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FOUNTAIN-JET TURBULENCE.(U)
SEP 80 W H FOLEY, D B FINLAY

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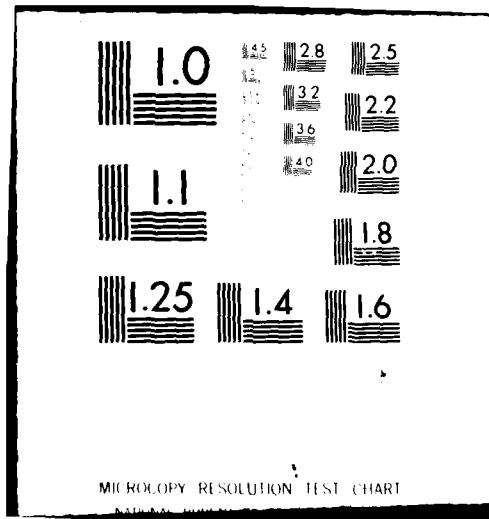
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FOUNTAIN-JET TURBULENCE

By

William H. Foley*

and

Dennis B. Finlay**

GENERAL DYNAMICS CORPORATION

FORT WORTH DIVISION

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*Engineering Specialist, Aerospace Technology Dept.
**Associate Engineer, Aerospace Technology Dept.

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ABSTRACT

A series of experiments was conducted on a model to investigate the characteristics of fountain jets that develop beneath hovering VSTOL aircraft. The results confirm the results of previous studies in that normally developing fountains possess abnormally high turbulence levels that can be reduced by the presence of trip devices placed along the fountain stagnation line. The present work shows that fountain turbulence is highly anisotropic with the intensity of the streamwise component an order of magnitude greater than the cross component. Further, the anomaly appears to occur only in fountains produced by jets of air that strike normal to the ground surface; jets that strike at angles other than the perpendicular do not appear to generate highly turbulent fountains.

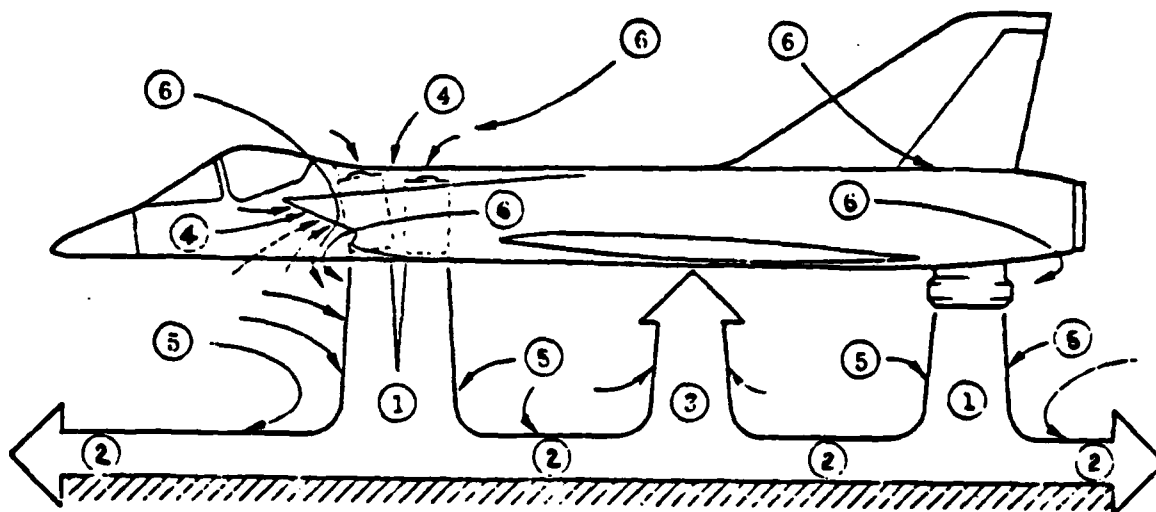
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INTRODUCTION

The flow field in the immediate vicinity of a VSTOL aircraft hovering in ground proximity can be divided into six more or less distinct regions (Figure 1). Of particular interest here are Regions 1, 2, 3, and 5, i.e., those regions wherein the flow causes forces and moments to be induced upon the airframe. The induced forces are usually divided into two parts for convenience. The first, "suck-down", is a negative (thrust degrading) force caused by the fact that the turbulent, high-speed jets beneath the aircraft planform entrain considerable quantities of ambient air that induce lower-than-ambient static pressures on the planform under-surface. The other force, which is positive (thrust enhancing), is usually referred to as "fountain buoyancy." It can occur when the aircraft exhaust configuration consists of more than one jet so that upward moving jets, or fountain jets, are produced (Region 3); the pressure recovery that results from fountain jet/planform impingement produces an upward component of lift. Since the magnitude of both suckdown and fountain buoyancy are configuration dependent, they often represent significant percentages of total engine thrust.

A number of anomalies in the basic behavior of fountain jets as compared with the behavior of other turbulent free jets have been observed. When the subject of VSTOL ground effects was first exposed to study, a reasonable simplification in experiments appeared to be the use of image planes for geometrically symmetric flows. However, the results of such tests were quite different than those obtained from complete jet models (References 1 and 2). An explanation was obtained by Adarkar and Hall (Reference 3) who observed that fountain jets decayed much more rapidly than jets produced on image planes. A subsequent investigation of the characteristics of fountains produced by the impaction of two plane jets flowing along a ground plane was made by Kind and Suthanthiran (Reference 4); they observed that, although the fountains so produced had local velocity distributions similar to that of a two-dimensional free jet, the fountains differed in that both the spreading rate, the associated decay rate, and the longitudinal turbulent intensities were about three times higher than those usually observed in free jets. Witze (Reference 5) encountered similar spreading rate anomalies in his work with fountains produced by circular jets after ground impacts; those fountains had spreading rates between 2 and 3 times higher than expected from free-jet results. Hill et al., (Reference 6) in work with fountain jets impacting fuselage models, detected an oscillatory behavior in fountain-jet locations, whereas Foley (Reference 7), in an experiment with two-dimensional fountains, ob-



