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*Summary*

The principle results and conclusions of research into slush drag, wheel spray and aquaplaning, using a moving runway and water layer model test facility, are described. The method has proved a valuable compliment to full scale research into these problems.

Suggestions for future research are made.

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*Replaces A.R.C. Report 32 355.

CONTENTS

## 1. *Introduction.*

Wet or slush-covered runways can seriously affect the field performance and safety of aircraft. There are three basic problems; the fluid dynamic drag on the wheels in deep water or slush; the spray thrown up by the wheels which on striking the airframe can cause damage, additional drag and engine malfunction; and thirdly, low friction between tyre and runway. The latter is manifest in its most serious form as aquaplaning when tyre/runway contact and all braking and steering ability are lost.

Research into these problems at Bristol University began in 1961 with the building of a model test facility under a Ministry of Aviation contract. Up to 1965 the research was concerned mainly with the drag and spray problems of single and twin wheels. The work as a whole is described by Barrett in Ref. 1, while References 2 and 3 deal with the basic drag and spray results from, respectively, single and twin wheels. In the second stage of the work, 1966–1967, the facility was used mainly to investigate means of preventing aquaplaning and suppressing spray. This work is described by Roberts, Ref. 4. Since 1967 the research has been concerned with understanding the aquaplaning phenomenon more fully and the outcome of this, prior to 1970, is described by I'Anson in Reference 5.

This note discusses briefly the principle results and conclusions of the work at Bristol and indicates where further research effort might usefully be directed.

## 2. *Model Test Facility.*

The principle of the test method is to run the model wheel on an endless belt onto the surface of which a layer of water is ejected tangentially at the speed of the belt. In this way the forward motion of a wheel on a fluid-covered runway is simulated, except that the air motion relative to the wheel is not represented. The great advantage of this method is that steady test conditions can be maintained for a long time, enabling, for example, detailed spray measurements such as cannot be made in the short time an aircraft traverses a prepared test bed. The limitations and disadvantages of the method, which should be borne in mind when considering and applying the results, are listed below.

(i) Only water is used: differences in behaviour in slush need to be determined from full scale results.
(ii) The tyres used are only approximate scale models. Exactly scaled tyres are extremely difficult and expensive to produce.
(iii) As relative air motion is not represented, spray measurements can only be made fairly close to the wheel, where air drag will have had insufficient time to alter trajectories.
(iv) The condition of water lying on the ground is not represented exactly, as it is impossible to keep the water velocity absolutely constant over the depth of the jet due to air entrainment.

The problems and implications of scaling and of the method are dealt with fully in Ref. 1, where a comprehensive description of the test facility is also to be found. The facility is shown in Figure 1, the test condition it achieves being:—

Speeds to 118 ft/sec
Water depth to 0·5 in. (up to 0·25 in. at full speed)
Wheels to 16 in. diamter (9 in. wheels side by side and in tandem)
Wheel loads to 500 lbs.

## 3. *Principle Results and Conclusions.*

### 3.1. *Single Wheel Drag* (References 1 and 2).

A typical drag curve is shown in Figure 2. In all cases, as speed increased, the drag due to the water at first increased approximately parabolically, then levelled off and decreased. The maximum drag speed, $V_C$, was associated with aquaplaning, as evidenced by wheel spin down; it varied as the square root of the tyre pressure and approximately as the reciprocal of the water depth, but was independent of wheel load. Below $V_C$ drag varied linearly with water depth, while above $V_C$ it decreased more rapidly in deeper water. A circumferentially grooved tyre gave slightly lower values of $V_C$.

Values of a drag coefficient, $C_{DW}$, based on a reference area of water depth × immersed width of the tyre measured at water surface, agreed broadly with full scale values, but showed considerable variation with water depth and tyre load. A second drag coefficient based on tyre footprint width, rather than immersed width, showed greater consistency.

Differently shaped tyres gave different drag coefficients, the main factor being the fineness ratio (diameter/width) of the tyre.

A universal formula for hydrodynamic drag below $V_C$ was suggested which fitted the data from all the tyres examined.

3.2. *Single Wheel Spray* (References 1 and 2).

The spray was examined both photographically and quantitatively. A spray mass flow meter and a spray intensity probe were developed. The latter proved most successful, giving a quick and reliable means of mapping the spray field.

Figure 3 shows an example of spray intensity measurements taken in a plane through one of the main plumes behind the wheel; the intense core was a common feature. Spray intensity was defined as $\tau$, the ratio of the pressure measured by the intensity probe to the dynamic pressure of the water on the runway. Interpretation of the readings is discussed in Reference 1.

The spray patterns varied with speed. Forward and side spray was thrown out at an increasingly acute angle to the ground as speed increased. All the forward spray and the front part of the side spray disappeared above the maximum drag speed. The main spray plumes behind the wheel were thrown higher and further out as speed increased and also became more intense. Increasing the water depth caused a general increase of spray intensity and slight lifting of the main plumes without changing their shape. Grooved and smooth tyres gave similar spray patterns.

The results compared well with photographs of full scale aircraft spray patterns.

3.3. *Drag and Spray from a Pair of Wheels Mounted Side by Side* (References 1 and 3).

The spacing between the wheels was varied and the interference effects on drag and spray examined. As shown by Figure 4, drag increased rapidly as the wheels were brought together, reaching 1·5 times the basic drag when the gap between wheels was 10 per cent of the tyre width. The interference drag extended to greater wheel spacings at the higher speeds, but had reduced to zero in all cases when the gap between wheels was one tyre width.

The spray differed from the single wheel spray pattern in that a central plume was thrown up between the wheels, as illustrated by Figure 5. This was generally more intense and rose higher than the plumes thrown from the outside edges of the two tyres.

3.4. *Experiments with Rigid Models* (Reference 1).

The immersed shape of the tyre, and hence its drag and spray, depended on many factors which could not all be isolated and examined independently in the experiments with pneumatic tyres. The rigid model approach overcame this difficulty to some extent and also allowed more detailed examination of the flow processes.

Drag measurements on straight-sided disks gave constant values of drag coefficient below $V_C$, thus indicating that the variations in drag coefficient with speed shown by the tyres must have been the result of shape changes. These would be due to the progressive lifting of the tyre with increasing speed and to local tyre distortions resulting from hydrodynamic pressure. A unique relationship between the disk drag coefficient and the immersed shape was found.

Spray patterns from the disks were similar to those from the tyres, but showed less change with speed, thus illustrating another effect of the tyres' flexibility.

Flow patterns under the disks were determined by flow visualization techniques and surface pressure measurements, as described in Reference 1. (*See* also Section 3.9 below for extensions of this approach).

A theory of spray formation was shown to be in general agreement with experimental observations of the spray development from an inclined wedge and from the disks.

3.5. *Experiments with Wheels of Reduced Scale* (Reference 1).

