R. & M. No. 3604

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MINISTRY OF TECHNOLOGY

AERONAUTICAL RESEARCH COUNCIL
REPORTS AND MEMORANDA

The Measurement of the Effects of Slush and Water on Aircraft During Take-Off

Part I—The Technique

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Part II—Results of Measurements on Three Aircraft

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LONDON: HER MAJESTY'S STATIONERY OFFICE
1969
PRICE £1 17*s.* 6*d.* NET

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Reports and Memoranda No. 3604*
May, 1968

Summary.

Part I of this report describes the construction of ponds laid down on the runway at the Royal Aircraft Establishment, Bedford, in which a number of different aircraft have been tested for drag in slush and water and for water ingestion into engine intakes. The method of testing is described with some of the problems and solutions. Some suggestions and recommendations are made for future improvements.

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*Part I replaces RAE Technical Report 65 175—(A.R.C. 27 529).
Part II replaces RAE Technical Report 68 107—(A.R.C. 30 445).

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1. *Introduction.*

It has long been recognised that standing water or slush on runways present hazards to an aircraft taking off by virtue of increased drag, impact damage, ingestion into engine intakes and the freezing of accumulated slush in recesses of wheel bays, flaps and other openings.

The increased drag of a wheel running in water and slush, and the associated spray patterns have been investigated by NASA on a special testing track[1]. Very elaborate full-scale tests have also been made by NASA on a Convair 880 using a runway covered with manufactured slush[2]. It is clear from these experiments that the extra drag due to slush can be very large and that its magnitude depends on the particular geometrical layout of an aircraft in relation to the spray thrown up from the wheels. Similarly, the problem of spray ingestion into the engines which is known to be critical in certain wing and rear fuselage mounted jet engine installations, depends on the extent to which the engines are sited in wheel spray.

In view of the implications of these effects on the safety of operation of both civil and military aircraft, most new aircraft types will have to be shown to be clear of dangerous spray effects or, at least, the limits of safe operation will have to be demonstrated[3].

To provide a reasonably cheap and reliable method of testing individual aircraft for these effects, experiments have been made at R.A.E. Bedford with two sets of artificial water ponds laid out on the runway (Fig. 1). The construction of these ponds and the techniques of testing aircraft in them are described in this Report; the results of tests on aircraft of differing configurations are described in Part II of this Report.

The method of testing depends firstly on the observation that the drag due to slush can be related to that due to water on a simple density basis, at least up to the tyre aquaplaning speed. There is still some doubt, however, on the exact effect of slush density on aquaplaning. Although there is some indication that the trajectory of the spray from slush is rather lower than that from water, the drag due to the spray is not greatly affected because it arises mostly from impact in the immediate neighbourhood of the undercarriage.

Secondly it depends on the fact that the spray develops very rapidly after the aircraft enters the ponds and that the drag quickly builds up to a steady value; this means that the ponds need only be long enough for the full drag to be developed, measured, and recorded. Experience has shown that the ponds should be at least one and a half times the length of the aircraft to achieve satisfactory results. The measurements of long term effects of slush on the aircraft, for instance, the effect of slush or water ingestion on the functioning of the engines, would require a much longer installation.

When the ponds have been filled to a known depth of water the aircraft is accelerated along the runway towards them until the desired speed has been reached a little short of the ponds. At this point the engine conditions are held constant (usually at idling power) and the aircraft is steered through the ponds. The drag due to the water is then calculated from the change in deceleration caused by the ponds as measured by a sensitive accelerometer in the aircraft. The records from a free gyro allow the measured accelerations to be corrected for changes in pitch attitude, and a kinetheodolite installation is used to measure the exact ground speed. Similar tests made with the ponds filled with artificial slush instead of water in order to establish the correlation are described in Part II.

2. *Description of the Ponds Installation.*

2.1. *Requirement.*

The basic requirements for a suitable pond installation can be summarised as follows:

(a) The runway must be long enough to provide adequate acceleration and braking distance.

(b) There must be a level surface on the runway at a suitable point along its length.

(c) There must be adequate water supply and drainage facilities in the neighbourhood of the installation.

(d) The construction of the ponds must be designed so that they present no hazard to the test aircraft or to other aircraft using the runway.

The installation at R.A.E. Bedford was designed with those requirements in mind and the following detailed description is given to assist in the design of future installations.

2.2. *The Runway.*

The main runway at R.A.E. Bedford is 10 500 feet long, 300 feet wide and approximately level lengthwise for three-fifths of its length with a rise of 10 feet in the last 3000 feet at the western end. The surface is concrete in 10 foot squares with bitumen expansion joints between. An accurate survey established that the best longitudinal level strip was in an area which is approximately 3000 feet from the western end and 6000 feet from the eastern end. (Fig. 1).

When tests were made with the engines at idling power at the ponds, it was found that a long run up was needed to stabilise the speed at the required figure before the power was reduced. Pilots generally used most of the available length of 6000 feet for this run-up, steering by reference to the joint marks in the concrete and the white painted side lines.

Tests with the engines at higher power settings (mainly for water ingestion work) required only a short acceleration run, although the later reduction in power meant that a longer deceleration distance was required. The 3000 feet available was usually sufficient, particularly when reversed thrust was available. On some occasions these tests were made in the easterly direction in order to make 6000 feet available for stopping.

Some hundreds of runs have been successfully made at speeds up to 100 knots with the 3000 foot stopping distance.

In the area where the ponds were laid, there is about a 1 per cent fall across the runway which proved useful for drainage purposes in the test area but is too great to form the bases of the ponds without extra levelling. The method used for this levelling is described in the next section.

The 300 foot width of the runway is large enough to permit the installation of the ponds near one side and to leave sufficient unobstructed width for normal flying operations.

2.3. *The Pond Bases.*

Although the runway has only a small height variation in the longitudinal direction, the fall of 1 per cent across the pond area would require a large volume of material to make a single large level slab, which would range from 1 inch to 6 inches thick. This was avoided by constructing three narrow level bases stepwise across the runway to suit the various wheel tracks (Fig. 2). The maximum thickness of material was thus about 3 inches and the difference in level between the two main wheel ponds was about the same. Thus for a wheel track of 25 feet the tilt was about 1 per cent which was similar to the slope of the runway itself and would not affect the tests. The smaller set of ponds was better than this.

The spaces between the ponds were faired in, the ends were feathered to a slope of 1 inch in 10 feet and the sides to a slope of 1 inch in 5 feet.

The choice of material for the levelled bases was dictated by the need to ensure a firm bond with the runway surface without causing any damage to it. Furthermore the material had to be capable of being levelled to a specified accuracy of $\pm 1/16$ inch and had to provide a surface which would be suitable for bonding on the pond walls. There are a number of suitable materials available which are normally intended for the repair of worn concrete surfaces but there is a wide difference in price between them, which becomes significant when large areas have to be covered.

Two materials (Appendix A) were used in the installation at Bedford, one for each set of ponds. One of these, a Polymer cement, was used for the first set of ponds and gave a fine, hard cement-like surface which was excellent for bonding the pond walls. It was quick drying and so could be repaired easily. The second, a bituminous material known as Stonhard Resurfacer, was used for the second larger set of ponds in order to save expense. This material was found to be less satisfactory for a number of reasons which are discussed below.

A third material, used as a matter of convenience to carry out repairs to the pond bases, was Latex Cement which proved excellent for the purpose but like the Polymer cement was expensive compared with the bituminous material.

Both sets of ponds were laid during non-flying periods at weekends, as uninterrupted working was essential.

The first and smaller set of ponds was *initially* laid with 'Stonhard Resurfacer', the bituminous material, but the surface was ruined by repeated heavy rainstorms which occurred immediately after the bases were laid and before hardening could take place. As a result the whole of the material had to be scraped up. It was then decided to use Polymer cement which, although much more expensive, was not so slow in setting and was less liable to rain damage. Wet weather however again interfered with the laying and necessitated some hand trowelling after the initial levelling, with the result that the final accuracy of levels was only $\pm 1/4$ inch over the area. This could be compensated for to a certain extent by dividing the ponds into sections as described later.

These ponds were completed in November but as a result of being laid without expansion joints, cracks developed in use and water penetrated which, with the severe winter of 1962/63 loosened several large pieces of cement. During the spring of 1963 the area was repaired with Latex cement, expansion joints were cut and filled with bitumen compound and the ponds were brought back into use. No further serious trouble was experienced with the concrete during the period of use, but a close watch was needed to detect and repair slight cracks in good time.

The second set of ponds were much larger and for this reason the less expensive 'Stonhard Resurfacer' was again used. This material was laid during weekends in June and July and it was hoped that more favourable weather would allow this material to set reasonably and enable the job to be completed in 3 or 4 weeks. In fact wet weather again interfered with progress and the job was finally completed after eight weekends. This involved a change of operators and resulted in variations in the texture of the surface probably from a variation in mixes and different weather conditions. The accuracy in levels was no better than $\pm 1/8$ inch over most of the area with up to $\pm 1/4$ inch in the worst places.

The surface presented a firm cement-like skin in some places and a tar-like surface in others, and varying success in bonding the rubber pond walls was experienced; in some cases the surface had to be cleaned with petrol before the adhesive would take.

In use the levelling material failed in many places instead of the bonded joint, and held moisture to such an extent that re-bonding the rubber strip was impossible.

The difficulties were finally resolved by taking up the rubber pond walls and cutting out the material immediately underneath right down to the runway concrete, the narrow channel thus made was then filled with Latex cement which is much firmer and to which the rubber strip bonds well.

No trouble has been experienced with cracking or lifting of Stonhard Resurfacer, except in places at the thin feather edges. These points were patched satisfactorily with Latex cement. Expansion joints had been cut in these bases to match the existing runway joints.

2.4. *Flexible Pond Walls.*

The flexible walls of the ponds consisted of an inverted T-section rubber extrusion which was bonded to the levelled surfaces with an impact adhesive and sealed at the edges and joins. Details of the adhesive and sealer are given in Appendix B. This type of wall was found to be very durable when properly assembled and had no measurable effect on the drag measurements.

The bonding of the walls had to be done on a clean, thoroughly dry surface. Firstly, the position of the pond walls was marked out on the levelled area by the chalked string method. The 100 ft lengths of rubber extrusion were laid out, each on its side, along the chalked line and both rubber and runway were given a coat of adhesive. A period of 15 minutes was allowed for the adhesive to dry, then starting from one end the rubber was turned over and, keeping to the line, the coated surfaces were pressed firmly together, care being taken not to stretch the rubber. This gave an immediate and firm bond. A small roller was useful to apply pressure to each side of the wall (Fig. 3).

The edges of the extrusion had now to be sealed before use and it was very important not to do this within at least 24 hours of sticking down the rubber, otherwise the interaction of the sealer and adhesive caused the edge of the rubber to lift, thus weakening the joint. This effect also occurred at the bitumen expansion joints but could be safely ignored over this very small length.

The methods recommended to form joints and corners are shown in Fig. 4. It was found advisable to use bolts and large washers at the corners to hold the rubber together against its natural elasticity whilst sticking, and all bolts should be in the longitudinal wall of the pond with no portions protruding through the nuts, as illustrated.

The ponds were divided along their length by cross dams placed every 30 feet (Fig. 1). This was found necessary to ensure an even depth of water in stronger winds, which tended to pile up water at one end and to form wavelets which made depth measurement difficult. The cross dams also help to compensate for any errors in levelling of the pond bases.

It is preferable to do all trials at windspeeds below 10 knots for accurate depth measurement and never above 18 knots, when excessive spillage occurs at the downwind end of the ponds.

To prevent the ponds filling during wet weather, a 1 inch hole was punched in the longitudinal wall in each section. Before this was done it was found that rainwater in the ponds sometimes attracted birds, including seagulls, and, on at least two occasions, wild swans. The holes were closed during trials by standard rubber dinghy leak stoppers (R.A.F. Stores Ref. 27C/2176).

The parts of the ponds most liable to damage in use are the ends and cross dams, but it was found that when the aircraft was not on the correct line, the longitudinal pond walls were severely damaged. The rubber strip was tough and survived all tests but, as previously described, the surface immediately below the bonded joint failed in some cases, and the joint itself in others where it had not been properly bonded. The bonded joint is very strong if properly made under good conditions and as experience was gained by the repairers little trouble was experienced from this cause (*See* Appendix B). An attempt to reinforce the bonded joint was made by nailing thin metal strips over the flat portion of the rubber extrusion, using a gun to fire nails into the concrete. This idea was abandoned however because of the risk that the nails would pull out and damage the aircraft.

2.5. *Water Supply and Drainage.*

To fill a total pond area of 4500 square feet to a depth of 1 inch requires approximately 2300 gallons of water. A fast run by an aircraft may lower the level by at least one third so that large quantities of water are required which can be delivered into the ponds at a reasonable rate.

At Bedford, a pipeline was laid from a convenient reservoir and water was pumped by a trailer fire pump to hydrants at the side of the runway adjacent to the ponds. Final delivery to the ponds was through standard $2\frac{1}{2}$ inch fire hoses at up to 200 gallons per minute; faster rates than this caused excessive turbulence and spillage from the shallow ponds and made the hoses unwieldy. To avoid obstruction the hydrants were located in a walled pit near the runway edge, the stand pipes were easily detachable and could be stowed in the pit. The original high load bearing covers of the pit were discarded as they were extremely heavy and dangerous to handle over the pit. Short lengths of wooden railway sleeper were cut to cover the hole and proved easy to manhandle and were of adequate strength to support any aircraft which might leave the runway. Alternatively, water tankers could be used to fill the ponds but at least two or three would be required, depending on capacity, and this would be slow even if a shuttle service were operated for refilling.

During testing a large quantity of water is displaced from the ponds and this had to be cleared from the runway between each run. The cross fall on the runway was of great assistance in this problem and the runway drains were adequate to carry away surplus water and to prevent the grass at the side of the runway from becoming waterlogged. As a result no difficulties were experienced with mud. A convenient concrete crossing point provided a hard standing for vehicles used during the tests and its slope assisted with drainage from the pond area.

When the ponds were first laid, a calm day was chosen and each section was half filled with water and the depths systematically checked all over at 1 foot intervals, the results were plotted, the average depth in each section was determined and some spots giving this average were marked with white paint in each section. These were used as quick check points for all subsequent operations.

3. *Operation of Test Facility.*

3.1. *Preparing the Ponds.*

Under radio surveillance from Air Traffic control the hydrants were uncovered and fire hoses connected and run out to the ponds, the leak stoppers were fitted in the drain holes in the pond walls and filling proceeded. A supervisor/inspector and three labourers were sufficient to manage the preparation of the ponds efficiently and were considered the optimum number, the radio surveillance being independently operated. A fitter was also provided at the reservoir to operate the fire trailer pump.

The water was allowed to settle in the ponds and quick checks of depths were made at the marked spots in each section. It was usual to overfill slightly so that the ponds could be balanced quickly by bending and holding down the pond wall to release surplus water. Between runs the same routine was followed, but it was sometimes possible, by using hand squeegees, (MOW Stores Ref. 55.80.100.105) to push back into a shallower section enough of the spilled water to raise the level to that of the others, to avoid having to run out the hoses to refill. This made it possible to save time by starting a series of tests with $1\frac{1}{2}$ inch or 2 inch of water, and by balancing up between runs at lesser depths, to avoid refilling until the levels had dropped to say $\frac{3}{4}$ inch or less.

When balanced, all depths were measured and recorded at four equal intervals on the line in each section where the wheels could be expected to run. The time taken to prepare the ponds between runs varied from 15 minutes without refilling, to 30 minutes when more water was required.

When testing for drag it was the practice to measure the effect on nose and main wheels separately to find the contribution from each and also simulate the effect of lifting the nosewheel clear. This meant that water splashed into adjacent (dry) ponds had to be removed between runs and this was done quickly by locally made rubber squeegees designed to fit the ponds and the channels between ponds, Fig. 5. The 12 ft squeegee was lightly constructed using a single board, and Dexion angle strips carrying a wooden handle. In order to make it manageable by two men, small carrying handles were also screwed to the wooden board. In use, it was found that water being swept from the 12 foot pond tended to float the squeegee as the water piled up between the tool and the end of the pond, and a third man was therefore required to hold the board down. Nevertheless, this tool was very useful.

3.2. *Tests with Manufactured Slush.*

When it was necessary to provide correlation between the effects of water and of slush, the ponds were filled with an artificial slush manufactured from crushed ice by the method used in the NASA tests on the Convair 880 (Ref. 2). In this method, block ice is crushed in a machine which contains a rotating drum from which protrudes a number of hardened steel spikes. The resulting output consists of a snow-like material mixed with a proportion of ice chips which are sometimes as large as 1 inch in diameter. A poorer quality of material with more lumps is delivered if the steel spikes become worn. It is suggested that the output should be delivered through a builders screen of about $\frac{1}{4}$ in. mesh to filter out the lumps.

For the tests at Bedford, the ice was delivered and crushed by a contractor (Appendix C). The output from the crushing machine was fed directly into an open truck which transported it to the ponds. Here it was found easier to shovel out evenly than to tip, the tendency being for the load to stick in the tipper until the whole lot avalanched in an uncontrollable manner.

The crushed ice was levelled to the required depth by a locally made adjustable scraper (Fig. 6); again it was found that the ice tended to coalesce into lumps at first, but as it thawed and became wetter it became easier to handle and the scraper levelled it quite evenly and quickly. One ton of ice produced approximately 75 cubic feet of 'snow' and the pond area of 900 square feet took roughly three tons of ice to cover to a 3 inch depth.

It is necessary to have a reasonably high ambient temperature to enable the ice to melt evenly; a successful trial was carried out in a temperature of 10°C rising to 12°C, whilst an attempt made in an ambient temperature of 3 to 5°C was unrepresentative, slush only being induced by a fine water spray from a tanker at a temperature a degree or so above air temperature.

When the mixture reached the required consistency at a Sp.Gr. of 0·7 to 0·8, the aircraft made its run, the Sp.Gr. being immediately checked by weighing a known volume, the method being similar to that described in Ref. 2 (*see* also Appendix C).

These tests required more manpower than the water trials, a minimum of six men being required in addition to the two lorry drivers and the two contractors men crushing the ice.

3.3. *Instrumentation.*

For slush drag measurements it was required to measure ground speed, aircraft pitch in the ponds, and longitudinal acceleration. In addition full photographic coverage from three axes was necessary for the study of spray patterns and other effects.

Change of pitch attitude was measured in order to correct the readings from the longitudinal accelerometer for the effect of pitching when the aircraft entered the ponds. A Mark II gyro unit (RAF Stores Ref. 6W 7) was used to measure pitch angle through $\pm 5°$, which gave full scale deflection on a Beaudouin A13 continuous trace recorder. The diameter of the wire on the potentiometer pick-off was such that resolution and measuring accuracy were limited to steps of 0·46°. On one aircraft a smoother record was obtained from a Mark 3 Artificial Horizon (RAF Stores Ref. 6A/6035) modified to use an ac pick-off on the roll axis. The instrument was mounted to measure pitch on this axis, and with the ac pick-off gave infinite resolution.

Absolute values of pitch were not easy to obtain due to precession of the gyro, and the change of pitch as the aircraft ran through the ponds was therefore used to correct the accelerometer readings.

Deceleration was measured by a McLaren ac accelerometer[4], the range being $\pm 1{\cdot}0$g. The trace was expanded to give full scale deflection at $\pm 0{\cdot}5$g on the Beaudouin A.13 continuous trace recorder, which also gave a time base graduated in half seconds.

Ground speed was measured from kinetheodolite records. As the position of the aircraft in the ponds was known, only one kinetheodolite was normally used, but two were used when it was considered they would provide useful information on spray patterns. The kinetheodolite thus also provided a side view of the spray patterns taken at 5 frames/sec, which gave about 5 pictures of the aircraft in the pond during each run. The type used was KTH Askania 41 at a range of 1400 feet. It was fitted with a 60 cm lens giving a field of view about 95 feet wide at the ponds. This was sufficient for most purposes, but ideally it should be about $1\frac{1}{2}$ aircraft lengths. It was inadequate, for example, to give the best information on water ingestion on the VC10 which is about 158 feet long.

Almost any ciné camera will suffice for other side views and a variety were used by various firms during ingestion trials. A filming speed of 48 frames/sec or more is preferred.

The front view was provided by a 35 mm Vinten H.S. 300 camera with a 12 inch 5·6 Dallmeyer Tele-Anastigmat lens, and fitted with a tuning fork time base. This camera was sited about 600 feet ahead of the aircraft and as close to the runway edge as possible, the angle being about 6° to one side. The filming speed was 64 frames/sec and it was hoped that a quick check of the aircraft ground speed would be obtained by observing exactly when the wheels entered and left the pond. Unfortunately the spray sometimes obscured the wheel and made the method unreliable.

The overhead view from a helicopter hovering about 200 feet above and ahead of the ponds was obtained with a 16 mm Bolex Type H16 Reflex ciné camera with Pan Cinar 17–85 mm zoom lens, running at up to 64 frames/sec if the lighting allowed. Colour film was used in this camera because it gave better definition than Black and White. This angle gave a better overall view of what was happening than any other camera position, particularly on the water ingestion trials.

A M.P.P. 54 plate camera with a Polaroid attachment was used to take a three-quarter front view of the aircraft in the ponds; these photographs could be inspected between runs and provided useful information for the trials controller regarding the conditions during the run. The aircraft took only a second or so to pass through the ponds and it was otherwise impossible to observe all the facts of its passage in so short a time, such as, for example, did the aircraft run cleanly through the middle of the ponds? Did it aquaplane? Was there any ingestion and/or steam from the exhaust? Was flap position right? Was there any special occurence? And so on.

Cameras were carried in the aircraft to observe at close range, wheel behaviour, spray patterns, engine ingestion etc. and it was important to site these carefully to ensure that the view would not be obscured by spray. A Telford type N16 mm camera running at 100 frames/sec was installed in a wing tip pod on a Canberra and gave information on spray patterns from the wheels. On an Ambassador a similar camera was used from the forward part of the cabin to film the wheels but spray sometimes interferred with the view.

3.4. *Test Procedure.*

The tests were carried out on the main runway and therefore close liaison with Air Traffic Control (A.T.C.) was essential. This was accomplished by radio, but to avoid possible clashes on aircraft frequencies a special ground control frequency was employed. By this means time was saved during the trials by allowing work to proceed on the preparation of the ponds whilst other aircraft continued to use the runway where it was safe to do so. Work could also be stopped and restarted instantly when necessary.

The experimental organisation consisted of:

(a) The experiment controller, stationed at the ponds with his radio vehicle,

(b) A supervisor/inspector and three men preparing the ponds,

(c) The pump operator at the reservoir,

(d) The two kinétheodolite operating positions,

(e) The ground camera positions (two or three),

(f) A helicopter with ciné photographer,

(g) The test aircraft.

The experiment controller passed all instructions to aircraft through A.T.C. who also relayed messages to kinétheodolite control and elsewhere by telephone.

Direct visual communication with camera positions, kinés and aircraft was by means of a simple coloured flag system with codes for (i) Stand by for imminent run, (ii) Delay, prepare for next run and (iii) Experiment completed—stand down.

A field telephone between the ponds and the pump operator gave control of water supplies.

When the ponds and camera were ready the controller called for the aircraft to make its run and confirmed the speed required, the appropriate flag signal was flown from the radio vehicle and A.T.C. took over and gave the pilot his taxying instructions and the headwind component. The helicopter was directed into position and when the two aircraft were ready A.T.C. gave the pilot clearance for the run.

The pilot used the white side line and the continuous joints on the runway as a guide to lead into the ponds. The flaps were set as requested and the aircraft was accelerated to the required ground speed by using the ASI and adding the headwind component. In order to stabilize at the correct speed pilots generally used the whole of the available runway. Just before entering the ponds the pilot reduced the power to idling, switched on the camera and the aircraft was allowed to coast through the water with the control column held well forward to prevent the nosewheel lifting clear of the water should it aquaplane. The brakes were not used for steering, especially on entering the ponds.

On leaving the ponds the high speed camera was switched off, and flaps and airbrakes were extended to assist with braking which was kept to a minimum to avoid overheating. The aircraft was taxied back to the starting point using the brakes sparingly. It was important to keep the brakes as cool as possible as the next run might be required within 15–30 minutes.

On very slow runs, below the minimum ASI reading, the aircraft was paced by a radio vehicle running on the edge of the runway as it was found that otherwise pilots would rarely get below 50–55 knots.

The observer normally operated the recorders and also kept a log of windspeed and direction, RPM through the ponds, and weight of fuel at the time of each run.

3.5. *Aircraft Inspection between Runs.*

The hazards to the aircraft during these tests can be listed under (a) brake overheating and tyre damage (b) spray impact damage and (c) water or ice ingestion into engines.

