



ESDU TECHNICAL MEMORANDUM

Impact forces resulting from wheel generated spray: a re-assessment of existing data

A. Stanbrook

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The development and preparation of this Technical Memorandum was undertaken by

Mr A. Stanbrook

— Consultant to ESDU.

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IMPACT FORCES RESULTING FROM WHEEL GENERATED SPRAY: A RE-ASSESSMENT OF EXISTING DATA

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IMPACT FORCES RESULTING FROM WHEEL GENERATED SPRAY: A RE-ASSESSMENT OF EXISTING DATA

1. NOTATION

		SI	British
a	constant in Equation (4.1)	N/m ²	lbf/in ²
b	constant in Equation (4.1)	—	—
c	constant in Equation (4.1)	m ² /N	in ² /lbf
FMD	reading from Force Measuring Device	N/m ²	lbf/in ²
IP	reading from Spray Intensity Probe	N/m ²	lbf/in ²
$K[\theta]$	function of flow angle, θ	—	—
V	free stream speed	m/s	ft/s
V_A	reference speed (see Reference 1)	m/s	ft/s
x	distance downstream (measured from wheel/surface contact)	cm	in
y	distance laterally (measured from wheel/surface contact)	cm	in
z	distance vertically, +ve up (measured from wheel/surface contact)	cm	in
θ	angle between flow and axis of probe	—	—
σ	effective density	kg/m ³	slug/ft ³
τ	spray intensity (ratio of measured pressure to nozzle pitot pressure)	—	—
ϕ	mass flow reading (ratio of measured mass flow to nozzle mass flow)	—	—
Subscripts			
s	spray		
T	true value		

2. INTRODUCTION

ESDU 83042 (Reference 5) gives a method for estimating the location of spray patterns based, in part, on research work at Bristol University (References 1 and 2) using a *Spray Intensity Probe* (IP) to obtain surveys of spray kinetic pressure behind a wheel running in water.

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Other work at Bristol University found that integration of the pressures measured by this probe gave forces some 35–45% lower than direct measurements of the force on a large square plate. Further studies were made at Bristol University using a *Force Measuring Device* (FMD) to measure the force on a small plate in an attempt to provide an understanding of the IP results.

This memorandum presents a re-assessment of these various experiments to determine how results from the IP can best be used to predict the loads resulting when the spray impinges on an airframe.

3. SUMMARY OF WORK COMPLETED AT THE UNIVERSITY OF BRISTOL

It should be noted that, with the succession of experimenters involved, the axis system varies between the reports on the University of Bristol experiments. Where coordinates are referred to here, they follow the convention of x streamwise, y spanwise and z vertically up, all measured from the wheel/surface contact point. Where figures have been copied, coordinates have been altered to suit.

3.1 Measurement of Spray Intensity Patterns from Small Pneumatic Tyres (Reference 1)

Tests were made using the University of Bristol flooded-runway wheel test facility, which consisted of an endless belt upon which the wheel ran freely, and onto which a layer of water was ejected, from a slot nozzle, at the same speed as that of the belt. Measurements were made of spray intensity using a probe consisting of a pressure transducer mounted in a cavity behind a 0.1 in diameter, sharp-edged orifice (Figure 1 and Appendix A).

Typical contours obtained are shown in Figure 2.

3.2 Comparison of Forces Obtained by Integrating IP Results with Forces Measured on Large “Impingement” Plate (Reference 3)

In order to produce a consistent spray pattern in which it would be possible to make comparative measurements, the wheel/tyre combination was replaced by a rigid perspex wheel (20.3 cm diameter, thickness not quoted[†]) resting on a stationary plate. A section of spray was isolated by a screen presenting a square aperture to the spray and deflecting the remainder of the spray away from the test area (Figure 3). The square aperture was at $x = 18$ cm. Its position in the y and z directions is not quoted; the only indications being

- (1) in an isometric diagram of the relationship of survey planes to the wheel and
- (2) in a graph showing the locus of the core of the spray.

Unfortunately, these do not agree.