The possibility of using much smaller wheels (3 in. diameter) was investigated, as a means of extending the operating range of the facility and also with a view to developing the facility for airframe and engine spray impingement investigations with airflow past the model included. Success was found to depend very much on the tyres used. Initially, foam-filled casings were tried and found to be unsatisfactory. Pneumatic tyres of 3 in. diameter with stiffened casings were then developed for the investigation by the British Aircraft Corporation Wind Tunnel Department at Filton. These proved fairly successful, both single and twin wheel configurations having drag and spray characteristics similar to the larger model wheels. It was considered, however, that the small wheels did not give sufficiently accurate representation in all respects to justify extending the work to airframe and engine spray impingement measurements. (Recently the Royal Aircraft Establishment have developed small model pneumatic tyres which would possibly be more suitable for this).

### 3.6. *Investigations with an Auxiliary 'Sweeper' Wheel* (Reference 1).

A wheel clears a track in water or slush considerably greater than its own width; hence the possibility was investigated of using a small wheel to clear a path for a larger one, in a reversed 'penny-farthing' arrangement. This was shown to be a highly effective way of reducing drag and spray and delaying aquaplaning.

A 3 in. wheel was mounted at distances of 6 and 8 ins. ahead of a 9 in. wheel. The total hydrodynamic drag was considerably reduced over the important part of the speed range, as shown in the example of Figure 6, with the maximum reduction of nearly 50 per cent occurring just below the normal aquaplaning speed of the large wheel. The height and intensity of the spray were also reduced, virtually all the spray coming from the small wheel.

Aquaplaning of the main wheel was delayed until after the small wheel had aquaplaned and allowed water to penetrate to it. By choosing a sufficiently high auxiliary wheel tyre pressure, or by using a special solid auxiliary wheel designed not to aquaplane, it should be possible to eliminate aquaplaning within the normal ground speed range of an aircraft.

### 3.7. *Wheel Path Clearance by Airjets* (Reference 4).

The use of airjets directed at the runway ahead of a wheel was investigated as a means of clearing a path through slush or water and so alleviating drag, spray and aquaplaning.

The best path clearance effect was obtained with a 45 degree rearward inclination of the jet. Nozzle height had little effect and minimum height for safe ground clearance was recommended. Specially shaped nozzles were not successful, but two inclined nozzles in tandem had a greater effect than one for the same total mass flow of air. The optimum arrangement found was with the two nozzles close together and about 1·3 wheel diameters forward of the wheel centre. The most efficient path clearance was obtained with the airjet stagnation pressure approximately the same as the dynamic pressure of the ground water; greater pressures generated too much spray. Other factors being equal, the width of path cleared was proportional to the square root of the air mass flow.

Figure 7 shows an example of the effect of airjet stagnation pressure on the drag of the wheel. It can be seen that moderate jet pressures which produce large drag reductions at speeds below aquaplaning have the opposite effect at higher speeds and that here much greater jet pressures are necessary.

The method was perhaps most effective as a means of delaying aquaplaning. Aquaplaning speed was found to increase as the square root of the airjet stagnation pressure.

Limited tests to determine the effect of the airjets on spray showed that forward spray could be eliminated and that the main plumes were flattened and pushed out sideways as air pressure was increased.

It was concluded that the airjet method could beneficially be applied to aircraft. Due to the large mass flow required and weight of ducting, it would normally be impractical to bleed the air from the engine compressors, and an arrangement of rechargeable high pressure air vessels was suggested.

### 3.8. *Chined Tyres* (Reference 4).

The use of chines on the sidewalls of tyres has been found an effective way of inhibiting spray and a number of chined aircraft tyres are in everyday use. An investigation was made to determine the best shape of chine for spray suppression, using, for simplicity, solid disks in place of tyres. Some of the shapes examined and their effect on the main spray plume angles are shown in Figure 8. More detailed measurements were made with the spray intensity probe. Results showed that chines of practicable dimensions produced relatively small, but perhaps sufficient, changes in spray angle. A simple 45 degree chamfer was found most effective. It was suggested that more elaborate chine shapes giving greater spray suppression could be incorporated on special auxiliary small wheels mounted ahead of the landing gear on the principle discussed in Section 3.6 above.

### 3.9. *Aquaplaning Investigations* (Reference 5 and later unpublished results).

Since 1967 the model test facility has been used for research into aquaplaning with emphasis on determining the mechanisms involved, i.e. the nature of the flow under the tyre which earlier work had shown was not constant with speed, and the tyre deformations which cause these flow changes.

An internal casting technique was developed whereby the shape of the tyre in the proximity of the ground could be determined while it was aquaplaning and not rotating. Rigid models were then made of the external aquaplaning shape of the tyre and by measuring the drag and spray characteristics which these gave and comparing with the actual tyre, it was verified that the casting technique gave a fairly accurate representation of the aquaplaning shape. Tyres of 9, 10 and 16 ins. diameter were investigated in this manner, the latter size in two different casing stiffnesses.

Figure 9 shows a typical aquaplaning tyre shape; three distinct regions are apparent. To the rear of the tyre/water contact area is a horseshoe-shaped region of close proximity to the ground. Within this the tyre is lifted to form a hollow, while further forward the tyre surface is fairly flat and inclined at a shallow angle to the ground. Small variations in this basic shape occurred as forward speed was increased relative to the initial aquaplaning speed and for changes in the combination of tyre pressure and load (see Reference 5). The shape was also influenced by the casing stiffness of the tyre, but for the range of stiffnesses used the effect was only minor.

Aquaplaning height was determined by measuring the rise of the rigid aquaplaning shape models. For the 9 in. diameter tyre it was found to be fairly constant at about 0·02 ins. under all aquaplaning conditions that could be attained.

Static pressures were measured on the surfaces of the tyres and were related to the aquaplaning shapes. A typical result is shown in Figure 10. Two pressure peaks normally occurred, one near the front of the water contact region on the forward slope of the tyre, and the other further back in the enclosed hollow region. The rear peak, which was the higher, started off with a value close to the water stagnation pressure when the tyre was just aquaplaning, but did not then increase appreciably as speed was raised.

The tyre deformation and pressure data and also pressure measurements under rigid straight-sided disks have been compared with results predicted by existing aquaplaning theories. In general, they confirm the validity of the theoretical model which considers the flow in two regions, an inviscid forward region and a close proximity 'footprint' region where viscosity has an important influence.

Straight-sided rigid disks were used to investigate some effects of tyre geometry on aquaplaning speed. It was shown that aquaplaning speed increased as the ratio of disk diameter to disk width was increased. The effect on aquaplaning speed of various configurations of circumferential grooves cut in the disks was measured. In general, adding grooves allows water drainage in the footprint region of a tyre, so reducing hydrodynamic pressures and increasing aquaplaning speed. A number of grooves were found most effective if they were equally spaced across the width of the disk. For the same total groove area, the greater the number of grooves, the higher the aquaplaning speed, provided that the depth of the grooves was greater than the water depth to allow the full drainage effect.

