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A Review of the Problems of Aircraft Wheel Braking on Wet Surfaces and a Description of a Method of Artificially Wetting Runways for Test Purposes

By

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A Review of the Problems of Aircraft Wheel Braking on Wet Surfaces and a Description of a Method of Artificially Wetting Runways for Test Purposes

- By -

H. J. Keyes, B.A., A.F.R.Ae.S.

SUMMARY

A brief summary is given of the available information concerning the braking of tyres on wet surfaces. There is a serious shortage of data in regard to the braking of aircraft, particularly at high speeds on wet surfaces, but there is sufficient evidence to show that the braking is so low that landing distances on wet runways could constitute a serious problem on current and future high-performance aircraft in the absence of some other means of decelerating, for instance reverse thrust or a completely reliable tail parachute. A method is described of artificially wetting runway surfaces by which some measurements have been made of the braking achieved by aircraft under wet-surface conditions; some tentative values of braking force coefficient so obtained are given.

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1. Introduction

Increasing concern has recently been felt about the lack of braking obtained from aircraft wheels on wet runway surfaces, a factor which has contributed to a number of landing overrun accidents to both civil and military aircraft. For instance, the overrun accidents in civil transport aircraft not fitted with reverse thrust has been reliably estimated as 1 in 37,000 landings for operations on wet runways and 1 in 11,000,000 landings for operations on dry runways (Ref. 1). When allowance is made for the number of operations in which the landing distance available greatly exceeds that required by airworthiness regulations, then the accident rates for critical operations (distance available not markedly greater than called for by safety regulations) are approximately 1 in 4,000 for wet runway conditions and 1 in 1,000,000 for dry runway conditions. Reference 1 also states that, at British aerodromes (civil presumably), approximately 1 in 6 operations take place on wet runways and on a world-wide basis 1 in 12 operations take place on wet runways. It will be seen therefore that it is essential to establish the landing performance on wet runways of projected aircraft and this is particularly the case for those with high landing speeds.

It is unfortunate that although there is a considerable amount of published work on the behaviour of tyres, both in relation to the mechanical characteristics and the braking performance, most of this relates to road vehicles so that the speeds and tyre pressures and contact areas are appreciably lower than those pertaining to aircraft practice. This lack of data applicable to aircraft is widely acknowledged and long term research has been put in hand both in the United States (Ref. 2) and in this country (meeting at Ministry of Supply Headquarters on 15th February 1957, Reference AF/S42/03/RDT1). Pending this further information, values of the brake force coefficient to be used for design purposes remain as suggested in Paper No. 680 of the Joint Airworthiness Committee, May 1956 (Ref. 3). Soon after this latter meeting, however, there arose an urgent need for information on a particular aircraft; it was apparent that this need could only be met by artificially wetting the runway surfaces since the aircraft could only be made available for a short period and natural wetting might involve too long a wait for appropriate weather besides involving difficulties in making the necessary performance

2. Brief Outline of Tyre-Runway Behaviour

Giles (Ref. 4) gives an extensive review of the mechanism of tyre behaviour in "Skidding and the Slippery Road" from which the following extracts are taken.

> "At any instant the tyre makes contact with the surface over an area that is roughly elliptical in shape ..... Each portion of the tread comes onto the road surface in turn, makes contact with part of it, and remains in contact with the same part of the road until it is lifted clear at the end of the contact patch ..... To steer, propel, or brake the vehicle, forces in the plane of the road are exerted through the various contact areas and are resisted by the friction between tyre and road. If the forces required for these purposes are more than the available friction the contact patch will slide, that is, the wheel will skid .....
>
> Like all friction problems, that of skidding is complicated and it is now generally recognised, from the work of Bowden (Ref. 5) and others, that the idea that the frictional force between two bodies in contact depends only on the normal force between them and on the materials in contact is a considerable simplification of the phenomena that may occur. Bickerman (Ref. 6), for example, has grouped the various types of friction that occur as:
>
> | | |
> |---|---|
> | Hydrodynamic | - sliding in which the two surfaces are separated completely by a liquid film. |
> | Transitional | - sliding in which the separation is incomplete and the sliders are either partly in contact or else separated by films of lubricant only one or two molecules thick. |
> | Dry friction | - sliding in which there is no intervening liquid. |
> | Scratching friction | - friction in which, as the surfaces slide over one another, the projections on one plough through or tear out portions of the other ..... |
>
> Unlike the sliding bodies in most instances of friction, the tyre and wheel are relatively flexible and they deform to an appreciable extent under the action of applied forces before actual sliding of the contact patch occurs: thus a wheel may appear to slip in relation to the road surface although there may be no actual sliding at the contact between tyre and road."