- 1 EXHAUST FLOW (FREE JET)
- 2 GROUND JET
- 3 FOUNTAIN JET
- 4 ENGINE INLET FLOW
- 5 & 6 ENTRAINED AMBIENT AIR

Figure 1 Flow Field Near a Hovering VTOL Aircraft

served that the insertion of a trip wire on the ground plane at the stagnation line produced a fountain jet whose spreading rate was much smaller than that of a usual fountain; in fact, the fountain with the trip wire produced a jet whose spreading rate was about the same as a normal two-dimensional free jet. (This may provide some explanation of the results of References 8 and 9 wherein small grids placed on ground planes produced major changes in the flow fields.)

Foley speculated that the high spreading rates, turbulence levels, and decay rates were possibly due to oscillation of the stagnation zone and large scale turbulence in the fountain.

An experimental investigation of fountain jet velocities and turbulence levels was conducted to delineate the origins of the turbulent anomalies associated with fountain jets by extending the previous studies. The results are presented herein.

EXPERIMENT

A. Test Facility

The test program was conducted at the General Dynamics' Fort Worth Division Ground Effect Test Facility with a 1 m by 1 m ground plane. Two nozzles 4 cm in diameter, D , were mounted 46 cm apart and 41 cm above a ground plane. Figure 2 shows a representation of the test flow field. In addition, the ground board could be fitted with three trips - a 0.32-cm square rod, a 2.54-cm high plate, and a rod 0.32 cm in diameter - along the mean stagnation line. The ground plane could be tilted to vary ϕ so that STOL jet/ground plane angles as well as VTOL ($\phi = 90$ degrees) could be simulated. Air was supplied by the plant service air system. Although nozzle pressure ratio (NPR) could be varied, it was determined early on that NPR had little effect on the results of interest. Therefore, NPR was set at 2.0 for all data reported herein.

B. Data Acquisition Equipment

Fountain jet velocities were detected with a Thermal Systems Inc. Model 1050 dual-channel constant-temperature anemometer equipped with a Thermal Systems Inc. Model 1232 AF miniature hot-film cross probe. The probe was mounted on a remotely-actuated surveying arm so that h , x , and ϕ could be varied at will. The probe was calibrated in a DISA calibration wind tunnel at the beginning of each test day

and was recalibrated twice each test day to check for drift. Turbulent intensities were measured with a Systron Donner Model 7003 true RMS voltmeter; spectral measurements were obtained with a Spectral Dynamics model SD2001 DM spectrum analysis system.

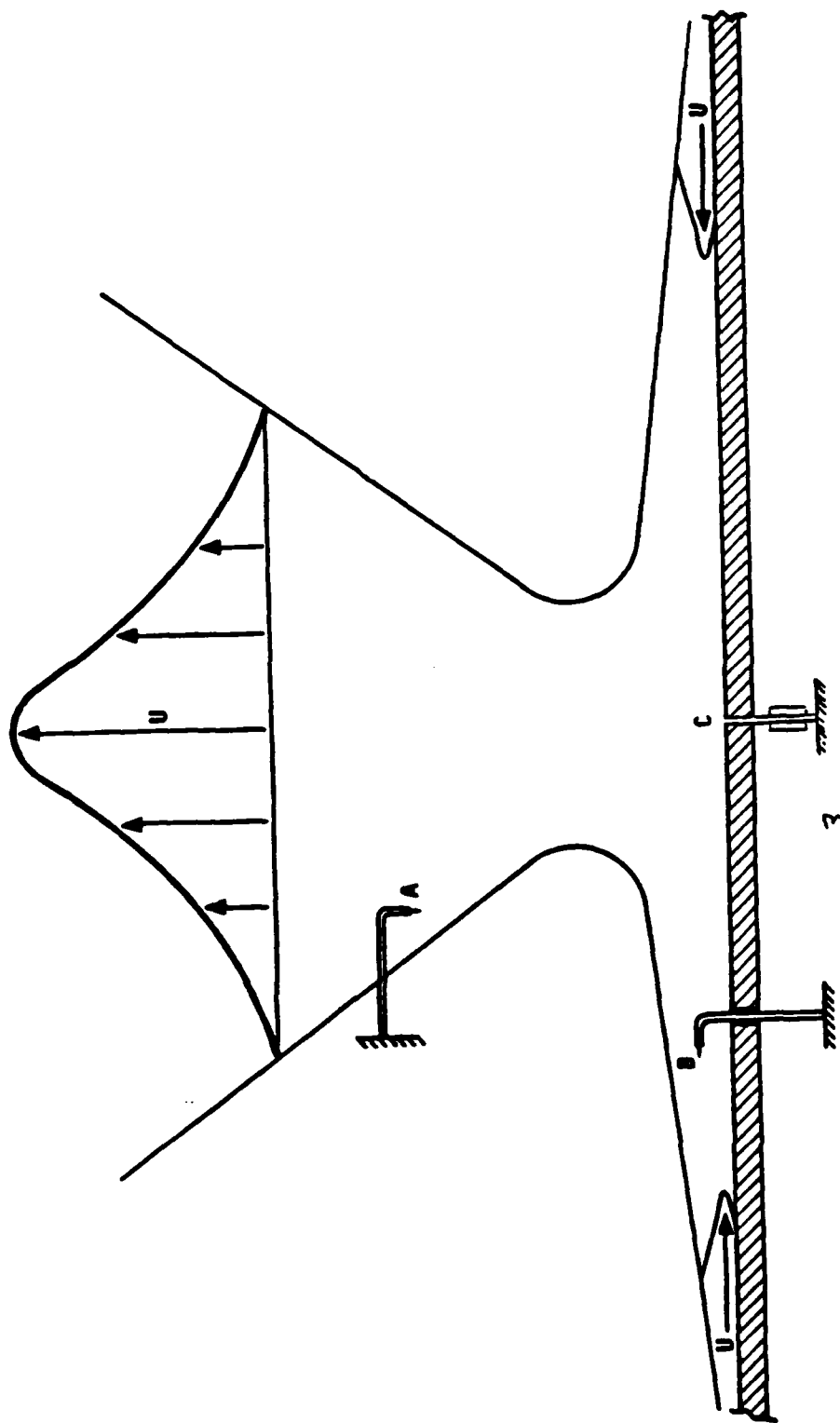
Cross-correlations were obtained at two locations: (1) between two Thermal Systems Inc. Model 1264 sub-miniature conical hot-film sensors, one mounted in the ground plane (Figure 3 (B)) and one in the fountain flow (A), and (2) between probe (A) and a Kulite pressure transducer flush-mounted at the nominal stagnation point (C).