The resulting spray pattern was surveyed by the IP at six streamwise positions, $x = 24.1, 29.2, 35.2, 44.2, 51.6$ and 58.8 cm. Contours of spray intensity at the six positions are shown (at full scale dimensions and spaced across the page in proportion to the x dimension) in Figure 5[‡]. The outermost contour is for $\tau = 0.02$, where τ is the ratio of spray intensity pressure to the nozzle pitot pressure. Contours are also given for $\tau = 0.08, 0.14, 0.20, 0.26, 0.32, 0.38$ and 0.44 , as appropriate for the peak value at each station.

[†] Another study on the same rig used a wheel of 20.3 cm diameter and 2.76 cm thick.

[‡] Another contour map was produced at $x = 35.3$ in the course of another part of the study, but is not displayed in Figure 5.

A 10×10 cm plate was then placed normal to the spray at three streamwise positions, $x = 35.3, 47.0$ and 58.8 cm, and the force on it measured at each. Figure 4 shows the plate and its spray shields. The y and z positions of this “impingement” plate at each streamwise station are not quoted any more precisely than “the centre of the plate was close to the centre of the plume”. No tare measurements were taken, *i.e.* measurements with the plate supported in position but not connected to the measuring beam, with gaps represented as well as possible. The tare forces are probably small and positive. They should have been measured; their absence results in some uncertainty about the results.

Figure 6 shows the relative positions of the wheel, screen and the various survey positions.

Figure 7 shows the comparison obtained between the direct force measurements on the plate and the integrated pressures from the probe (as reported in Reference 3). It will be seen that the measured force decreased only slightly with distance downstream but that the force estimated from integrated pressures decreased significantly over the same range. At $x = 35.3$ cm it was 61–66% of the direct measurements and at $x = 58.8$ cm it was only 57%.

Further direct force measurements were taken with the 10×10 cm plate (and a larger one) at various angles to the spray. These results will be discussed later.

3.3 Comparison of Readings from IP with Forces Measured on a Small FMD (References 6 and 7)

The differences between measured forces and integrated pressures were interpreted as resulting from lack of efficacy of the spray intensity probe. In an attempt to provide some form of calibration for the probe readings, comparative surveys were made between the probe and a small FMD consisting of a small square plate mounted from a cantilevered beam (Figure 8). The plate was 0.48 cm square (compared with the 0.25 cm (0.1 in) diameter of the probe). The beam was, in fact, a double beam, comprising

- a thin one to which the plate was attached, which operated on its own when applied loads were low
- and • a thicker one which provided additional stiffness when applied loads were larger.

The beams were housed within a streamlined fairing in an attempt to protect them from spray impact.

Readings from the undamped device were found to be erratic due to severe vibration of the thinner of the two beams and it was obvious that damping was necessary. This was introduced in the form of a paddle attached to the forward beam and suspended in a viscous fluid. Three degrees of damping were tried, using different size paddles. The readings inevitably varied with the degree of damping because they were taken in a continuous, *i.e.* non-stop, traverse. The two highest levels of damping were considered excessive, the undamped results suffered from severe vibration, so the best results were judged to be from the lightly damped device. Again, no tare measurements were taken, *i.e.* on the FMD without the small plate attached. The FMD pressure pattern for the lightly damped device is shown in isometric projection in Figure 9[†] and as a contour map in Figure 10[†]. Results from comparative traverses at two longitudinal stations are shown in Figure 11[†]. The positions are quoted as $x = 18$ and 36 cm, but the 18 cm figure is unlikely, since the deflector screen is, presumably, at the same position as in Reference 3, *i.e.* $x = 18$ cm.

[†] Copied from Reference 6

Further comparative measurements were made (Reference 7), modifying the FMD in an attempt to reduce errors from, in particular, loss of damping fluid. Water getting into the fairing resulted in loss of damping fluid and the tests were eventually made in an undamped condition (contrary to the earlier decision). Problems in positioning the FMD and IP accurately made it difficult to ensure that they traversed the same region of spray. Consequently, comparisons were obtained by interpolating data from contour maps from the two devices running at the same conditions. The results at $x = 28$ cm are shown in Figure 12[†].

The impingement plate used in the Reference 6 tests was 10×6.5 cm (no reason was given for the change). Measurements were made at three different values of the nozzle pitot pressure and comparisons[‡] between average pressures from the various devices are shown in Table 3.1. Again, no tare measurements were taken.