The brake force coefficient (= ratio of the braking force to the load on the wheel) varies with the amount of this "slip" as shown in Figure 1 which is reproduced from Reference 4. Many measurements of both this coefficient and also the side-force coefficient have been made on road vehicle tyres at relatively low speeds, though generally with locked wheels so that the results cannot be applied directly to operation with anti-skid devices when the "incipient skid" condition becomes important. References 7 to 11 contain some of these measurements whilst Mann (Ref. 1), Gough (Ref. 2) and Pike (Ref. 12) summarise the known position in relation to aircraft operation.

Mann concludes that on clean, dry surfaces "the adhesion with a rubber tyre is high and provided there is no melting of tyre and surface by the heat produced, high values of coefficient of the order of 0.7 to 0.8 are obtainable over the whole range of conditions likely to be encountered,"

that/

that is, there appears to be little variation with speed or with tyre tread. In wet conditions, "very wide differences in performance can arise. For example at a given speed, coefficients with the same tyre and conditions of loading may easily range from 0.1 to 0.8 on different wet surfaces, whilst in an extreme case the coefficient on a single surface could vary by as much as from 0.8 to 0.1 over the range of speeds from 0 to 30 miles an hour."

Mann continues, "Essentially the differences in behaviour on wet surfaces can be explained by the lubricating action of the liquid film. This impedes direct contact between the tyre and the surface and must be displaced or penetrated before direct contact between tyre and surface can be established and a high resistance to skidding obtained. This process takes time and, as with increasing speed the time of contact between each part of the surface and the tyre is reduced, so the coefficient will tend to fall as more and more of the load on the tyre is supported by the intervening liquid film.*

In ensuring a high resistance to skidding under wet conditions ..... the texture of the road or the runway surface is of the greatest importance. Ideally it should have a texture of projecting elements to facilitate the escape or drainage of the liquid film, but more important still these elements, where they make contact with the tyre, must be harsh to the touch, having sharp peaks and ridges. It is the intense localised pressures where these make contact with the tyre which play the essential role in breaking through the last traces of the liquid film. Where a surface is relatively smooth so that it does not supply sufficient drainage to enable the liquid film to escape from the zone of contact rapidly enough, this can be supplied by the pattern of the tyre tread, and under these conditions an effective pattern on the tyre can make a valuable contribution by increasing the resistance to skidding.

Ultimately at some sufficiently high speed it is, of course, to be expected that even the best possible measures would fail to defeat the lubricating effect of the liquid film, giving rise to the very low coefficients indicating purely hydrodynamic conditions between tyre and surface."

To some extent, however, the above presents a somewhat too simplified picture of the problem as tests of a coarse-textured surface and a fine-grained surface (Ref. 9) indicate that some surfaces, in spite of their smooth appearance, have given extremely high values of coefficient. The further factor in the attainment of a high skidding resistance in wet conditions is the shape of the projections which make up the surface of the road and come into contact with the tyre tread. Grime and Giles (Ref. 9) state that "although most of the liquid film may escape rapidly, the chief problem on wet surfaces appears to arise from a thin film no more than a few thousandths of an inch thick, which is very difficult to expel. Elasticity theory shows that when projections such as those making up the road surface are forced into an elastic solid, such as the tyre tread rubber may be supposed to be, the localised pressure distribution over the surface of the projections depends particularly upon their shape and the hardness of the solid but not upon the size of the projections. Theoretically, if the edges are sharp, or there are discontinuities, the pressures would be infinitely high ..... Pressures up to 8,000 lb per sq in. have been indicated in this way. With such intense localised pressures, the last traces of liquid film

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* This picture of the friction problem on a wet road was first put forward by Saal who applied Reynolds' theory of lubrication to it and deduced the following expression for the fall through a water film of a smooth-tread tyre onto a smooth surface:

$$t = k\left({}^{1}/h^{2} - {}^{1}/h_{o}^{2}\right)$$

where t = time
h_o = initial film thickness at $t = o$
h = film thickness at time t

and k is a constant depending on the viscosity of the liquid film, the area of contact, and the pressure per unit area beneath the tyre (Giles, Ref. 4).

should be easy to disperse and only a small area of surface need be freed of liquid to ensure that a large proportion of load on the wheel is supported by portions of the tyre in direct contact with the road surface ..... It is the sharpness of comparatively small areas on the peaks and ridges of the projections which will play a decisive role in determining resistance to skidding when the surface is wet ..... Where projections are sharp, stresses are necessarily high and, particularly in the presence of dust, traffic will tend to polish the surface and consequently make it more slippery. Such changes due to polishing are often very small and a magnification of 100 times is necessary to make them measurable, but it is changes of this magnitude in quite small areas of the road surface which can account for much of the variability in the skid-resisting properties of road surfaces."