(a) Inspection for these effects was made between each run. Brakes were always liable to overheat, especially when reversed thrust was not available, and precautions had to be taken against failures. The best method would appear to be measurement of rim temperatures and/or tyre pressures and to let these fall to safe levels between runs. This, rather than the time to prepare the ponds, can be the limiting factor in the rate at which trials can proceed.

Drag in slush or water, and aquaplaning speed depend, in part, on tyre pressure and it was considered advisable to adjust tyre pressure prior to each run to eliminate this variable. It was usually necessary to do this by releasing excess pressure due to heating, and care was taken to delay this check until all other preparations for the next run had been made. No trouble was experienced with tyre damage other than normal wear.

(b) Impact damage can be serious, an extreme case sustained in water at 60 knots being shown in Fig. 7 and further examples in Fig. 8.

A case of repeated fracture of a light alloy stay tube on an undercarriage nosewheel door was overcome by making up a steel tube for the purpose of the trials, and a frequently fractured Perspex panel under the Canberra fuselage, leading to distortion of secondary structure, was replaced by a metal panel (Fig. 9). These modifications enabled the correct aircraft configuration to be maintained for the drag trials.

On later aircraft, fibreglass panels covering aerials etc. have been detached in the ponds, but details are not available of the method of securing these covers. It is well established however that doped on fabric and paint are liable to be stripped. Where flaps are drooped to take-off settings for drag tests, it is necessary to inspect hinge brackets, actuators and their mountings for damage. Landing configurations have been used on some aircraft during ingestion trials which render this check even more advisable.

(c) Water or slush ingestion. One case of severe damage to a gas turbine engine occured when an aircraft was run through water more than $\frac{1}{2}$ in. deep, whilst in other cases flame outs and loud bangs from the engines have been observed but without apparent damage. It is recommended that, when water ingestion is possible, tests of this kind should be started in water less than $\frac{1}{2}$ in. deep. In natural crusted snow conditions two engines suffered compressor blade fracture on a Canberra, which is not normally subject to ingestion trouble, but the cause in this case was severe nosewheel shimmy induced by uneven snow conditions, when irregular showers of crusted snow were thrown up into the intakes.

In some water ingestion trials for aircraft firms, it was thought wise to minimise the risk of engine flame out by keeping the engine igniters on during the runs. It is not clear whether the bangs from the engine were connected with the use of the igniters.

This experience seems to provide good reasons to stop engines for external inspection between runs where ingestion is suspected. In this case time would be saved if the inspection was done at the end of the runway and personnel and engine starting equipment were positioned accordingly.

3.6. *Analysis of Results.*

Ingestion trials were qualitative and no measurements other than engine parameters were taken. These latter were done by the firms concerned and were not required by the R.A.E.

The measurement of drag however was required as part of a general research programme into the problems of slush and water on runways. The results of trials on an Ambassador, Viscount and Canberra are described in Part II.

The speed measured by the kinétheodolite is the average during the time the aircraft traversed the ponds, from just before entry of the nosewheel to immediately after the mainwheels left the ponds. The known distance of the aircraft from the theodolite and the angular velocity measured at the theodolite enabled the average ground speed to be calculated.

The deceleration in the water was recorded as a continuous trace. At the lower speeds and water depths these traces were very even and the mean deceleration was easily read. At higher speeds, particularly in deep water, the deceleration tended to be unsteady, due in part, to the structural oscillations following the initial impact and due to loading if aquaplaning should suddenly cease. In analysing these traces it was found best to estimate the mean deceleration after ignoring the excursions due to transistory conditions. Some examples are given in Fig. 10. Even in the most difficult cases consistent results were usually obtained in this way. The drag was deduced from the known weight at the time of the run, then corrected to unit depth of water and plotted against the square of the speed. (In the tests with slush, the relative slush density times the square of the speed.) The drag should be linear up to a maximum corresponding roughly to the speed at which aquaplaning takes place; at speeds above this a progressive reduction in drag results.

4. *Discussion.*

4.1. *Dimensions of Ponds.*

For reasons of cost it was considered desirable to use the minimum pond size possible. Preliminary tests with a Canberra, overall length 66 feet, showed that the spray pattern was fully developed and peak deceleration recorded within $1\frac{1}{2}$ aircraft lengths. The first ponds were therefore made 90 feet long. For the Viscount and Ambassador trials larger ponds 150 feet long were used.

There is insufficient evidence at the present time to make firm recommendations on the best length of pond for drag measurement but the arbitrary size of $1\frac{1}{2}$ lengths should be regarded as a minimum, and for ingestion tests is sufficient to give information on spray trajectory without subjecting engines to too long exposure to ingestion. A longer pond would be needed however if the effect of prolonged ingestion is required, and should also enable a more accurate assessment of the drag to be made.

A pond of three aircraft lengths would probably be the maximum economical size to construct and operate, but this length may not be necessary for drag measurement if the response characteristics of the instrumentation are tailored to suit the structural characteristics of the aircraft.

As regards the width of the ponds, for the Canberra on which the man wheels are approximately 1 foot wide and the twin nosewheels about 2 feet overall, the ponds were each made 5 feet wide as this was judged at the time to be adequate for both the Canberra and a Swift, the wheel tracks of which differed by only 6 inches. The basis for this decision was the width of the tracks made by a Canberra in snow conditions at an earlier date.

It became evident during the trials that the spray pattern from a wheel in close proximity to the side of the pond could be modified by the presence of the wall, and the Canberra wheel track shown in Fig. 11 shows clearly that the path cleared by the wheel is approximately three times the width of the wheel.

To allow for errors in alignment it is therefore desirable to make the ponds as wide as possible and, in the light of present knowledge, not less than three times the width of each wheel arrangement. The nosewheel should run in its own pond so that its effect may be studied separately from the main wheels. Where the runway is level laterally a single wide pond divided into three sections by longitudinal walls could be used, but it must be borne in mind that drainage problems may arise if the site is too level. A set of ponds of this type is illustrated in Fig. 12 which indicates that owing to the wide range of undercarriage layouts it is unlikely that a single pond could be designed to cater for all aircraft. Assuming that the drainage problem can be resolved and omitting the Trident as a special case, it can be seen that the minimum width of the nosewheel pond should be about 6 feet. This is also the maximum width for the BAC1–11, otherwise the mainwheels would have insufficient side clearance. The main wheel ponds are uneconomically wide for all other aircraft with the possible exception of the four wheel bogie types, and of marginal width for the Britannia and Argosy, which requires accurate handling of the aircraft.

It is evident that two or more sets of ponds of different sizes, on a runway with a slight cross fall would be the ideal set-up, and if laid down at various manufacturers airfields, the sizes could be decided by mutual agreement to provide versatility instead of duplication.

4.2. *Crosswinds.*

As may be expected, cross winds modify the spray trajectory and consequently the areas of impingement on the aircraft. The effects of cross winds could not be studied extensively during the Bedford trials but experimental scatter of drag points may be attributed in part to this effect, probably to the largest degree in shallow depths of water.

During ingestion trials it became evident that cross winds significantly affect the amount of water entering the engines, and a rear engined jet aircraft which could take off safely from a wet runway in a headwind might suffer considerable ingestion on one side in a crosswind, to the extent of stopping an engine. The effect could also be serious before application of reversed thrust when attempting to stop. The reversed thrust jet when applied would seem, from limited observation, to break up and diffuse any spray from the wheels, so the danger period would be from touch down of the nosewheel to application of reversed thrust.

The use of the Polaroid camera is recommended and should be extended, a suggested layout being two threequarter front views and two side views; these could be independently timed by the operators or simultaneously taken from a remote control.

A Whirlwind helicopter is preferred for overhead photography due to the freedom given to the photographer in the cabin with the door removed. In cases where the wind direction prevented photography from the open door the photographer sat next to the pilot. In the case of a Sycamore it was necessary for the aircraft to be flown on occasion from either seat for the convenience of the photographer.

When a helicopter was not available, a light aircraft such as an Auster was used with some success. The pilot should time his run parallel to the test aircraft at about 600 feet distant and then turn gently across in front about 200 feet away from the ponds so that the photographer can obtain a frontal overhead shot. This required a little practice and direct communication between the two aircraft, with the manoeuvre directed from the photographic aircraft, but is quite easy to do.

4.3. *Costs.*

No exact figures can be given to the particular conditions likely to be encountered on each site but the main items are likely to be:

(a) Survey of site

(b) Materials and labour for levelling

(c) Provision of rubber and adhesives and laying costs

(d) Water supply

(e) Maintenance

(f) Instrumentation

The cost for levelling is an important element and its extent will depend on the area to be levelled and the accuracy demanded. Areas at least $1\frac{1}{2}$ times the length of the aircraft and at least 3 times the width of each wheel group need to be levelled to an accuracy of about $\pm\frac{1}{8}$ in. to utilise water depths down to $\frac{1}{2}$ in. If larger variations in level are allowed, the minimum usable water depth is increased.

The essential requirements for instrumentation are as follows:

(a) For drag measurement
  (1) Water depth must be accurately known
  (2) The average ground speed through the ponds must be measured
  (3) Deceleration and pitch attitude must be measured to the required accuracy.

(b) For ingestion tests
  (1) Photographic coverage must be adequate to give at least two views of the engine intakes from different angles
  (2) Engine conditions must be noted.

4.4. *Damage to Ponds and Suggestions for Improvements.*

The rubber extrusion is very tough and not a single case of failure has occurred with even the heaviest aircraft. The main type of failure has been separation of the rubber from the runway and this is thought to be due to

(a) Incorrect sticking procedure. The surface *must* be dry and clean, and sufficient time allowed for adhesive to almost dry before joining. The joint should not be stressed for at least 24 hours, nor sealing compound applied within this period. (Appendix B).

(b) Bad surface of the levelling material, this having failed before the bonded joint. A remedy for this is suggested in Appendix A—(Fig. 13).

(c) Incorrect positioning of the aircraft in the pond, the aircraft running along the longitudinal wall.

(d) Multiple wheel bogies. This damage has been mainly to the longitudinal walls and no satisfactory explanation can be offered as to whether the multiple wheel layout, incorrect positioning of the aircraft or high weight has been the cause. The only aircraft with this wheel arrangement which has been tested is the VC10 for which the Bedford ponds are unsuitable due to the comparatively narrow track of the undercarriage.

The strength of the bonded joint can be increased by using a wider base rubber extrusion for the walls; this presents no manufacturing problems and is probably the cheapest way to improve the adhesion.

It has been suggested that the rubber should be bedded in the concrete (or whatever material forms the surface) but this is undesirable for the following reasons:

(a) Assuming a T-shaped extrusion, the concrete or other surface material will be weakened by the presence of the flange and liable to fracture.

(b) If adhesive is used before 'concreting', the job would have to be carried out in at least two phases with sufficient time between them to allow the concrete to dry thoroughly.

(c) If no adhesive is used repairs would be difficult if the rubber was pulled out of the concrete without breaking the surface.

5. *Conclusions.*

Comparatively small artificial ponds constructed on a runway and containing water are a suitable basis for testing the effects of standing water and slush on aircraft during take-off. The installation of the ponds is simple and relatively cheap and the method is therefore suitable for manufacturers' own clearance tests on new types.

The runway should be of sufficient length to allow for acceleration to take-off speed, a short run at that speed and deceleration. The variation in lengthwise contour in the pond area should be small; widthwise contours are not so critical, in fact, a slight cross-fall is useful for drainage.

A single set of ponds to test all types of aircraft is likely to be uneconomic to operate, but two or three sets disposed at various airfields could usefully be operated by manufacturers on a co-operative basis.

6. *Acknowledgements.*

The author wishes to acknowledge the assistance and services given by Stonhard Co., Ltd., Dunlop Rubber Company, and United Carlo Gatti Stevenson and Slaters Ltd., together with the aircraft manufacturers who used the test installation.

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APPENDIX A

Materials Used to Level and Repair Slush Pond Bases.

A.1. *Standard Polymer Flooring.* Consists of an unspecified polymer, sand and granite chippings, and cement. It can be laid as a concrete overlay at a thickness down to $\frac{1}{2}$ in. and sets hard in 24 to 36 hours. Expansion joints are required when laid on a concrete runway.

The surface is primed with a proprietary liquid before laying the mixture.

For increased strength at the feather edges 'toeing in' which means cutting a groove about 2 in. wide and $\frac{1}{4}$ in. to $\frac{1}{2}$ in. deep at the edge of the overlay is recommended so that there is a $\frac{1}{4}$ in. to $\frac{1}{2}$ in. minimum thickness where the overlay ends. This was not done at Bedford.

A.2. *Stonhard Resurfacer* is a semi-plastic bitumen compound mixed with cement, sand, and $\frac{1}{8}$ in. granite chips. A primer is applied before the mortar is placed to improve the bond, no roughing or keying being required. Minimum recommended thickness is $\frac{1}{2}$ in. and the firm claim that no expansion joints are necessary. These however are advisable on a surface with existing expansion joints.

The mixture is slightly compressive under initial service but no variation was detected in the Bedford ponds.

The mixture does not present a good surface for bonding the rubber strip and is weak in tension. It is however much cheaper than other materials, and the solution to this problem may be to build up the foundations where the rubber walls are to be bonded with good quality cement mix, making them about 6 inches wide and slightly convex to assist drying out when repairs are needed. The intervening spaces are then levelled accurately with the cheaper mixture. (Fig. 13).

A.3. *Latex Cement.* This being quick setting and easy to apply by semi-skilled labour, was used to repair broken or weakened feather edges on the first set of ponds. It was also used when the pond wall foundations were cut out and re-laid on the second set of ponds. It is expensive compared with Stonhard Resurfacer.

APPENDIX B

Rubber Extrusion and Adhesives for Pond Walls.

The extrusion can be supplied in 100 ft lengths and in various sections. That used at Bedford is of inverted T section, the base measuring 2 in. and the wall 3 in. A stronger bond may be obtained with a $2\frac{1}{2}$ in. or wider base but this was not tried at Bedford.

On earlier trials an L section measuring $1\frac{1}{2}$ in. high with a 1 in. base was tried. This was discontinued as depths up to 2 in. were required for the trials.

The adhesive supplied was Dunlop S.708; this is an impact adhesive and is applied to both surfaces and allowed to dry almost completely. About 15 minutes is an average time. The temptation to bond the surfaces when the adhesive is still quite tacky must be resisted if a good joint is to be made. The joint, once made, should not be moved, and firm pressure should be applied to ensure positive contact. Care in sticking down the rubber will be well repaid when aircraft trials are started.

A waterproofing additive can be supplied by the firm and is mixed with the adhesive just before use. Once mixed, the whole quantity must be used within an hour or so. It was not thought that the additive was essential and this disadvantage coupled with the fact that it was very poisonous and dangerous if the hands were not immediately washed, led to its use being discontinued.

The edges of all joints between rubber and concrete, rubber to rubber, and also any small holes at corners, were stopped with Dunlop S.480, a black 'rubber sealing' compound. This can be supplied, like S.708, in pint or quart tins but was found to be useful in tubes which made application easy. It is very important to let the bonded joints dry out thoroughly before applying the sealer, a minimum time of 24 hours should be allowed but 48 hours would be better. It was found that a reaction occurred between the adhesive and sealer if applied too soon, which caused the rubber to lift at the edges and weakened the bond.

As in all sticking operations it is essential that the surfaces are clean and thoroughly dry, it should be remembered that cement mixtures are porous to a certain extent and a newly dried surface may hold water to an amount sufficient to weaken the joint. It was found that a drying wind was much more effective than warm sunshine in getting surface moisture out of the concrete.

The rubber must also be clean and dry and free from dusting agents. It would be advisable to clean the rubber surface with a cloth soaked in Tuluene (R.559) or similar solvent.

APPENDIX C

Manufactured Slush.

The ice was delivered from London in six ton loads which arrived at Bedford airfield at 0730 hours each day. The crushing machine was supplied by the contractor and set up in advance, power supplies of 450V three phase at 50 cycles being supplied by R.A.E. Bedford for the 15 H.P. electric motor.

One ton of crushed ice was produced in 8 minutes; this amounted to one load for the lorry used to transport the ice out to the runway and covered 225 square feet to a depth of 3 inches in the ponds. Two lorries could keep the crushing machine busy at the rate the two operators could work.

The crushing machine delivers its output through a 4 inch rubber hose which is hand held. A better mixture would be obtained if a large wire screen of say $\frac{1}{4}$ in. mesh was set up and used to filter out the lumps which could be re-fed to the crusher. The maximum size of lump delivered was about 1 inch diameter.

At an average ambient temperature of 11°C a sample taken as soon as the slush was laid and levelled had an Sp.Gr. of 0·595. Forty minutes later the Sp.Gr. was 0·905 and a further twenty-five minutes later 0·935.

As the crushed ice settled and melted a fairly hard crust formed on the surface, this was broken down by tapping and raking lightly.

Summary of Tools and Manpower for Handling Slush.

Delivery and crushing of ice	— Contractors responsibility, one lorry for 6 tons of ice, driver and mate who also operate crushing machine.
Loading and transporting crushed ice.	— Two light lorries and two driver loaders.
Unloading and levelling crushed ice	— Six men with gumboots. Six snow shovels. Six brooms, two rakes. Six hand squeeges. One hand operated scraping and levelling board, adjustable.
Measuring depths and Sp.Gr.	— One depth gauge consisting of sliding disc on a graduated rod. One rectangular flat scoop with 3 in. perpendicular sides and 9 in. × 8 in. bottom (giving $\frac{1}{2}$ sq ft area). One strip of sheet metal to close the fourth side of the scoop. One 12 in. ruler. One plastic bucket. One spring balance 0–5 lb. One technician.

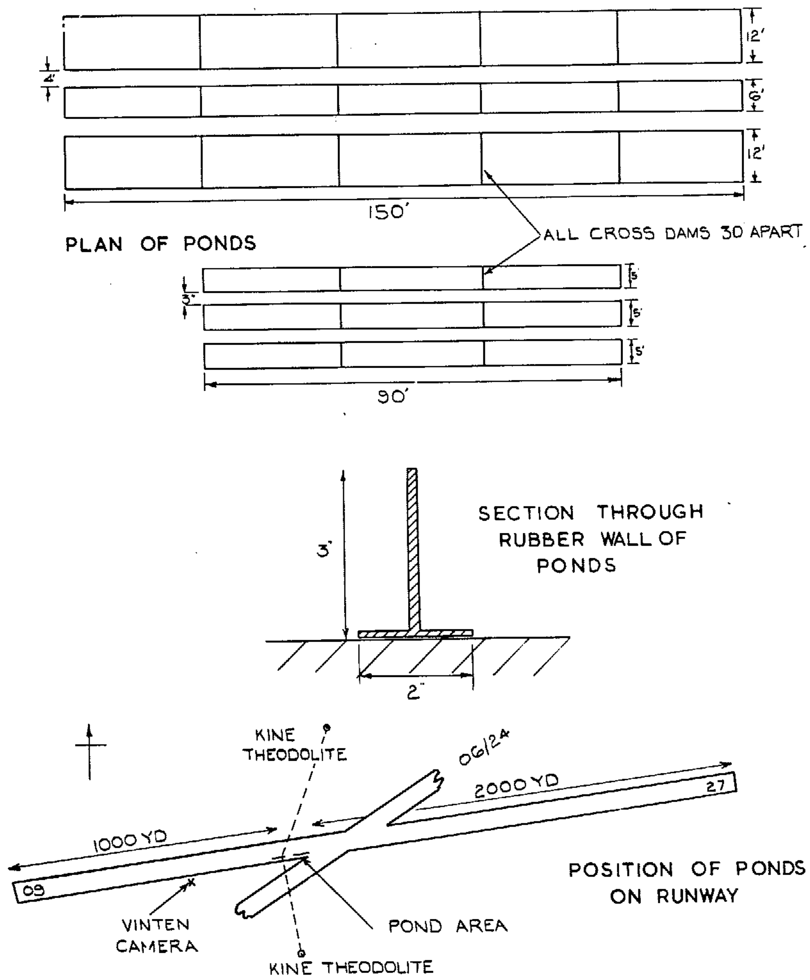

FIG. 1. Slush ponds at R.A.E. Bedford.

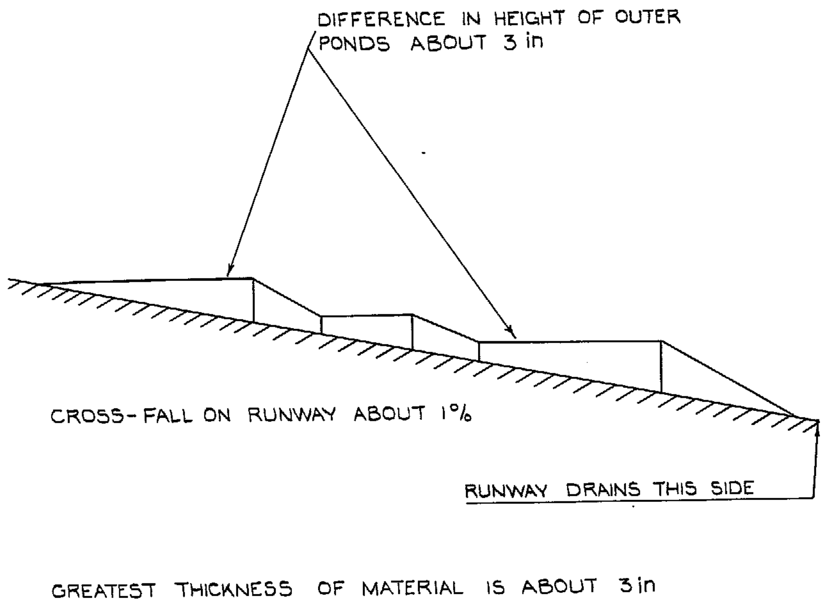

FIG. 2. Cross section through pond bases.
(not to scale)

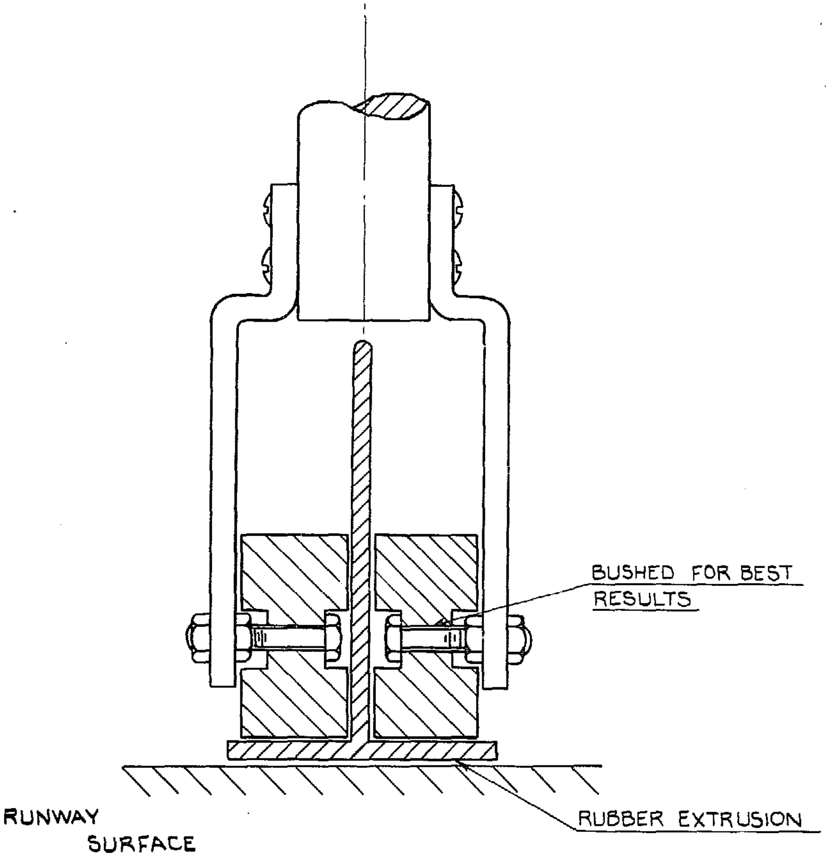

FIG. 3. Twin roller for applying pressure when sticking down pond walls.