## 4. *Concluding Remarks—Suggestions for Future Research.*

The model test facility has proved a valuable means of investigating the hazards to aircraft of wet and slush-covered runways. It is cheap and simple to operate compared to full scale testing. Perhaps its greatest advantage is that a given set of test conditions can be maintained indefinitely, so enabling detailed quantitative measurements to be made in the spray close to the wheel. In view of this it is suggested that one of the most profitable future uses of the facility would be as a means of developing spray deflectors and shields. There is an urgent need for such devices at the present time.

The moving runway method has also proved valuable for studying aquaplaning in detail. It is possible that data of the type obtained could lead to changes in tyre tread design. If so, the facility could be used to evaluate aquaplaning characteristics and optimise suggested new tread forms.

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| *No.* | *Author(s)* | *Title, etc.* |
|---|---|---|
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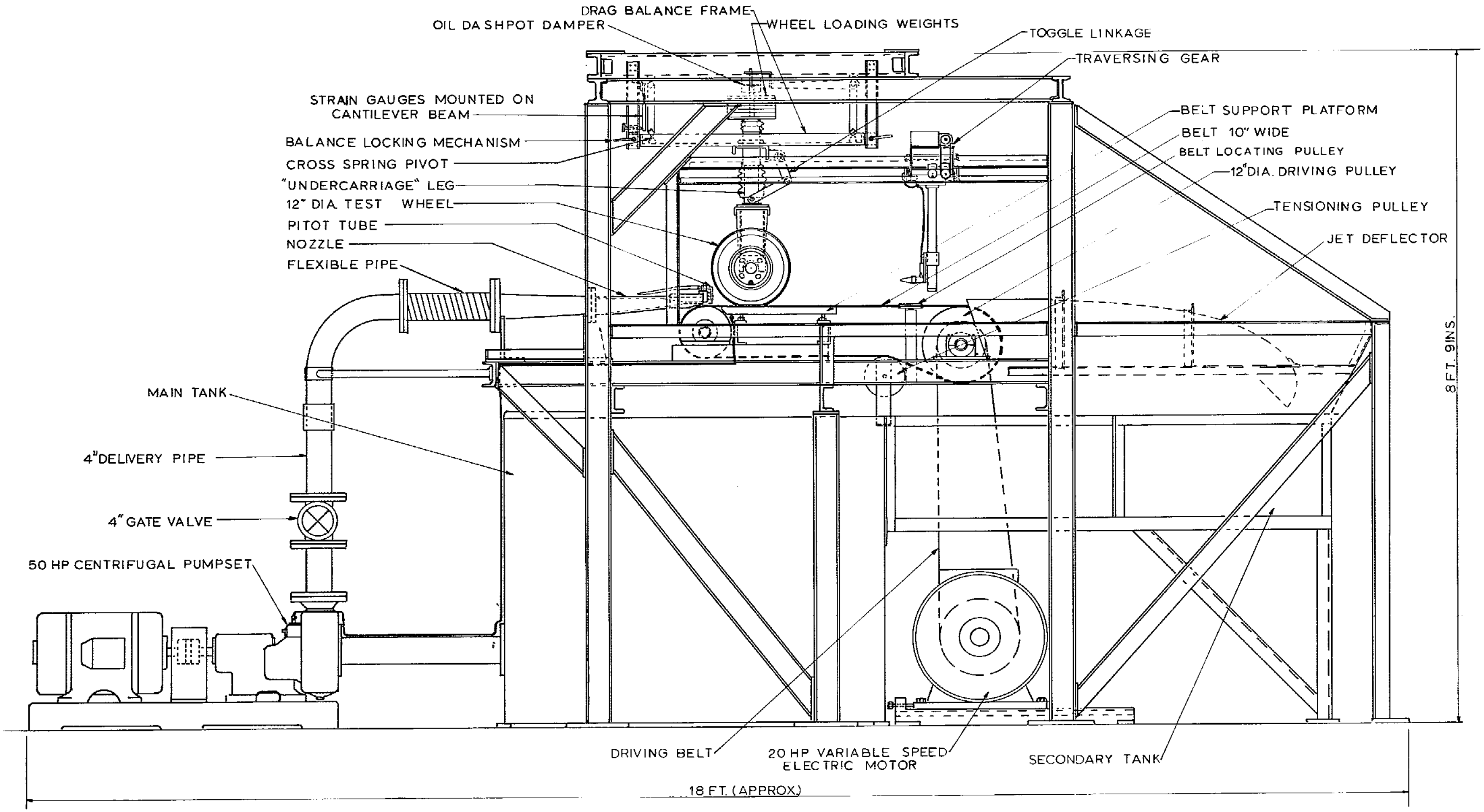

FIG. 1. General diagram of wheel test apparatus. Note: Spray shielding omitted for clarity.