In addition, the effects of tyre tread vary according to the road surface. Grime and Giles (Ref. 9) state "on the smooth or fine-grained surfaces having sideway force coefficients between about 0.2 and 0.6, all the patterned tyre treads give a marked increase in retardation, particularly for surfaces with coefficients in the region of 0.3. Below 0.2, even with the best pattern, however, the improvement is small, whilst above 0.6, better results are likely to be obtained with a smooth tyre than with a tyre having a patterned tread ..... Turning to the rough coarse-textured surfaces, on the other hand, it will be seen that on these the situation is quite different and that, quite contrary to popular expectations, when braking on these surfaces in the wet, smooth tyres tend to give rather better results than those with a pattern." The reasons for this are that "on the rough coarse-textured surface, so little of the tyre and road surface come into close contact that even with the smooth tyre it is easy for the film to escape. On this surface, the prints* obtained with the two tyres are almost indistinguishable, the main difference being that the patterned tyre misses some parts of the road surface which are recorded by the smooth one."

3. The Problem of Landing Distances on Wet Runways

Whilst, as stated earlier, there is little quantitative evidence of the braking force coefficient at the higher speeds on aircraft tyres, nevertheless some broad generalisations concerning the probable level of braking are possible and have been made by Pike (Ref. 12) and the Joint Airworthiness Committee (Ref. 3). All sources agree in affirming a reduction of brake force coefficient with speed, the value being put by Pike as 0.2 to 0.3 at 85 knots on wet concrete and by the Joint Airworthiness Committee as 0.25 at 85 knots and 0.17 at 140 knots. In addition however, as indicated by Mann (Ref. 1), there have been several incidents in which "after a careful study of all the known facts it appears that throughout the landing run of the aircraft the effective braking force coefficient was considerably less than 0.1, even down to quite low speeds. Moreover, the situation is complicated by the fact that such incidents have occurred on runways having a texture which would normally be associated with a good braking performance and on which other aircraft landing at about the same time showed no evidence of such abnormally slippery conditions."

Although it would be difficult to justify on economic grounds the preparation of airfields which would be adequate for the occasional very low coefficient of friction mentioned above, yet provision must obviously be made for the large numbers of landings which will be made under "normally" wet conditions. At the higher speeds, there can be little doubt that the coefficient will be very small, perhaps 0.1 to 0.2, and it may be argued that there is little point in paying attention to such low values since the load on the main wheels, being relieved generally by the lift generated on the wing, will then be small and the wheel braking force accordingly very small. The extent to which this argument can be sustained must obviously depend on the particular aircraft, its configuration and its attitude during the landing run but experience has shown that it is possible to achieve quite a high wheel loading early in the run (and could perhaps be increased further by the use

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* Areas of tyre and road surface in contact.

of, say, lift spoilers) so that improvements in braking coefficient could result in appreciable reduction in landing distances. Whilst in no way under-rating the importance of developing to a high standard of reliability such devices as brake parachutes and engine thrust reversers which are not dependent on wheel loading, there does nevertheless appear to be ample justification for devoting considerable attention to the problem of wheel braking coefficients on wet surfaces.

It is however opportune to consider at this stage what form this attention should take. From an academic point of view, it is incontrovertible that the research programmes currently in hand or being prepared in this country and in the United States should yield valuable basic information. On the other hand however it might be logical to face the situation as it is now seen, namely that some considerable reduction in braking force coefficients is to be expected in the presence of wetness but, more important, a critical situation can occasionally arise in which there is little or no deceleration and hence for which it is impractical to plan a runway length. It would seem then that any further research on the braking force coefficient should be aimed almost entirely at enabling conditions to be created to provide immunity from this critical situation of near zero braking: unless it can be foreseen that the research is likely to achieve this objective it can be argued that the research efforts should more profitably be diverted to other means of obtaining the deceleration, for instance in achieving maximum reliability of the braking parachute or even providing high-speed crash barriers at the ends of the runways. Whatever is the outcome of such deliberations, there will generally remain the need to make some determination of the landing distances on wet runways.

Two possible methods are available. Firstly, method (a), the distances can be measured on dry runways and the appropriate corrections made; from considerations of the case of carrying out the trials and also because a dry surface can be assumed to remain sensibly constant in its characteristics, this method is probably preferable. However it does entail, in the analysis and correction process, a knowledge of the variation of the lift and drag during the landing run (requiring the appropriate wind tunnel evidence), the idling thrust of the engines, the distribution of load between the main and nose or tail wheels, and the variation of the coefficient of friction on the particular type of surface in wet and dry conditions. Accordingly, method (b), that of making the measurements directly on a wet surface may prove easier. Here there is the difficulty of depending on the availability of the correct weather conditions and consistency of wetting layer.

A method of artificial wetting has therefore been tried since this has obvious advantages of being available as required and of giving a consistent degree of wetness. A serious shortcoming would be however if such a method did not produce the actual state of wetness already referred to as giving near zero deceleration. If the method could be proved to give representative conditions it could be used for establishing corrective methods with dry runway measurements of method (a) or for direct wet measurements of method (b). The following section describes the method tried while later sections attempt to assess its representativeness.