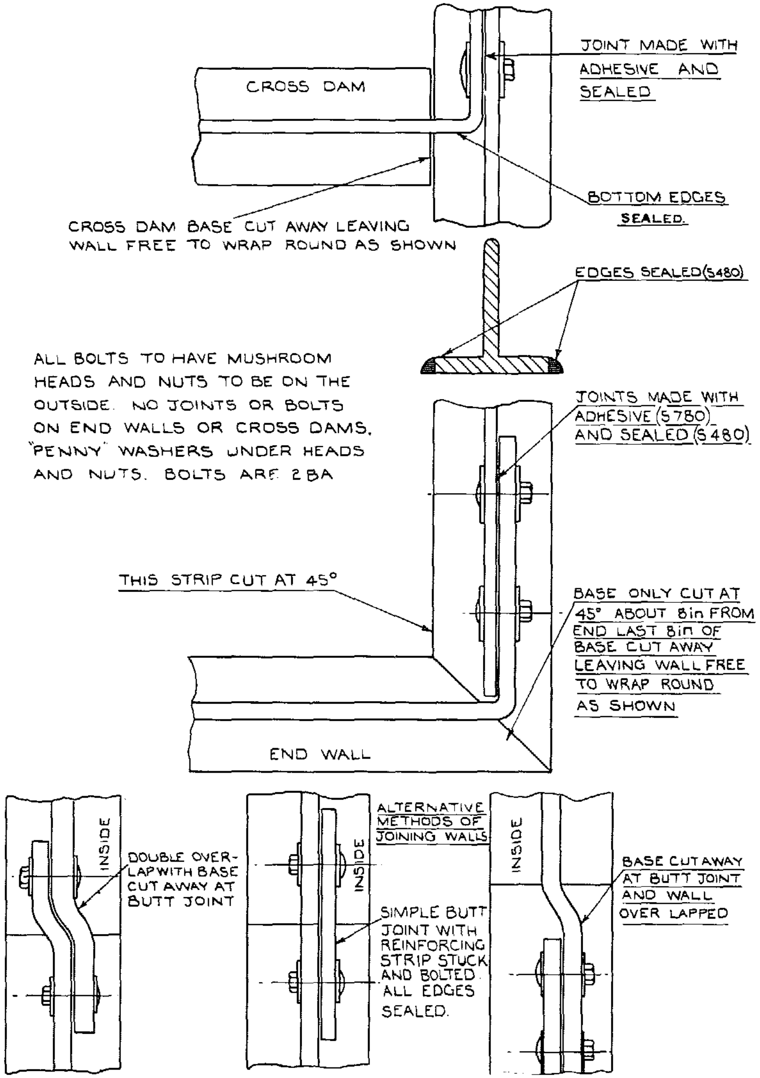

FIG. 4. Detail of joints in pond walls.

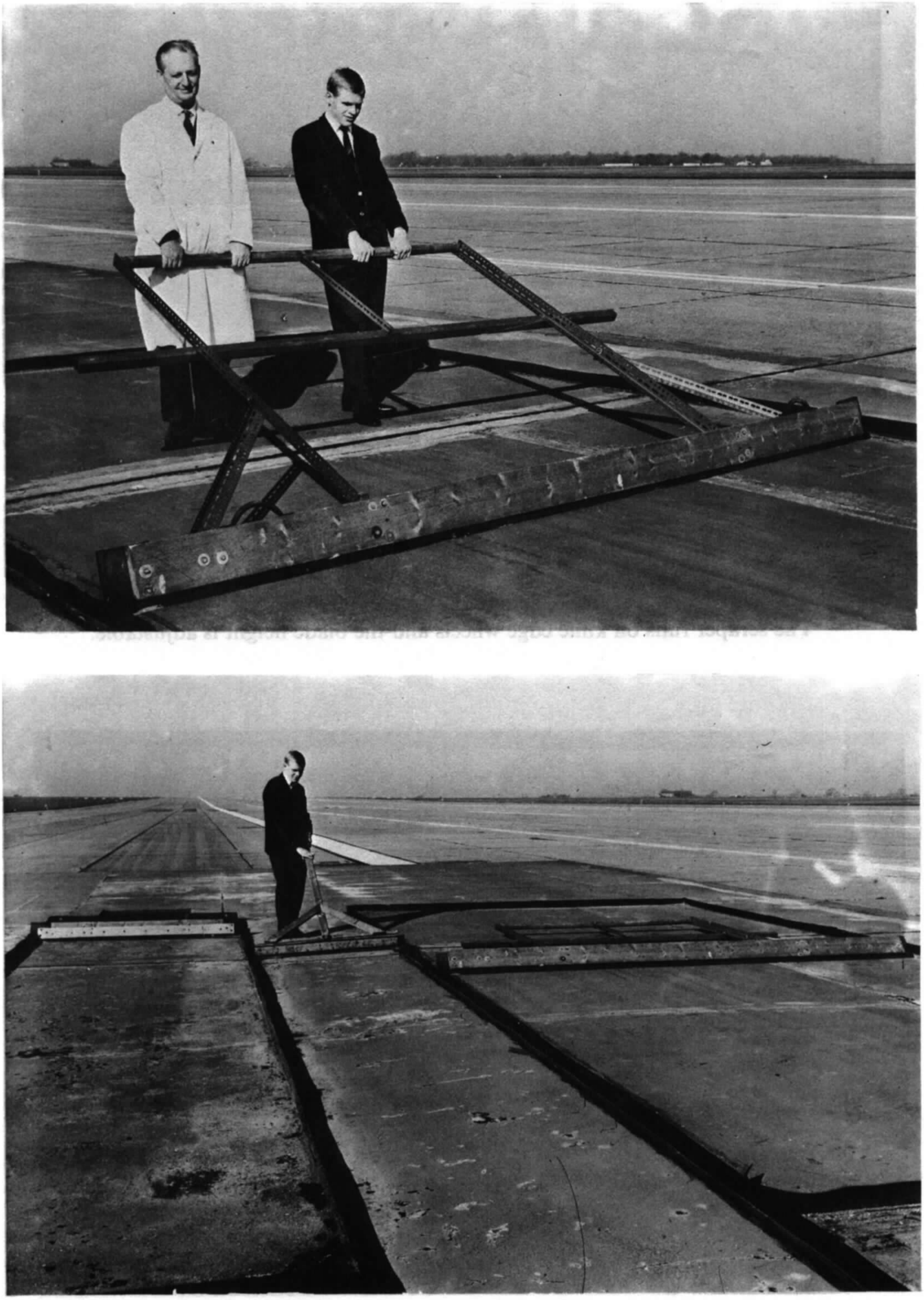

FIG. 5. Special squeegees for control of water.

FIG. 6. Scraper and ice in ponds.
The scraper runs on knife edge wheels and the blade height is adjustable.

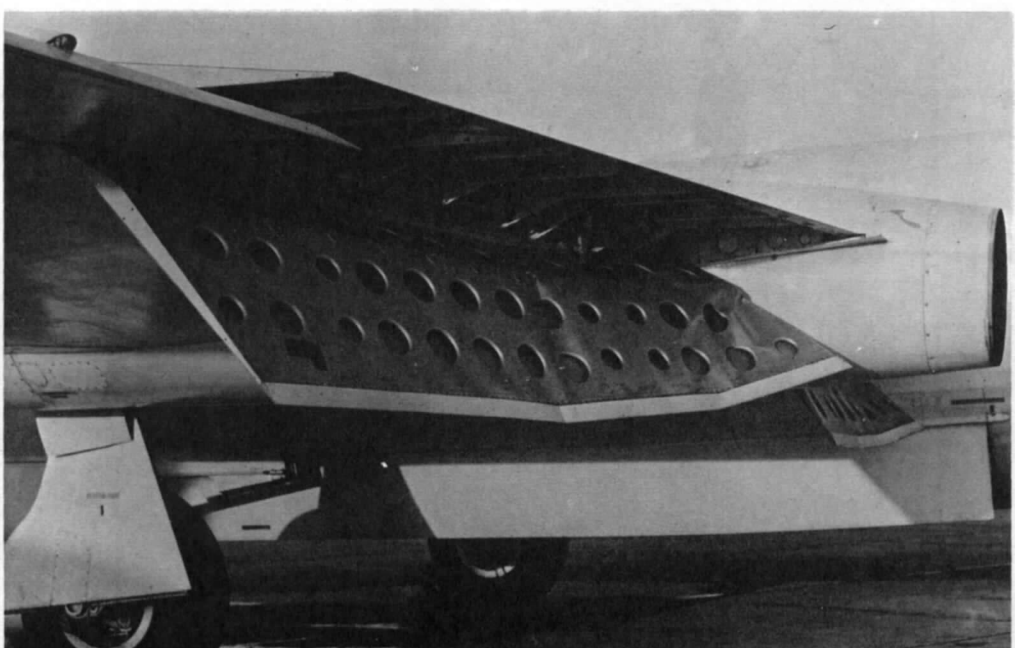

FIG. 7. Flap damage—Canberra.

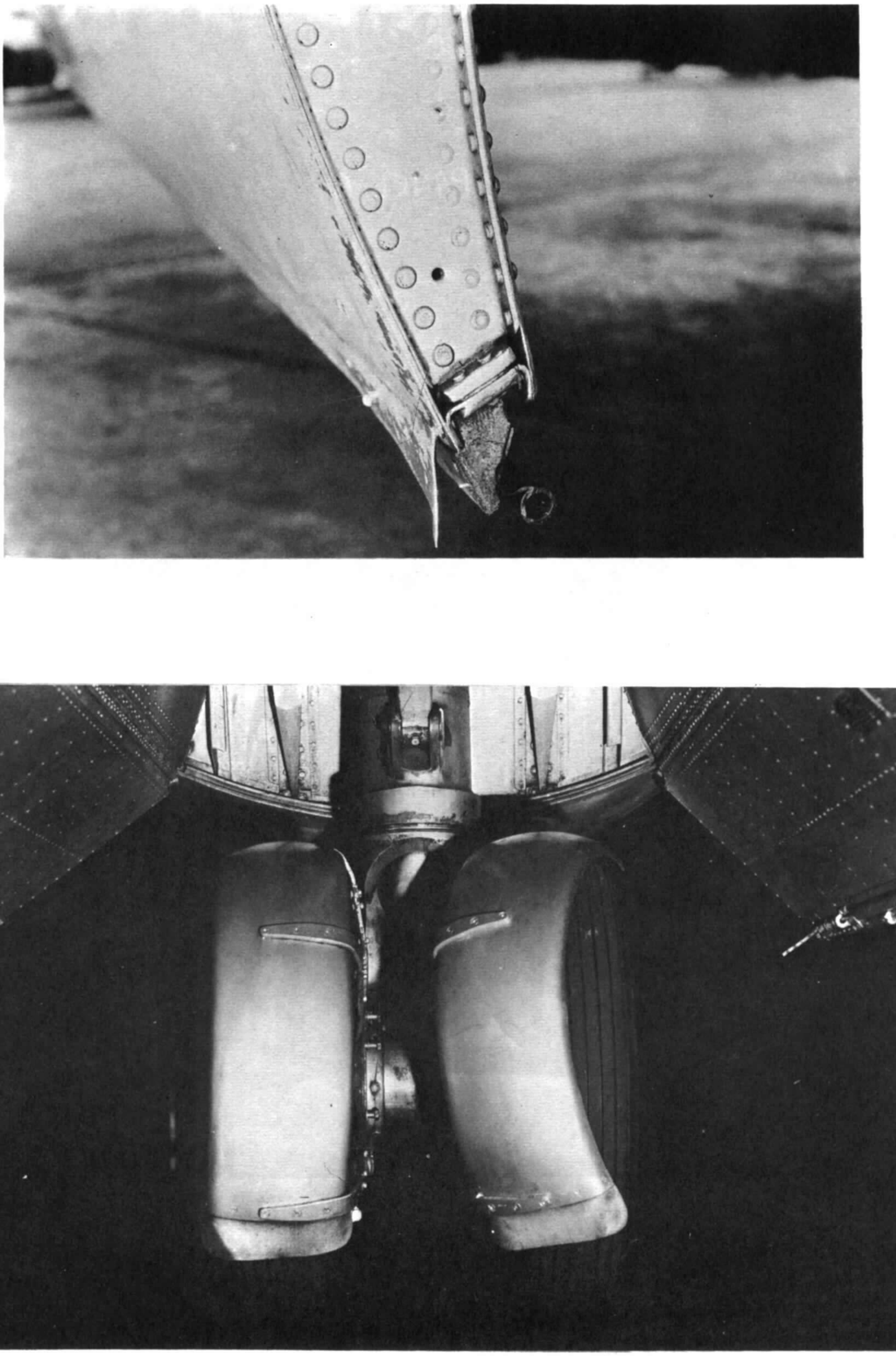

FIG. 8. **Impact damage.**

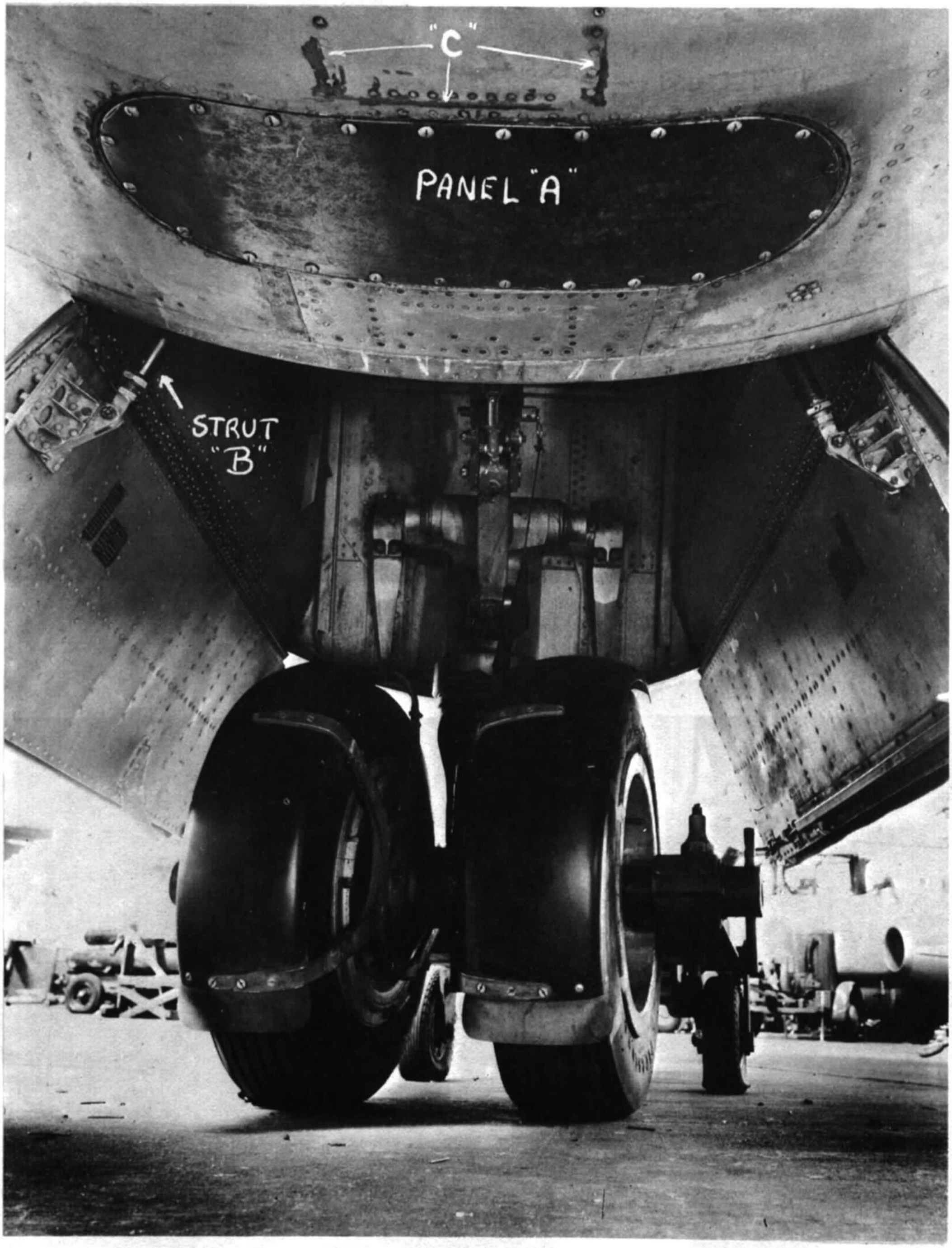

FIG. 9. Metal panel replacement in Canberra.
a. Perspex panel position
b. Steel replacement of light alloy strut
c. Discoloration resulting from distortion of internal members.

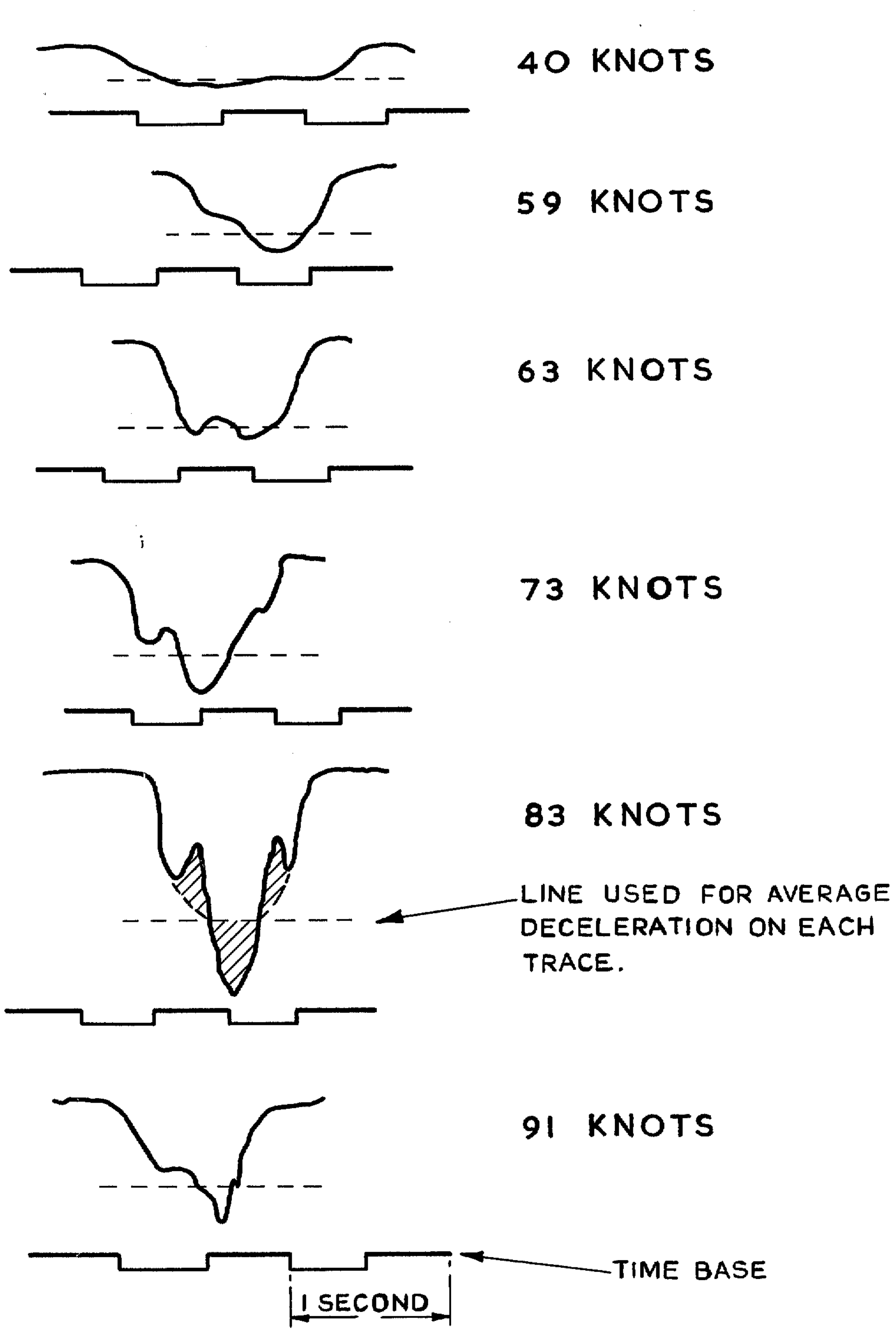

FIG. 10. Deceleration traces of Canberra—1 in. water—all wheels.

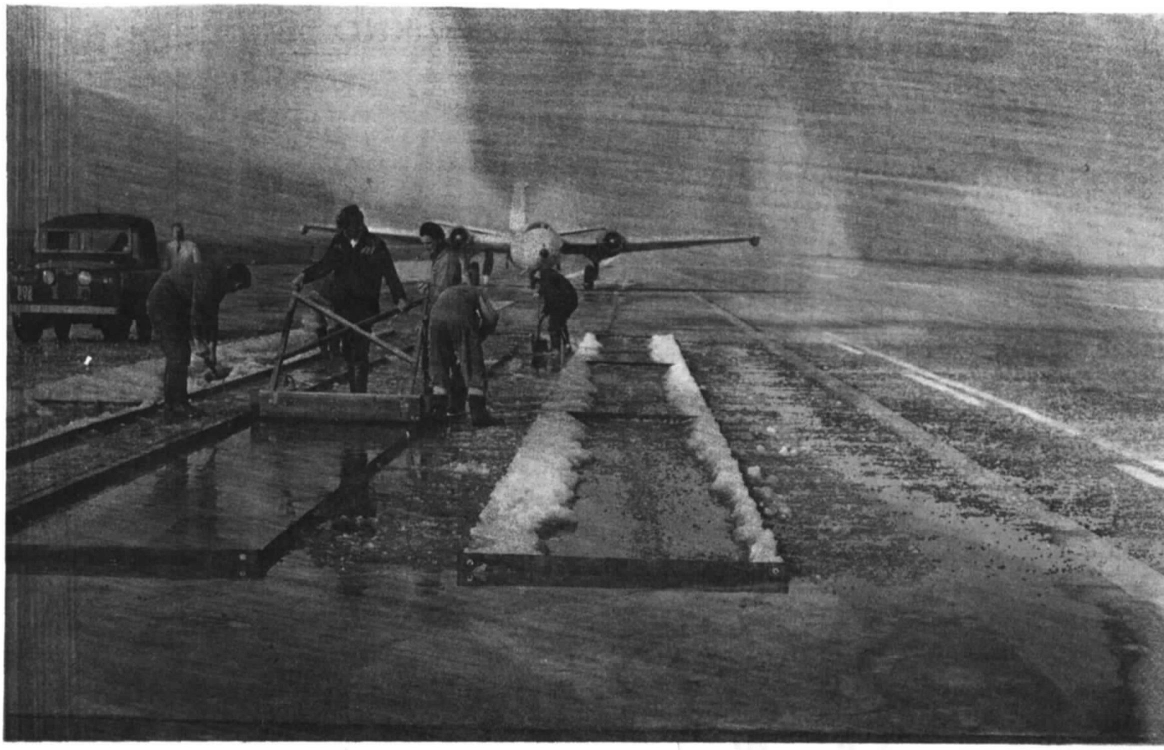

FIG. 11. Canberra wheel track in slush.
One of the squeegees also shown in use.

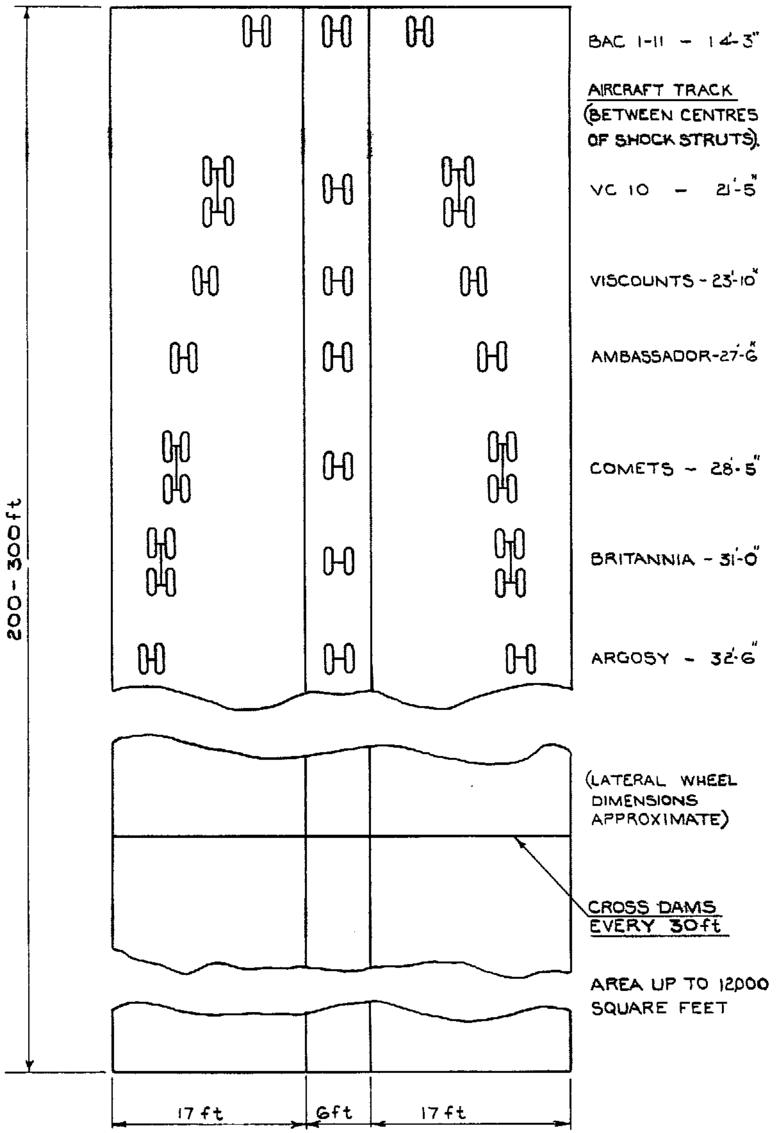

FIG. 12. Possible pond dimensions for wheel arrangements shown.