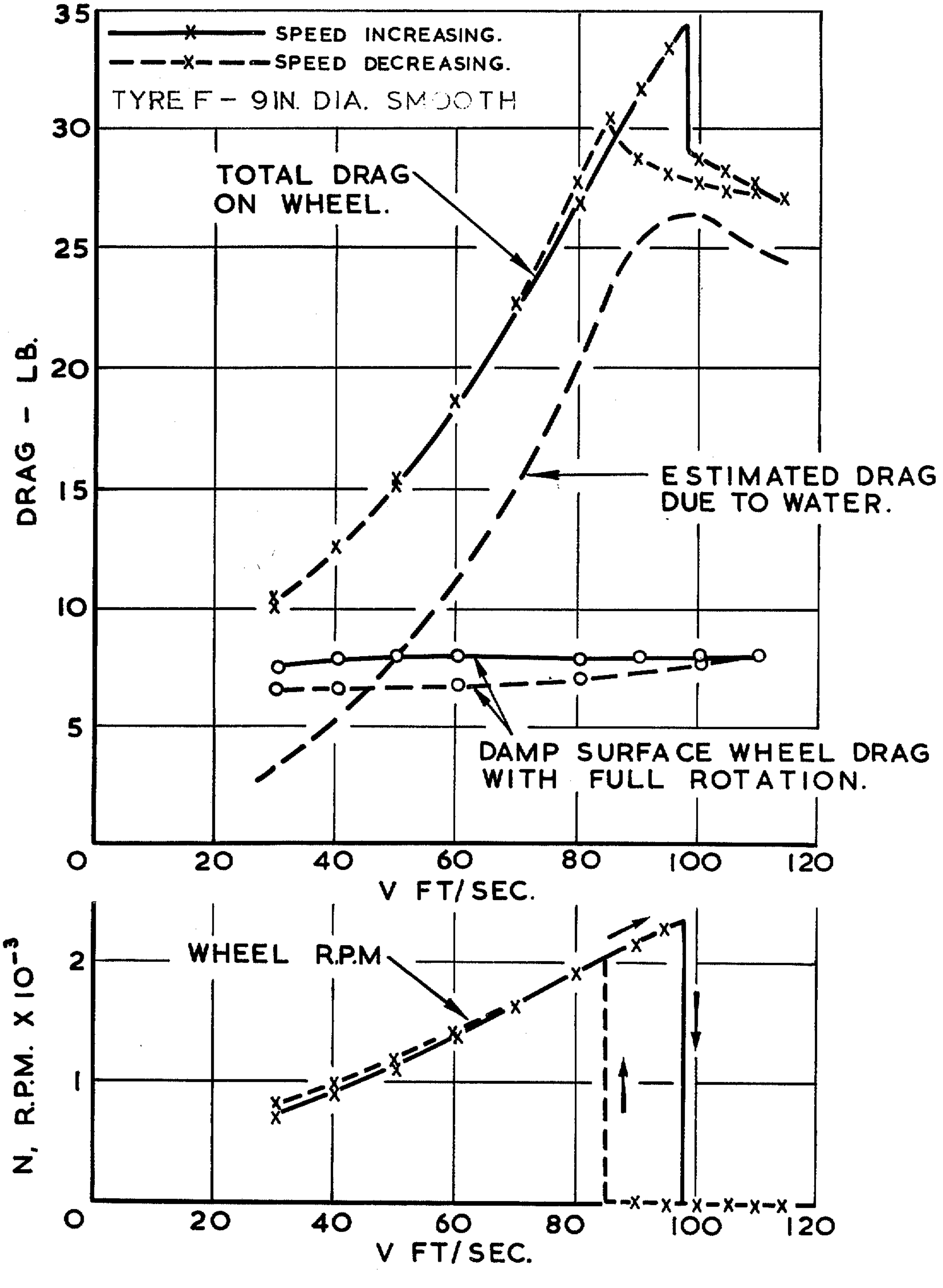

FIG. 2. Typical variation of drag with speed for tyre 'F' on rough surface. p = 30 p.s.i. W = 200 lb. d = 0·25 in.

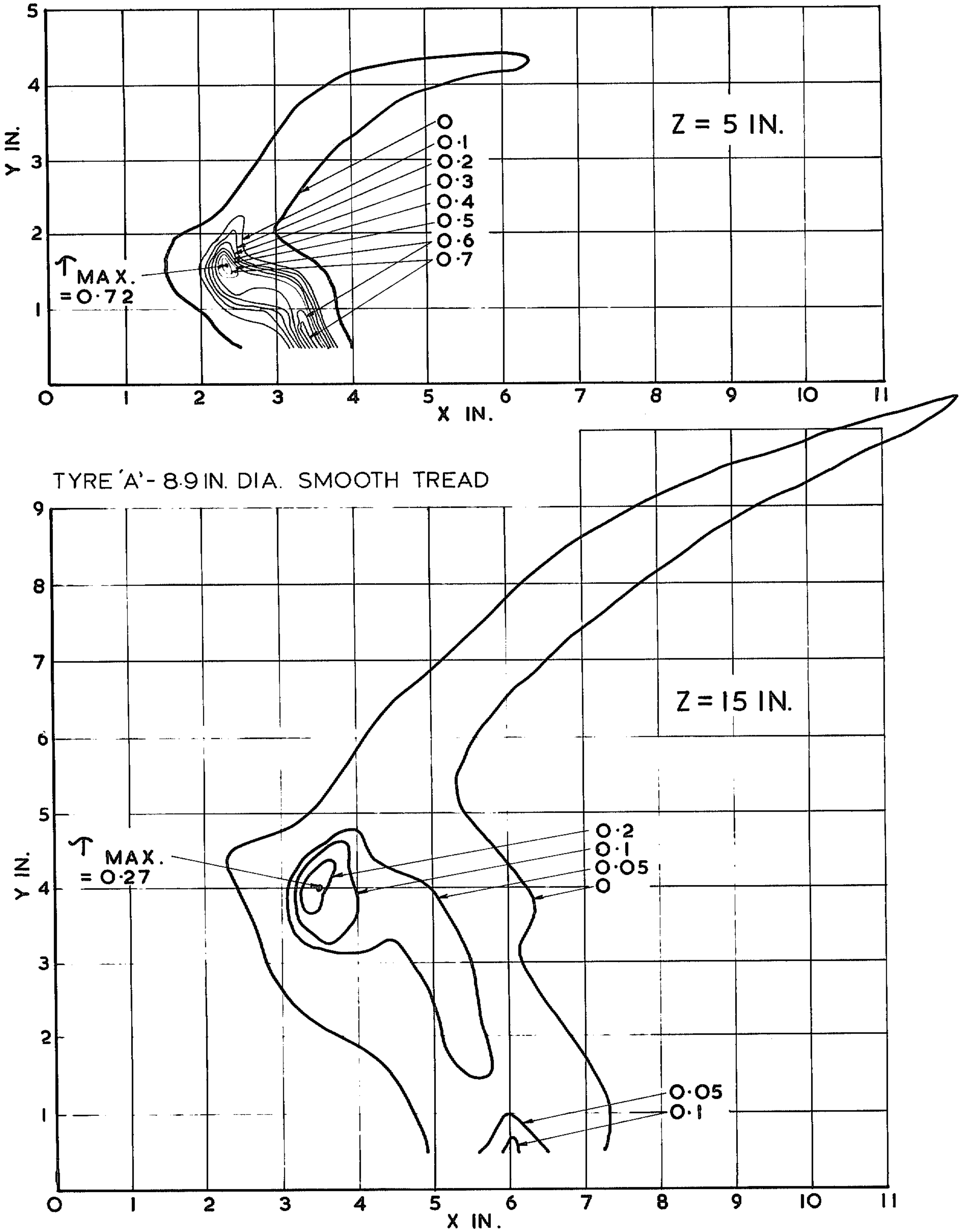

FIG. 3. Distribution of intensity within the main spray at $V$ = 115 ft./sec. Tyre 'A' on smooth surface, p = 30 p.s.i., W = 200 lb., d = 0·25 in. Zero wheel rotation. N.B. Contours are of constant $\tau$.