4. Artificially Wetting a Runway

(i) discharge under gravity from the parent vehicle,

(ii) discharge by pumps from the parent vehicle,

(iii) discharge by pumps on a towed vehicle, the water supply being on the parent vehicle.

(b) Wetting by numbers of pumps operating from the side of the runway, drawing water from stationary vehicles or static tanks and discharging through multi-nozzles on the runway.

Of these, discharge from vehicles moving along the runway using gravity or pump delivery from the parent vehicle, was considered the most likely to offer a reasonable prospect of success. As inadequate numbers of vehicles of suitable form were available at A.& A.E.E. a request was made to Air Ministry (OR.13) with the result that ten dual-purpose pressure refuelling bowsers of 2500 gallon capacity were made available. These vehicles are briefly described in the next section and the methods of their use will be given in the following section.

4.2 The wetting method used

4.2.1 The wetting vehicle

A photograph of one of the vehicles is given as Figure 2. Briefly, the 2500 gallon tank was filled through a trap on the upper surface and the water was discharged as required through two "priming" valves, one on each side of the vehicle, that is about 6 ft apart and pointing downwards at about 30° to the horizontal. The valves were operated by means of the pressure hose coupling which was separated from the hose and inserted into the priming valve. When the coupling was turned to the "open" position, a gravity rate of flow of approximately 180 gallons per minute from each valve was obtained with the tank full and a flow of 145 gallons per minute was still obtained with only 400 gallons remaining in the tank.

Used in this way, water was kept from the pumping and filter units, though of course on completion of the trials a thorough decontamination process was applied to all parts.

4.2.2 The wetting technique

Most of the landing trials were made on runways of lengths near 3,000 yards, of which some 2,000 yards at the approach end were wetted, leaving about 1,000 yards of dry surface as an emergency stopping region. Five vehicles were used to wet the first 1,000 yards whilst the other five vehicles simultaneously wetted the next 1,000 yards. Each set of five vehicles was disposed in echelon as shown in Figure 3, so that the wetted areas from all vehicles merged together to give a reasonably uniform coverage.

The speed of the vehicles and the number of runs to achieve a satisfactory wetting depended upon the texture of the surface. At Boscombe Down, with an asphalt over concrete surface as shown in Figure 4(a), a single run with the vehicles travelling at about 5 m.p.h. was sometimes sufficient. The wetting was then completed in just under 7 minutes, using about 1,200 gallons of water per vehicle. This was sufficient to fill up all the gaps between the constituent stones of the surface and flood over to give a virtually uninterrupted over-lying film of water over a lane about 60 feet wide. The wetting provided was equivalent to putting 1/15th inch of water over the wetted area. Under the sunny and windy conditions prevailing during the trials, a second run in the opposite direction was frequently necessary for fighter landings and was always adopted for bomber landings to give a wider landing lane. The second run was usually made at twice or three times the speed of the first run, with an increase in the water coverage to about 1/10th inch.

On the smoother brushed-concrete surface as at the R.A.F. airfield (Figure 4(b)), the water spread more rapidly and the vehicle speed for the first run of each wetting was increased to 7 to 8 m.p.h., reducing the time spent and the water used by about one-third. Here again, second runs were frequently made to counter the drying effects of sun and wind.

On the very rough surface of large granite chips on a rolled asphalt surface as at a contractor's airfield (Figure 4(c)), the coarseness prevented easy spreading and the double wetting was always used; in this case some 2,000 gallons of water per vehicle was used to attain a rapid wetting of a lane 70 feet wide and 1,700 yards long, equivalent to just over 1/10th inch over the wetted area.

On all types of surface, the wetting remained adequate for at least ten minutes but every effort was made to bring the aircraft in to land as soon as possible after the completion of the wetting. For this purpose, it was found invaluable during these trials to use radio communication for swift organisation. Thus it was arranged for each party of five vehicles to be under the control of a marshalling van equipped with radio so that communication could be maintained between each party, with the camera operators at the F-47 performance measuring cameras beside the runway, and with the air traffic control officer in the tower and, through him, with the pilot of the aircraft. The extent and type of such communication links varied for all three testing sites but were fundamental in, firstly, maintaining adequate control of a trial involving many widespread units and, secondly, in enabling time synchronising of the various types of recording equipment on the ground and in the aircraft. It may be noted that even with a somewhat restricted scale of radio communication it proved possible to achieve satisfactory measurements on aircraft coming in to land from other airfields after long sorties.

5. Results using the Artificial Wetting Method

As implied in the previous section, measurements of the landing distances of various aircraft were made at this Establishment, at an R.A.F. airfield and also at a contractor's airfield. The trials reported here were with a fighter type aircraft with tyres of pressures near 230 lb/sq in.; two types of tyre tread were used, as shown in Figure 6, the one being a plain ribbed pattern and the other modified by cross-cuts to promote water removal. As will be shown, the degree of wetness achieved by the method described above proved adequate to produce the very low, near zero conditions of braking that had been reported as occurring under certain flooded conditions in civil and Service use.

