characteristics of the sprays, the effective swath widths, and the delivery rates obtained with the airplane spray equipment which has been studied by the authors.

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The following agencies have cooperated with this Bureau in the development and evaluation of aerial spray equipment: Army Air Forces, Tennessee Valley Authority, National Defense Research Committee, Bureau of Medicine and Surgery of the U. S. Navy, the U. S. Coast Guard, the U. S. Marine Corps, and the Chemical Warfare Service.

Methods of Obtaining Data

Delivery Rate.—The delivery rate for any particular piece of equipment was the quantity of liquid discharged in a given time. This rate was usually expressed in quarts per minute, and was determined by placing a measured amount of material in the supply tank, flying the plane for 1 or 2 minutes, during which time a spray was being produced, and then measuring the material that remained.

Droplet-Size Range.—To determine the droplet-size distribution in the sprays produced by the aerial equipment, samples of the spray were caught on microscope slides coated with magnesium oxide. The slides were prepared by holding them in the smoke given off by burning magnesium turnings, the thickness of the coating depending on whether coarse or fine sprays were expected, since the layer of magnesium oxide must be slightly thicker than the radius of the largest droplet to be collected. The coated slide was held in the dense spray as it was discharged from an airplane flying into the wind at a minimum altitude (approximately 10 to 15 feet). The slide was moved about slowly in the spray to insure even distribution of the impinging droplets. Replicate samples were made from repeated flights. The diameters of the craters of 100 droplets were measured on each slide sample, using a microscope fitted with an ocular micrometer. Selected reading of droplet craters was avoided by making random measurements over as large an area of the slide as possible.

Swath Width.—The minimum effective swath width was determined by exposing to a DDT spray containing a tracer dye (1) larvae of *Anopheles quadrimaculatus* Say in half-pint ice cream cartons containing distilled water, (2) petri dishes, (3) slides coated with magnesium oxide, and (4) 6 by 6 inch glass plates. These articles were placed on the ground at stations 20 feet apart and in a straight line at right angles to the prevailing wind. The airplane was flown at an altitude of 35 to 40 feet into the wind across the center of the line.

Two of the glass plates were placed side by side at each station. They were collected as soon as possible after the test flight, and the exposed surfaces were placed in contact with each other and the plates fastened together with Scotch tape. The plates were also protected from sunlight to prevent the dye in the spray solution from fading. The amount of tracer dye in the spray deposit on the glass plates was determined with a photometer. The values obtained from the photometer readings were translated into milligrams of deposit by use of a previously prepared graph of readings where known dilutions of the dye were used.

The size of the droplets falling at any station was determined from the magnesium oxide-coated slide at that station. A comparison of these results with the droplet size range previously determined gave valuable data on the distribution of the spray in relation to the line of flight.

To determine the amount of DDT deposit on the petri dishes, houseflies (*Musca domestica* L.) were exposed to the sprayed surface and the knock-down rate was recorded. A 24-hour reading was taken on the mortality of the *Anopheles* larvae in the half-pint cartons.

The swath width was determined from the mortality of mosquito larvae and adult houseflies and from the quantity of DDT, as shown by the deposits on the slides and plates, at the different stations.

FACTORS CONTRIBUTING TO EFFICIENT AERIAL DISPERSAL OF SPRAYS

The primary consideration in the development of aerial spray equipment for applying DDT solutions was that the equipment be so designed that the highest concentration of DDT used would be deposited uniformly in the area to be treated. To evaluate the uniformity of a spray pattern it was necessary to determine the effective swath width and the amount of dispersion that was being obtained with each piece of equipment. Both these factors are affected by the design and speed of each airplane, and by the location of the dispersion orifices in relation to the slip stream. Since dispersion of a liquid by spraying is inversely proportional to the size of the droplets, the solution to the problem would seem to be equipment designed to produce the smallest possible droplets. Actually this solution would reduce the efficiency of applying spray material from the air. This becomes apparent when the meteorological conditions and terrestrial environment existing at any given time and place of spraying are taken into consideration.

Since aerial spraying is carried out fairly close to the ground, the wind velocity, wind direction, and temperature conditions that exist there, especially those in the atmospheric layer immediately adjacent to the ground, also affect the deposition of the spray droplets. The temperature difference between heights of 2 meters and 0.3 meter indicates the lapse rate, with a positive reading indicating inversion (stable air) and a negative reading lapse (turbulent air). All these conditions, except inversion, which generally exists only for a short time in the early morning and evening, are adverse to the deposition of small droplets (probably those below 100 microns in diameter). However, small droplets, which will remain airborne for a considerable time, may contact insects in flight. They are also desirable, when used in stable air, for penetrating jungle canopy and other foliage which would tend to obstruct the deposition of larger droplets on mosquito breeding places. Large droplets, by virtue of their mass, tend to overcome adverse atmospheric conditions and are therefore more easily controlled than small droplets. This advantage is counteracted by the fact that the predominance of large droplets in a spray reduces the efficient distribution of the spray solution.