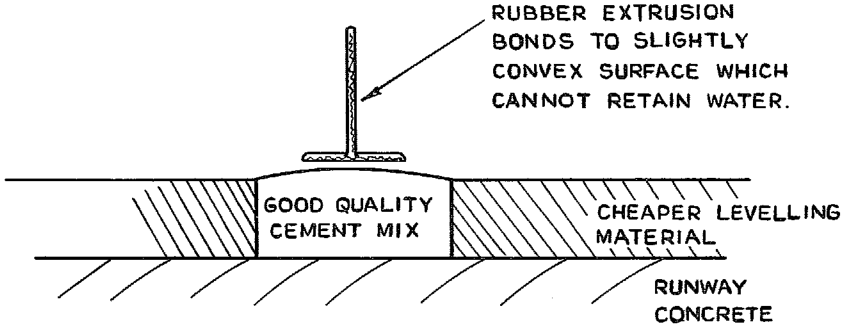

FIG. 13. Section through proposed pond wall foundation.

Part II—Results of Measurements on Three Aircraft

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Summary.

Full-scale tests were made on three aircraft to measure the extra drag arising from the wheels running through a layer of water or slush on the runway. The results were correlated in terms of a slush drag coefficient which remains constant for each aircraft at all speeds up to a speed close to the aquaplaning speed of the tyres. At higher speeds, the coefficient decreased with increasing speed. Further correlations in terms of aircraft weight and tyre pressure were also attempted.

The spray patterns made by the wheels were recorded and the behaviour of the two principal elements in the patterns was examined. The results were compared with some similar measurements on five other aircraft and some rough guides for the prediction of spray paths were deduced.

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1. *Introduction.*

The hazards to aircraft operation presented by slush and standing water on runways are now generally appreciated although it is still difficult to forecast the magnitude of the effects in particular cases. During takeoff, the main effects are the possible damage to airframe and engines due to spray impingement and the large increase in the rolling drag due to the displacement of fluid by the wheels, although the loss of steering control when the wheels are aquaplaning may also be serious. Aquaplaning is the main hazard when braking efficiency is important, that is during the landing run or during the deceleration from an abandoned take-off.

In order to investigate these effects on a number of aircraft a series of tests have been made at the Royal Aircraft Establishment, Bedford using shallow ponds of water constructed on the main runway. The installation is described in detail in Part I. This Report concerns the tests made on three aircraft to measure the drag due to fluid displacement and to investigate the development of spray patterns with the object of identifying the principal factors which need to be considered in the prediction of these characteristics in other aircraft. Some of the results given in this Report for the Ambassador aircraft have been reported[1] previously but they are repeated here for the sake of comparison.

The term 'slush' is normally understood to describe the state of melting snow when there is a high proportion of water present. If one stamps on ground covered with slush, spray is thrown up whereas snow would simply be compressed leaving the imprint of the boot in the surface. Slush is rarely a homogeneous material in natural conditions; the density varies from place to place and the material may contain lumps of ice distributed randomly within it. In order to simplify the argument in this Report an ideal slush is assumed and it is defined as melting snow which has reached a homogeneous fluid state. It is also to be understood that standing water is included in the definition of slush. The consistency of the material is defined simply by its specific gravity which normally lies between about 0·4 and 1, depending on the temperature. Changes in the viscosity may also be important but they are not considered in this Report.

This simplified concept of slush allows some general principles to be made clear but it is a simplification and should not be strained too far in application to operational conditions. In particular, it makes no contribution to the prediction of the trajectory of ice particles nor of the quality which determines how the material might adhere to the external parts of the aircraft.

The drag due to slush arises both from the resistance suffered by the wheel as it displaces the fluid while running along the ground and from the impact of the spray on the aircraft structure. It has already been established[3] that the drag of an isolated wheel running in slush can be expressed as:

$$D_s = C_{D_s} \tfrac{1}{2} \sigma_s \rho V^2 w d$$

where C_{D_s} is the slush drag coefficient, σ_s is the specific gravity of the fluid, ρ is the density of water, V is the ground speed of the wheel, w is the width of the tyre at the fluid surface and d is the depth of the fluid.

The value of C_{D_s} for the wheel has been shown[2] to remain constant at about 0·7 for all speeds up to the point where the wheel begins to aquaplane and then to reduce as the speed increases further. Aquaplaning occurs when the speed is sufficient for the hydrodynamic forces on the tyre to develop a lift equal to the load carried by the tyre so that it is entirely supported by the fluid.

Tests by the FAA and the NASA[3] on a Convair 880 running through beds of artificially produced slush have shown that the same relationship also remains valid for the complete aircraft. In this case, of course, the drag arising from spray impact as well as from interference between individual wheels, is included and the value of the slush drag coefficient is increased. The amount of increase will depend in general on how much of the spray impacts on the aircraft and on the arrangement of the bogies, but the total drag may be as much as two or three times the drag attributable to the sum of the contributions from the individual wheels. This increase in drag is large enough to make it essential to develop methods of estimation for other aircraft or, at least, to develop a simple method of slush drag measurement for any aircraft which is likely to operate in these conditions.

Three aircraft types of widely different configuration were chosen for the tests described here, the Canberra, the Ambassador and the Viscount. The Canberra (Fig. 1) is a mid-wing aircraft with a short, single-wheeled main undercarriage, the Ambassador (Fig. 2) is a high-wing aircraft with a long twin-wheeled main undercarriage and the Viscount (Fig. 3) is a low-wing aircraft also with a twin-wheeled main undercarriage. Details of the wheel arrangements of the three aircraft are given in Fig. 4. These differences in configuration allowed the effects of different amounts of spray impingement on the structure to be investigated. The tests were made between January 1963 and October 1964 at the Royal Aircraft Establishment, Bedford.

A supplementary test was made with an Argosy at Bedford in January 1965 on a runway covered with natural slush with the object of validating the method of test described in this Report.

2. *Experimental Method.*

2.1. *The Test Equipment.*

The details of the water pond installations on the runway are given in Fig. 1, Part I. Two sets of ponds were laid to suit the wheel spacings of the aircraft tested, each consisting of three strips, one for each wheel assembly. The ponds for the Canberra were 90 feet long and were each 3 feet wide, those for the Ambassador and the Viscount were 150 feet long with the outer ponds 12 feet wide and the centre one 6 feet wide.

Further details of the ground installation and the method of producing simulated slush are given in Part I.

A Canberra B2 was used as the main test aircraft both for the development of the test techniques and for the more detailed measurements. A general arrangement of a standard Canberra is given in Fig. 1.

An Ambassador and a Viscount 744 aircraft were used to study the effects of different configurations, particularly the effects of twin-wheeled main undercarriages. General arrangements of these aircraft are given in Figs. 2 and 3.

The Canberra and the Viscount were fitted with normal rib-pattern tyres, the Ambassador was fitted with block pattern tyres for most of its tests.

The equipment installed in the aircraft to measure the extra drag caused by running through the fluid consisted of an R.A.E. sensitive accelerometer and a Mark 2 gyro unit which were arranged to give continuous trace records against a common time base. In each of the test aircraft the accelerometer was installed longitudinally in the fuselage on rigid mountings close to the centre of gravity.

Further details of the instrumentation and the extraction of the results are given in Part I.

2.2. *Method of Test.*

2.2.1. *General.* After the ponds had been filled with water a careful measurement of the mean depth was made. When crushed ice was used to simulate slush, it was levelled to a constant depth in the ponds and was then allowed to melt until the required consistency was reached. Measurements were then made of the mean depth and specific gravity.

For most tests the aircraft was accelerated along the runway so that the desired speed was reached some distance before the aircraft entered the ponds. At this point the power was reduced to a convenient idling level and the aircraft was coasted through the ponds while acceleration and pitch attitude were recorded. The measurements were made at reduced power because this was found to give better control of the speed at which the aircraft entered the ponds, and in order to reduce the risk of damaging the engines and propellers. A few tests have been made at a constant power setting and these have indicated that the loss of slipstream in the main series of tests had little effect on the results.

The fuel state of the aircraft at the time of each run was recorded to establish the all-up weight for the calculation of drag. Further details of the test procedure are given in Part I.

2.2.2. *Canberra.* The tests were made with flaps retracted at all-up weights ranging from 26 500 lb to 33 900 lb although most of the work was done in the range 29 000 to 33 000 lb. The nominal tyre pressures used were 68 psi for the nose wheels and 76 psi for the main wheels. The tests covered a speed range of 40 knots to 110 knots, a water depth range of 1 inch to 2 inches and a slush density range of 0·7 to 1.

Tests were made with all wheels running through water, with the nose wheel running dry while the main wheels only ran through water or slush, and with the main wheels running dry while the nose wheel only ran through water.

During most of the tests the stick was held in a neutral position but in some cases the nose wheels lifted off the ground prematurely. The tests with nose wheel only running through water were repeated with the stick held fully forward in order to increase the load on the nose wheel.

Tyre pressures were set to the nominal figures before each batch of tests which contained between two and six runs through the ponds, but, during the subsequent tests on the Ambassador it was noticed that, due to brake heating, large variations in tyre pressure could occur between runs. Consequently, during the last set of runs with the Canberra which were done with the stick held forward, the tyre pressures were measured before each run.

The widths of the tyres were measured at 2 inches and 1 inch above the ground at the nominal tyre pressures and these figures were used in the calculation of slush drag coefficient at the corresponding nominal water depths.

2.2.3. *Ambassador.* The tests were made with flaps retracted over the following range of conditions:

Nominal weight and nominal tyre pressure	44 000 lb at 75 psi 53 000 lb at 75 and 85 psi
Ground speed	41 to 102 knots
Water depth	0·58 to 1·31 inches.

The actual weight changed from run to run according to the fuel state and the exact values are given in Table 3 with the results.

Measurements during the tests showed that the heating effects from braking caused considerable changes in tyre pressures, increases of 15 to 20 psi being recorded half an hour after stops from 85 or 95 knots at the higher weight. The pressures returned to normal after one and a half hours. It was not practicable to adjust the tyres to the desired pressure or to measure the pressures immediately before each run. The pressures for the first of each series of runs were therefore known reasonably accurately and the pressures for subsequent runs had to be estimated. The values used are given in Table 3.

The widths of the main tyres 1 inch above the ground were measured over the full range of pressures and aircraft weight. These were used throughout as a basis for the calculation of the slush drag coefficient.

Most of the tests were made with all three wheels running through water but some tests were also made with the nose wheel running dry while the main wheels only ran through the water.

Two runs were made through simulated slush made from crushed ice in the way described in Ref. 3. This method of producing slush requires a fairly high ambient temperature to reduce the ice to a reasonably representative form of slush. At the time of test, the temperature was only a few degrees above freezing and the resulting slush contained a large proportion of small lumps of ice. For this reason no further tests with simulated slush were made on this aircraft.

2.2.4. *Viscount.* The tests were made with flaps retracted over the following range of conditions:

Nominal weights	
All wheels	47 000 lb
Main wheels only	44 000 lb, 51 000 lb and 59 000 lb
Nominal tyre pressures	
Nose	90 psi
Main	106 psi
Ground speed	40 to 107 knots
Water depths	1 to 2 inches

The actual weight and tyre pressures varied from run to run according to fuel state and brake heating respectively. In these tests the tyre pressures were measured immediately before each run and the exact values are given in Table 4 with the results.

The widths of the main and nose wheel tyres were measured at 1 inch and 2 inches above the ground at aircraft weights of a nominal 40 000 and 45 000 lb. The widths at greater weights were obtained by extrapolation.

Tests were made with all wheels running through the water and with the nose wheel running dry while only the main wheels ran through the water. No runs were made in simulated slush.

2.2.5. *Supplementary test.* After the method of drag measurement had been established, tests were made on a number of different aircraft types by the manufacturers. In the course of these tests some measurements were made on an H.S. Argosy aircraft and the results[6] were used to calculate the effect of slush on the take-off performance.

Some time later it was found possible to measure the take-off performance of an Argosy in naturally-occurring slush at R.A.E. Bedford. The slush was unusually evenly distributed on the runway and consequently the results can be used as a validation of the test method.

The take-off performance test was made at an all-up weight of 78 000 lb and with a wind of 12 knots. The ambient air temperature was 2·6°C and the slush had a specific gravity of 0·4 and was evenly distributed with its depth varying between 0·6 inch and 0·9 inch. The mean depth was taken to be 0·75 inch. A single take-off was made and it was recorded on kinétheodolites.

3. *Discussion of Results.*

3.1. *Drag Measurements.*

The results of the measurements of drag on the three aircraft are given in Tables 2 to 5 in terms of the drag per inch depth and slush drag coefficient. The drag per inch depth is plotted against the relative slush density, times the square of speed, in Figs. 5 to 10.

The main characteristics can be seen in Fig. 5 which shows the results for the Canberra. Both with all wheels running in the water and with the main wheels only in the water, the drag per inch depth increases linearly with the square of speed up to a maximum which occurs at a speed close to the estimated aquaplaning speed (*see* below). The results for the main wheels only running in slush fall on the same line as the water results when the slush specific gravity is taken into account. After the maximum has been reached, the drag per inch depth falls steadily with speed as indicated by the dashed straight lines. The graphs are drawn as two straight lines meeting at a point only because there is insufficient evidence to show the true shape of the maximum.

There is, of course, considerable scatter of the points about the lines drawn and there are several important reasons for this. In the first place it was found difficult to maintain a constant load on the nose wheel with the result that it was not always in contact with the ground even at speeds below aquaplaning. Fig. 6 shows two sets of measurements with the nose wheel only running through water, in one case with the stick pushed fully forward to hold the nose wheel down and in the other with the stick held in the neutral position. The dashed lines represent the drag of the nose wheel as deduced from the difference between the two curves in Fig. 5. The scatter shown in this graph indicates an important source of the scatter in the measurement of the drag with all wheels in the slush shown in Fig. 5 where the elevator was held in a neutral position.

As mentioned in para. 2.2.2, there was some uncertainty about the actual values of the tyre pressures during the Canberra tests and this will also have contributed to the scatter in the results by making the appropriate tyre width uncertain. Further scatter may also be attributable to the measurement of tyre width at a standard depth of 1 inch instead of at the actual slush depth although, without a full understanding of the flow mechanism, the importance of this factor is debatable.

The effect of weight variation is significant and this is shown clearly in the results for the Ambassador and the Viscount where large weight ranges were investigated (Figs. 7 and 10). As with the Canberra the drag increases linearly with $\sigma_s V^2$ up to a maximum at a speed near the aquaplaning speed and then falls roughly linearly. However the drag is now seen to be strongly dependent on weight and separate lines can be drawn for each weight range, the drag being higher at the higher weights. There is also some evidence that the peak drag occurs at a higher speed when the weight is higher and this has been indicated in the figures somewhat arbitrarily.

The variation of drag with speed, weight and tyre pressure is more easily studied when the results are plotted in terms of the slush drag coefficient, C_{D_s}, since the initial variation with speed and also the change of tyre width with weight and tyre pressure when known are taken into account.

Figs. 11 to 13 show C_{D_s} plotted against ground speed for the three aircraft. The experimental points were derived on the basis of the appropriate tyre widths while the curves were derived from those of Figs. 5 to 10 using mean values for tyre width. The features discussed above are clearly shown including the sharp change in C_{D_s} in the neighbourhood of the aquaplaning speed and the variation with weight.

Since the drag results show a distinct change of character in the neighbourhood of the aquaplaning speed, some discussion of this phenomenon is necessary. It was observed in the tests on the drag of an isolated wheel running in water reported in Ref. 2 that, when a certain speed was reached, the wheel lost contact with the ground and tended to stop turning. This was accompanied by the reduction in slush drag coefficient mentioned above and the suppression of the bow wave. The mechanism of this effect is not yet fully understood and it is the subject of many investigations because of its importance in vehicle braking.

In Ref. 4, Horne suggests that the aquaplaning occurs when the velocity of the tyre relative to the water is sufficient to develop a hydrodynamic force on the tyre whose vertical component will lift the tyre clear of the runway. This force is assumed to be proportional to the tyre—ground contact area, the fluid density and the square of the ground speed. Thus the tyre will begin to aquaplane when

$$W = \tfrac{1}{2} C_{L_s} \rho_s S_G V_A^2$$

where W is the aircraft weight C_{L_s} is the hydrodynamic lift coefficient, ρ_s is the fluid density, S_G the tyre contact area and V_A is the aquaplaning speed, thus,

$$V_A = \sqrt{\frac{2W}{\rho_s C_{L_s} S_G}}.$$

If it is assumed that the tyre pressure, P, is the same as the tyre—ground contact pressure, W/S_G, then

$$V_A = \sqrt{\frac{2P}{\rho_s C_{L_s}}}.$$

Horne assumes, $C_{L_s} = 0{\cdot}7$, and derives the well known approximate formula for the aquaplaning speed in water: $V_A = 9\sqrt{P}$ knots where P is in pounds per square inch. This formula is substantiated in Ref. 4 by results obtained on a number of vehicles with tyre pressure ranging from 25 psi to 150 psi.

There are many objections to this simple concept, for instance it neglects the viscous effects when the gap between the tyre and the ground is small and it implies that the shape of the tyre in contact with the water is always related to the ground contact area irrespective of depth and weight. However it has proved in practice to give a useful, and often accurate guide to the aquaplaning speed and cannot therefore be lightly dismissed.

Considering now the influence of aquaplaning on drag, it should be noted that the derivation of Horne's formula does not include a justification for an assumption that the speed for maximum drag coincides with the aquaplaning speed. For an isolated wheel however the experimental evidence suggests that this assumption is fair, but for a complete aircraft, where some of the drag originates in the impact of spray on the structure, the speed for maximum drag must depend on the changes in spray pattern in relation to the structure (Section 3.2).

Once the speed has risen above the aquaplaning speed and the tyre is entirely supported in relatively deep water, it is not unreasonable to suppose that the drag forces on the wheel are mainly associated with the production of lift. Thus there could be a simple relationship between weight supported on the wheels and drag despite Horne's prediction that the onset of aquaplaning itself is independent of weight.

With this supposition in mind, the slush drag coefficients measured in these experiments have been reduced by the ratio of an arbitrarily chosen weight to the weight supported on the wheels, as shown in Figs. 14, 15 and 16 for the three aircraft. The proportion of the total weight supported on the wheels was calculated using assumed lift coefficients for the wings with due allowance for ground effect. With the Ambassador and the Viscount there is a tendency for the measurements to collapse onto single curves at the higher speeds which supports this approach to some extent.

The speeds for maximum drag, as indicated by the discontinuity in the C_{D_s} curves, also show a tendency to collapse to a single speed with the same weight correction. This suggests that either Horne's approximate formula may be incorrect or that the drag maximum is less closely correlated with loss of ground contact than had been thought. In fact the results showing the effects of tyre pressure discussed below tend to support the latter view.

The results for the Canberra in Fig. 14 are consistent with those for the Ambassador and the Viscount although the weight range tested was too small to give positive confirmation of the effects of weight.

The effect of water depth in the slush drag coefficient is illustrated in Fig. 14 for the Canberra and Fig. 16b for the Viscount using the weight correction outlined above. The differences in C_{D_s} between depths of 1 inch and 2 inches are small, although the smaller depth seems to be associated with higher values of C_{D_s} in the Canberra. Plots of the uncorrected C_{D_s} show the same trend but are not reproduced here.

Finally, the effect of tyre pressure on the speed at which the drag maximum occurs is shown for the Ambassador and the Viscount in Fig. 17. The drag coefficients are plotted against the ratio of ground speed in knots to the square root of tyre pressure in pounds per square inch. Here we are concerned only with the behaviour in the neighbourhood of the drag discontinuity and it is not suggested that this form of plot necessarily has much relevance elsewhere. In fact the lines as drawn are intended to indicate trends only and should not be taken too literally. The results for the Canberra are not plotted in this way because the exact tyre pressures are not known, however the speed corresponding to Horne's estimated aquaplaning speed has been included in Fig. 5.

With the Ambassador (Fig. 17) there is reasonable indication that the drag maximum occurs at a value of $V/\sqrt{P}$ between 8 and 9. Similarly with the Canberra the drag maximum in Fig. 5 occurs at $V/\sqrt{P} \doteqdot 9$. With the Viscount, however, the maximum clearly occurs much earlier, around $V/\sqrt{P} = 7$, although the exact value would be difficult to determine.

The reason for the early maximum on the Viscount is obscure but it may be due to a reduction in the drag due to spray impact associated with the changes in spray patterns with speed. The consideration of the relationship between the drag maximum and the onset of aquaplaning may help to explain the differences. Horne's experiments showed that the drag maximum and the onset of aquaplaning with an isolated wheel both occur when $V/\sqrt{P}$ is about 9 and the slush drag coefficient at lower speeds is between 0·7 and 0·75. When the wheel is in the neighbourhood of the aircraft structure extra drag arises from the impact of the spray thrown up from the wheel but, since the spray patterns change with speed (Section 3.2), the total drag will vary. The spray trajectory becomes very flat once the wheel is aquaplaning and therefore one would expect the impact drag to be small in this condition so that the total drag would approximate to the drag of the isolated wheels. Therefore it can be argued that, at the onset of aquaplaning the values of C_{D_s} will be about 0·7.

The following Table shows the speed at which $C_{D_s} = 0{\cdot}7$ in terms of the tyre pressure for the three aircraft.

Aircraft	$V/\sqrt{P}$ for $C_{D_s} = 0{\cdot}7$
Canberra	9·6
Ambassador	8·9
Viscount	8·2

Although the Viscount has a lower value than the others it gives some support to the suggestion that the wheels do not begin to aquaplane much before the predicted speed despite there being an earlier drag maximum. Unfortunately it was not possible to identify the onset of aquaplaning directly in these experiments because the 'spin down' of the wheels normally associated with aquaplaning was never recorded. This may have been due either to the short time spent in the ponds or to the disturbing effect of the cross-dams.

The discussion above refers specifically to aquaplaning in water although the general principles will also apply to aquaplaning in slush at a lower specific gravity. In this more general case Horne's formula for the aquaplaning speed becomes

$$V_A = 9\sqrt{\frac{P}{\sigma_s}}$$

where σ_s is the fluid Sp.Gr. Unfortunately there is very little experimental evidence which can be used to support this since the tests in slush on the Canberra and Ambassador were made at speeds too low to show the effect. Ref. 4 gives data obtained from the tests in slush on a Convair 880 and shows that the drag maximum occurs near $V = 9\sqrt{P}$. The same data are plotted in Fig. 18 which indicates the increase in the predicted aquaplaning speed when account is taken of the slush specific gravity. It will be seen that the drag maximum occurs a little before this speed is reached $\left(\text{about } V = 8{\cdot}7\sqrt{\frac{P}{\sigma_s}}\right)$ which compares well with the results from water on the other aircraft described above. This result is consistent with the form of the plots in Figs. 5 and 7 where the slush drag per inch depth is shown to be dependent on $\sigma_s V^2$ and supports the prediction made in Ref. 1 that the maximum drag per unit depth of slush for a given configuration is independent of the slush density and that the maximum drag per unit weight of precipitation (i.e. drag per unit depth of water equivalent) increases in inverse proportion to the slush specific gravity. These results have considerable importance in the prediction of an aeroplane's performance on a runway where the rate of melting is uneven.

The results of the measured take-off test on the Argosy are given in Fig. 19 in terms of the acceleration achieved at several speeds. The estimated accelerations derived from the slush drag measured by the pond technique[6] are plotted as a full line on the same figure and show excellent agreement with the measurements. This comparison shows that the drag coefficients measured in water can be applied successfully even when the slush is of quite low density.

The slush drag measured in these tests is summarised in Table 5 which also includes some earlier measurements on an isolated wheel[2] and on a Convair 880[3]. The most striking feature of Table 5 is high drag coefficient ($C_{D_s} = 2{\cdot}6$) for the nose wheels of the Convair 880 and this is presumed to be caused by the very large amount of spray impingement observed on this aircraft. There are no obvious reasons for the differences between the values found for the three test aircraft except that the single main wheels of the Canberra may have an intrinsically lower drag than the twin wheels of the Ambassador and the Viscount due to interference effects. The small difference between the values of C_{D_s} for the Ambassador and Viscount may be due to less spray impingement on the former due to its longer undercarriage legs. The nose wheel values which, except for the Canberra, were found by difference, have been shown to be dependent on the load imposed by the elevator and a large scatter is to be expected.