During all of the landings considered herein, the pilot technique remained sensibly constant, namely the normal nose-down rotation of the aircraft about the main-wheels on touching-down was assisted by moving the control column firmly into the fully forward position and holding it there throughout the ground run. The nose-wheel was thus brought down onto the runway immediately after the main wheels touched-down (usually within $\frac{1}{2}$ second but at most within 1 second, from the camera evidence). Full maxaret braking was applied within 1 second of touch-down and was maintained throughout the run.

Ideally the determination of the braking force coefficient of the braked main wheels could be obtained by direct measurement of compression and drag loads on the undercarriage legs but the time available for the experiment did not allow the adoption of such techniques. Accordingly, cine-camera records of the landings were analysed to give the total aircraft deceleration, and hence the total retarding force, as a function of speed during the braked portion of the ground roll. The wheel braking force was derived from this total force by making allowance for the aerodynamic drag, using the aircraft incidence observed during the run, and for the engine idling thrust. This braking was expressed as a brake force coefficient, defined as wheel braking force/weight on main wheels. The weight on the main wheels was derived by subtracting the aerodynamic lift, again using wind-tunnel evidence, from the aircraft weight and, finally, allowing for the proportion of the residual load carried by the unbraked nose-wheel. The results obtained are summarised in Figure 5.

The main conclusions to be drawn from Figure 5 are:

(a) the brake force coefficients under all conditions were lower than the values suggested by J.A.C. Paper No. 680, though the cross-cut tyres on the Boscombe Down surface came close to the J.A.C. value at the higher speeds. Such a comparison has to be made with caution as the J.A.C. values apply to the condition of 100% slip whereas the test values shown for the three airfields were obtained with Maxaret units operating. Comparison is not inappropriate however in the present instance. Referring to Figure 1, the Maxaret unit is stated to release brake pressure when the slip has reached 30 to 50%, slip is then reduced to a value between zero and the "impending skidding" value, brake pressure is re-applied and the slip again increased to the 30 to 50% value. In the present landings, an integration process applied to the Hussenot traces of applied brake pressure showed the mean pressure applied was approximately 80% of the maximum. It would thus seem that the retardation in the present trials would be of the same order as might be expected with fully-locked wheels, that is with 100% slip, particularly since some American evidence suggests that, at higher speeds, the reduction in coefficient with slip is somewhat more rapid than is shown in Figure 1.

An apparent anomaly in the results is the low values of coefficient achieved at low ground speeds, values lower than would be expected if a limit was set by available brake torque (in this instance it is understood that torque would limit the coefficient to about 0.35, a value which has some substantiation from the maximum braking that could be achieved on a dry portion of the concrete runway at the R.A.F. airfield). The Maxaret units were still functioning at these lower speeds, though the frequency of operation was appreciably lower than at the higher ground speeds. It could be that the operations of the units at the lower speeds were caused by the wheels passing over exceptionally slippery patches but this seems a tenuous premise. Nor does brake fade account for the low values since they were also obtained in decelerations from relatively low speeds in accelerate-stop manoeuvres.

(b) the cross-cut tyres were superior to the plain ribbed tyre on the two airfields at which comparative tests were made.

(c) the brushed concrete surface at the R.A.F. airfield was markedly inferior to the asphalt surfaces at Boscombe Down and at the contractor's airfield, except at the highest speeds, for the tyres of pressures near 230 lb/sq in. In the light of the information summarised in Section 2, this might be expected since the brushed concrete surface did not seem harsh to the touch. It is to be noted however that adequate braking was achieved at the R.A.F. airfield on a larger aircraft, with bigger wheels at approximately half the tyre pressure above. Recent work (Ref. 14) has indicated that on a dry runway there is a reduction in braking force coefficient with tyre pressure and it is quite clear that much more work will be required to provide an adequate picture of the likely behaviour of any aircraft under wet conditions.

6. Conclusions

Quantitative evidence on the braking force coefficient available between aircraft tyres and wet runways was scarce and of limited application but there have been sufficient incidents of aircraft over-running the available length of runway to show that lack of braking might be a serious problem in the operation of newer aircraft with high landing speeds. Research investigations of the braking coefficient are in hand in this country and in the United States as long-term measures. In the meantime, a method of artificially wetting runways, described within the report, although at first viewed with some scepticism, has justified itself as a possible crash-programme method since it did produce some instances of near-zero deceleration. The measurements made by this Establishment illustrate the considerable variation which can arise from surface and tyre tread conditions and show that much more work is needed to provide an adequate picture of likely behaviour.