RESULTS

A. VTOL Conditions ($\phi = 90$ degrees)

The measurements of the mean velocities U , both with and without trips in place, confirmed the results of Reference 7 (Figure 4). The 0.32-cm trips, which were sized to be about the height of the virtual boundary layer of the jet flowing along the ground plane at the stagnation line, increased peak velocity by $1/3$; the cross-section shape of the trip made little difference. The 2.54-cm trip increased peak velocity by $3/4$. It was sized to be of approximately the same as the virtual height of the ground flows at the stagnation line. The effect on the jet spread rates must be inferred because the presence of downward flows from the nozzles limited the range of surveys in the x -direction. Nonetheless, from momentum considerations, it seems reasonable to speculate that the trips decreased the fountain spreading rate. From a practical aspect, these results would indicate that a VSTOL aircraft should be careful about hovering over an irregular ground surface because of the possibility of encountering sudden changes of fountain buoyancy. When the data are plotted in non-dimensional form, that is, velocities normalized by centerline velocities and x by fountain jet half-widths, the shape factor is influenced neither by the trips nor by altitude (Figure 5).

The present results showed that the turbulent intensities were greatly decreased by the presence of a trip (Figure 6). Further, as can be seen by the power spectra shown on Figure 7, this decrease is predominate at the lower end of the spectrum where the larger-scale eddies are present. There is a fair amount of anisotropy in the untripped case with the streamwise intensity $(u'/u)^2$ an order of magnitude higher than the intensity in the x -direction $(v'/u)^2$. It must be mentioned that, especially at the intensity levels in the untripped flows, the hot-film probe used in the experiments was beyond its range of dependable accuracy. Although the exact numerical values of intensity



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Figure 3 Fountain Jet Cross-Section

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K-E 10 X 10 TO THE CENTIMETER 10 X 25 CM
KEUFFEL & ESSER CO. MADE IN U.S.A.