TABLE 3.1 Comparison of average pressure over same area for different instruments

	Reference 6			Reference 3			
Position of survey, x (cm)	36.0			35.3	44.2	47.0	58.8
Nozzle pitot pressure (lbf/in ²) (kN/m ²)	40 276	30 207	20 138	79 545			
Size of large static plate	10×6.5 cm			10×10 cm			
Instrument	Average pressure (kN/m ²)			Average pressure (kN/m ²)			
Large static plate	2.9	2.4	1.75	10.4	–	10.3	10.2
FMD heavily damped	3.1	–	–				
medium damped	3.0	2.5	1.7				
lightly damped	2.8	2.5	1.6				
undamped	2.9		1.95				
shrouded/heavily damped	2.0		0.5				
IP	2.0	1.5	1.0	6.8 6.4	6.4	–	5.8

The intention in choosing the original size of the impingement plate (10×10 cm) was to ensure that the whole of the spray plume would lie within the confines of the plate. If this was achieved then the larger plate should have a smaller average pressure. This does not appear to be the case. As a further check, Table 3.2 compares the total force measured (or integrated) on the plate, normalised by dividing by the nozzle pitot pressure.

[†] Copied from Reference 7

[‡] The data in Table 3.1 have been adapted from those in Reference 6 so that pressures are in comparable units. For convenience, additional columns showing similar results from Reference 3 are also shown.

TABLE 3.2 Comparison of forces for different instruments

	Reference 6				Reference 3			
Position of survey, x (cm)	36.0				35.3	44.2	47.0	58.8
Nozzle pitot pressure (lbf/in ²) (kN/m ²)	40 276	30 207	20 138		79 545			
Instrument	Force/Nozzle pitot pressure [†] (m ² /1000)							
Large static plate	0.68	0.76	0.82		1.91	–	1.89	1.87
FMD heavily damped	0.73	–	–					
medium damped	0.71	0.78	0.80					
lightly damped	0.66	0.78	0.75					
undamped	0.68		0.92					
shrouded/heavily damped	0.47		0.24					
IP	0.47	0.47	0.47		1.25 1.17	1.17	–	1.06

[†] Force = Area × Average pressure (as quoted in Table 3.1)

Two points should be noted here.

- Results from Reference 3 and 6 differ greatly. This could indicate that the spray is larger than assumed and not entirely within the confines of the Reference 6 plate. It is also possible that the spray pattern under investigation had been affected by the change in nozzle pitot pressure.
- The results from the spray intensity probe reported in Reference 6 are more consistent than those from the other devices, not changing at all with nozzle pitot pressure. Again, there are differences between References 3 and 6. It will be seen later that there is uncertainty about the numerical integration process used in References 3 and 6.

4. RE-ANALYSIS OF EXPERIMENTAL DATA

It is suggested in Reference 9 that the discrepancy between direct force measurements and integrated pressures stems from the following two effects:

- errors in the IP measurements, particularly at low pressure
- and
- failure to include that part of the pressure field outside the $\tau = 0.02$ contour (the lowest value in the Reference 3 contour plots).

These will be discussed in Sections 4.1 and 4.2.

4.1 Calibration of IP Against FMD

On the assumption that FMD results are more reliable than those from the spray intensity probe, it should be possible to produce a calibration curve linking FMD results with the corresponding probe results.

It is known that problems had been experienced with the FMD device in Reference 6. Two levels of damping and the undamped state were discarded as unreliable and the lowest level of damping accepted as a compromise. Despite this, follow-up measurements in Reference 7 were taken in the undamped state, because of problems with the damping. Furthermore, in Reference 7 it was not possible to position the probe and FMD sufficiently accurately to make actual comparative traverses; cross-sections of contour maps produced by the two devices were used instead. This is not entirely satisfactory. It throws doubt on the earlier results (which were produced by comparative traverses) and, indeed, on the value of any of these results. The following analysis must be viewed in the light of these problems.

Comparative values from the Reference 6 results for the IP and the FMD can be obtained easily, since data from the devices were taken at identical y -positions. It is simply a matter of listing the (lightly-damped) FMD values against the intensity probe values from Figure 11.

The same is not true of Reference 7 data. In this case it is necessary to find values on the curve through the FMD points at the y -positions of the IP data. It is, therefore, important that suitable curves are fitted to the FMD data. The curves in Figure 12 (from Reference 7) have clearly been drawn manually, by someone with a rooted objection to allowing the curve to go above the highest measured point. Figure 13 shows the same data with curves fitted by various numerical techniques. With the help of these it is possible to find FMD values at y -values corresponding to the IP readings.