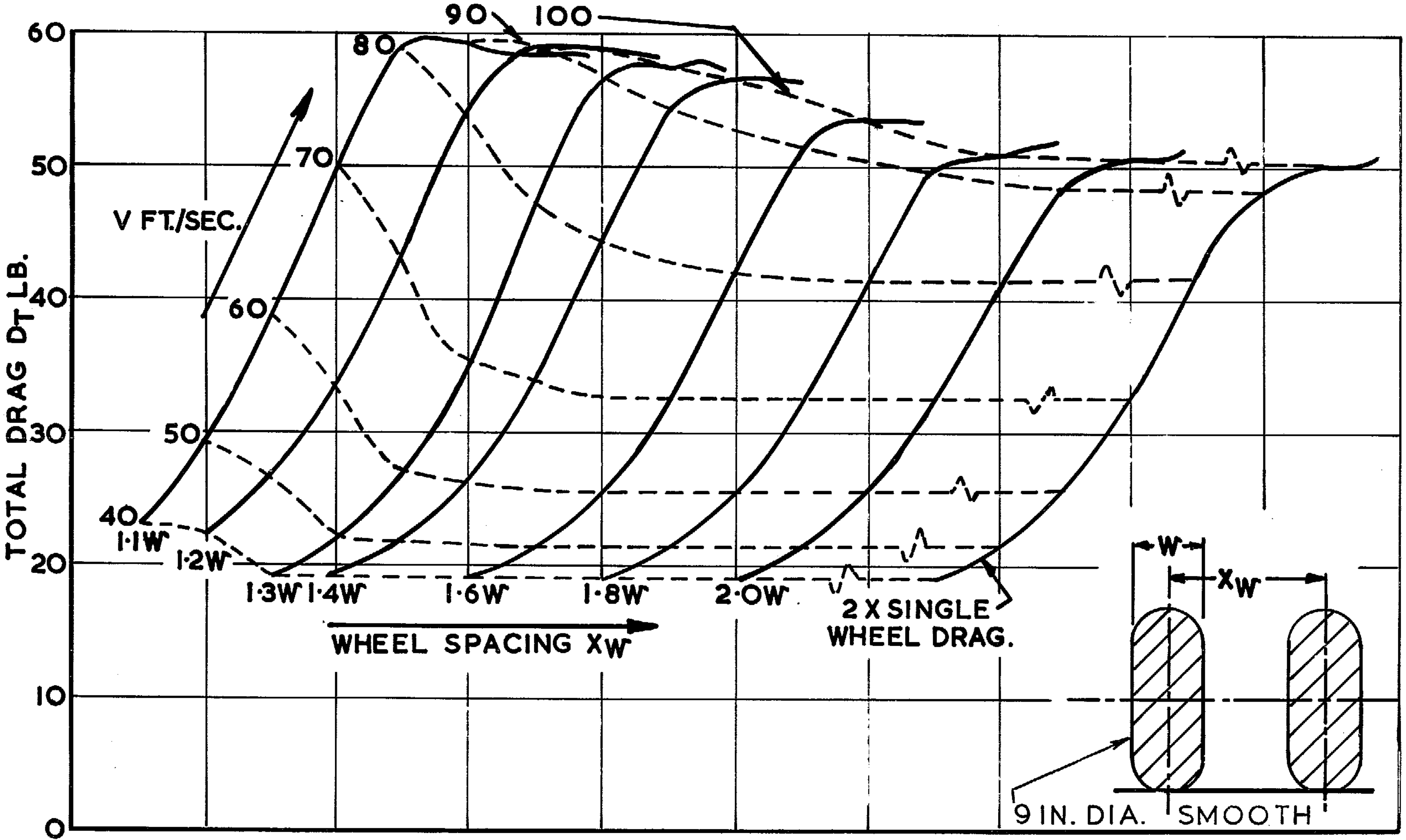

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FIG. 4. Twin wheels—Variation of total drag with forward speed and wheel spacing. 2X tyre 'F' on smooth surface, $p = 30$ p.s.i., $W = 200$ lb./wheel, $d = 0{\cdot}20$ in. Wheel rotation $< 100$ r.p.m. for $V = 40$ and $50$ ft./sec., and zero for higher speeds.

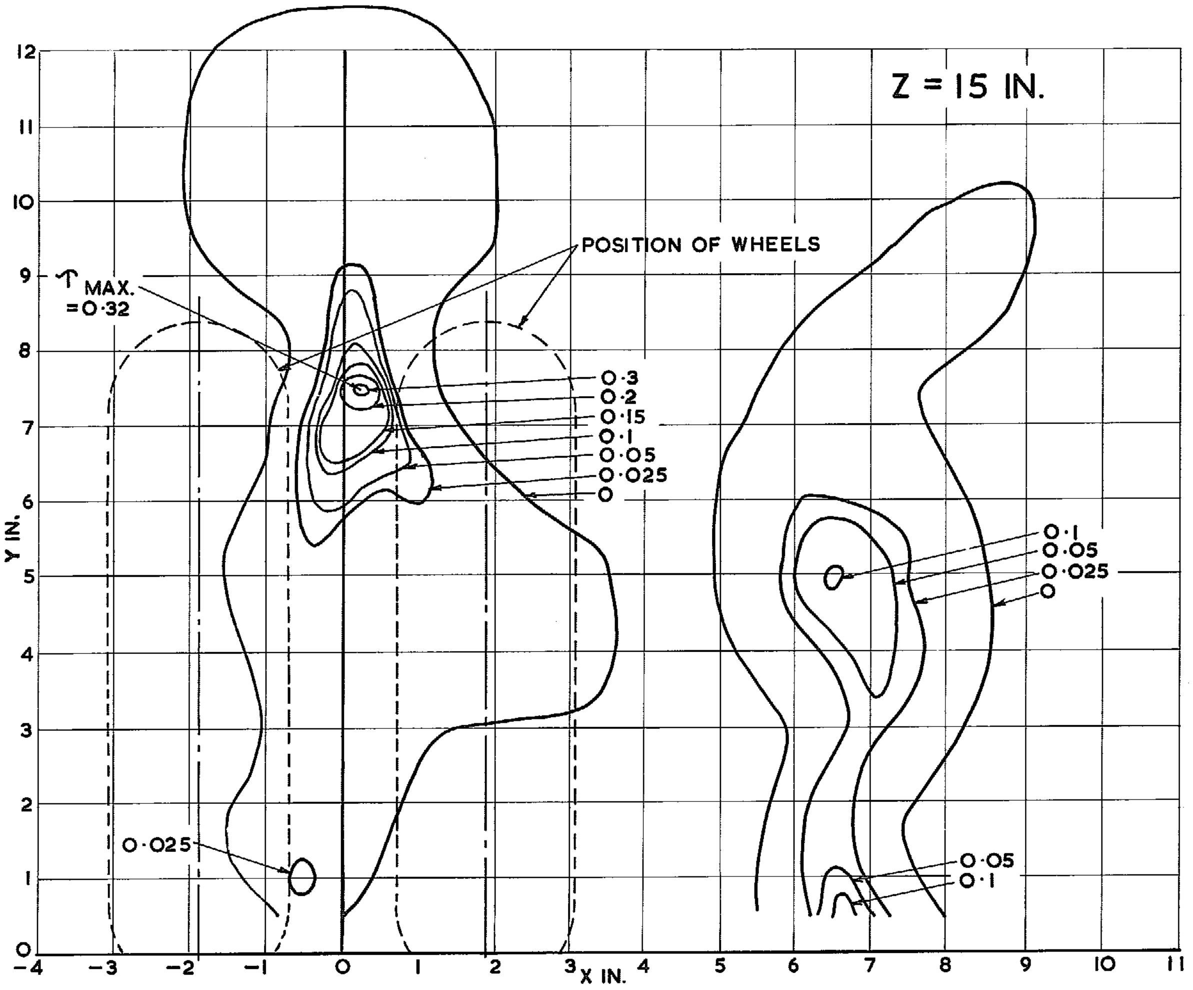
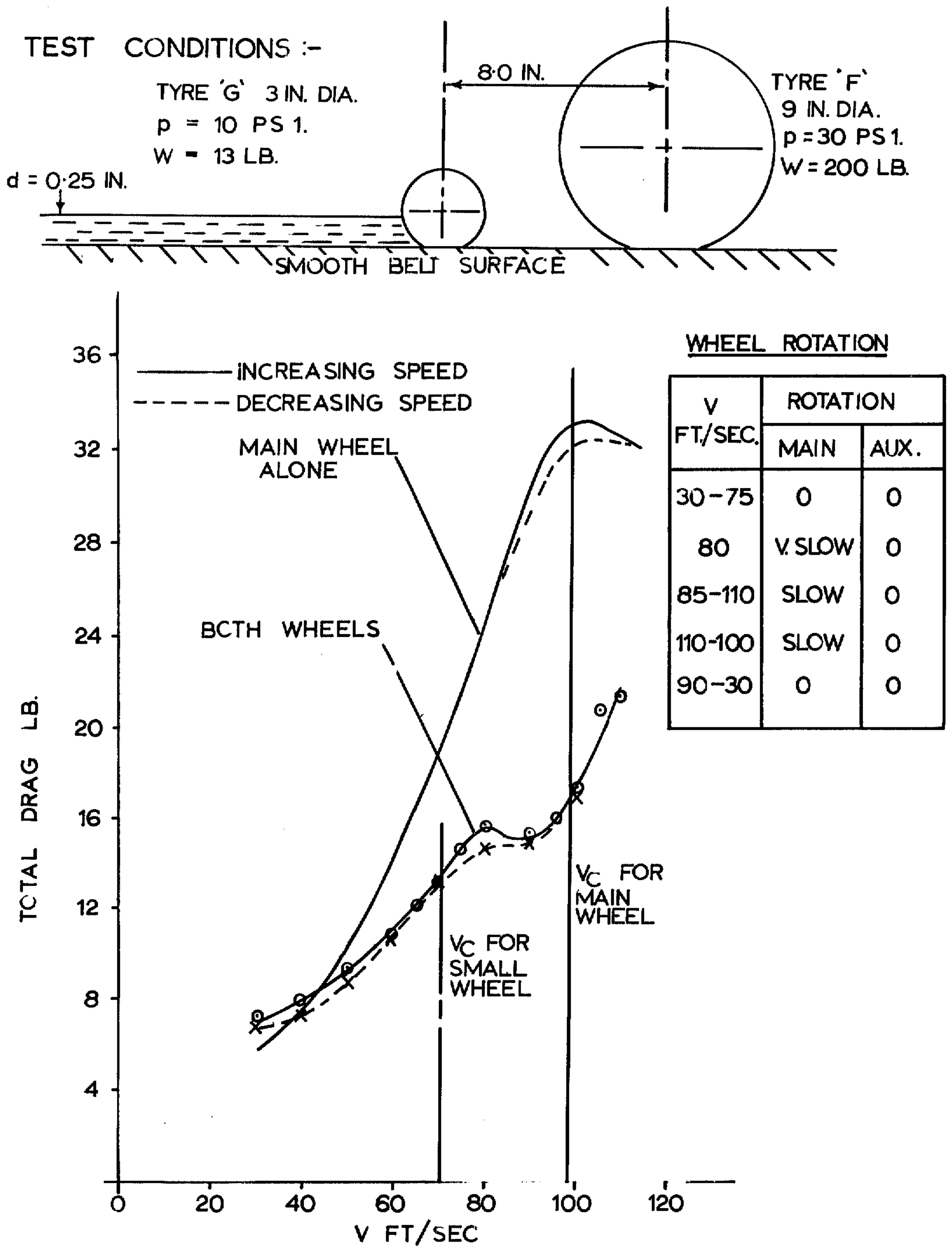