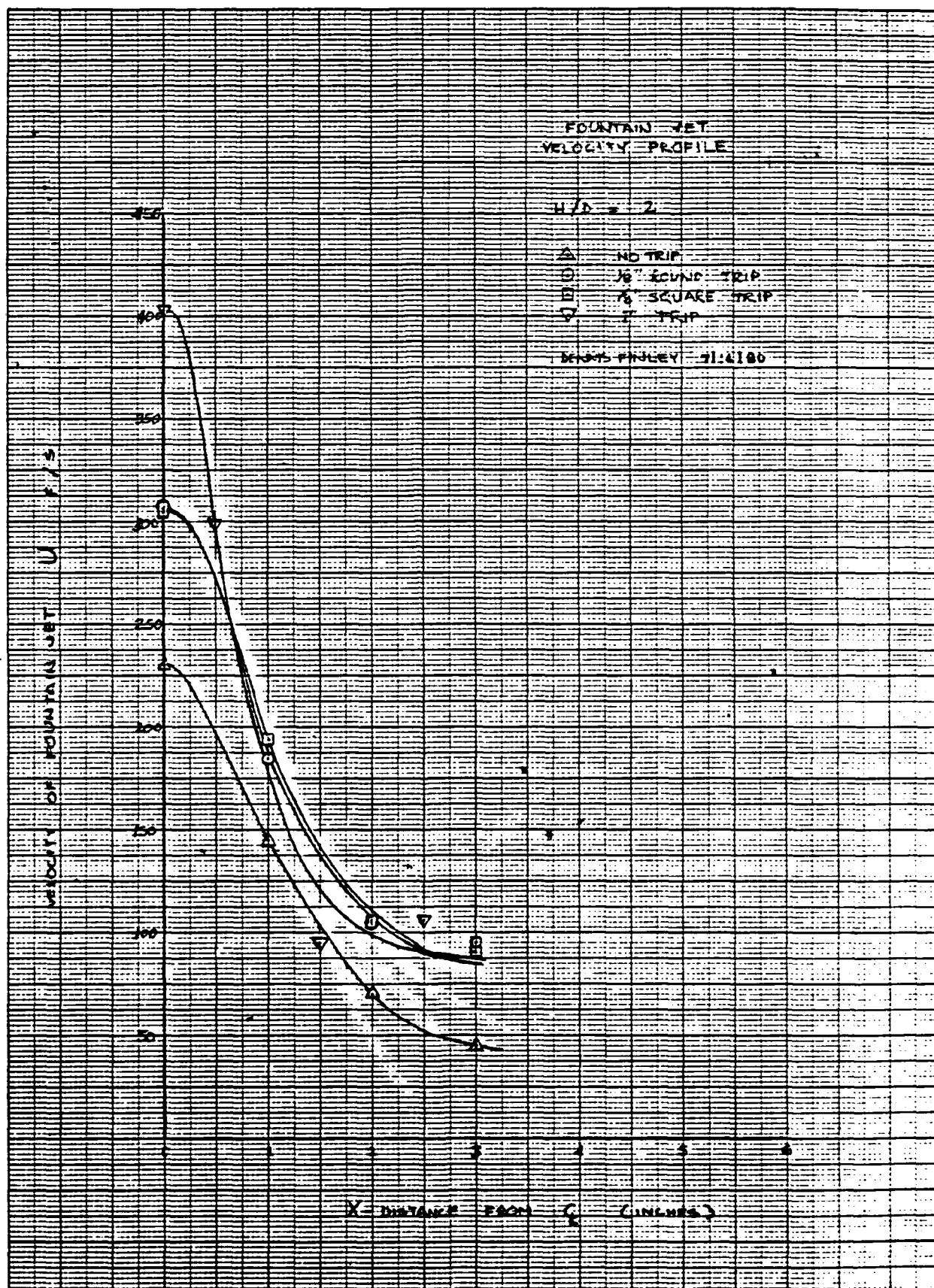


Figure 4. Fountain Jet Velocity Profile

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FOUNTAIN JET SHAPE FACTOR VS NON-DIMENSIONAL DISTANCE FROM G. S.

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K·E 10 X 10 TO THE CENTIMETER 18 X 25 CM
NEUFEL & ESER CO. MADE IN U.S.A.

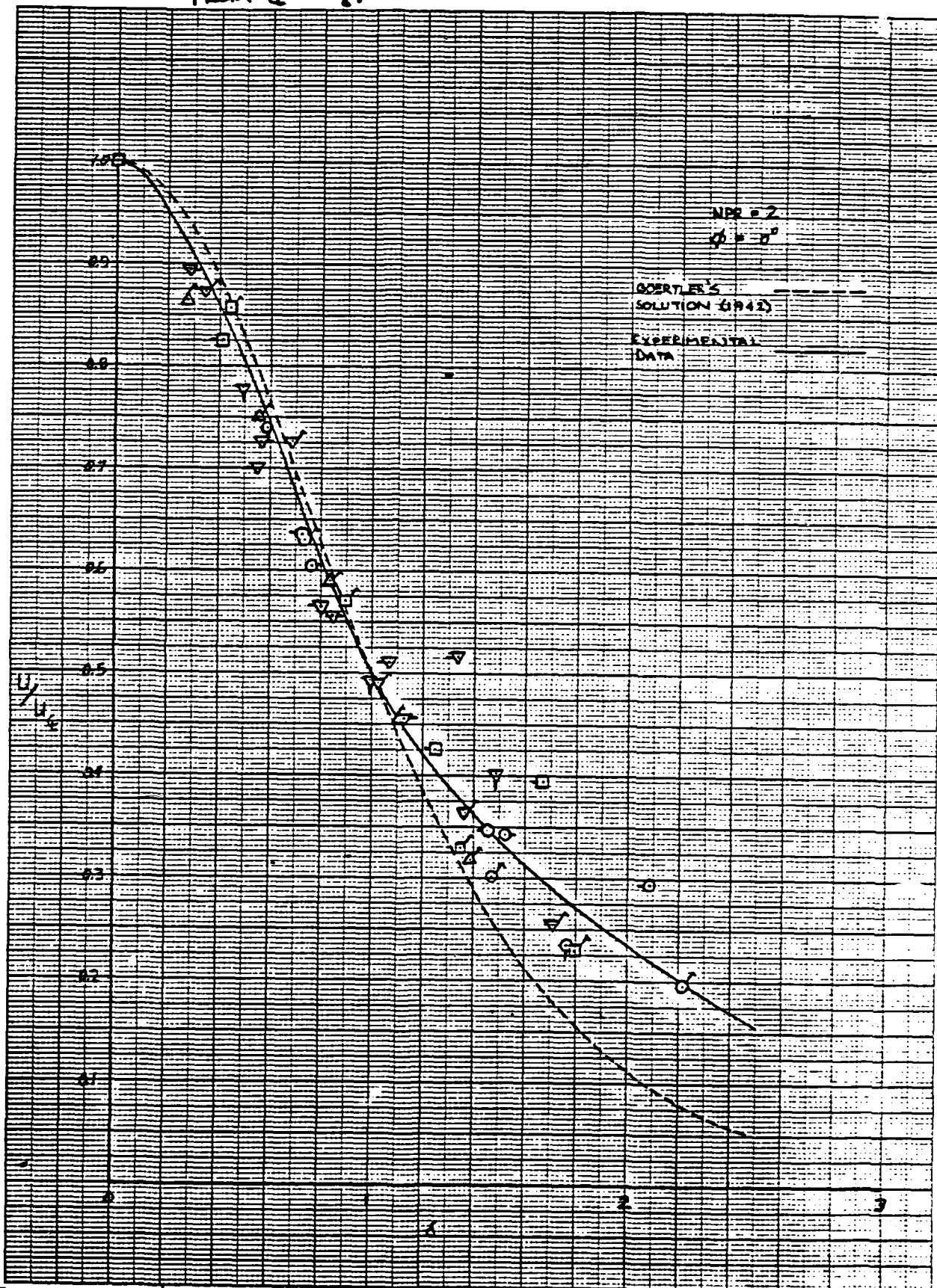


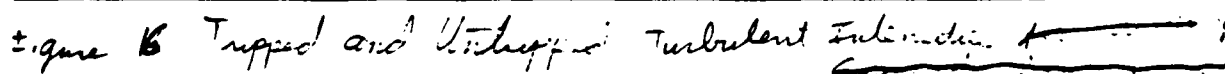
Figure 6 Fountain Jet
Shape Factor vs Non-Dimensional
Distance from G. S.

