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PERFORMANCE OF AN α-VANE AND PITOT TUBE IN SIMULATED HEAVY RAIN ENVIRONMENT

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ABSTRACT

Experimental tests were conducted in the UDRI Environmental Wind/Rain Tunnel to establish the performance of an α-vane, that measures angle of attack, in a simulated heavy rain environment. The tests consisted of emersing the α-vane in an airstream with a concurrent water spray penetrating vertically through the airstream. The direction of the spray was varied to make an angle of 5.8 to 18° with the airstream direction in order to simulate the conditions that occur when an aircraft lands in a heavy rain environment. Rainrates simulated varied from 1000-1200 mm/hr which are the most severe ever expected to be encountered by an aircraft over even a 30 second period. Tunnel airspeeds ranged from 85 to 125 miles per hour. The results showed that even the most severe rainrates produced a misalignment in the α-vane of only 1° away from the airstream direction. Thus for normal rain conditions experienced by landing aircraft no significant deterioration in α-vane performance is expected. A second series of tests was designed to evaluate the validity of techniques used in simulating heavy rain in a wind tunnel. If a water spray is introduced at a velocity unequal to the airstream velocity, then momentum change between the two mediums could result in local variations in the airstream velocity. Tests were conducted at mismatched speeds to evaluate this conjecture. Results showed thus some variation in airspeed velocity was observed when a large mismatch occurred. For a tunnel in which the spray is introduced at a very low speed and allowed to accelerate to near the air speed, a measurable local decrease in test section air speed may result. A third test series examined possible deterioration in performance of a pitot tube for measuring air speed when a concurrent water spray is present. Results showed that under rainrate simulations of less than 180 mm/hr no significant performance penalties occur. However, when

a water drop directly impacted a critical locaton on the pitot tube a positive velocity spike occurred even if the water was moving at a slower speed than the air.

SECTION 1

1.1 HEAVY RAIN INFLUENCE ON α-VANE

Today's commercial aviation fleet relies heavily upon the angle of attack sensor to warn of an approaching aircraft stall condition. The angle of attack sensor, or α-vane, is generaly mounted on the fuselage of the aircraft beneath the cockpit area. The α-vane, by aligning itself with the direction of the air stream is used to deduce the angle of attack of the airplane. If the angle of attack approaches the stall angle of attack, α max, to within approximately 3° the stick shaker activates in the cockpit and warns the pilot that he is approaching stall. In most commercial airplanes the angle of attack sensor gives the only warning that the pilot will receive before the aircraft stalls. If stall occurs at a low altitude during takeoff or landing, recovery is virtually impossible.

The performance of the angle of attack sensor has never been evaluated in a thunderstorm environment where severe heavy rain may effect its performance. Its performance in these conditions is extremely important since severe wind shear can reduce the safety margin of flight to near stick shaker activation speed. History has shown that many of these severe wind shear encounters that caused aircraft accidents were accompanied by a simultaneous penetration of very heavy rain. Under severe wind shear conditions, advisory circulars have encouraged pilots to pull up the nose of the aircraft until positive rate of climb is established even to the point of activating the stick shaker. Consequently, reliable and accurate angle of attack measurements are extremely important when experiencing wind shear conditions.

In a simultaneous encounter of heavy rain and wind shear the direction of the rain is, in general, not the same as that of the prevailing airstream. The rain impacting the α-vane will tend to misalign it from the direction of the airstream. For an aircraft traveling at 125 knots the direction of the incoming rain (due to the terminal velocity of rain falling through the air) is approximately 8° above the direction of the air stream. Consequently, if the α-vane were to align with the direction of the rain, then the angle of attack indicated by the α-vane would be 8° lower than the actual angle of attack of the airplane. In this situation, the pilot would receive no stick shaker warning prior to stall. A theoretical analysis of the relative magnitude of water and rain forces, however, leads one to believe that the α-vane would not align itself with the incoming rain direction. The rain, however, might be expected to exert some influence on the alignment of the α-vane. If this influence translated to even a 2° to 3° change in the measured angle of attack, it would be significant because it would effectively preclude the warning provided by activation of the stick shaker before the aircraft stalled. Misalignment of the α-vane in heavy rain may occur not only because of the momentum of the water drop impacts in the α-vane but possibly because of a change in drag coefficient between the wetted upper side of the α-vane and the presumably dry lower surface. Atmospheric turbulence in the thunderstorm environment is also expected to add a random component of error to instantaneous α-vane measurements. To experimentally determine any detrimental influences of heavy rain on the performance of an angle of attack (α-vane) sensor a test program was conducted in the UDRI Environmental Rain/Wind Tunnel. Prior to conducting this test program a calibration of the water spray and airflow characteristics of the tunnel were undertaken.