3.2. *Water Spray Patterns.*

3.2.1. *The nature of the patterns.* The spray pattern produced by a single wheel travelling through a layer of water is discussed in some detail in Ref. 5. It consists of several elements the chief of which are referred to here as the bow wave and the main plume (Fig. 20).

The bow wave is seen only at speeds below the aquaplaning speed and it appears as an unsteady mass of spray immediately in front of the wheel. This mass of spray is continuously fed from water projected forwards and upwards from the front of the ground contact area of the wheel. The forward motion of the water is arrested by the relative wind so that the wheel advances through it, deflecting the spray to each side. Characteristically, the height of the bow wave first increases with increasing speed and then decreases at higher speeds until it becomes entirely suppressed when the aquaplaning speed has been reached. This behaviour is believed to be associated with the distortion of the shape of the tyre in the following manner. The motion of the water relative to the centreline of the advancing wheel is shown in Fig. 21. The water is brought to rest at the stagnation point A which represents the division between the flow which is deflected upwards and forwards and the flow which is deflected sideways around the wheel. The region between A and B (the front of the ground contact area) is subjected to a pressure approaching the dynamic pressure of the advancing water. At lower speeds (Fig. 21a) this pressure will have little effect on the profile of the tyre so that the angle of deflection of the water remains constant with increasing speed although, of course, the vertical component of velocity and therefore the maximum height reached by the spray will increase. When a speed is reached which is large enough for the dynamic pressure to bend the surface of the tyre inwards in the region AB, the angle of deflection of the water will be decreased (Fig. 21b). A speed will be reached when the vertical component of velocity will actually be reduced because the reduction in the angle α overcomes the effect of the increased total velocity. Thereafter increasing speed will produce a flatter trajectory. As indicated in Section 3.1, the tyre will aquaplane at a speed somewhat higher than that at which the water dynamic pressure becomes equal to the tyre pressure. Thus it is to be expected that large deflections in the region AB will occur before aquaplaning and that considerable reductions in the bow wave are possible. In fact, it has been observed that, by the time the aquaplaning speed has been reached, virtually all the water is deflected round the tyre (Fig. 21c). There is no evidence that the onset of aquaplaning can be identified exactly with the suppression of the bow wave although the foregoing argument suggests that a large change in the spray pattern may be expected at such a speed and experience shows that this is a useful approximation.

It will be noted that the form of the bow wave is essentially affected by the drag due to the relative wind and that quite different spray patterns are produced when a stationary wheel is run through water on a moving belt without the airspeed of the wheel being represented as in the tests reported in Ref. 5.

The main plumes are formed from spray projected upwards and outwards from the sides of the ground contact area and account for most of the displaced water. In side elevation the main plume appears to a stationary observer as a wedge shaped curtain of spray which rises to a considerable height (Figs. 22 to 24). In front elevation the main plumes are mainly confined to quite narrow bands rising at an angle of about 45°.

The source of the main plumes is believed to be the displacement of that part of the water in the path of the wheel which lies beneath the stagnation line (i.e. below the point A in Fig. 21). This water is displaced sideways by the approaching wheel and then upwards by the action of the relatively undisturbed water to the side of the wheel. A tentative theoretical treatment of this mechanism is given in Ref. 6 but the actual trajectory is difficult to predict because the basic ballistic parabola will be modified considerably by the air drag on the droplets.

With multiple wheel arrangements there are interactions between the sprays from the component wheels which modify the basic pattern. For instance, the intense jet of spray which rises between a pair of wheels or from the middle of a double tandom bogie is formed in this way. However the spray plumes formed at the outer edges of the outer tyres are not greatly affected.

Examples of the change of flow pattern with speed for the three aircraft are given in Figs. 21 to 24. It is clear from these that it is often difficult to identify the various elements of the patterns because so much of the detail is hidden, particularly at the lower speeds. The observations made in the following Sections are based on the examination of many thousands of photographs taken from the front, the side and from a helicopter above. Nevertheless it was not possible to devise a method of making accurate measurements and a large amount of scatter was unavoidable.

3.2.2. *Measurement of spray patterns.*

(a) *The bow wave.*

Examination of many photographic records of the behaviour of the bow wave on the three test aircraft showed the mass of spray which builds up in front of the wheel fluctuates greatly in height and no consistent measurements were possible. The general impression was, however, that the height first increased with speed and then decreased as aquaplaning approaches, confirming the description given in the previous Section. The maximum height to which the spray was observed to rise in front of the wheel was about $2\frac{1}{2}$ times the wheel diameter. Greater heights might have been reached in some cases had not the presence of the structure limited development.

In front elevation, the plumes from the bow wave after deflection to the sides of the wheel could sometimes be identified below the main plumes. Measurements of the angle of elevation of the bow wave plumes are shown in Fig. 25 together with those for the main plume. With each of the three test aircraft there was a tendency for this angle to decrease as the speed increased from 40 or 50 knots towards the aquaplaning speed.

(b) *The main plumes.*

Examination of cine films taken from a helicopter directly over the ponds with the three test aircraft showed that, at all speeds, most of the water was thrown sideways with practically no longitudinal motion relative to the ground except when there was a strong longitudinal wind component. Consideration of the wedge shaped curtain of spray seen in side elevation can therefore be concentrated on the vertical component of the spray velocity.

The maximum height which the spray reaches may be expected to be proportional to the kinetic energy associated with the vertical component of the velocity of projection, at least in the absence of air drag. The effect of air drag on the trajectory cannot be estimated because of the unknown variations in droplet size. The velocity of projection is likely to be proportional to the ground speed so in Figs. 26a, 27a and 28a the maximum height reached by the spray is plotted in terms of the square of the ground speed, the height having been estimated from the high speed cine records of the front elevation. Because of the large scatter found in the results, no distinction is drawn between the values for different depths of water.

There is some support for the suggestion that the maximum height should be proportional to the square of ground speed at the lower speeds particularly with the Canberra (Fig. 26a). The main feature is, however, the great height reached by the spray, over 30 feet in some cases.

The side elevation of the spray pattern appears as a triangular wedge in the neighbourhood of the wheels and the parabolic form is only noticeable at some distance behind. It was therefore possible to measure the angle of elevation of the wedge in many cases, neglecting the curvature. These angles are plotted for the three aircraft in Figs. 26b, 27b and 28b. Despite the large scatter it can be clearly seen that the angle is sensibly independent of speed and that it is of the order of 19° to 20° for all three aircraft.

Some measurements were also made from photographs of spray patterns obtained from unpublished results of tests on a number of other aircraft (Fig. 29). These showed that, over a large range of wheel arrangements, the wedge angle lies close to 20° and is independent of speed. This result of course, would be modified by the use of tyres specifically designed to alter the spray patterns, for instance tyres fitted with chines, but it appears to have some generality for conventional tyre and undercarriage arrangements.

In front elevation, plumes from both the bow wave and the main plume can often be identified (Section 3.2.2(a)). Measurements of the angle of the main plumes are shown in Fig. 26 and again show that they were constant with speed within the accuracy of measurement and had mean values between 40° and 50° for the three test aircraft. Similar measurements made on the other aircraft mentioned above confirmed this conclusion and it is suggested that a mean angle of 45° could be used for estimating purposes.

The plume angle was found to be sensitive to cross-winds, displacements of about 10° in front elevation having been measured in a cross-wing component of 15 knots.

Using the measured values of maximum height reached, the suggested mean spray angles in front and side elevation, and neglecting the effect of air drag on the trajectory, it is possible to calculate that the speed of projection for some of the spray is not less than half of the forward speed. In practice, however, the effects of the air drag are likely to be large and it is suggested that the speed of projection of some of the spray is probably as large as the ground speed of the wheel.

No reliable observations could be made in these tests of the behaviour of the spray pattern formed between the pairs of wheels. It is thought, however, that the spray from this source could be critical in some cases.

4. *Conclusions.*

The method described in which aircraft were run through small water ponds constructed on the runway, allows the slush drag to be measured with reasonable accuracy. For operational purposes there is little justification for trying to improve the accuracy of measurement because of the low level of accuracy expected from assessments of the runway conditions. Greater accuracy would be valuable for research purposes, however, since there are a number of effects which are still not satisfactorily explained. The measurements of drag on each of the three aircraft gave generally consistent results and there was little to suggest that differences in configuration had much effect on the total drag coefficient. There are, however, few indications that an accurate method of predicting slush drag coefficients of new aircraft will be found; the best that can be suggested as a result of this work is that $C_{D_s} = 1{\cdot}0$ can be used as a first approximation at speeds below the aquaplaning speed unless there is reason to believe that there will be an unusually large amount of spray impingement. The drag coefficient starts to fall below this value at speeds a little below the aquaplaning speed given by Horne's formula ($V = 9\sqrt{P}$). The actual speed at which this reduction occurs appears to depend to some extent on the amount of spray impact drag and the weight supported on the wheels. In fact the drag coefficient appears to scale linearly with the load on the wheels at these speeds.

Comparison of the actual performance of an Argosy taking off in slush with the estimated performance calculated from results obtained from tests in small ponds gives a useful validation of the method.

The results of the measurement of spray patterns showed consistent trends for all three aircraft despite a large degree of scatter. These trends have been confirmed by some measurements on a number of other types of aircraft and a rough guide to the prediction of spray paths has been deduced.

The bow wave may rise at least $2\frac{1}{2}$ times the wheel diameter in front of the wheel at low speeds. In front elevation it passes on each side of the wheel and rises at an angle of about 30° at low speeds decreasing to about 15° or less at high speeds. The bulk of the water is contained in the main plume which may rise to a height of 30 feet behind the aircraft. In front elevation it rises on each side of the wheel at an angle between 40° and 50° while in side elevation it rises at an angle of about 20° to the horizontal.

It must be emphasised that these numbers are offered only as a rough guide and that they are subject to significant modification in cross-winds and other special conditions, particularly from multi-wheel units. Drag and spray measurements should always be made when the performance in slush or water is likely to be critical.

Acknowledgements.

The authors wish to acknowledge the assistance given by the Empire Test Pilots School, Messrs. Danair, and Mr. J. K. B. Illingworth, as well as by many other individuals and organisations.

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TABLE 1

Tyre Dimensions for Test Aircraft.

	Canberra		Ambassador		Viscount	
	Nose	Main	Nose	Main	Nose	Main
Diameter	26	43	26·6	37	24	36
*Nominal width	6·5	13·5	7·75	11·75	7·25	10·7
Distance between centre lines (twin)	15	—	14	23	13·625	18·5
Nominal pressure lb/in^2	68	76	73	85	90	106

Dimensions in inches.

*Tyre widths are increased by ground contact by varying amounts according to all up weight and pressure.

TABLE 2

Results of Drag Measurements on Canberra.

Weight lb	Tyre pressure lb/in²	Ground speed knots	Water drag lb/inch depth	Slush drag coefficient
		All wheels in water		
32 709		40·0	1375	1·03
35 509		41·5	1105	0·746
32 309		55·5	2300	0·864
33 029		55·8	2570	1·00
33 429		57·0	2325	0·826
27 509	Nominal	57·13	2408	0·85
31 909	values:	59·6	2870	0·983
26 749	68 psi nose	60·1	2860	0·96
29 189	72 psi main	60·3	2534	0·805
28 389		63·4	3660	1·1
29 749		66·5	3060	0·804
32 789		69·28	4360	1·1
33 589		69·56	3995	0·95
28 869		69·9	3600	0·896
31 269		77·73	4078	0·815
32 069		79·43	4008	0·735
26 269		82·3	3508	0·623
31 989		82·49	4320	0·825
25 309		83·1	3600	0·625
33 349		88·98	3709	0·55
31 989		91·27	3070	0·426
31 669		92·01	3100	0·444
		Main wheels in water		
32 549		42·1	1010	0·975
33 269	Nominal	42·7	1098	0·997
31 749	value:	56·3	1840	0·96
31 349	72 psi	59·73	2110	1·03
29 989		65·91	2266	0·863
29 109		72·26	2590	0·855
27 429		73·8	2390	0·725
27 957		73·9	2445	0·742
29 429		74·9	2560	0·759
28 389		75·47	2780	0·834
26 629		76·15	2663	0·79
26 669		75·47	2507	0·727
31 429		76·49	2955	0·87
32 149		77·3	2860	0·791
32 309		80·38	3005	0·800
32·869		86·71	2270	0·49
33 509		87·6	2270	0·491
33 109		89·25	2515	0·545

TABLE 2—*continued*

Weight lb	Tyre pressure lb/in^2	Ground speed knots	Water drag lb/inch depth	Slush drag coefficient
	Nose wheels in water (stick central)			
30 869	Nominal	38·5	436	1·15
30 629	value:	41·4	645	1·57
28 549	60 psi	55·3	915	1·14
27 949		57·6	1188	1·48
26 549		60·0	1088	1·26
26 949		62·4	1000	0·995
29 389		67·6	1520	1·39
29 429		71·0	1247	0·960
29 989		78·8	1414	0·885
29 909		79·6	2100	1·38
29 589		82·18	2191	1·36
31 109		82·6	1327	0·76
33 509		87·6	980	0·495
33 109		89·1	2027	1·09
		Stick fully forward		
33 405		38·26	501	1·32
32 925		41·62	724	1·74
33 101	66	47·36	860	1·6
33 701	70	54·1	876	1·16
33 941	60/66	61·23	1525	1·58
31 941	66	64·38	2268	2·13
33 501	54/62	64·38	1509	1·52
33 071	54/62	67·26	2563	2·20
33 645	70	71·78	2255	1·69
29 909		72·47	2015	1·49
33 209		74·73	2300	1·71
33 085	70	76·78	2647	1·88
33 965	64/58	79·09	2123	1·31
32 069		81·49	2630	1·65
33 405	63	81·5	2381	1·49
31 269		86·56	2970	1·54
32 645	66	88·14	2460	1·23
30 629		89·88	2250	1·16
32 125	70	94·98	2660	1·23
31 045	68	99·71	2235	0·94
31 565	69	108·18	2175	0·72

TABLE 2—*continued*

Canberra.

Weight lb	Slush Specific gravity	Ground speed knots	Drag per inch lb	Slush drag coefficient
		Main wheels in slush		
33 270	0·77	44·44	864	0·937
32 470	0·725*	61·17	1488	0·905*
31 030	0·77	61·22	1471	0·853
33 030	0·585*	61·97	1023	0·73*
32 470	0·71	68·96	1948	0·982
33 270	0·84	70·53	1907	0·736
30 870	0·84	72·76	2116	0·797
29 670	0·71	74·47	2136	0·940
32 470	0·90	75·34	2207	0·743
30 710	0·81	75·86	2460	0·920
31 510	0·88	79·93	2030	0·605

*These points have been adjusted to take account of an error believed to have been made in the measurement of specific gravity. They should therefore be regarded as less reliable than the remainder.

TABLE 3

Results of Drag Measurements on Ambassador.

All wheels in water

Weight lb	Estimated tyre pressure lb/in^2	Ground speed knots	Water depth inches	Water drag lb/inch depth	Slush drag coefficient C_{D_s}
44 240	75	41·0	1·25	2230	1·00
46 000*	75	51·8	1·0	3520	0·99
44 520	90	54·5	0·65	3630	0·931
45 260	75	57·4	1·03	3913	0·896
45 700*	75	60·0	1·06	4480	0·937
44 150	75	60·6	1·26	4450	0·922
45 770*	85	63·7	0·85	5080	0·96
44 740	75	64·0	1·05	5150	0·956
44 070	85	64·8	1·00	4940	0·887
45 100	75	65·8	1·08	4800	0·841
45 160	85	71·3	0·8	5650	0·836
43 910	90	72·0	0·83	5770	0·851
44 460	75	75·5	1·00	5950	0·822
44 950	75	77·1	1·03	5330	0·677
45 010	85	81·7	0·8	4460	0·506
43 570	75	82·3	1·27	5220	0·585
44 620	85	87·1	0·82	4950	0·494
44 360	85	89·0	0·75	4200	0·398
44 170	85	91·0	1·03	4680	0·427
44 830	85	92·1	0·8	4650	0·416
43 320	85	101·0	0·84	3710	0·276
54 650	85	50·5	1·27	3660	1·03
53 310	90	56·0	1·27	4460	1·057
54 540	95	64·3	0·97	5680	0·99
53 250	95	66·9	0·88	6230	1·033
51 960	85	69·3	0·96	6500	0·975
53 380	105	71·1	0·87	6260	0·948
54 400	100	75·0	0·73	7450	0·99
53 860	75	78·5	1·28	6820	0·804
54 080	85	81·9	1·25	7050	0·84
53 130	95	89·5	0·58	5780	0·533
53 920	95	95·1	0·80	5820	0·46
53 520	85	102·0	1·25	4190	0·296

TABLE 3—*continued*

All wheels in simulated slush.

Weight lb	Estimated tyre pressure lb/in^2	Ground speed knots	Slush depth inches	Slush specific gravity	Slush drag lb/inch depth	Slush drag coefficient C_{D_s}
55 200	85	53	0·875	0·62	3900	1·00
55 100	95	62	1·0	0·79	4700	0·88

Main wheels only in water

Weight lb	Estimated tyre pressure lb/in^2	Ground speed knots	Water depth inches	Water drag lb/inch depth	Slush drag coefficient C_{D_s}
52 946	100	53·6	0·99	2990	1·025
53 760	95	60·47	0·97	5100	1·35
52 856	90	61·5	0·80	3300	0·826
53 840	85	65·44	1·31	5100	1·13
52 360	105	68·4	0·78	5030	1·06
52 426	100	74·4	1·0	5300	0·965
53 700	95	79·4	0·74	6090	0·93
52 506	85	80·5	1·28	4690	0·695
53 046	85	87·0	1·3	4160	0·523

Note:—The slush drag coefficients are based on the measured widths of the tyres 1 inch above the ground. The width of each main wheel tyre varied from 1·06 feet to 1·14 feet according to weight and pressure. The nose wheel tyres were each 0·645 feet wide.

*Rib tread tyres. All other results with block tread tyres.

TABLE 4

Results of Drag Measurements on Viscount.

Main wheels in water

Weight lb	Tyre pressure lb/in^2	Water depth inches	Ground speed knots	Water drag lb/inch depth	Slush drag coefficient
Nominal weight = 44000 lb					
43 285	132	1·53	40·08	1500	1·06
43 685	106	2·0	41·58	1355	0·874
44 005	127	1·56	52·62	2485	1·02
44 635	106	2·0	52·98	2745	1·075
42 615	106	2·0	61·88	3645	1·055
44 245	118	2·03	71·07	4290	0·94
43 645	120	1·53	77·57	4745	0·90
43 345	120	1·17	89·33	4760	0·703
43 145	122	1·0	99·19	4140	0·494
Nominal weight = 51000 lb					
51 245	135	1·28	48·41	2835	1·395
51 945	120	2·0	51·21	2825	1·185
51 545	128	1·55	53·34	2930	1·175
50 945	123	2·03	60·07	3960	1·21
50 745	128	1·55	79·78	5460	0·972
50 545	120	1·23	80·9	5740	1·03
50 145	111	2·08	94·04	5330	0·665
49 695	135	1·45	96·72	5120	0·628
49 145	125	1·05	100·03	4960	0·581
48 845	115	1·95	100·5	4710	0·516
Nominal weight = 54000 lb					
56 685	116	2·0	45·72	2180	1·13
56 285	120	1·59	63·86	4460	1·24
59 445	130	1·49	74·34	5930	1·19
58 745	135	1·04	76·18	6440	1·27
60 455	117	1·95	80·9	6780	1·13
57 245	130	1·55	82·83	6420	1·045
57 445	120	2·07	88·92	7160	0·985
58 765	135	1·22	92·48	7180	0·954
58 565	140	1·15	106·96	5390	0·544
58 865	140	1·5	107·38	5460	0·525

TABLE 4—*continued*

Weight lb	Tyre pressure lb/in^2 main/nose	Water depth inches	Ground speed knots	Water drag lb/inch depth	Slush drag coefficient
47 575	116/90	1·55	33·77	1630	0·975
42 815	120/90	0·59	47·93	3690	1·43
47 125	119/88	1·36	49·50	2875	1·01
50 575	120/90	1·5	52·04	3380	1·08
50 275	120/90	1·2	53·39	3680	1·135
48 975	112/85	1·5	53·39	3540	1·07
48 475	116/88	1·26	58·24	4570	1·19
47 065	120/90	1·0	60·83	4600	1·07
46 875	120/90	1·1	63·5	4430	1·09
46 475	120/90	1·02	72·34	6240	1·04
47 975	120/90	1·1	87·47	6130	0·71
45 775	120/90	1·21	109·2	4575	0·337

TABLE 5

Summary of Measured Slush Drag Coefficients Measured at Speeds Below the Aquaplaning Speeds.

Aircraft	C_{D_s}			Weight range, lb	Reference
	Main	Nose	Total		
Isolated wheel	—	—	0·7–0·75	—	Ref. 2
Convair 880	1·3	2·6	1·6	150 000 average	Ref. 3
Canberra B2	0·84	1·1–1·6*	0·88	26 500–33 900	Fig. 11
Ambassador	0·94	1·5	0·93–1·03†	44 000–53 000	Figs. 7 & 8
Viscount	1·05–1·28†	1·13	1·09	44 000–59 000	Fig. 13
Argosy	0·94	1·5	1·09	78 000	Ref. 6

*Depending on load on nose wheel.

†Depending on weight.

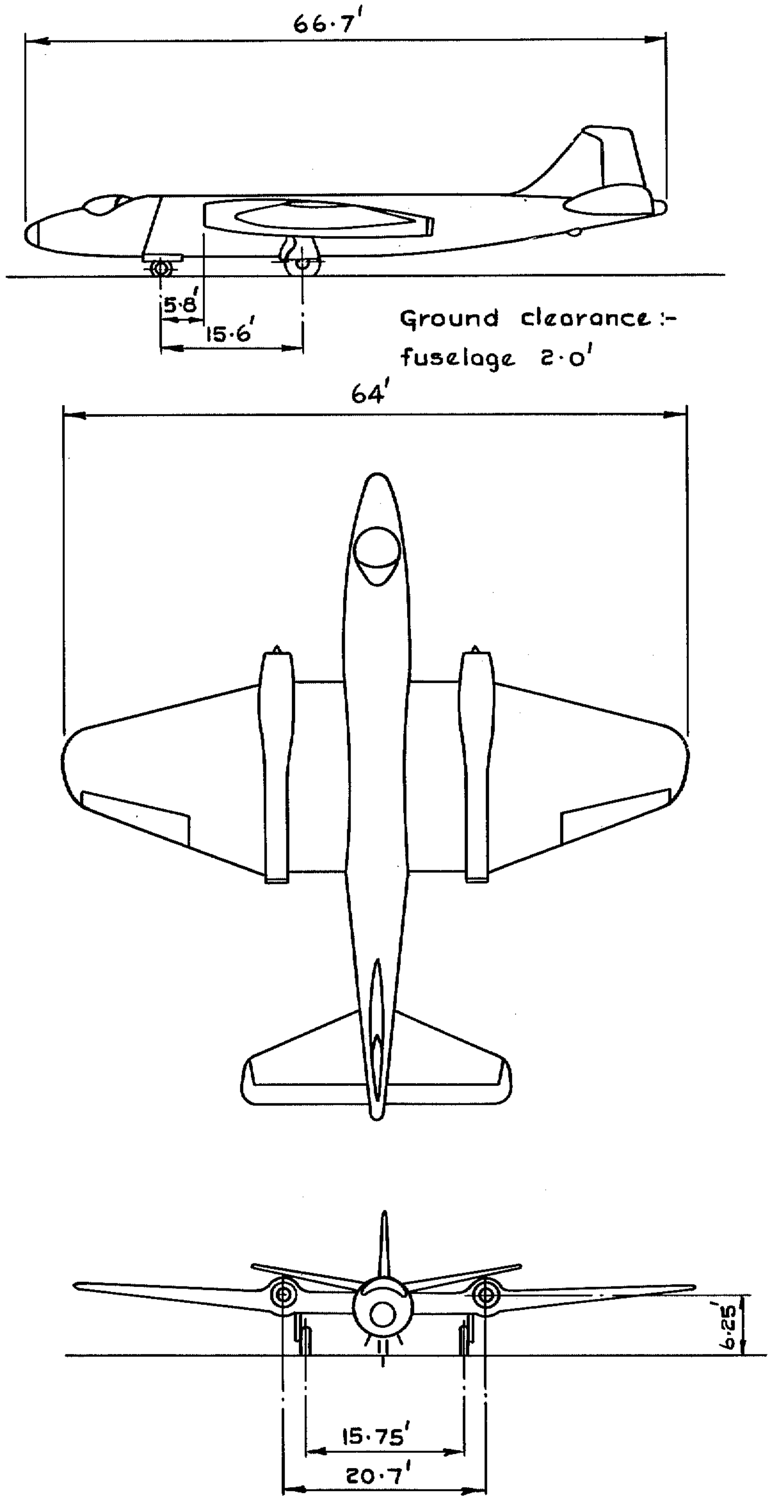


FIG. 1. G.A. of Canberra B2.