The problem of producing an efficient aerial spray, in this endeavor, was also complicated by the armed forces' requirement of dispersing DDT solutions as efficiently as possible for all conditions that might be encountered by them. Therefore, equipment was developed which produced a spray with a wide droplet-size range, with the idea of overdosing sufficiently to compensate for any loss of efficiency at the extremes of the droplet size range. The delivery rates were adjusted so that each piece of equipment put out material sufficient to deposit 2 or 3 quarts of liquid per acre, depending on the speed and effective swath width of each type of airplane.

DISCUSSION OF EQUIPMENT AND RESULTS

Only the salient features of the equipment used in these tests, with regard to their performance in applying sprays, are briefly described.

L-4 (Piper Cub). VENTURI WITH FERN-TYPE NOZZLES.—The first aerial spray equipment developed in these studies was designed for the Piper Cub (Army L-4) airplane. The spray unit as released to the armed forces was known as the "Husman-Longcoy Spray Unit for the J3 Piper Cub," and consisted of a supply tank, a gear pump powered by a small wind-driven propeller, and a semiventuri with spray boom and nozzles, together with a cut-off valve, connecting hose, and fittings. (Husman *et al.* 1947.)

The venturi hung under the fuselage at the center of gravity of the plane. The six brass fern-type nozzles located on the trailing edge of the venturi had adjustable jets whose discharge impinged on wide angle conical breaker plates. The nozzles, fitted with No. 54 wire-gage orifice jets, delivered 11 quarts of oil spray per minute at a pressure of about 40 pounds per square inch. This equipment produced a spray containing droplets of various sizes, most of them being over 200 microns in diameter. The minimum effective swath width was 40 feet. Results of field tests using this equipment are given by Deonier *et al* (1945), Lindquist *et al.* (1945), and Wisecup *et al.* (1945).

In spite of this narrow swath width and the wide variation in mass distribution and droplet-size range created by this spray unit, it was widely used by our armed forces and served as a satisfactory expedient while work on what proved to be more efficient equipment was in progress.

BREAKER-BAR EQUIPMENT.—The breaker-bar equipment, together with the underwing spray boom and attached impinging bar, was originally developed for the Navy TBF airplane by C. N. Husman. The modification of this equipment for the Piper Cub (L-4) utilized the supply tank and pump assembly from the Husman-Longcoy unit. The spray was discharged through a row of orifices in two ½-inch pipes. The pipes, each 38 inches long and containing 24 No. 71 wire-gage orifices equally spaced along their lengths, are attached under the wings of the airplane with the orifices directed toward the rear of the plane. The spray material discharged from the orifices is impinged on one edge of a prismatic bar, which is situated ½-inch away from and directly opposite the line of orifices.

The droplet distribution, both as to number and mass, was similar to that from the fern-type nozzles, which was to be expected as the basic principle is the same. However, by making changes in the pump assembly it was possible to double the pressure and produce a spray in which the larger drops were eliminated. The use of the more powerful pump was not practical for general field use, and it has not been recommended.

Placing the outlets under the wings produced two distinct spray clouds which tended to roll together and produce a swath 80 feet wide, double that achieved with the venturi. This increase in swath width required the delivery of twice the amount of material, and resulted in only half the flying to cover a given area.

L-5 (Stinson). SPRAY BOOM.—A spray boom equipped with modified fern-type nozzles was suspended beneath the fuselage of an L-5 without the venturi. A 4-bladed propeller was used which gave a pump pressure of 120 pounds per square inch. In other respects the equipment was similar to that for the Piper Cub.

The increased speed of this airplane (90 m.p.h.) as compared with that of the Cub (70 m.p.h.) and the greater pump pressure gave an increased break-up of spray but a swath width of only 40 feet.

BREAKER-BAR EQUIPMENT.—The breaker-bar equipment for the L-5 plane was similar to that for the Cub, except that 80 orifices were used to secure delivery of the 40 quarts per minute. This amount covered approximately a 75-foot swath with the 3 quarts of liquid per acre the Army desired. An effective swath of 110 feet was actually achieved by this airplane, and this swath interval could be used to secure the more commonly used dosage of 2 quarts of liquid per acre.