1.1.1 Preliminary Wind Tunnel Calibrations

Calibration tests were conducted to establish the air flow and water spray characteristics in the test section of the UDRI Environmental Wind/Rain Tunnel. The mean velocity in the text section, the turbulence level, and the water flow characteristics of the nozzle system were each surveyed and/or calibrated. The test section average velocity was measured at the center of the test section by attaching a pitot tube to both a manometer and a pressure transducer. The pressure differential thus measured was converted to velocity taking into account the density and temperature of the air. Two static pressure probes located at a foreward and aft location (ahead of the test section) in the tunnel inlet provided a measurement of differential pressure which was calibrated with respect to the manometer velocity measurement in the center of the test section. The static probes thus allowed the measurement of free stream velocity in the test section when an object which alters the test section air flow pattern was present.

The turbulence level of the tunnel was measured by scanning the pitot tube horizontally across the test section. The pitot tube was varied in height from the bottom of the test section to near the top and the scanning process repeated at each height. In this manner, the air flow velocity and turbulence was established throughout the test section. Without the water spray present, the Root Mean Square (RMS) turbulence level of the central 18" square region of the test section was less than 1%. For the outer 9" region of the test section the RMS turbulence level was on the order of 2%.

Nozzle flow rate calibration tests were conducted with a 0.9, 1.4, and 1.6 mm diameter tube nozzles. The tests consisted of measuring the amount of water exiting each tube at a fixed pressure level over a fixed period of time. Knowing the inside diameter of the tube allowed the determination of the exit flow velocity of the nozzle. The results from these nozzle calibration tests were consistent with previous nozzle calibration measurements reported in Reference 1. Figure 1 shows the