The resulting pairs of values are plotted in Figure 14 in which it should be noted that the demonstrated correlation between FMD and IP readings does not, in itself, imply that either reading is more nearly correct than the other.

It will be noted that, up to 20 lbf/in², FMD is greater than IP whilst at higher values FMD becomes less than IP. Since (a) uncertainty about the spray intensity probe readings only relates to very low pressures and (b) there is no obvious physical reason why the spray intensity probe should read high, there is inevitably some doubt about the FMD at high pressures.

The curve shown (a Least Squares fit) has the equation

$$FMD = a \left(1 - e^{-c IP} \right) + b IP, \quad (4.1)$$

in which FMD is the reading from Force Measuring Device (lbf/in^2) and IP is the reading from the Spray Intensity Probe (lbf/in^2),

where $a = 4.935112 \text{ lbf/in}^2$,

$b = 0.674142$

and $c = 0.6815 \text{ in}^2/\text{lbf}$.

This curve is virtually a straight line except near zero where it dips to go through the origin. The lower graph shows the region near the origin. The data are plotted using different symbols depending on whether the FMD was operating at High or Low sensitivity, in order to confirm that the dip to the origin had not resulted from the two-beam design of the FMD.

4.2 Comparison of Spray Intensity Contour Areas

4.2.1 Intensity probe contours

The areas of the various contours in Figure 5 have been measured (by planimeter[†]) and are plotted against the corresponding values in Figure 15a. Not surprisingly, the points are spread over a wide band.

Once the spray has resolved itself into individual droplets, as it moves downstream it spreads in both y and z dimensions in a linear relationship with the distance from the spray origin (which from Reference 5 can be expected to be forward of the wheel/plate contact point). The contour area for a particular value of τ at one station will become a larger area and an inversely smaller τ at a station further downstream[‡]. This has been studied by adjusting all data to their equivalent at a station at $x = 35.3 \text{ cm}$, using an “offset” distance to define how far the spray origin is upstream of the contact point. The power relationship was also taken as a parameter to be investigated in case the (logical) square rule was altered by other factors.

The best correlation was obtained with an offset in the range 11 to 13.5 cm, and a power of 2. Results for the four stations furthest from the aperture, show very good correlation (Figure 15b). The earlier stations fail to conform^{††} (Figure 15c), presumably because the spray had not yet settled into a simple pattern, although it will be noted that the points for the lowest τ do appear to agree with the curve fitted to the data in Figure 15b.

If the FMD/IP calibration (derived in Section 4.1) gives a better representation of the true spray pressure, then using data converted by the calibration curve should give an even better correlation than that shown in Figure 15b. Figure 16 shows results equivalent to those in Figure 15 with the data converted by the FMD/IP calibration curve (Figure 14). The basic converted data is in Figure 16a. Figure 16b shows that using the previous optimum parameters (offset 11, power 2) does not produce an acceptable correlation. The best correlation of these data is obtained with an offset of zero and a power of 0.5, the results being shown in Figure 16c. Note, however, that

- the correlation of the data in Figure 16c is far less close than that in Figure 15b
- and
- a power of 0.5 has no physical justification at all.

[†] There is an irregularity in the spacing of the ordinate scale marks in some of the contour plots in Reference 3. This certainly affected some of the measurements of contour areas for Reference 9 and, possibly, even for Reference 3.

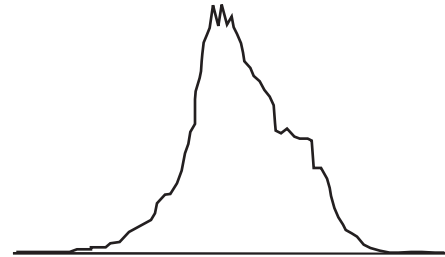
[‡] It is assumed that, at the distances involved, there is no significant reduction in droplet speed due to air resistance.

^{††} The fact that the $x = 35.2$ pattern does not agree, while the 35.3 pattern does, suggests that there may have been something wrong with the “35.2” survey, possibly in positioning.