7. Acknowledgements

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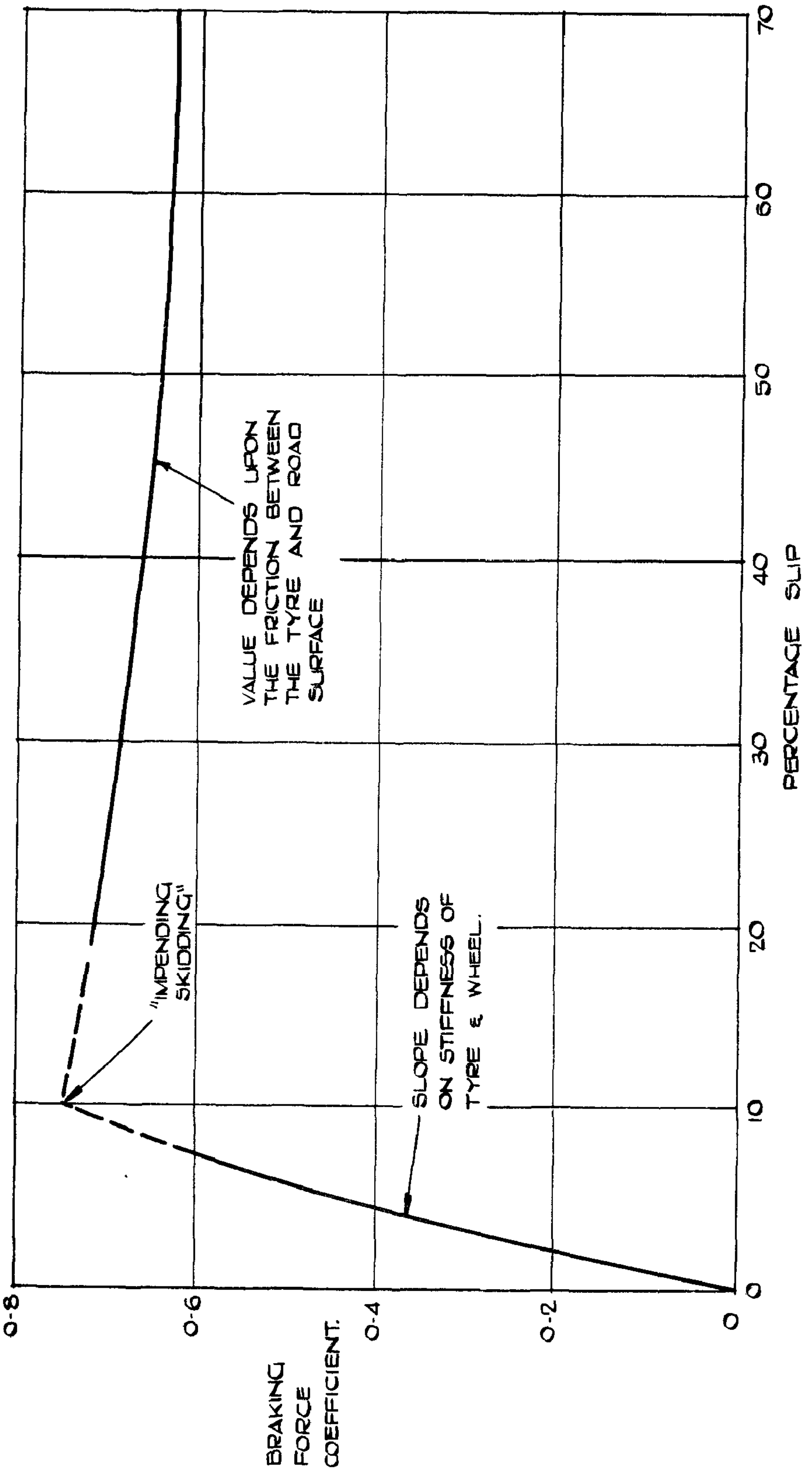
FIG. 1.