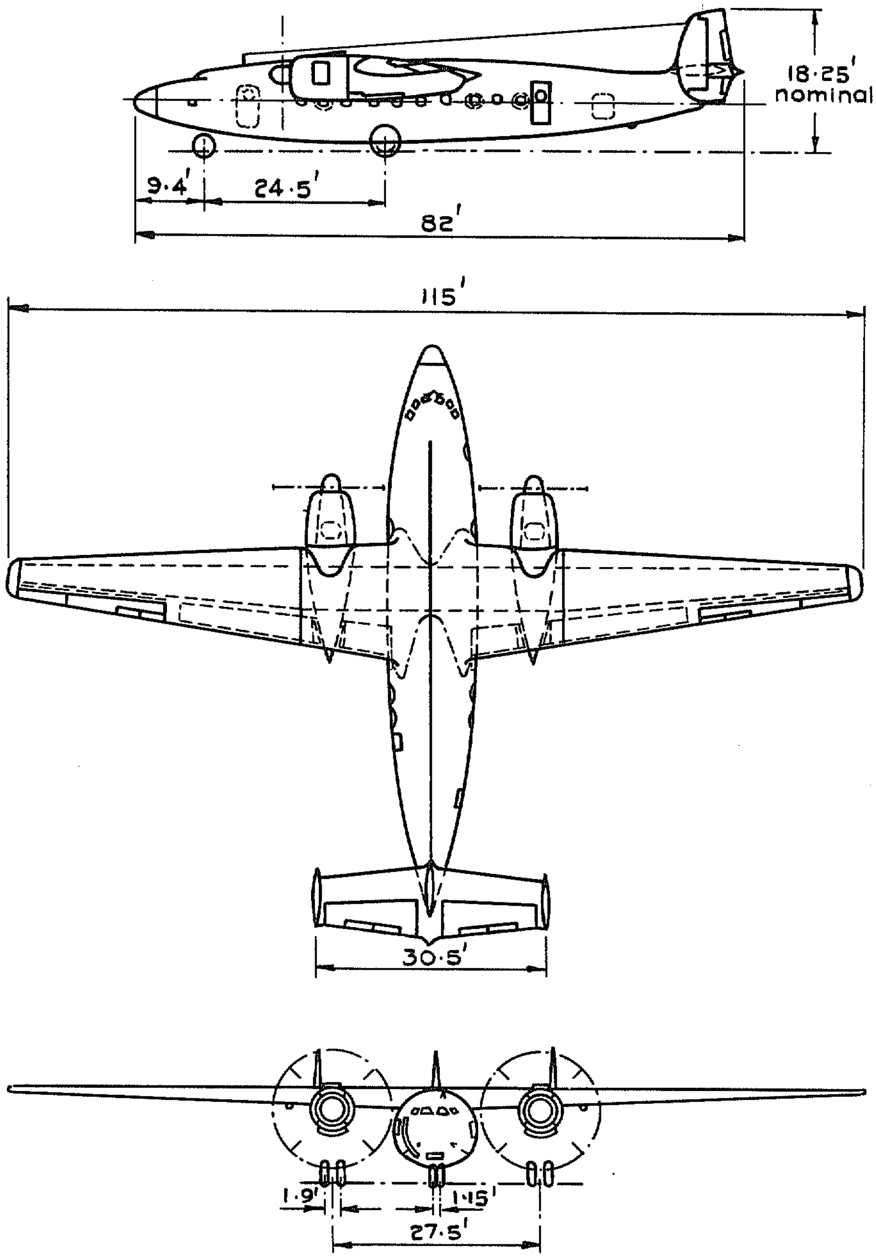


FIG. 2. G.A. of Ambassador.

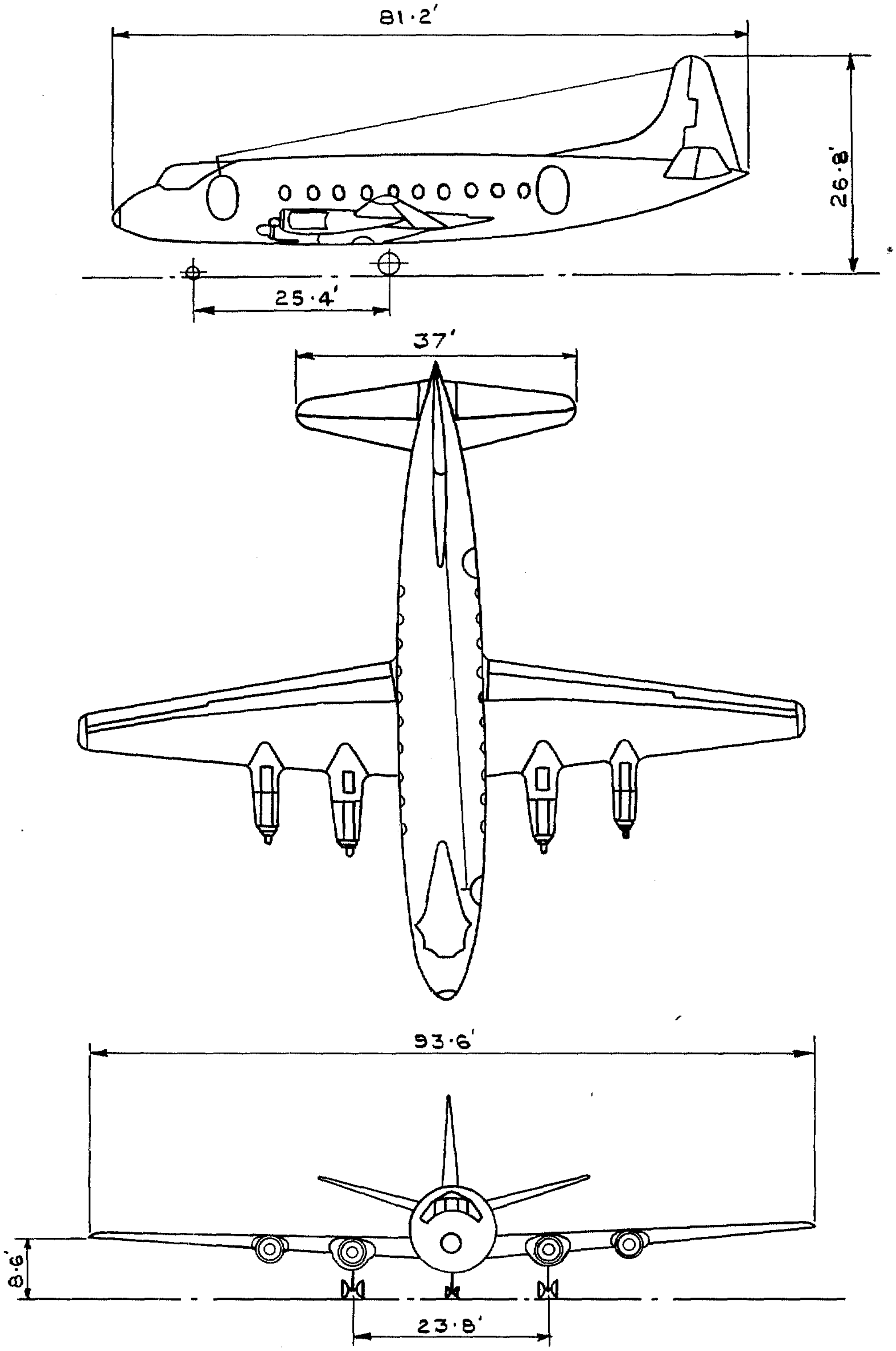


FIG. 3. G.A. of Viscount.

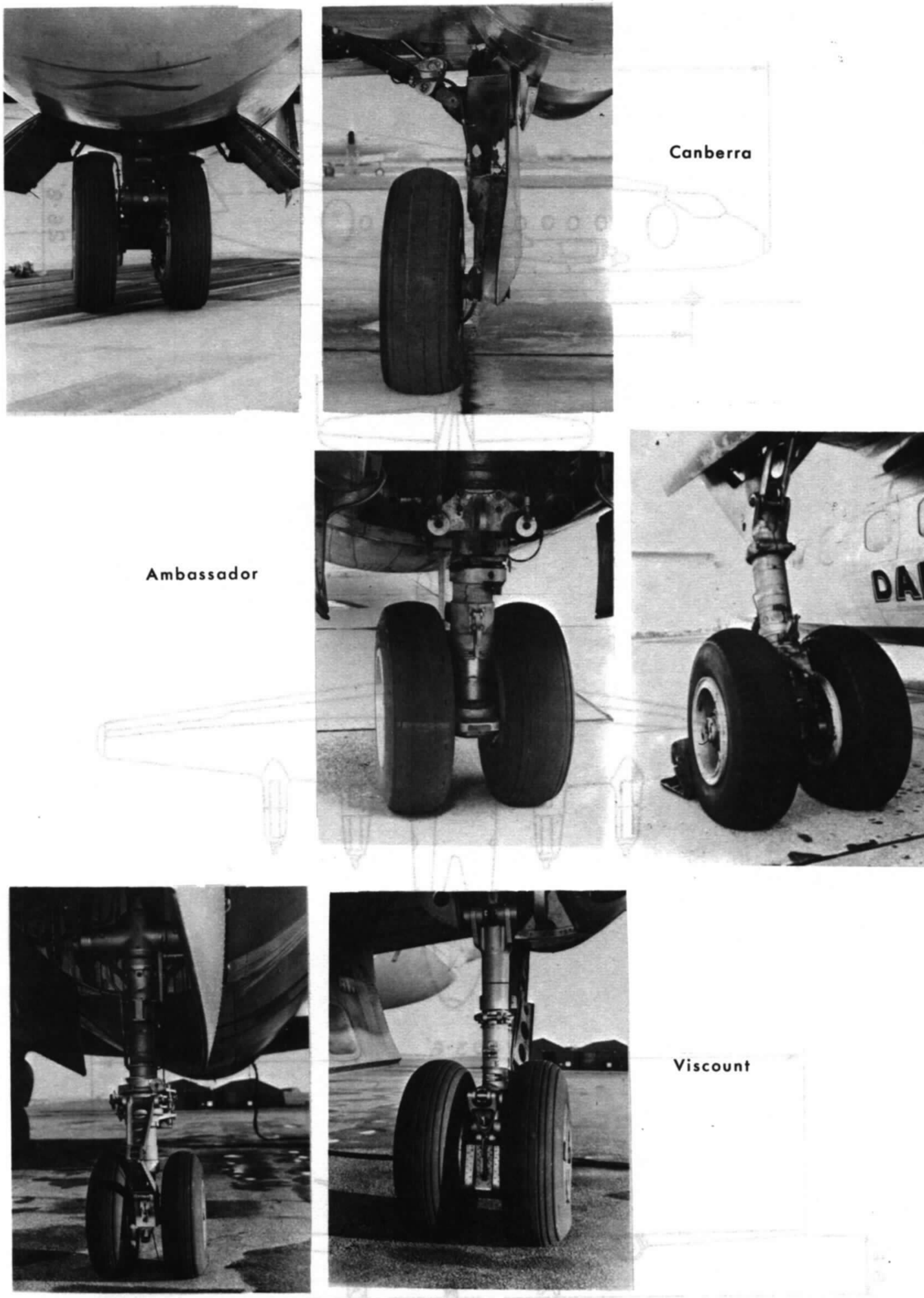


FIG. 4. Test aircraft—nose and mainwheel layouts—nose wheels on the left.

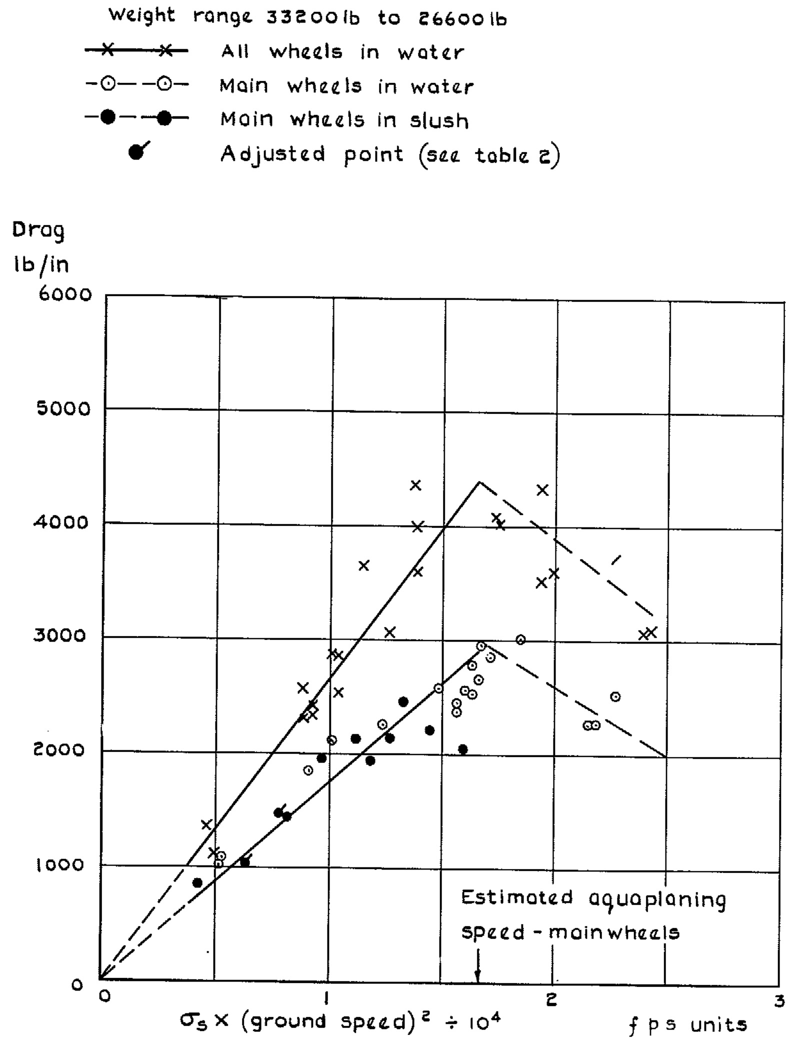


FIG. 5. Canberra: variation of drag per unit depth with equivalent speed.

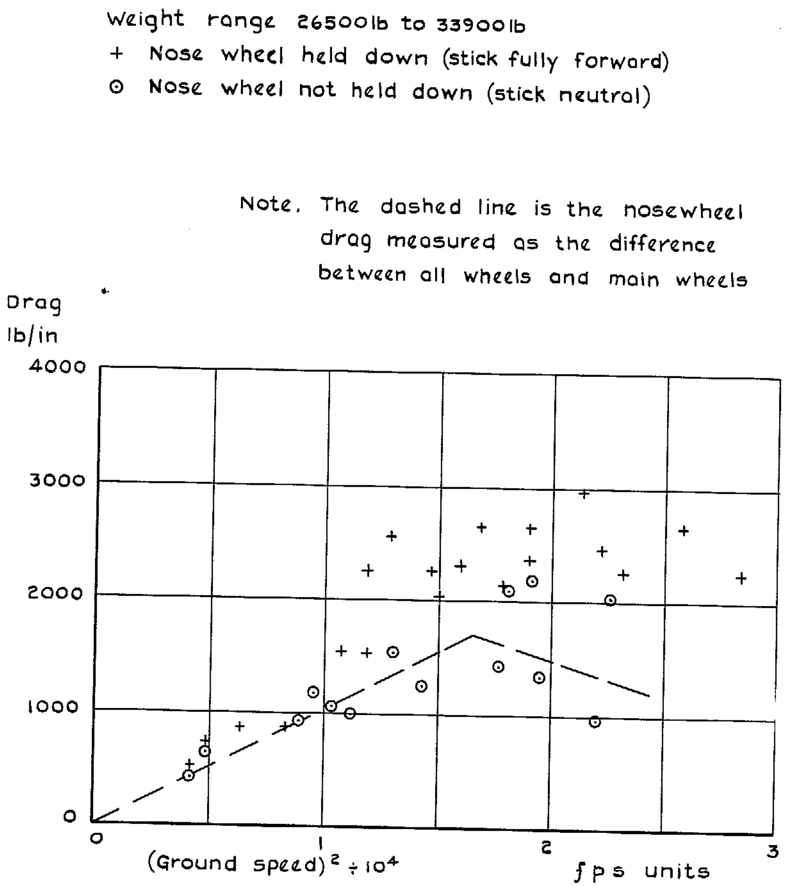


FIG. 6. Canberra: variation of nosewheel drag with speed in water.

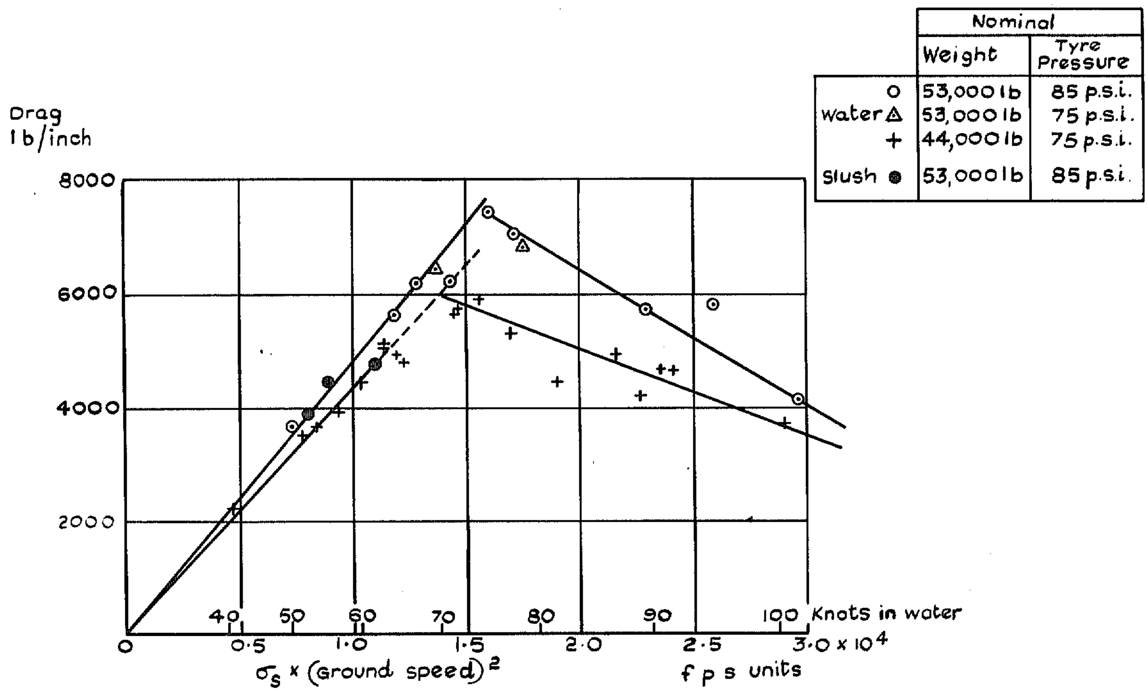


FIG. 7. Ambassador: variation of drag per unit depth with equivalent speed; all wheels.

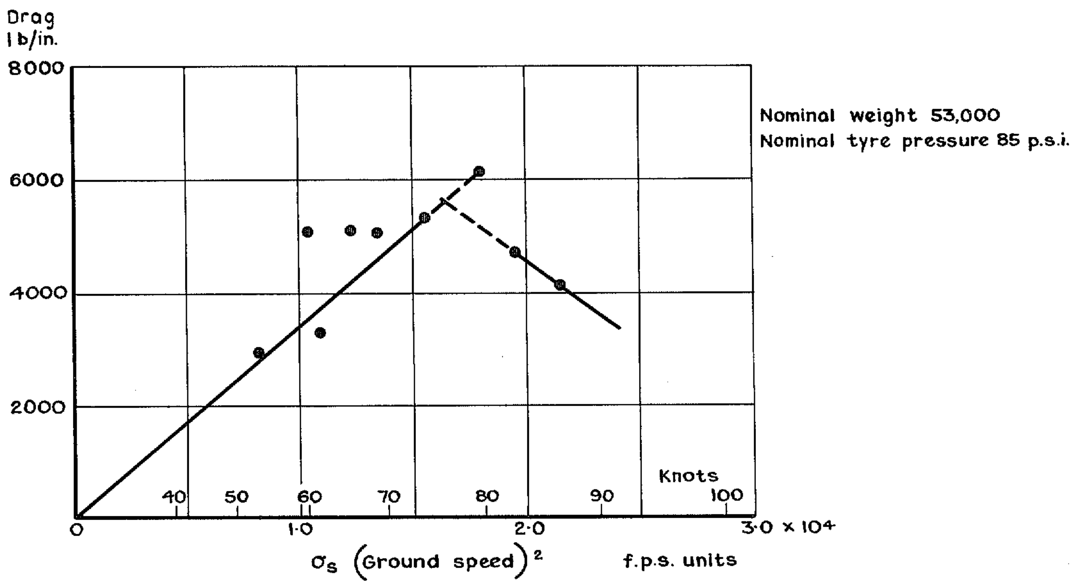


FIG. 8. Ambassador: variation of drag per unit depth with equivalent speed; main wheels only.

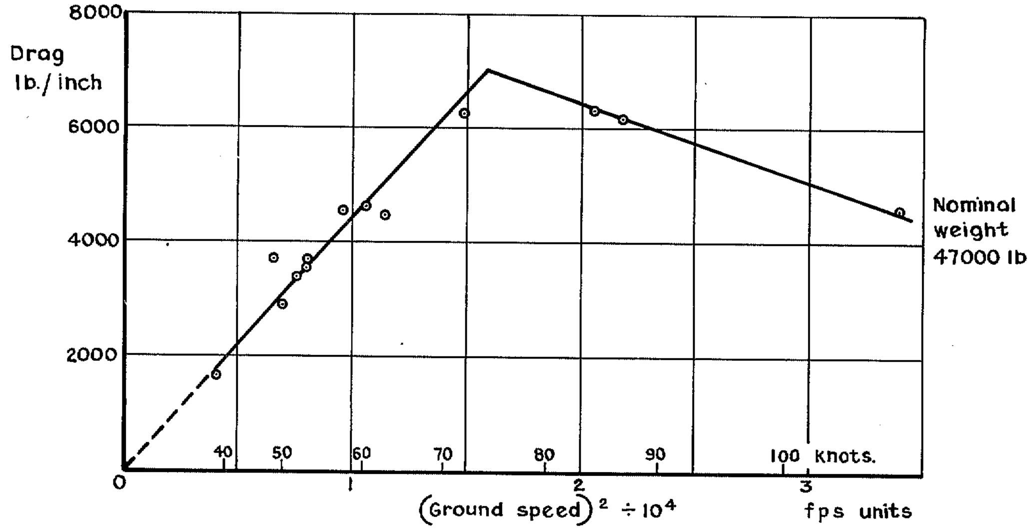


FIG. 9. Viscount: variation of drag per unit depth with speed; all wheels.

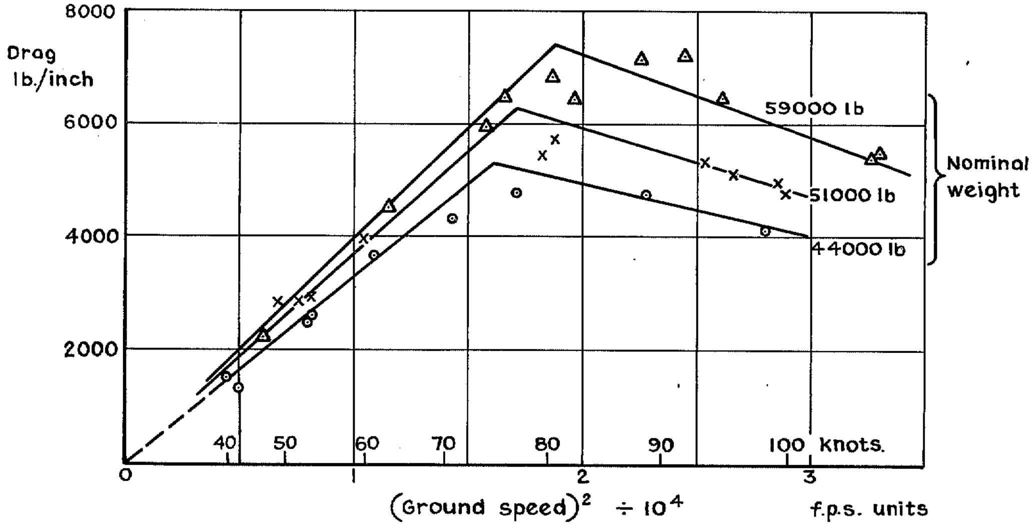


FIG. 10. Viscount: variation of drag per unit depth with speed; main wheels only.