Fig. 5. Distribution of intensity within the main spray at V = 108 ft./sec., wheel spacing $X_W$ = 1·6W. 2X tyre 'F' on smooth surface, p = 30 p.s.i., W = 200 lb./wheel, d = 0·20 in. zero wheel rotation. N.B. Contours are of constant τ.



WHEEL ROTATION

| V FT./SEC. | ROTATION | |
|---|---|---|
| | MAIN | AUX. |
| 30–75 | 0 | 0 |
| 80 | V. SLOW | 0 |
| 85–110 | SLOW | 0 |
| 110–100 | SLOW | 0 |
| 90–30 | 0 | 0 |

FIG. 6. Effect of the auxiliary wheel on the total drag variation with speed.

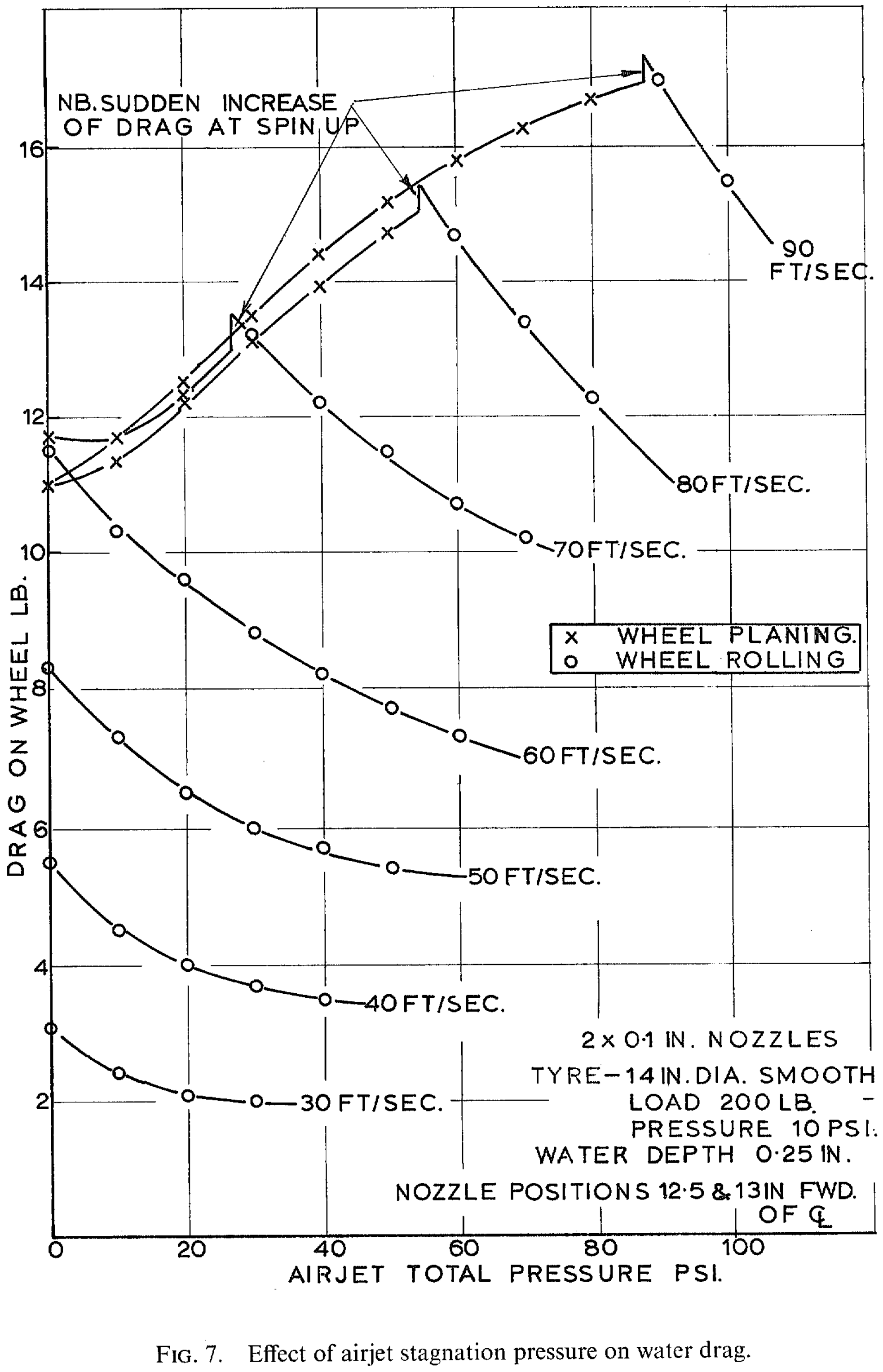


FIG. 7. Effect of airjet stagnation pressure on water drag.

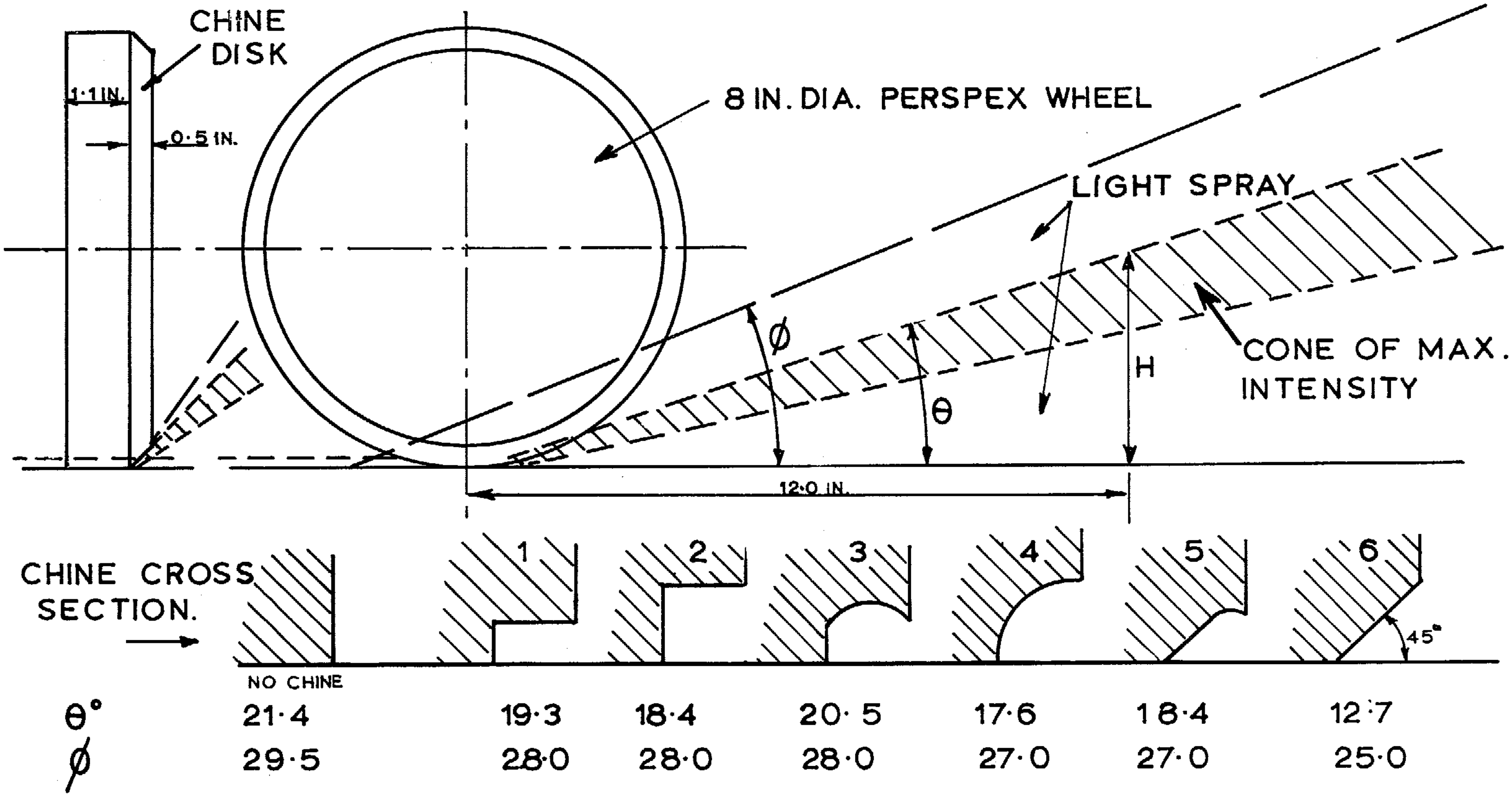


FIG. 8. Preliminary investigation of spray deflection by chines.