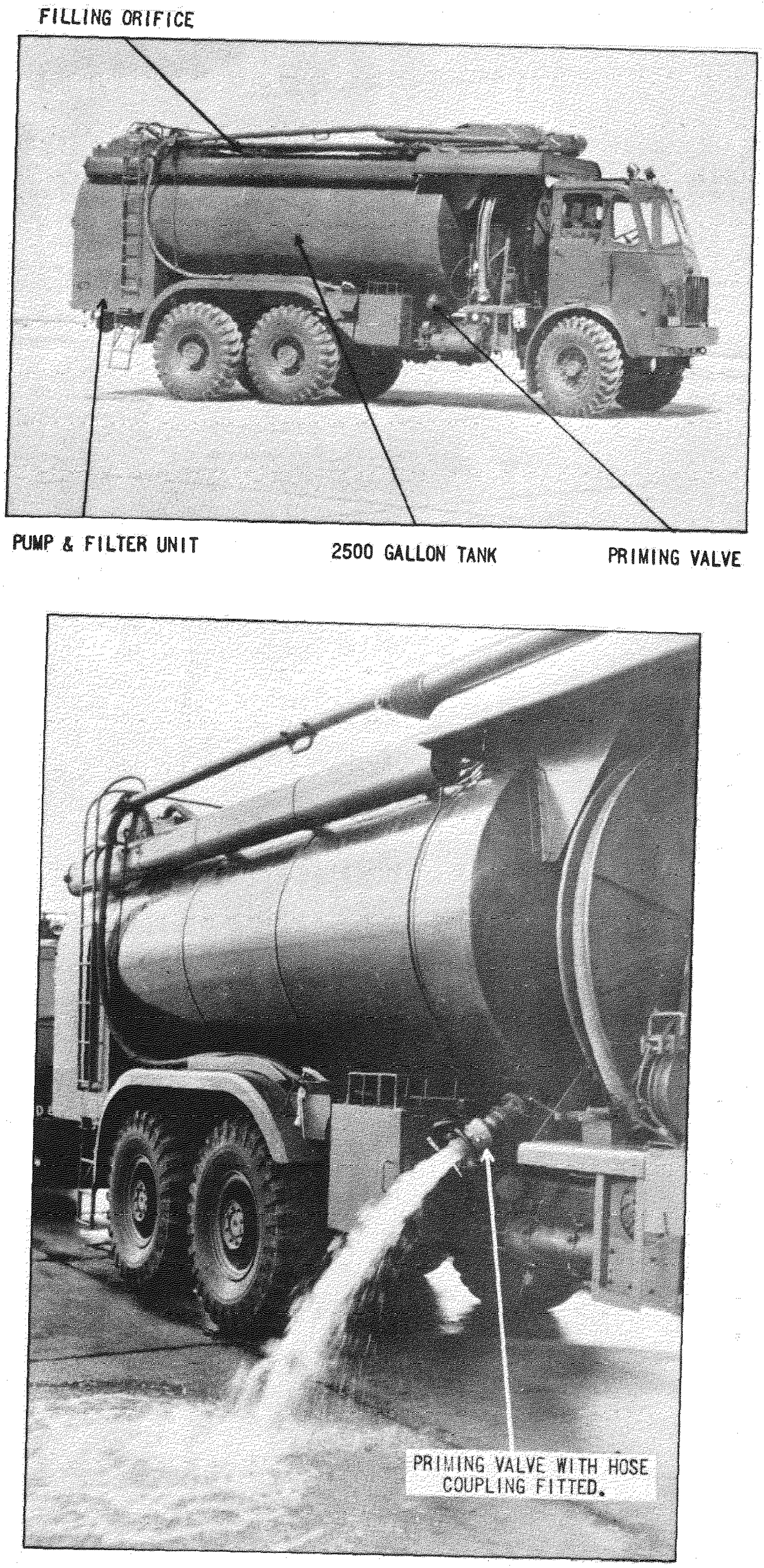
REPRODUCED FROM ref: 4.



VARIATION OF BRAKING FORCE COEFFICIENT WITH SLIP.