The conclusion can be drawn that the spray intensity probe is more reliable than any of the other devices. The consistency of the data over the range of measured pressures in Figure 15b is encouraging. Nevertheless, it must be remembered that the above analysis has not covered the range below $\tau = 0.02$ and, particularly, the values of τ very near to zero.

4.2.2 Contour $\tau = 0.0$

It was suggested in Reference 9 that one of the factors explaining the discrepancy between direct force measurements and integrated pressures was that integration of the measured pressures apparently only extended as far as the $\tau = 0.02$ contour. No $\tau = 0.0$ contours were presented in Reference 3 and without them it is not possible to integrate spray intensity readings over the whole area affected with certainty. It must be recognised that determining the position of $\tau = 0.0$ contours is inherently difficult, requiring assessment of where the trace of spray intensity (Sketch 4.1) runs into the horizontal axis.



Sketch 4.1 Typical trace from IP

Nevertheless, an indication of the effective extent of the $\tau = 0.0$ contours is available which, coupled with an assumption as to how the areas within the contours vary between $\tau = 0.02$ and 0.0, will enable integration of spray intensity probe pressures over the whole area affected.

This indication of the probable extent of the pressure field arises from forces measured on the impingement plate tilted relative to the spray (reported in Reference 3). The position of the plate is shown in Figure 17 relative to the wheel and the upper, lower and lateral limits of the $\tau = 0.02$ contours[†]. Variation of the measured forces with the angle of the plate to the horizontal is shown in Figure 18. In the reference a cosine curve is shown with a maximum of 104 at -10° . The values 104 and -10° were clearly obtained by visual examination, a Least Squares analysis shows that a better estimate of the maximum is 103.735 at -8.79° (the difference is small but significant for subsequent analysis).

As the plate angle was increased past 40° the plate no longer received the whole of the spray and the force measurements fell away from the cosine curve. The positions of the tips of the plate at this angle suggest that the spray extends about 50% further than the local $\tau = 0.02$ contours. Corresponding lines are shown in Figure 17.

The 10×10 cm plate was subsequently replaced by a 10×26 cm and measurements at the higher angles were repeated. Figure 18 shows that these results continue to follow the cosine curve to higher angles. However, even on this plate the force eventually falls away, starting at about 60° , as may be seen from Figure 19, where the cosine effect is removed by replotting the results as $\text{force}/\cos[\theta - \theta_0]$.

Figure 17 shows that the extended plate, adjusted in vertical position to be central to the spray, should still receive the whole of the spray at 65° . It is not known how meticulously the vertical position of either of the plates was adjusted to suit the spray, but it is more likely to have been done with the smaller plate than the larger (the test with the larger plate was only to confirm the reason for the fall off of the forces). If the extended plate was not central to the $\tau = 0.0$ contour then one edge would move within the plume sooner than the other and the height of the plume would appear to be greater than it was. If the plate was simply

[†] The broken line shown is a Least Squares fit to the centre of these limits. It crosses the ground level at $x = -13.5$ cm, i.e. close to the offset figure above.

pivoted at the centre of the spray plume at station 35.3 then its upper tip would move within the suggested edge of the plume at about 60° inclination. This tends to confirm the position of the edge of the spray.

As the edges of the plate approach the outer limits of the plume they inevitably do so at x -stations different from the nominal position of the plate. It will be seen from Figure 17 that when the 10×10 cm plate is at about 40° the upper edge of the plate is about 3 cm downstream of the centre, while its lower edge is the same distance upstream, about halfway between stations 29.2 and 35.3. This is only of concern in that, as has already been noted, the plume appears not to have settled into a regular form until station 35.3. However, the situation is more marked with the 26×10 cm plate where, as may again be seen in Figure 17, the plate (shown tilted at 65°) extends from upstream of station 24.1 to downstream of station 44.2. In this position some of the variation in forces will be due to the different nature of the contours at the various stations covered (see Figure 5).

If the $\tau = 0.0$ contour is 50% larger than that for $\tau = 0.02$ in width as well as height then the area contained by it will be 2.25 times that contained by the 0.02 contour (provided that both contours are similar in shape). It is this ratio of areas which will be used when calculating the force on the large plate by integrating pressures.

4.3 Integration of IP Readings

4.3.1 Integration method

The force due to impact of the spray on the large plate is to be estimated by integration of pressure (as represented by τ) against contour area. In order to make the integration complete it is necessary to decide what is happening at the extremes of the integrand.