PT-17 (Stearman). VENTURI WITH FERN-TYPE NOZZLES.—A venturi with attached spray boom similar to but much larger than that for the liaison-type planes was developed for the PT-17. This biplane, with a 250 hp. engine, had greater power, appeared to create a greater down thrust of spray, and was nearly as maneuverable as the liaison-type plane.

The two propellor-driven pumps, mounted on the landing gear struts, produced a pressure of 120 pounds per square inch in the spray line. Twelve modified fern-type nozzles were required to deliver sufficient spray to disperse 2 quarts of liquid at 90 m.p.h. and an effective swath width of 80 feet. Swath-width studies under adverse conditions indicated that the spray cloud was frequently confined entirely to the slip stream and was then less than 80 feet wide.

The increased spraying pressure and greater power and speed of this plane produced a spray with a droplet-size range similar to that of the L-5 but a finer spray than that secured with the L-4.

BREAKER-BAR EQUIPMENT.—Breaker-bar spray booms similar to those developed for the L-4 and L-5 airplanes were designed for the PT-17 airplane. This spray unit used the same tank and pump system as the venturi unit, the venturi being replaced by a breaker-bar assembly under both lower wings. Each boom was 12½ feet long with 50 No. 70 wire-gage orifices and suspended 12 inches below the center of the wings. The fine spray and the effective swath width of 110 feet produced by this equipment, combined with an increased pay load as compared with the L-4 and L-5 series airplanes, makes it more desirable for dispensing insecticide solutions from the air.

In an endeavor to further atomize the spray, a strip of wire screen was attached behind the impinging bar. Preliminary trials indicated that many more small droplets were produced with the screen than without it, but no marked change in the mass distribution was evident. Less control of the swath was obtained with this attachment, and its use would be limited to the most favorable climatic conditions.

N2S-3 (Stearman). THE GREENFIELD MODEL SPRAY APPARATUS.—In cooperation with the U. S. Navy and the U. S. Marine Corps, the Greenfield model spray apparatus on the N2S-3 airplane was evaluated by the Orlando laboratory and found to compare favorably with similar equipment in which a pressure system was used. In this apparatus the spray solution, supplied from a tank situated in the front cockpit, was fed by gravity through two pipes extending out about 3 feet and at right angles to the fuselage on each side of the airplane, midway between the wings and tail assembly (Dowden *et al.* 1945). The solution was dispersed from a series of rotating, wide-angle conical metal discs connected to the ends of the pipes on each side of the fuselage. The discs were rotated by the metal propellers attached to them. The flow of liquid was regulated by a control valve operated by the pilot.

The chief objection to gravity-feed equipment is, of course, that the delivery rate varies with the change in head of the solution in the supply tank. Although the abrupt ending of the tests prevented complete determination of the flow rate, it was apparent that a fairly constant discharge could be achieved by gradually increasing the outlet to compensate for decreasing head as the tank was emptied.

Swath width tests indicated that the two spray clouds, as they left the spraying discs, were in the turbulent air outside the slip stream of the fuselage and that the spray spread sufficiently to give an effective swath of 100 feet. At a delivery rate of 35 quarts per minute this plane would disperse 1.8 quarts of spray per acre.

The droplet-size range of the sprays from this equipment was similar to that from the pressure spray units on the same type of plane. This indicates that satisfactory atomization was being secured by the whirling discs throwing the liquid into the air without the assistance of pressure equipment.

This equipment had the advantage that suspensions could also be dispersed.

TBF (U. S. Navy).—The breaker-bar equipment for the TBF airplane was originally designed to be installed beneath the wing tips so that the plane could readily be reconverted for combat duty. This equipment has subsequently been redesigned for use on other types of aircraft. In the TBF the supply of spray material was carried in an auxiliary bomb-bay tank, and pumped to the booms by 4 electric booster pumps. Each 92-inch boom contained 19 orifices of No. 50 wire-gage size. The output of 62 quarts of liquid per minute dispersed only 1½ quarts per acre with a 150-foot swath at a flying speed of 130 m.p.h. (20° flaps). The longer spray booms and greater delivery of more recent equipment gave a swath width of 250 feet.

The atomization of the spray covered a broad range of droplet sizes, with only 5 per cent of the drops and 40 per cent of the mass occurring in the range above 200 microns.

Helicopter (Model HNS-1).—In cooperation with the U. S. Navy and the U. S. Coast Guard, an extensive series of tests were conducted with a light helicopter. A more complete report on the development of spraying equipment for this aircraft has been presented by Yuill *et al.* (1946a), and only the data relating to swath width, output, and droplet spectra obtained with the various types of equipment have been included here. It was evident that the air turbulence created by the whirling rotary blades definitely limited the swath from any spray equipment to a width of 60 feet with this plane.