H/D = 2
 Δ NO TRIP
 $\square$ 1/8" ROUND
 ∇ 1/8" SQUARE

H/D = 4
 Δ NO TRIP
 $\square$ 1/8" SQUARE

H/D = 6
 Δ NO TRIP
 $\square$ 1/8" ROUND
 ∇ 1/8" SQUARE

H/D = 8
 Δ NO TRIP



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K.E. SEMI-LOGARITHMIC 48 6012

TURBULENT INTENSITIES $(\frac{u'}{U})^2, (\frac{v'}{U})^2$

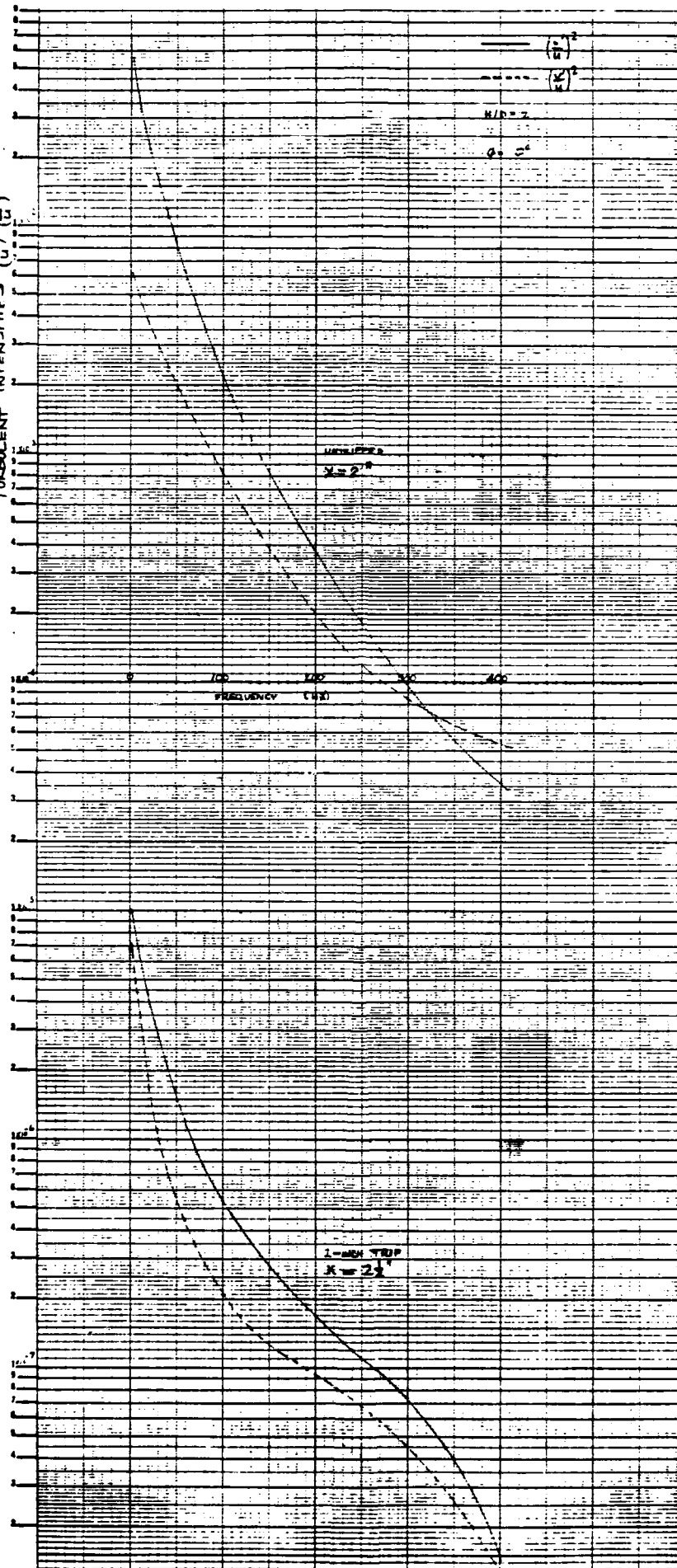


Figure 7. Turbulent Intensity, Power at $r = 2.5$ in.