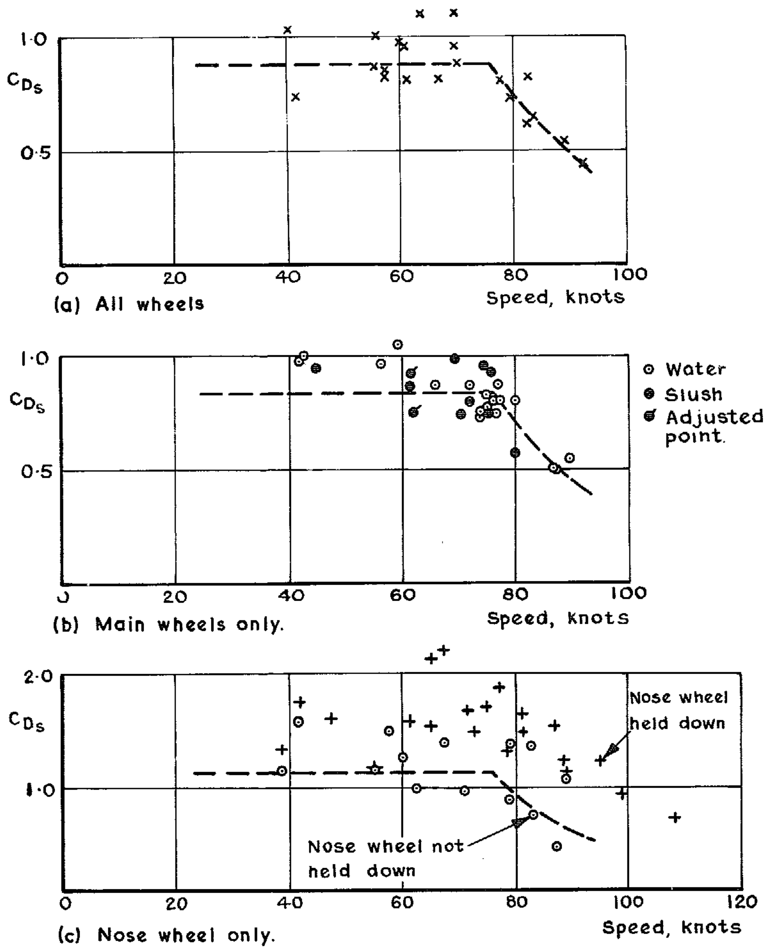


FIG. 11 a to c. Canberra: variation of slush drag coefficient with speed.

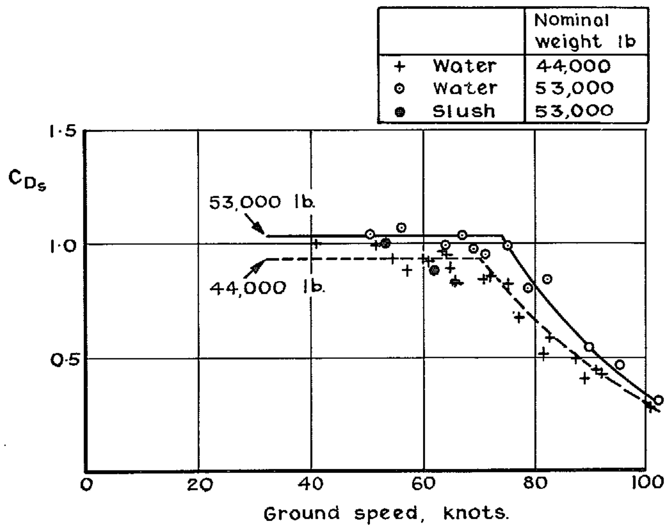


FIG. 12. Ambassador: variation of slush drag coefficient with speed—all wheels.

Note The individual points are calculated for the appropriate tyre widths. The lines are derived from Fig. 10 & 11 and a mean total tyre width of 3·9 ft in Fig.(a) & 5 ft in Fig.(b)

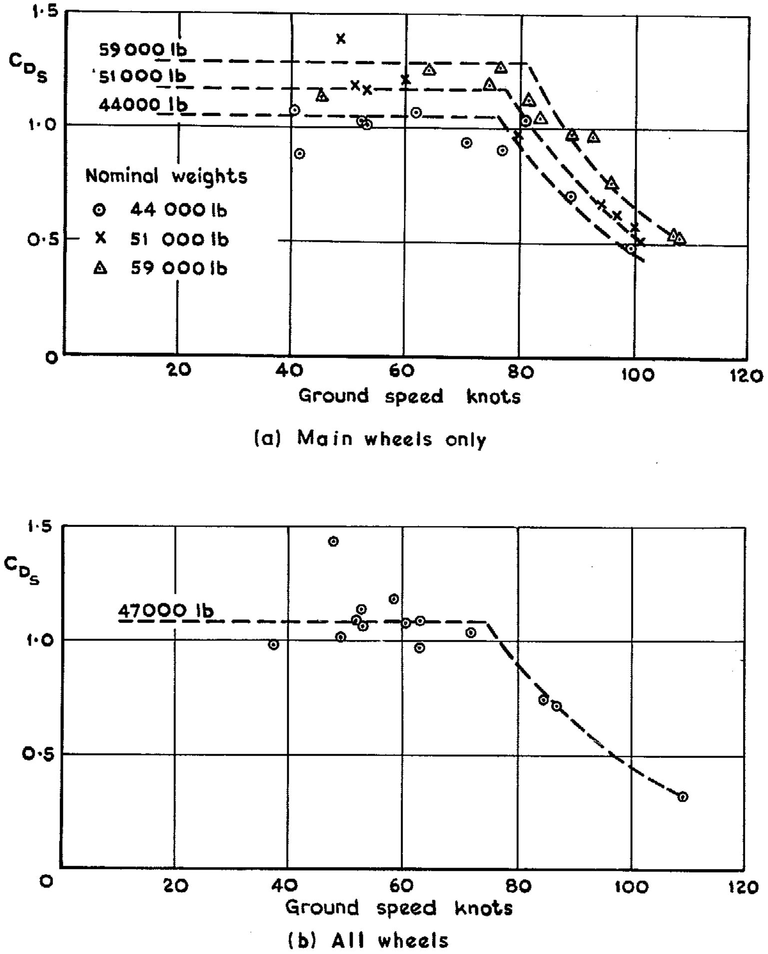


FIG. 13 a & b. Viscount: variation of slush drag coefficient with speed.

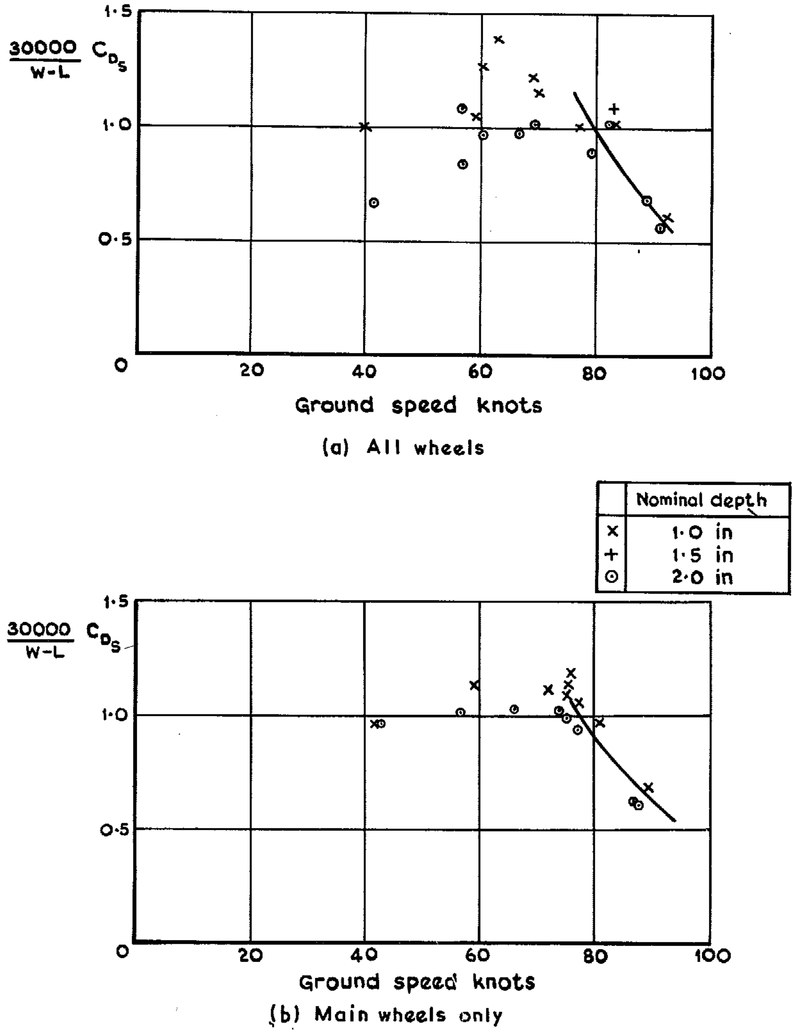


FIG. 14 a & b. Canberra: slush drag coefficient corrected to a wheel load of 30 000 lb.

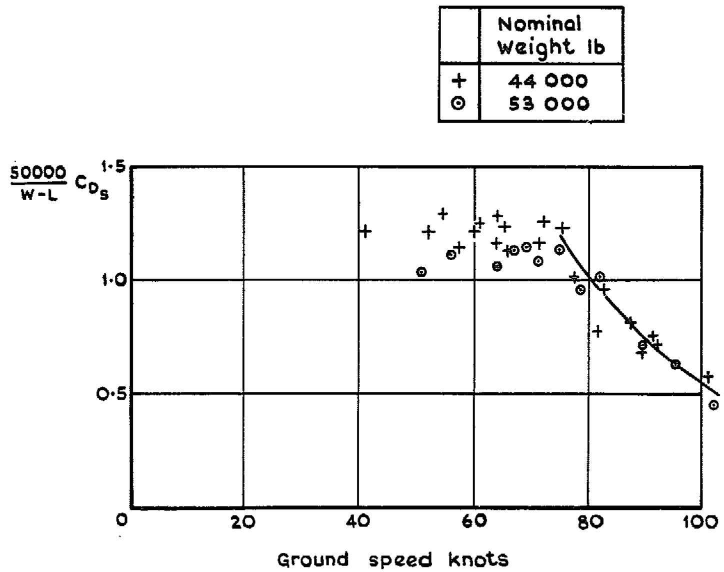


FIG. 15. Ambassador: slush drag coefficient corrected to a wheel load of 50 000 lb.

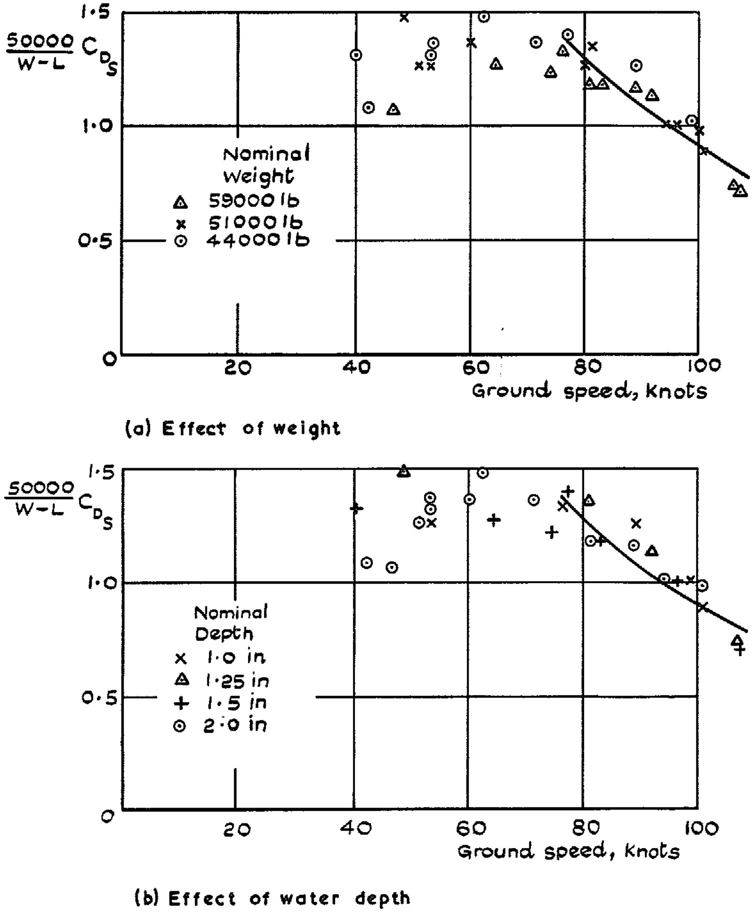
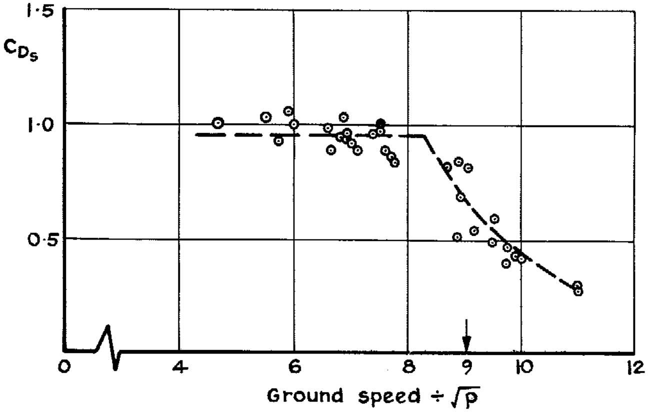
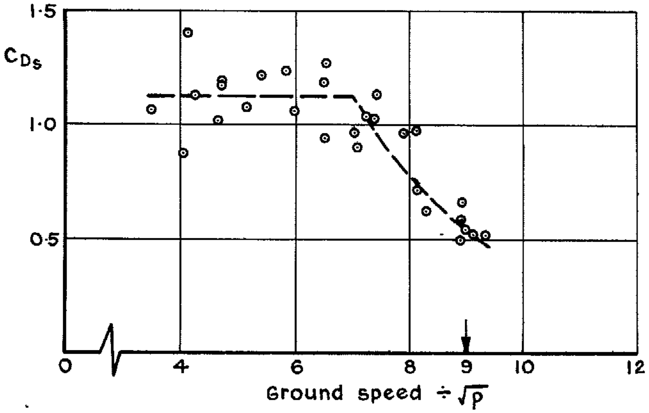


FIG. 16 a & b. Viscount: Slush drag coefficients corrected to a wheel load of 50 000 lb.



(a) Ambassador: all wheels



(b) Viscount: main wheels

FIG. 17 a & b. Slush drag coefficient in terms of $V/\sqrt{P}$.

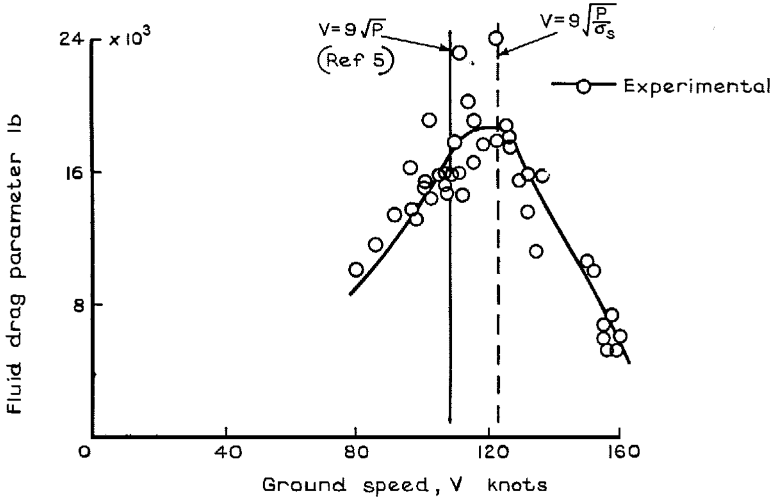


FIG. 18. Convair 880: drag measured in slush $\sigma_s = 0{\cdot}817$ $P = 150$ psi (figure taken from Ref. 4, dashed line added).

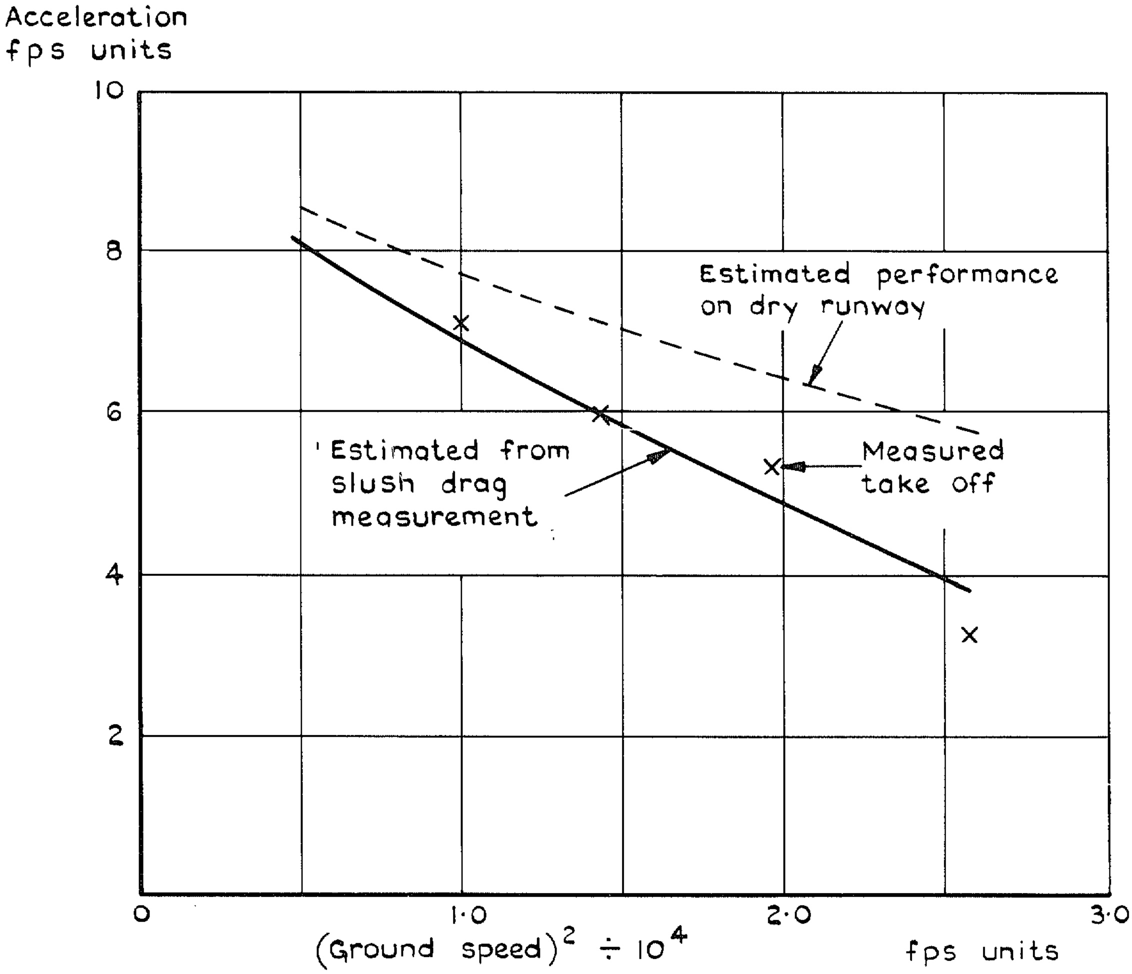


FIG. 19. Argosy take-off in slush.

(a) Bow wave and main plume at $V/\sqrt{P} \doteqdot 9$

(b) Main plume at $V/\sqrt{P} \doteqdot 7$

FIG. 20. Characteristic spray patterns.

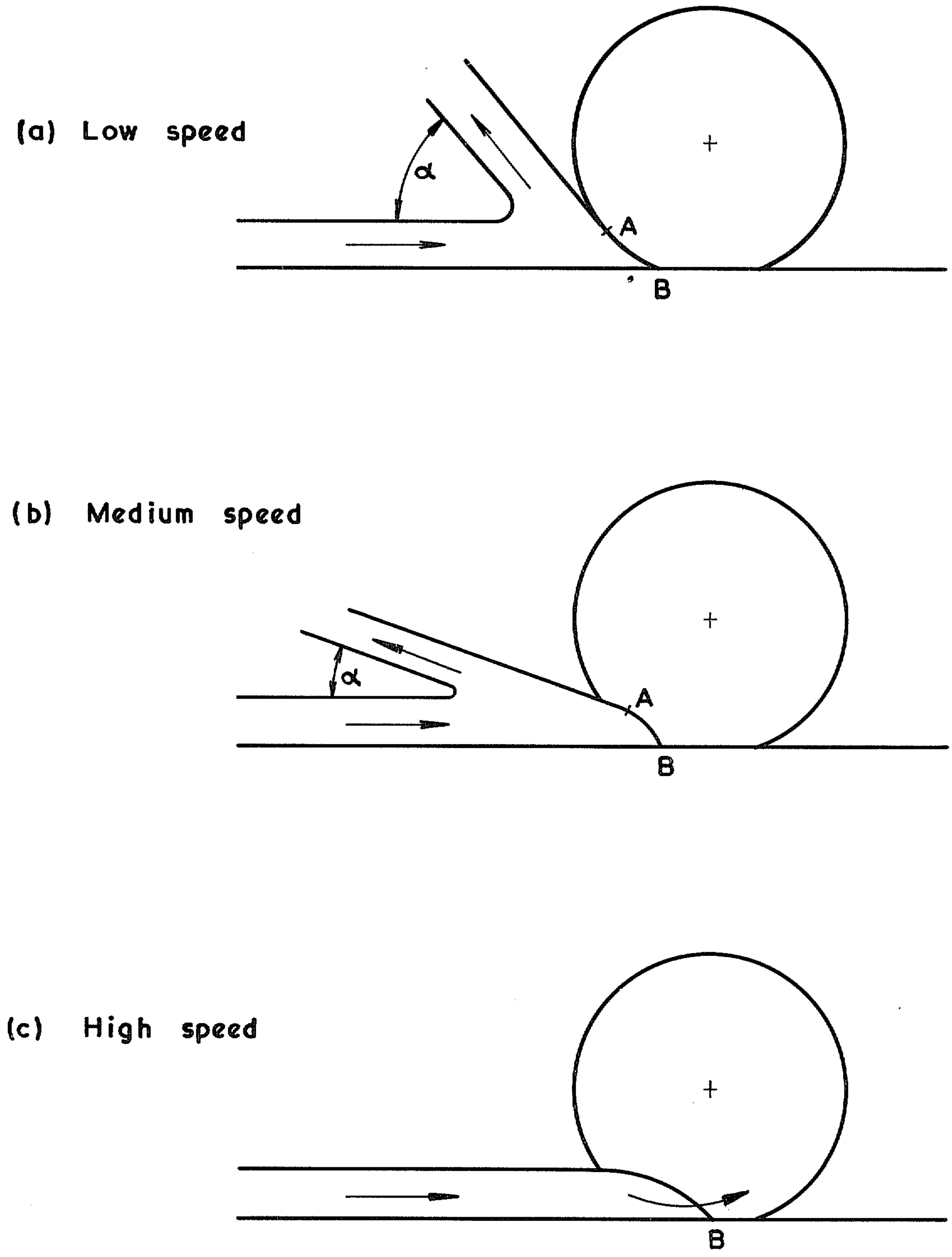


FIG. 21 a to c. Development of bow wave with speed.