The maximum value for τ (occurring at contour area = 0.0) was not quoted in Reference 3 (a probe reading would, in any case, have been lower than the true value because of averaging over the orifice area). It may be estimated from existing data by a number of methods. That used here is based on a careful analysis of the variation of contour area with $1/\tau$ (see Figure 20).

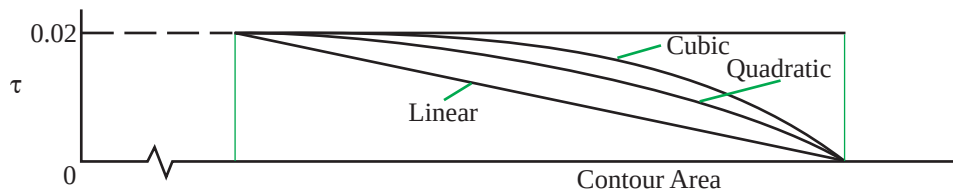
The unknown behaviour outside the $\tau = 0.02$ contour has already been mentioned and will be dealt with in Section 4.3.2.

The chosen method for integration is to fit a cubic spline to the data, with contour area as abscissa and τ as ordinate, setting the slope at contour area = 0.0 to zero, and to integrate the resulting curve. It is not certain what numerical integration methods were used in References 3, 6 and 9, but it is probable that the constant intervals in τ tempted them to integrate contour area as a function of τ , using a polynomial formula. This carries the risk that the implied variation between data points can be excessive, with dire results on the integral. Reference 9 certainly integrated contour area as a function of τ , without any indication of a check for smoothness of the resulting curve. In contrast, the curves used here have been checked visually: typical splines fitted to data are shown in Figure 21.

4.3.2 Variation of τ with contour area between $\tau = 0.02$ and 0.0

Since no readings are available outside the $\tau = 0.02$ contour, it is necessary to make an assumption of the form of variation of with contour area in order for integration to proceed past $\tau = 0.02$. The choice is, at this stage, arbitrary and all that can be expected is that the selected variation should be plausible.

It is unlikely that it will lie outside the rectangle from $\tau = 0.02$ to the $\tau = 0.0$ contour area (Sketch 4.2). Possible simple forms of variation within this rectangle are shown in this Sketch. The cubic and quadratic have zero slope at $\tau = 0.02$, nearly matching the slope of the main part of the curve (see Figure 21).



Sketch 4.2 Possible variation of τ with contour area

4.3.3 Integrated forces

The estimates of the force on the large plate are compared with the measured forces in Figure 22. The lowest set of points shows the integral of the spray intensity readings from contour area 0.0 to that corresponding to $\tau = 0.02$. The line through them shows their average. It will be seen that the values disagree with those from earlier reports, being more nearly constant. The difference is probably due to shortcomings in the numerical integration procedure in the earlier reports. These data also indicate the level of scatter arising from (a) variations in the way in which the maximum value of τ is estimated, (b) variations in the spline resulting from different assumptions at the $\tau = 0.02$ end, and (c) accuracy of measurement of the contour areas by planimeter (the diamond points are those measured (independently) for Reference 9 but integrated using the present method, after correction for the effect of the scale errors mentioned earlier).

The middle sets of points in Figure 22 show the result of assuming a quadratic variation for τ versus contour area for τ between 0.02 and 0.0.

When the IP was first developed (Reference 2) it was accepted that the results were not quantitative. However, analysis (Appendix A) indicates that the readings from the probe may simply be low by a factor of $1/(1.285 \pm 0.065)$. If an IP Correction Factor of 1.285 is applied to the middle set of points in Figure 22, then the upper set of points is obtained. It will be seen that agreement with the measured forces is very close except at $x = 58.8$ cm.

5. CONCLUSIONS

Re-assessment of the data has shown that the IP is a reliable tool. The pressure measured by the probe needs to be multiplied by 1.285 to give the kinetic pressure in a spray plume.

To estimate the whole of the impact force it is essential to take the integration over the whole area affected, *i.e.* out to the $\tau = 0.0$ contour. This may introduce problems because of the difficulty in measuring τ near zero.

Comparison of measurements of mass flow with those from the IP suggest that the velocity in the spray is close to that of the water layer and that the effective density decreases with increase of distance from the centre of the spray plume.