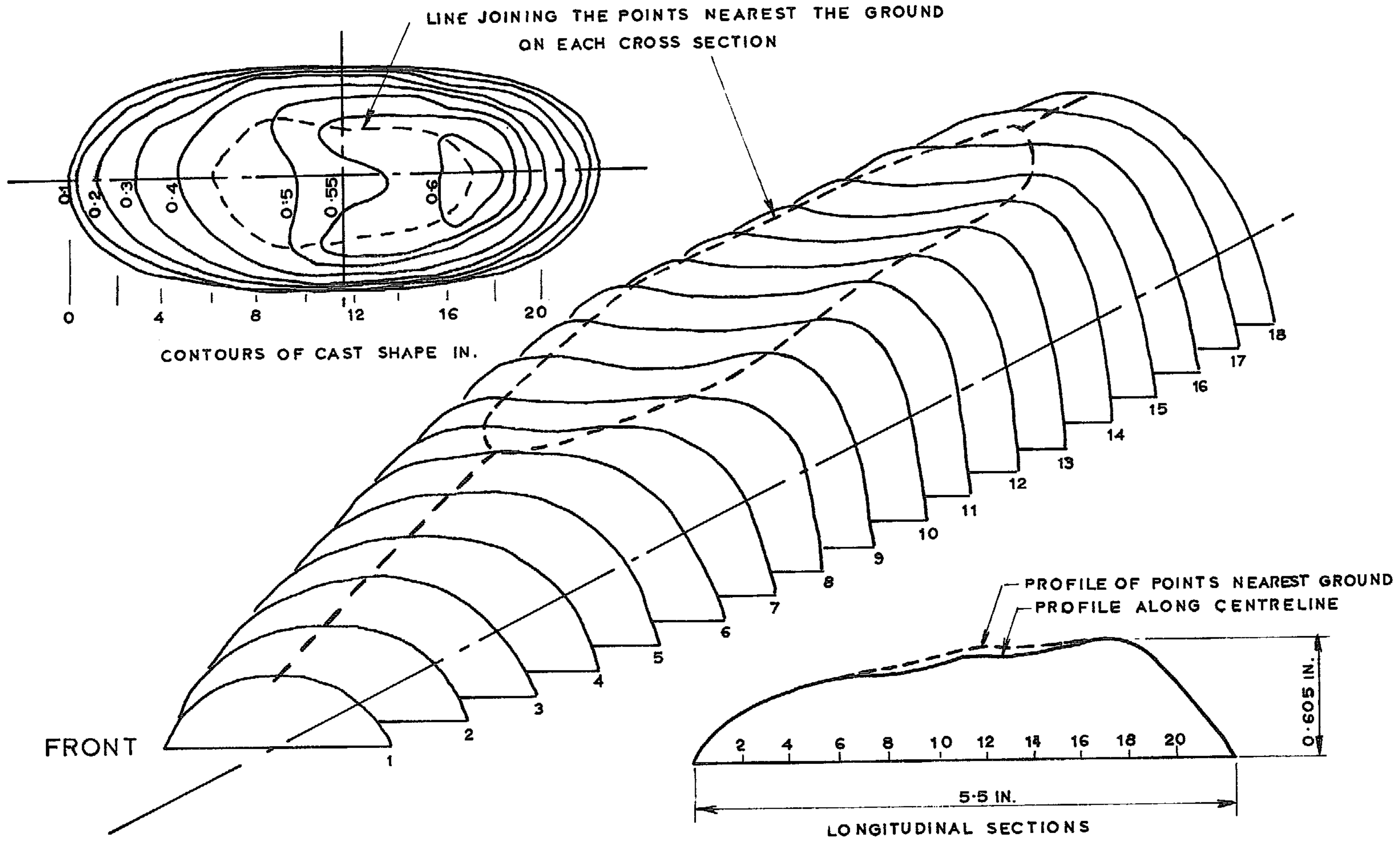
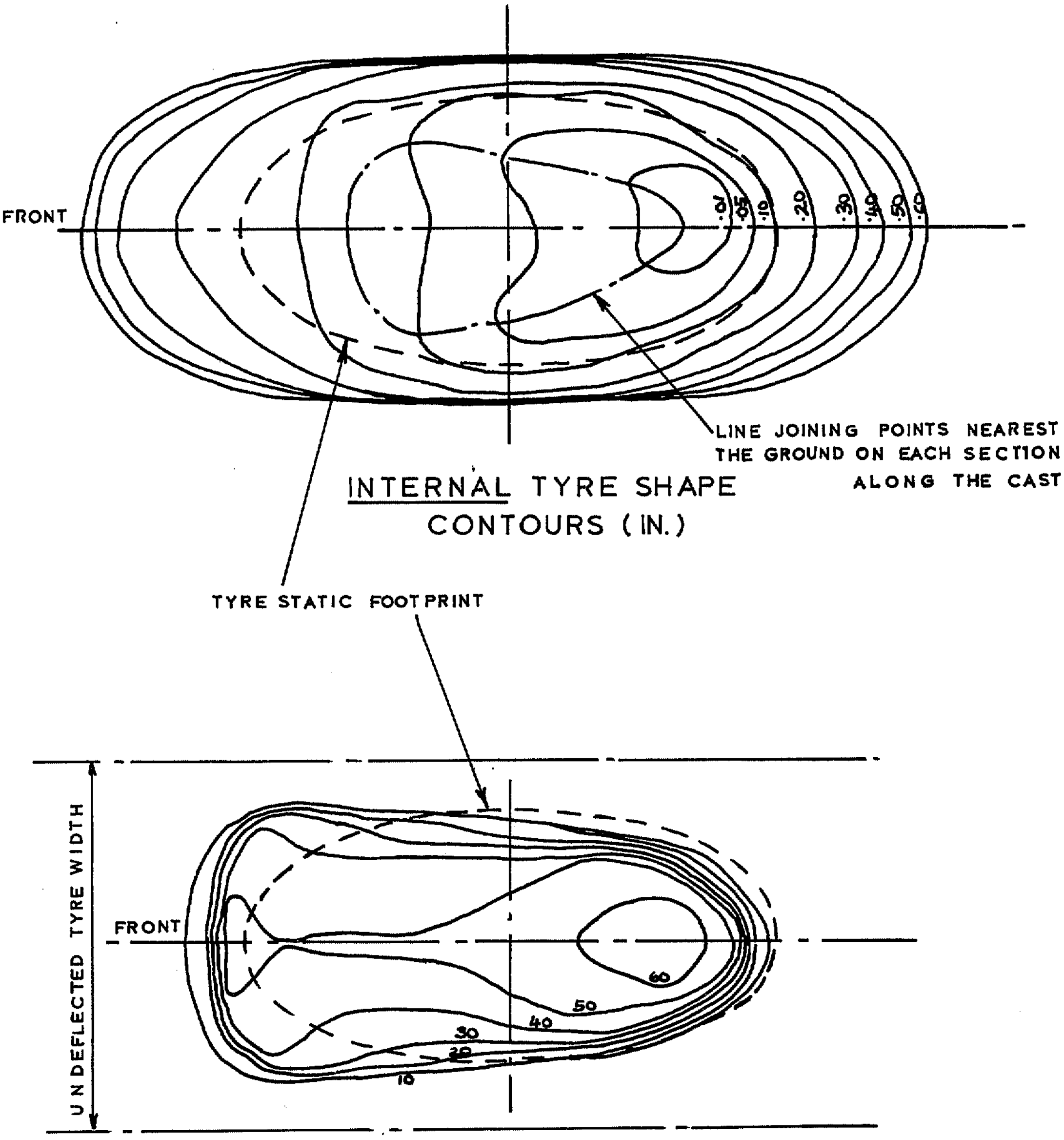


FIG. 9. Deflected shape of aquaplaning tyre.

$P_t = 20$ lb./in$^2$ $\quad V = 100$ ft/s
$d = 0{\cdot}25$ in. $\quad W = 150$ lb.



INTERNAL TYRE SHAPE CONTOURS (IN.)

PRESSURE CONTOURS (P.S.I.)

FIG. 10. Comparison of aquaplaning tyre shape with tyre surface pressure distribution.

$Pt = 40$ lb/in$^2$

$W = 200$ lb.

$h = 0{\cdot}25$ in.

$$\frac{Pd}{pt} = 2{\cdot}04.$$

$$\frac{\delta}{w} = 2x{\cdot}8\,\%$$

$$\frac{W}{pt} = 5.$$

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