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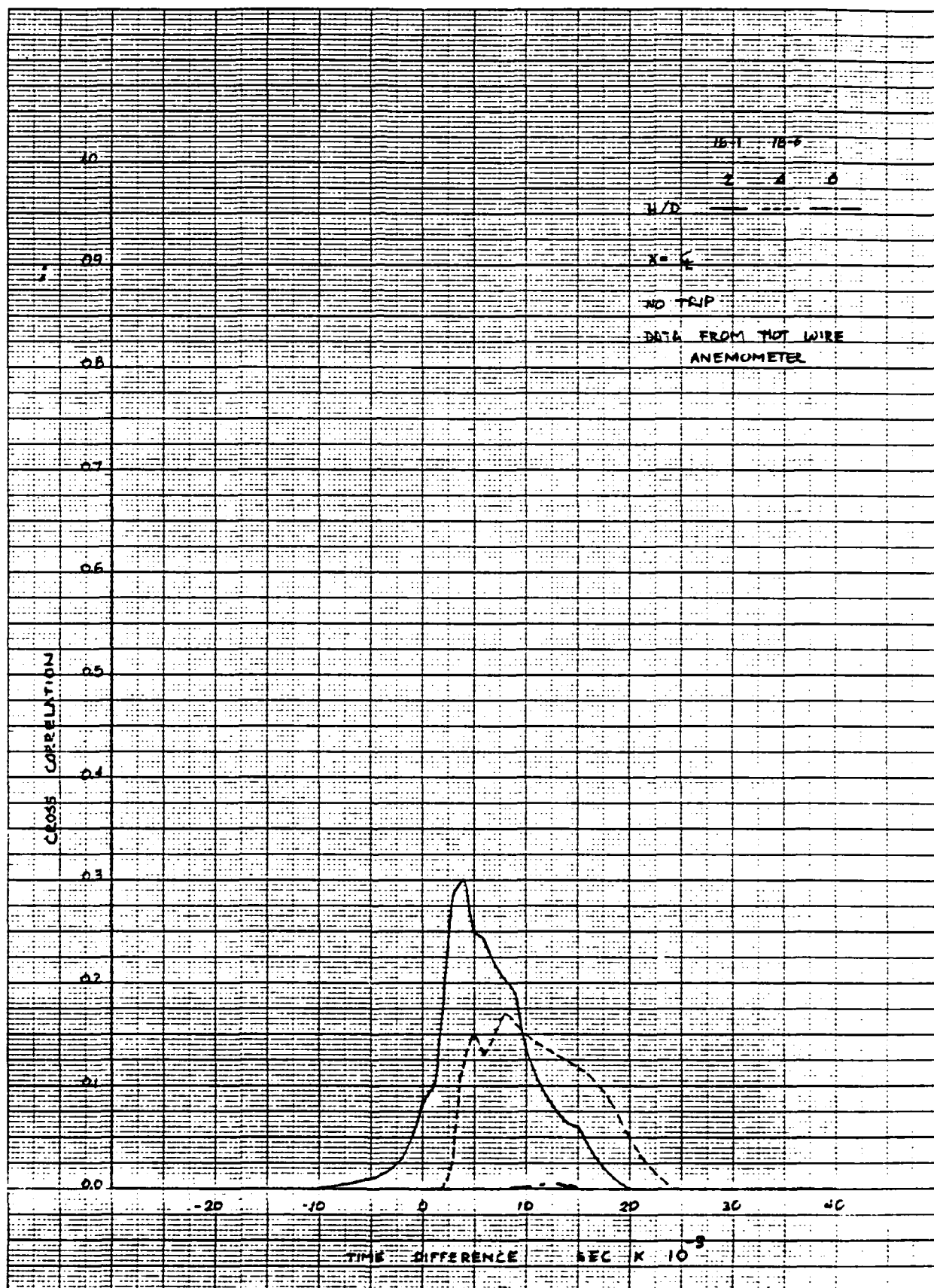
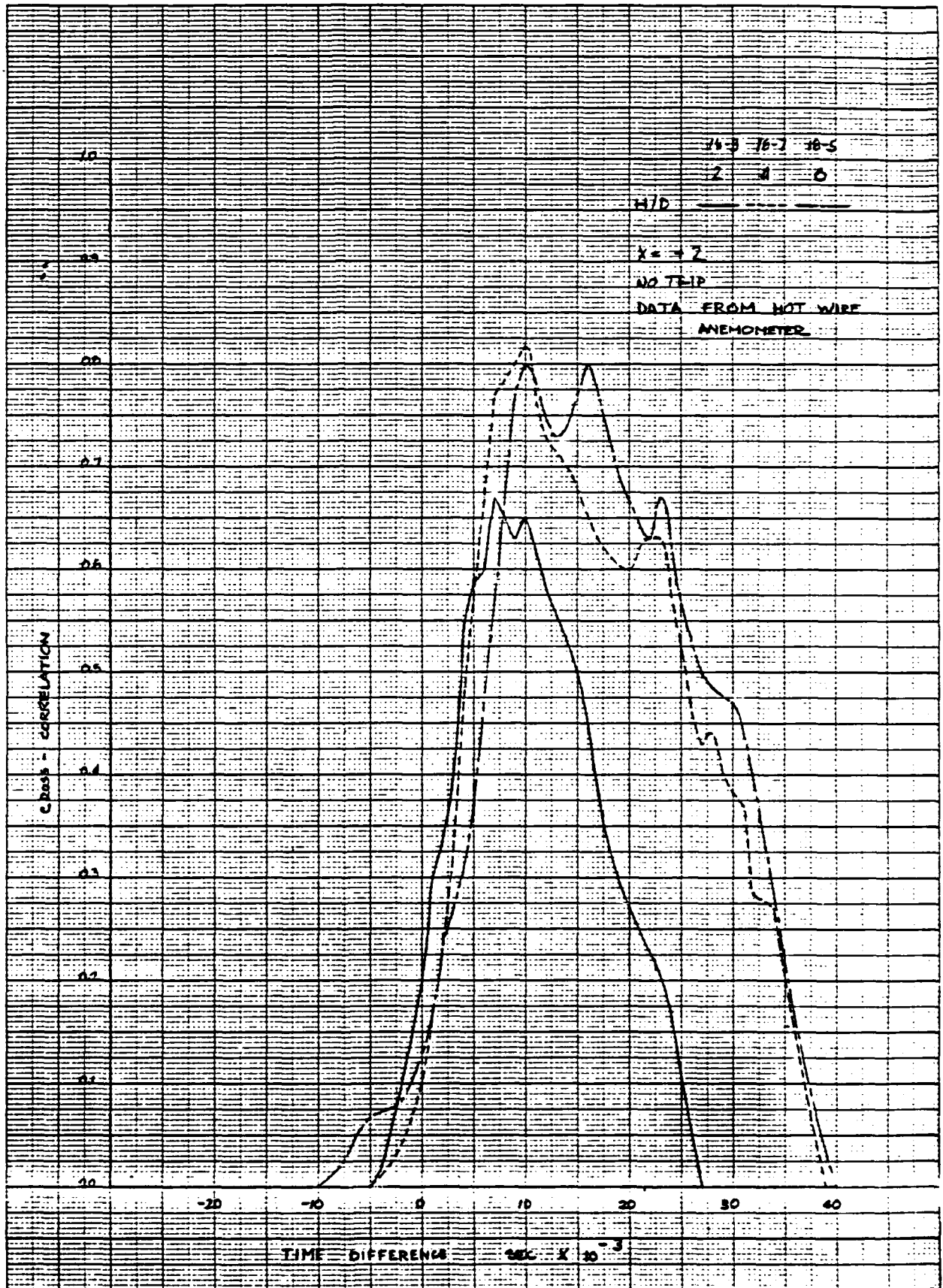
K-E 10 X 10 TO 1/4 CENTIMETER 18 X 25 CM
KEUFFEL & ESSER CO. MADE IN U.S.A.