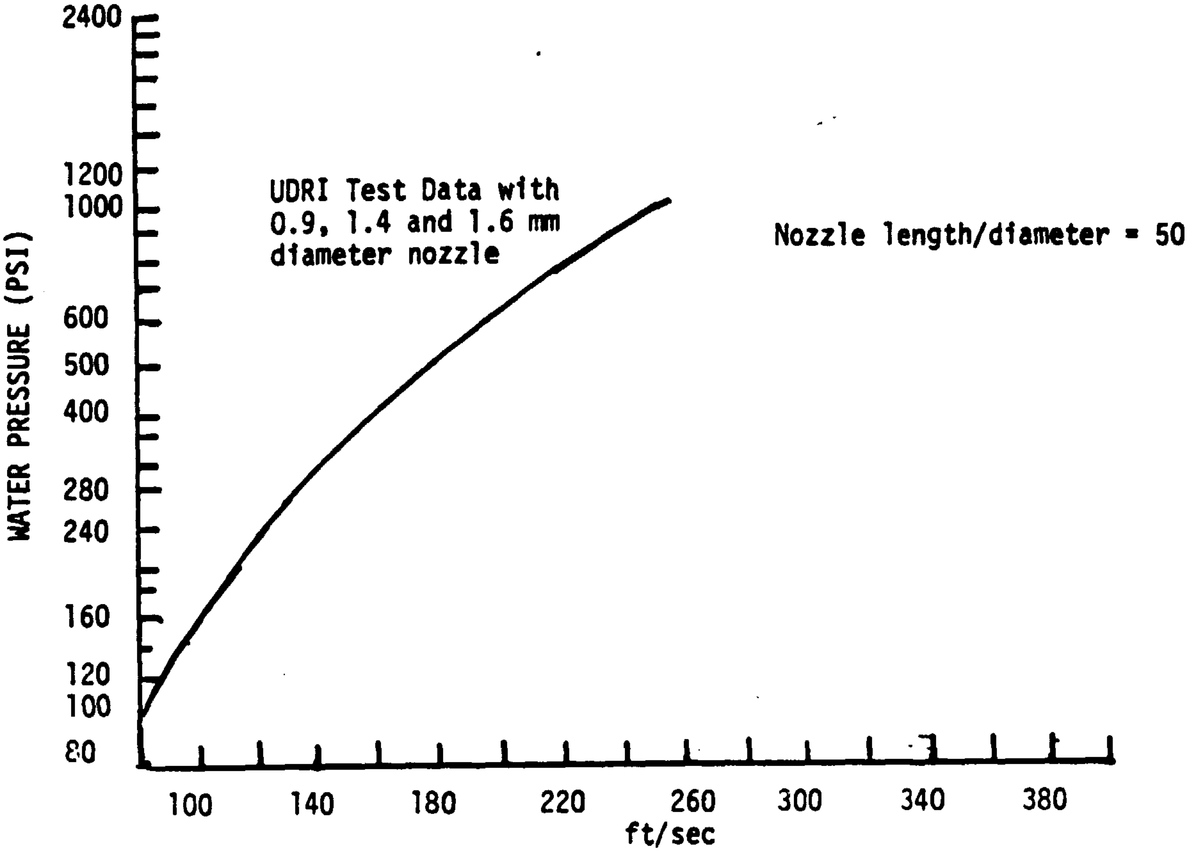

Figure 1. Water Pressure vs. Exit Velocity for 0.9, 1.4 and 1.6 mm Nozzles.

relationship of exit velocity with pressure for 0.9 to 1.6 mm diameter tube nozzles with length to diameter ratio of 50:1.

1.1.2 Tunnel Tests of α-Vane

The UDRI Environmental Rain/Wind Tunnel posseses the unique capabilities necessary to test the α vane sensor. The tunnel can simulate the natural heavy rain environment at air speeds typical of takeoff and landing aircraft. The tunnel is capable of simulating the liquid water content, a representative drop size distribution, and the direction of the incoming water drops for heavy rain rates in the range of 100 mm to over 1000 mm per hour. The α-vane was mounted in the center of the three foot square test section on a support panel that resembeled the curvature of a fuselage segment of an aircraft. Instrumentation was attached to the α-vane to give a direct analog readout of angle of attack under each test condition. The analog signal was recorded on a strip chart. Tests were conducted at three air speeds 87, 110, and 125 mm/hr under an extreme rainrate of approximately 1000 to 1200 mm/hr. The direction of the water spray was varied to form angles of 5.8° and 18° above that of the incoming air. These test conditions represented the range of landing conditions for general aviation to commercial aircraft under the most extreme rainrates possible. A 1000 mm/hr rainrate is so severe that only a few measurements have ever been recorded in nature for even a one minute period. The water spray angle of 5.8° represents a nominal landing condition for a commercial aircraft in which the α-vane is mounted on the fuselage at a location where the local flow is parallel to the fuselage centerline. The 18° water spray angle represents an extreme condition in which on some commercial aircraft the α-vane is mounted at a location influenced by local flow anomalies so that the rain direction may differ greatly from the airflow direction over the α-vane. The above test conditions, because of the extreme rainrates simulated were expected to exagerate any rain induced effects that are likely to occur under operational conditions. Consequently, if no significant influences were measured in the test series, satisfactory α-vane performance in heavy rain conditions could be assured.

The first test series was conducted at a test section tunnel speed at 87 mph, and a water pressure of 300 psi which produced a water spray velocity of approximately 85 to 90 mph in the test section. A nozzle containing two 1.6 mm diameter tubes was oscillated in a two-dimensional sinusoidal pattern at frequencies approaching 50 hz (see Ref. 1) to generate a water spray that covered a 12" x 12" region in the test section of the tunnel surrounding the α-vane. The spray nozzle located 108 inches forward of the α-vane at a height of 11 inches above the height of the α-vane was aimed directly downward at the α-vane (see Figure 2). This configuration produced a 5.8 degree angle between the direction of the water spray and the air. The rainrate simulated in the 12" x 12" area in the tunnel varied from 1000 to 1200 mm per hour, depending upon the location of the α-vane within the spray. An initial dry test run was conducted to determine the variation in angle of attack due to turbulence and structural vibrations, present in the tunnel. These factors produced a random variation of ± 1 to 2 degrees in angle of attack. Water spray tests of the α-vane were then conducted by opening and shutting a water valve which instantaneously activated and deactivated the water spray. This valve was manually cycled at approximately 10-15 second intervals throughout each test run. Figure 3 shows the angle of attack recordings both for a dry run (no spray present) and then with on/off cycling of the water spray. The air speed was fixed at 87 mph and a 5.8° spray angle. The smallest (vertical) division on the graph relates to a 1.5 degree change in angle of attack. Superimposed on Figure 3 is a line representing an eyeball average of the angle of attack α - VANE TEST CONDITIONS