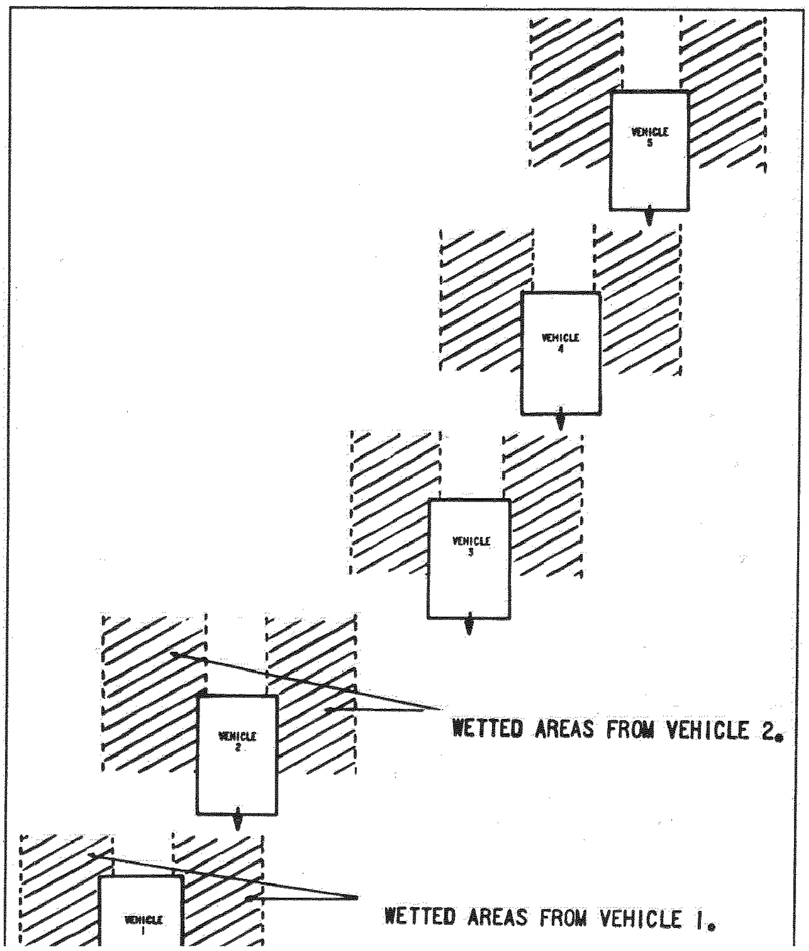
DS 63930/1 Wt. 58 K4 5/62 CL

FIG.2.



DUAL-PURPOSE REFUELLING VEHICLE

FIG.3.


VEHICLE 5
VEHICLE 4
VEHICLE 3
VEHICLE 2
WETTED AREAS FROM VEHICLE 2.
VEHICLE 1
WETTED AREAS FROM VEHICLE 1.

FIGS. 4(A), 4(B), & 4(C).

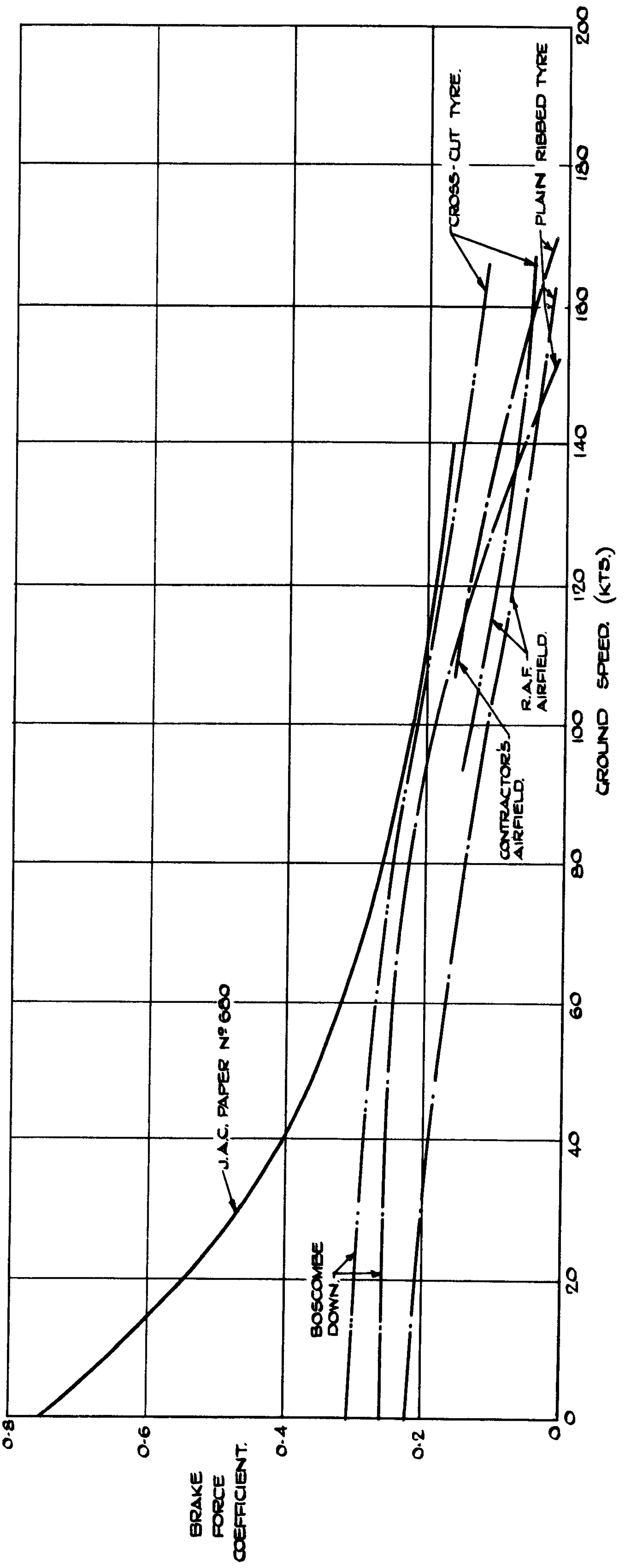
FIG. 4(A). BOSCOMBE DOWN.

FIG. 4(B). R.A.F. AIRFIELD.

FIG. 4(C). CONTRACTOR'S AIRFIELD.

TEXTURE OF SOME RUNWAY SURFACES.- FULL SCALE.

RESULTS ARE FOR FIGHTER AIRCRAFT TYRES OF PRESSURES NEAR 230 LB./SQ.IN.



BRAKING FORCE COEFFICIENTS ON WET RUNWAYS.

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