Figure 8 Untrapped F correlation plot

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K-E 10 X 10 TO THE CENTIMETER 10 X 25 CM
KUPFER & ESSER CO. MADE IN U.S.A.



F16. 9.

shown are somewhat suspect, it is felt that the trends shown are valid. A more appropriate split-film probe was considered, but the idea was discarded because the fragility of the probe was incompatible with the flow environment.

The hot-film data show that, in the flow with the 2.54 cm trip in place, there was virtually no correlation between the turbulence in the ground jet and that in the fountain. However, in the untripped case, the opposite was observed. Figure 8 displays the correlation where the fountain probe altitude varied at the centerline; the probe in Figure 9 was positioned at $x = 5.08$ cm or in the fountain jet wing. It can be seen that the correlations are highly persistent and by far the strongest in the area of the greatest turbulent intensity; the correlation on the centerline rapidly decays. On both figures, the times to the peaks are consistent with the flow times for a particle to traverse the distance between the two probes. The correlations between the pressure transducer mounted on the stagnation line and the hot-film probe in the fountain showed similar trends.

Surveys made at $\theta = 60$ degrees and 30 degrees showed that the effectiveness of the trip diminished somewhat, but that the general results observed at $\theta = 90$ degrees remained the same.

B. STOL Case ($\phi \neq 90$ degrees)

A surprising result was produced by inclining the nozzles to the ground plane. The fountain anomalies of high turbulence, etc., completely disappeared with deflections of as little as 15 degrees from the vertical. As can be seen on Figures 10 and 11, insertion of the trip has almost no difference in either the mean velocities or in the turbulence levels.

CONCLUSIONS AND RECOMMENDATIONS

The previously observed high turbulence levels in fountain jets has been reconfirmed. The present data would indicate that, in the vicinity of the stagnation line on the ground plane, there is a strong turbulence amplification mechanism, which seems to act at all frequency levels but which has its most dramatic influence in amplifying the larger turbulent eddies. Previous speculation that the mechanism consisted of a oscillation of the stagnation line which gave rise to a fountain whose flow undulated is not consistent with the present data. Had this speculation been correct, the fountain centerline correlations would have persisted with altitude to the same extent as those in the

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K-E 10 X 10 TO 1/2 INCH 7 X 10 INCHES
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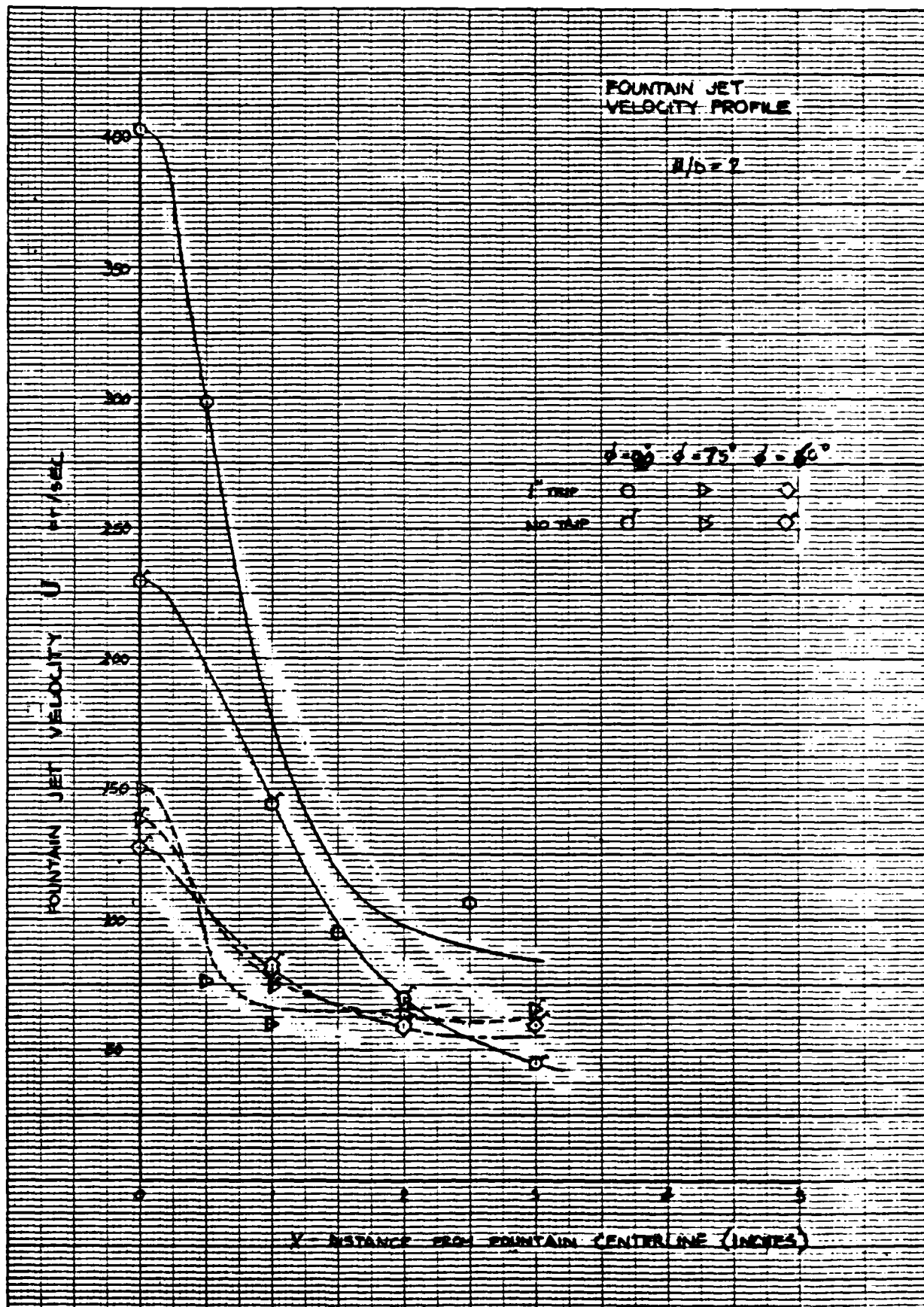