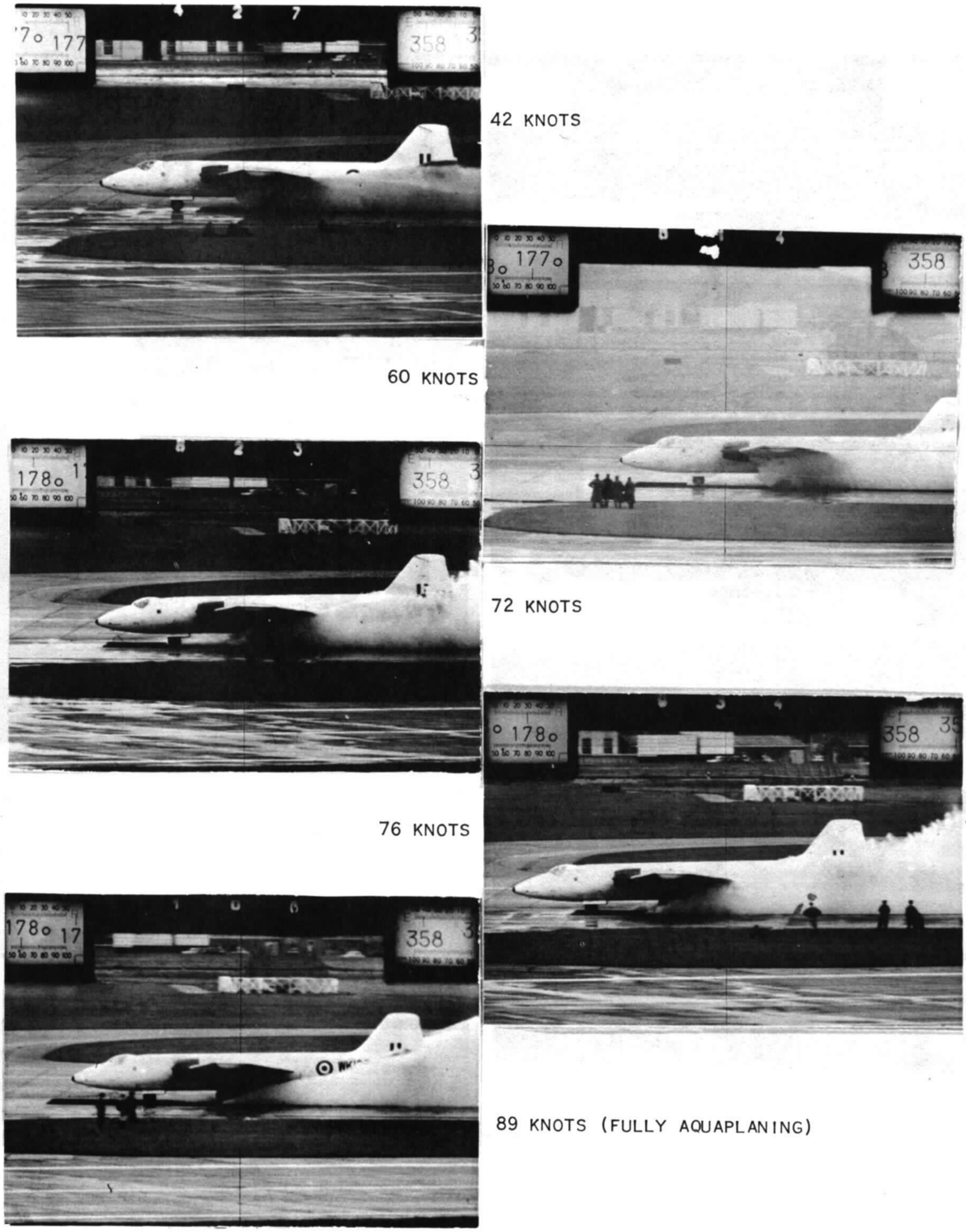


FIG. 22. Variation of spray pattern with speed; Canberra.

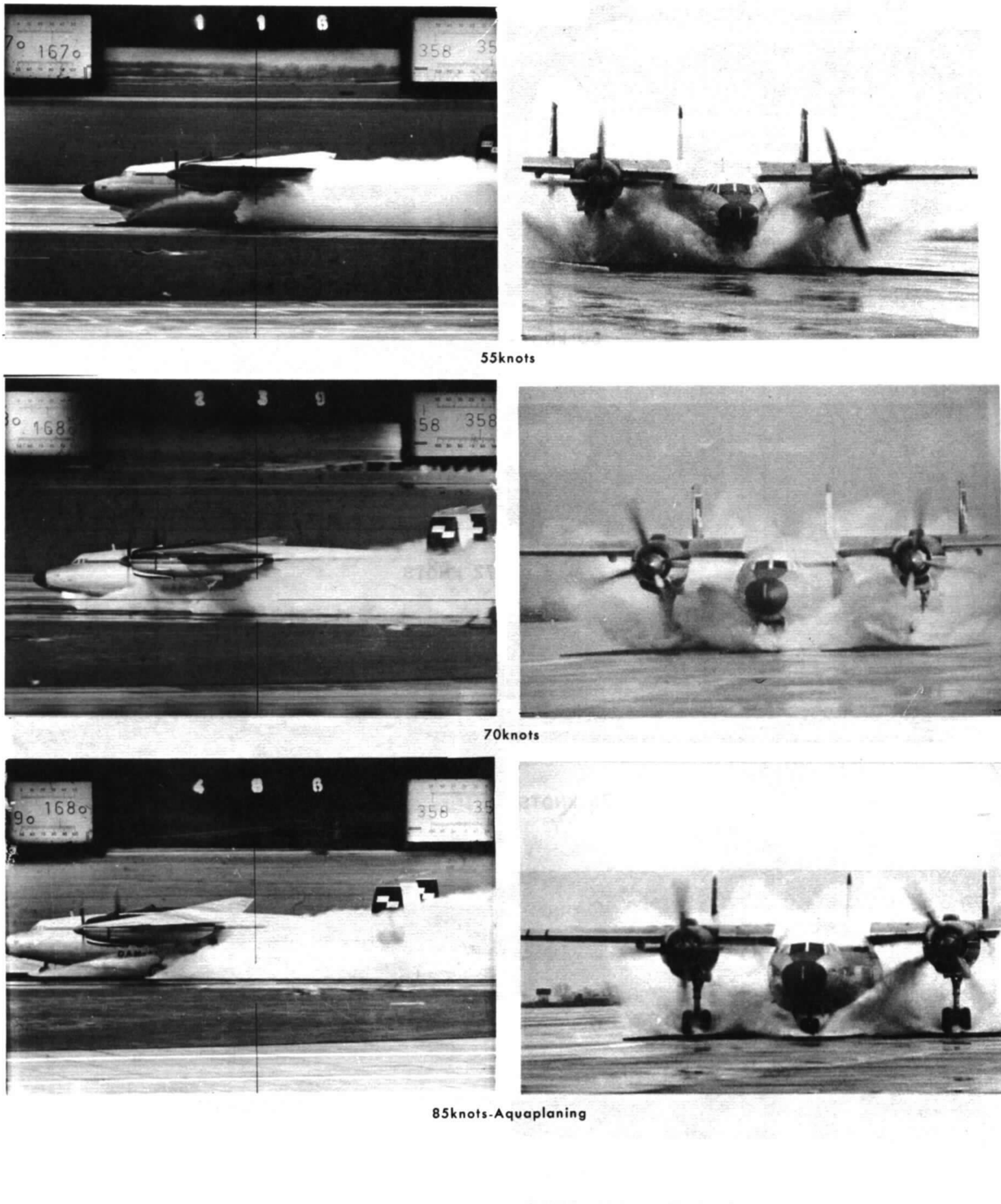
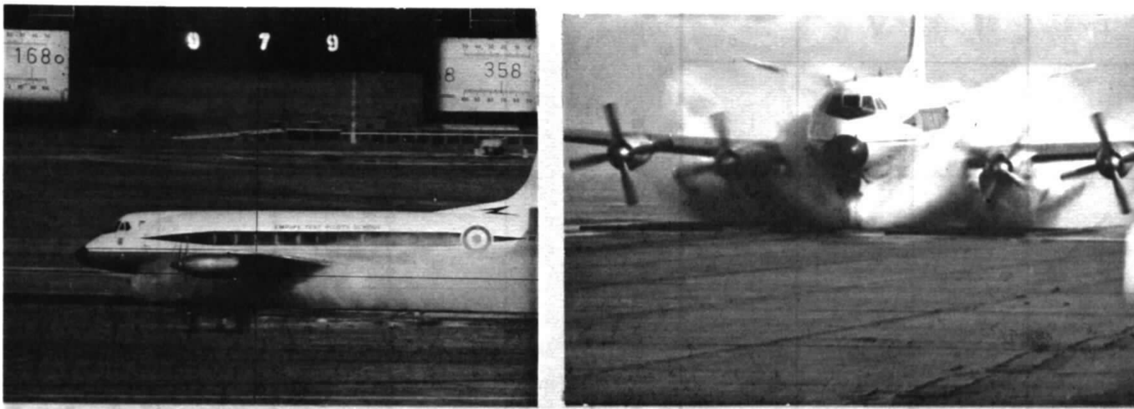
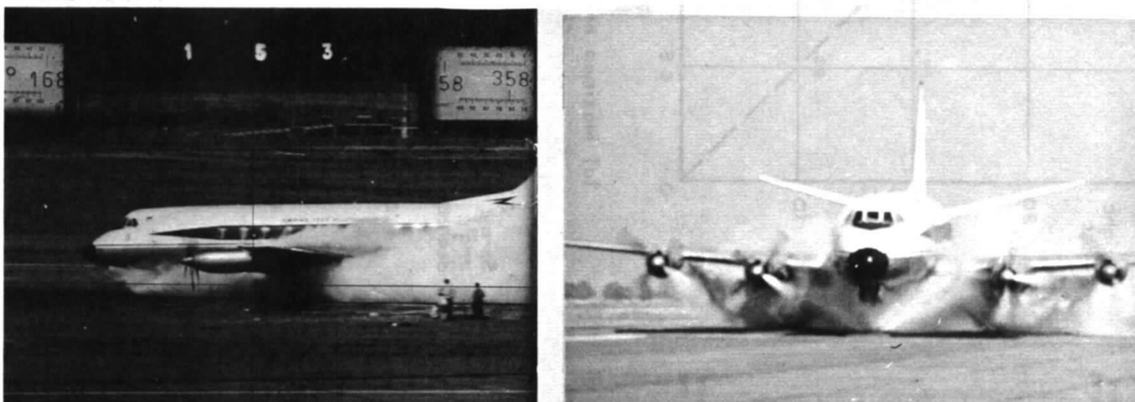


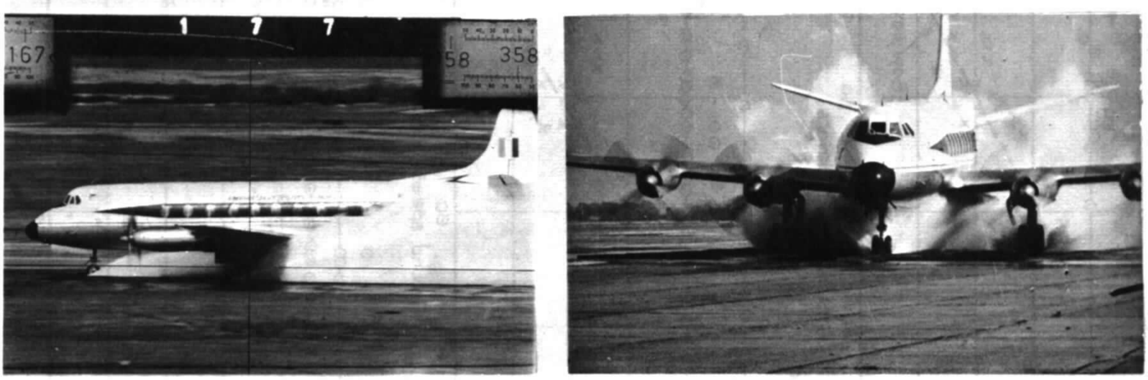
FIG. 23. Variation of spray pattern with speed; Ambassador.



54knots



85knots



109knots-Aquaplaning

FIG. 24. Variation of spray pattern with speed; Viscount.

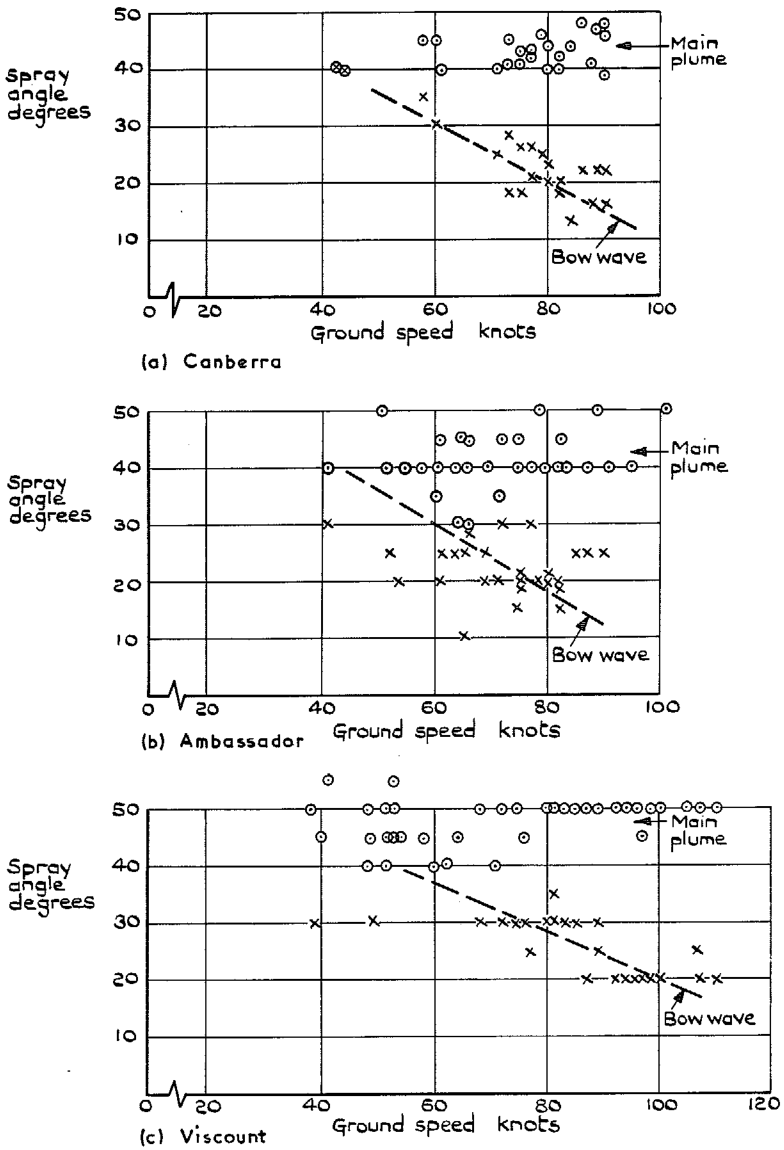


FIG. 25 a to c. Development of spray plumes in front elevation.

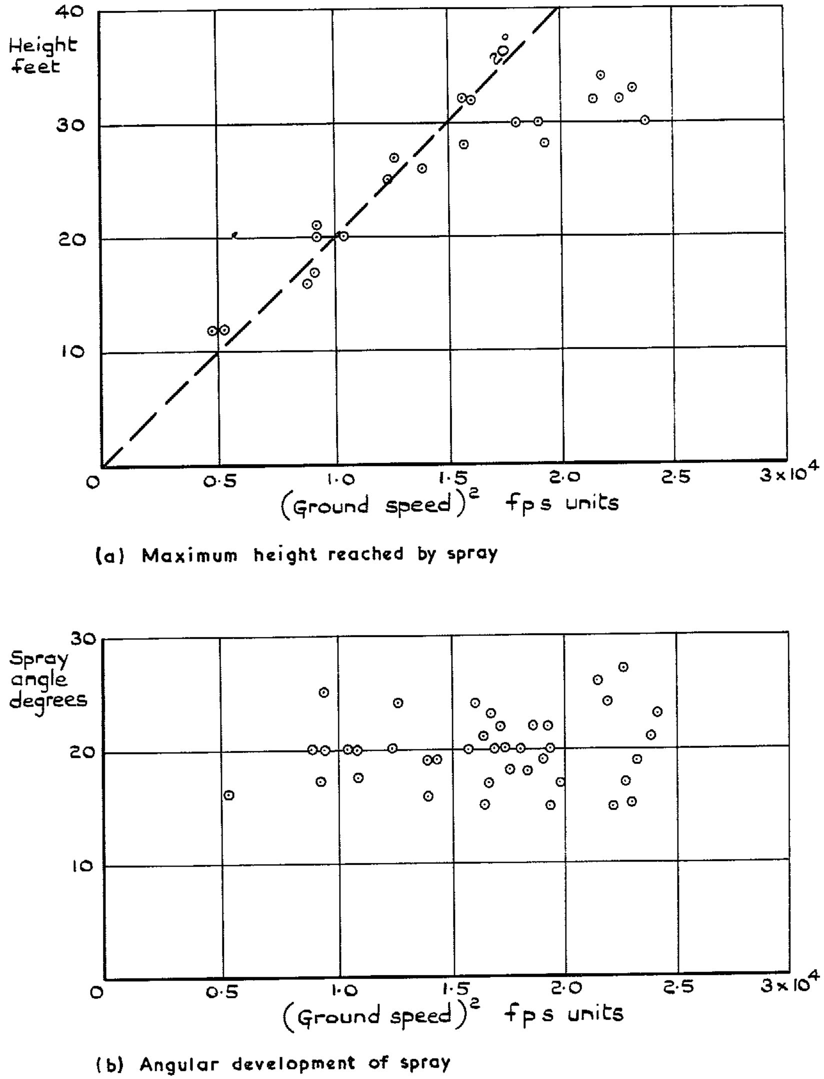
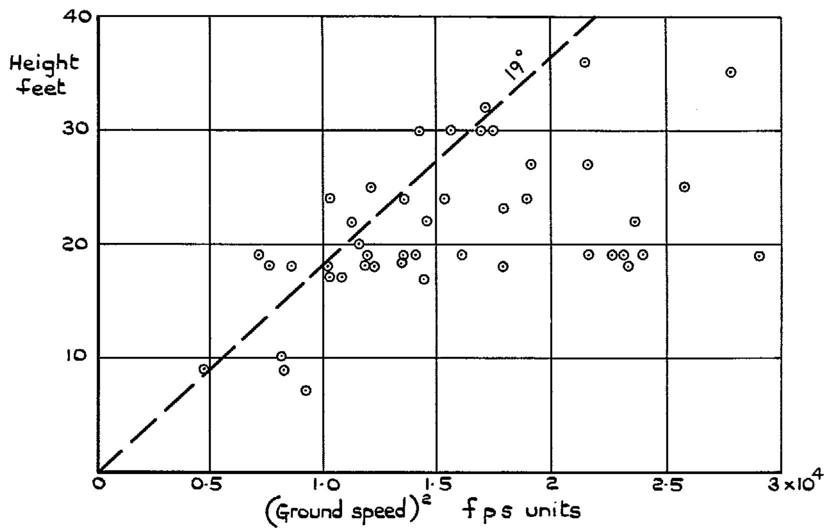
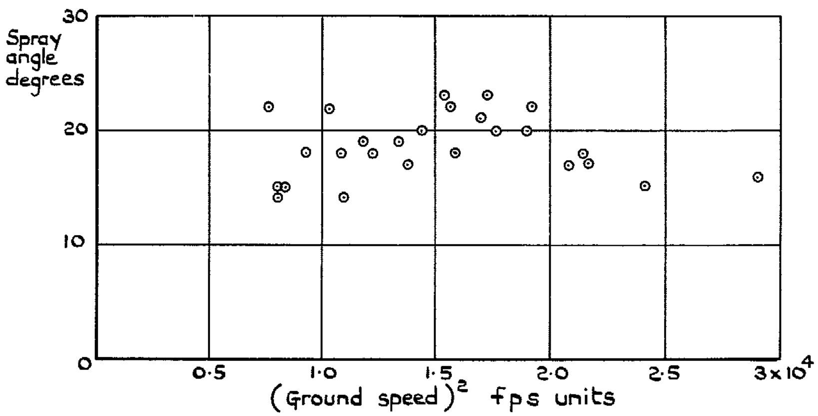


FIG. 26 a & b. Canberra development of main spray plume in side elevation.

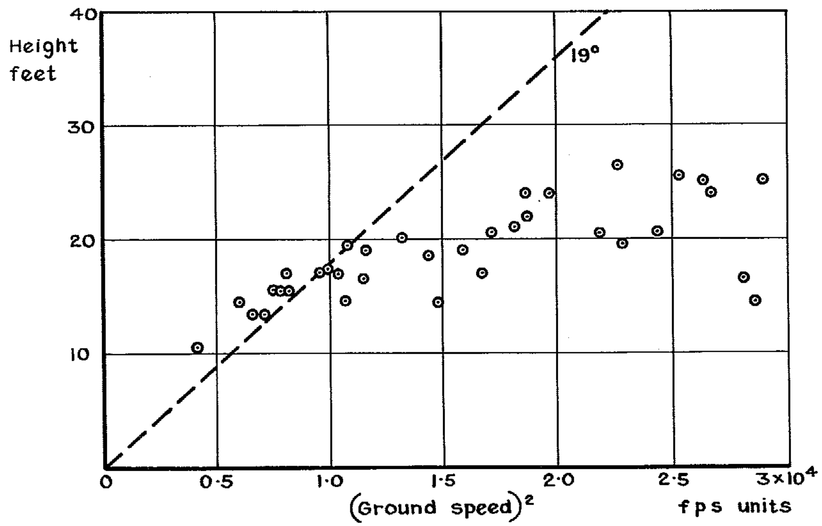


(a) Maximum height reached by spray

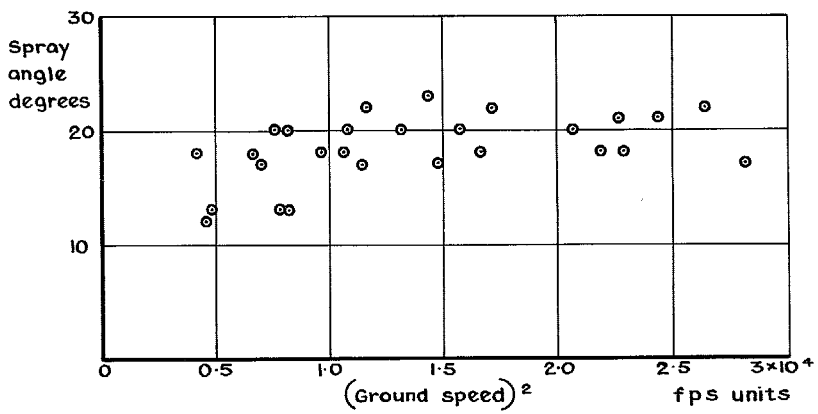


(b) Angular development of spray

FIG. 27 a & b. Ambassador: development of main spray plume in side elevation.



(a) Maximum height reached by spray.



(b) Angular development of spray.

FIG. 28 a & b. Viscount: development of main spray plume in side elevation.

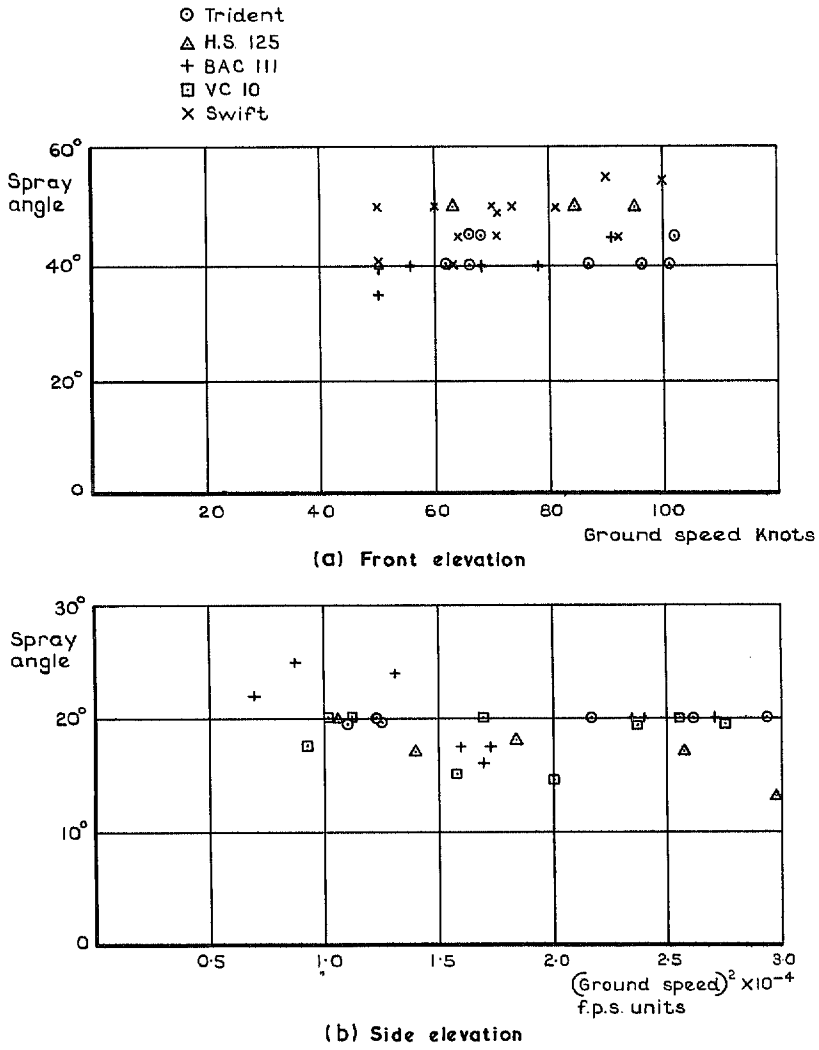


FIG. 29 a & b. Spray angles; other aircraft.

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