A pump connected directly with the helicopter motor allowed a pressure of 150 pounds per square inch to be used for the sprays. Very fine break-up of spray was secured by using a group of TT8001 nozzles for much of the subsequent spraying of test plots. Comparative studies on coarse and fine sprays at different concentrations were made by Yuill *et al.* (1946b).

Performance of Equipment

Data were obtained on (1) the performance of the Husman-Longcoy spray

TABLE 1. Droplet-size Range Obtained with Various Types of Aerial Spray Equipment.

Type of Plane and Equipment	Pressure (Pounds)	Type of Distribution	Percent of Droplets of Indicated Diameter								
			10-40 microns	41-100 microns	101-160 microns	161-220 microns	221-280 microns	281-340 microns	341-400 microns	401-460 microns	461+ microns
L-4 (Piper Cub):											
Venturi with fern-type nozzles (54 gage)	40	Number	6	37.0	20.0	17.0	7.0	5.0	4.0	2.0	2.0
		Mass	<0.1	2.0	7.0	12.0	14.0	15.0	18.0	14.0	18.0
Breaker-bar (71 gage)	70	Number	16.0	45.0	17.0	10.0	7.0	2.0	2.0	1.0	1.0
		Mass	0.14	3.5	7.4	10.4	17.5	8.4	17.4	14.9	20.4
	150	Number	0	42.1	36.8	15.5	1.8	1.8	1.8	0	0
		Mass	0	3.3	19.9	33.5	7.5	14.6	21.2	0	0
L-5 (Stinson):											
Spray boom with fern-type nozzles (60 gage)	45	Number	8.0	41.0	32.0	15.0	2.0	2.0	0	0	0
		Mass	0.14	7.2	27.2	35.9	10.7	18.5	0	0	0
Breaker-bar (71 gage)	120	Number	5.4	64.3	26.7	2.7	0.9	0	0	0	0
		Mass	0.32	25.6	50.9	13.0	10.1	0	0	0	0
PT-17 (Stearman):											
Venturi with fern-type nozzles (54 gage)	100	Number	11.0	36.0	37.0	11.0	4.0	1.0	0	0	0
		Mass	0.2	5.8	31.4	27.4	23.9	11.2	0	0	0
Breaker-bar (70 gage)	120	Number	5.0	43.0	31.0	16.0	5.0	0	0	0	0
		Mass	0.14	10.3	26.5	40.9	22.0	0	0	0	0
Breaker-bar screen (70 gage)	120	Number	20.9	54.9	16.3	5.0	2.4	0.5	0	0	0
		Mass	0.5	12.6	31.9	6.0	49.5	<.1	0	0	0
N2S-3 (Stearman):											
Greenfield model spray apparatus	Gravity	Number	2.0	54.0	29.0	11.0	3.0	1.0	0	0	0
		Mass	0.05	11.2	57.3	35.0	15.8	10.7	0	0	0
TBF:											
Breaker-bar (50 gage)	25	Number	24.0	49.0	16.6	5.6	3.0	0.9	0.9	0	0
		Mass	1.0	15.0	24.0	18.0	18.0	11.0	13.0	0	0
HNS-1 (Helicopter):											
TT8001 nozzles	150	Number	23.1	61.5	11.5	2.3	0.8	0.8	0	0	0
		Mass	1.1	24.2	29.4	12.7	11.9	20.6	0	0	0
Breaker-bar (80 gage)	150	Number	18.8	54.1	17.7	6.2	2.1	1.0	0	0	0
		Mass	0.6	12.9	23.8	25.6	21.6	15.8	0	0	0
Fern-type nozzles (70 gage)	150	Number	7.7	53.4	22.3	8.7	2.9	1.9	0	1.9	0
		Mass	0.5	3.3	6.4	6.4	5.8	7.0	0	21.4	49.6
Exhaust spray (fishtail stacks)	15	Number	11.0	55.0	20.0	12.0	1.0	1.0	0	0	0
		Mass	0.3	13.4	21.7	44.0	6.4	14.2	0	0	0

unit and modifications of this equipment on a Piper Cub (L-4) and Stearman (PT-17), (2) a nozzle boom without the venturi on a Stinson (L-5), (3) underwing booms with impinging bars (breaker-bar) on the L-4, L-5, PT-17, TBF, and an HNS-1 helicopter, (4) the Greenfield model spray apparatus on a Navy Stearman (N2S-3), (5) nozzle boom with both modified fern-type nozzles and TT8001 nozzles on the helicopter, and (6) an exhaust-generated spray from the helicopter.