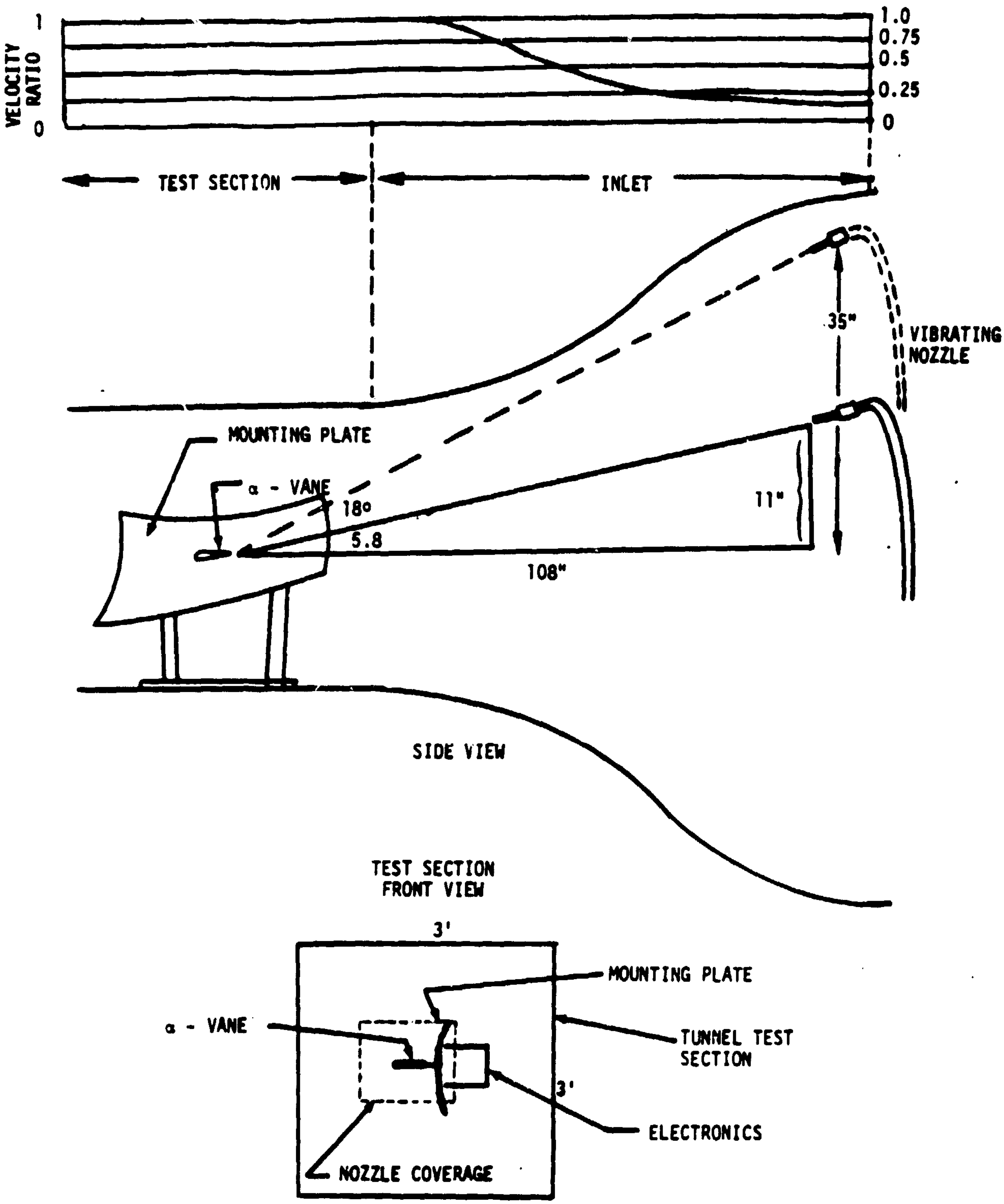

Figure 2. Schematic of α-Vane in Wind/Rain Tunnel.