Figure 10. Fountain Jet Velocity for Varying ϕ and R/D

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K-E 10 X 10 TO 1/2 INCH 7 X 10 INCHES
NEUTRON A 1/2 INCH TO 1/2 INCH

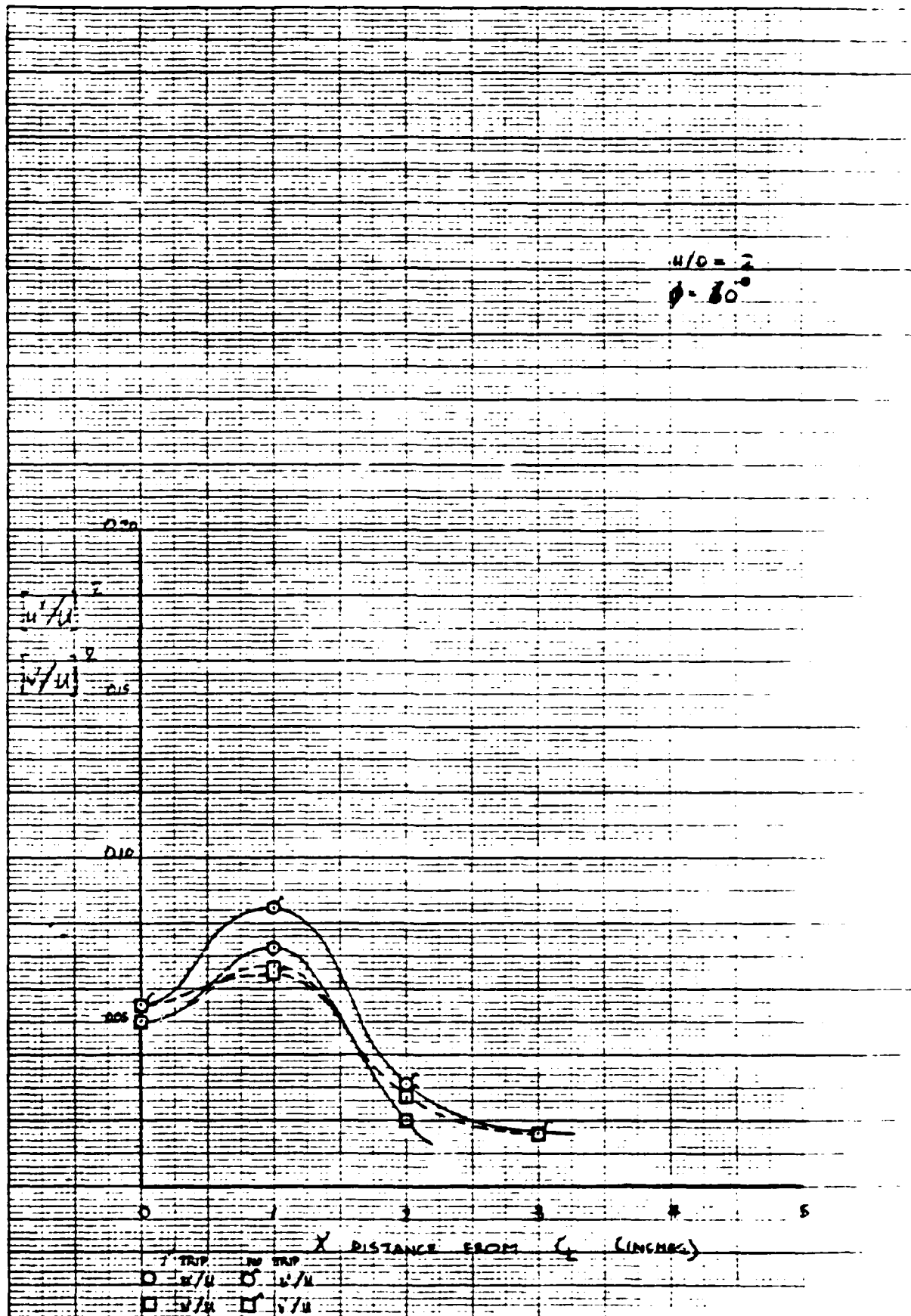


FIGURE 11

fountain wings; the data, of course, showed otherwise. Nonetheless, certain of the data seem consistent with the undulation speculation, in particular, the anisotropy of fountain turbulence with extra strong amplification of the streamwise component. There seems, however, to be little doubt that the amplification does take place within the stagnation line region because of the effect of even small trips on the fountain flow.

The measurements made at $\phi = 90$ degrees, $\theta \neq 90$ degrees seems contradictory to those at $\phi \neq 90$ degrees. In both cases, the fountain flows developed from ground jets that did not impact head-on but rather at an angle. However, in the former case, the strongest part of the fountain developed from jets that did impact normally, and, thus, the turbulence amplification that resulted may well have propagated down the stagnation line, whereas, in the latter case, it did not.

The present experiment, in all, has confirmed some aspects of fountain jet behavior only to raise further questions of the underlying physics involved. It is the authors' opinion that further investigation into the physics is required. While the present work was done with flow velocities appropriate for aircraft engines, it is felt that future investigations should be conducted at much lower, laminar conditions so that controlled disturbances could be introduced into the ground flows and the stagnation process studied in detail both by anemometry instrumentation and, possibly, flow visualization.

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