The data on the droplet size ranges are presented in Table 1. The type of distribution is given as percentage of droplets by number and by mass within the various micron ranges. Table 2 presents the data on a number of nozzles or orifices which were used to give the

TABLE 2. Performance of Various Types of Equipment on Airplanes Tested at Orlando, Fla., 1944-45.

Type of Plane and Equipment	Orifices Number	Orifices Gage	Delivery (Quarts per Minute)	Air Speed (M.p.h.)	Swath (Feet)	Indicated Coverage (Quarts per Acre)
L-4 (Piper Cub):						
Venturi with fern-type nozzles	6	54	11	70	40	2
Breaker-bar	48	71	22.4	70	80	2
L-5 (Stinson):						
Spray boom with fern-type nozzles	8	60	16	90	40	2.2
Breaker-bar	80	71	40	90	80	2.8
PT-17 (Stearman):						
Venturi with fern-type nozzles	12	54	29	90	80	2
Breaker-bar	100	70	40	90	110	2
N2S-3 (Stearman):						
Greenfield model spray apparatus			35.2	90	100	1.8
TBF:						
Breaker-bar	38	50	60	132	150	1.5
Helicopter (HNS-1):						
Spray boom—TT8001 nozzles	18		13.6	60	60	1.85
Fern-type nozzles	8	70	6.4	60	60	.85
Breaker-bar	48	80	16.4	60	60	2.3
Exhaust spray (fishtail stacks)	24		20.4	60	60	2.8

indicated delivery rate, and the effective swath width that was obtained with the given equipment on the designated airplane, together with the indicated deposit of liquid in quarts per acre.

Experiments were conducted with several types of spray apparatus for dispersing DDT solutions by using the exhaust from small airplanes. Dispersion was accomplished by injecting the solution into an extension of the exhaust pipe. Preliminary tests with this type of equipment on airplanes and extensive studies with a highly developed type of equipment on a helicopter (Model HNS-1) revealed deficiencies which made further developments along this line inadvisable. One serious disadvantage in this method of dispersing DDT petroleum-oil solutions is the inefficiency due to the partial vaporization of the solution to an ineffective smoke, the amount being inversely proportional to the distance of the point of injection from the airplane engine. The spray droplets are so small that their effectiveness is negligible against larvae under all but the most favorable inversion conditions.

In cooperation with the U. S. Navy and the Army Air Forces Board studies were made on exhaust-generated sprays from equipment developed at the University of Illinois by H. F. Johnstone and coworkers. This equipment was designed to spray droplets about 5 microns in diameter. However, a wide range of droplet sizes could be obtained by changing flow rates of spray solution and power settings of the plane. Solutions containing 20 per cent of DDT were used which greatly increased the pay load over that possible when 5 and 10 per cent DDT solutions were used. This equipment was tested on the Navy TBM and the Army C-47. The exhaust-generated sprays were so fine as to require inversion to obtain the best results. They were more rapid in their action against adult mosquitoes than the coarser sprays. The equipment was rejected by the Navy as too complicated. Units adapted to the exhaust of a Stearman biplane having 450 hp. motors were reported (Metcalf *et al.* 1945) as being very satisfactory.

Simpler means of dispersing insect sprays from combat aircraft have been devised. The early work was done with M-10 tanks of the Chemical Warfare Service (Jones *et al.* 1945). The Army Air Forces Board later developed equipment utilizing the auxiliary bomb-bay tanks with simple valve controls and gravity feed to streamline grids and discharge pipes on C-47 and B-25 airplanes. Spray particles of 300 microns or less in diameter could be obtained.

The efficiency of the exhaust-generated sprays having a particle size of 50 to 100 microns, as compared with the gravity-feed streamlined discharge pipes, which gave droplets of approximately 300 microns, was the subject of extensive studies. The simple discharge pipes on a B-25 were satisfactory for dispersing concentrated sprays in dosages as low as 1½ pints per acre. At a dosage of 0.3 pound of DDT per acre the coarse sprays were found to be as effective as the fine sprays. The use of combat aircraft with high air speeds is practical only for military operations requiring treatment of large areas.

DDT sprays were effective against insects over a wide range of droplet sizes. At the dosages that have been used, control has been obtained regardless of the type of spray. There is probably no ideal particle size. The desirable droplet size will depend upon the insect to be attacked, the climatic conditions, and the environment of the insects. Thus far the most practical approach has been to have a range of droplet sizes that can be controlled under the most adverse conditions encountered.

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