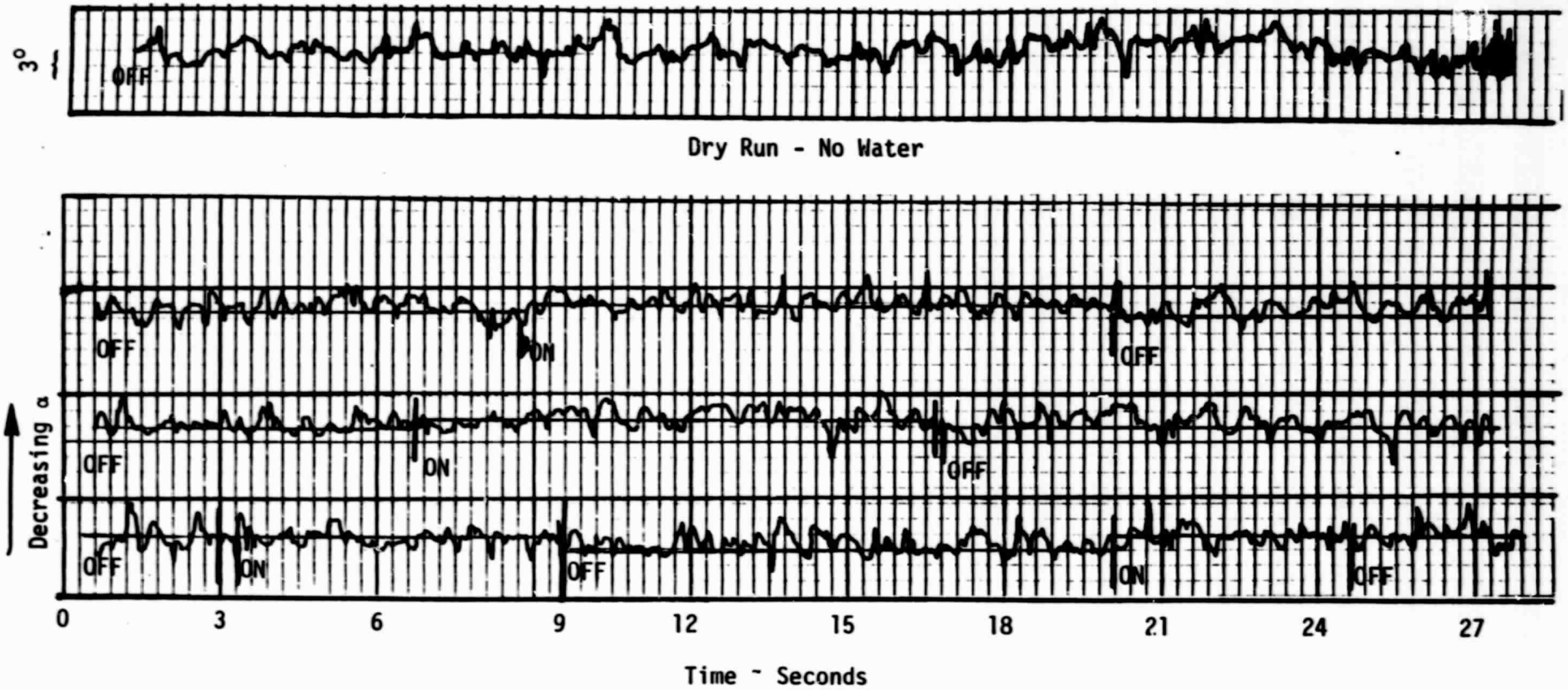

Figure 3. Angle of Attack measurements with and without Water Spray; 87 mph, 5.8° Spray angle, 1000-1200 mm/hr Rain Rate

throughout each cycle time. In nearly all test runs a slightly lower measurement of average angle of attack is observed with the water spray on. However the magnitude of this change is generally less than or equal to 1 degree. Figure 4 shows a similar series of tests conducted at air speeds of 87 and 110 mph with the spray angle increased to 18 degrees, the maximum attainable in the rain tunnel. The 18° spray angle was achieved by raising the spray nozzle system to 35 inches above the center line height of the α-vane. These tests show similar type results with a deflection of up to 1.5 degrees in angle of attack measurement occurring under the higher spray angle. No discernable difference can be observed between results at the two different air speeds. A third test series was conducted at an air speed of 125 mph and a spray angle of 18 degrees (see Figure 5). This test series shows similar results, with an approximate decreased angle of attack of 1 degrees resulting from the water spray. In analyzing each recording, one generally observes an immediate decrease in angle of attack during the first few seconds after the spray is activated.

1.2 SUMMARY AND CONCLUSIONS

The tests conducted to establish any influence of heavy rain upon the alignment of an α-vane produced consistent results throughout the range of air speeds and spray angles simulated. Although some influence of the water spray on α-vane alignment (approximately 1.5 degree maximum), was observed in many test situations, this influence must be considered minor when relating it to the extreme rain rate and impact angles simulated. The test simulation conditions are more severe than is ever likely to be experienced by an aircraft flying through nature. Thus, the experimental tests tend to conclude that misalignment of an σ-vane resulting from water spray impingement from a direction different than the air flow direction (as generally occurs in a

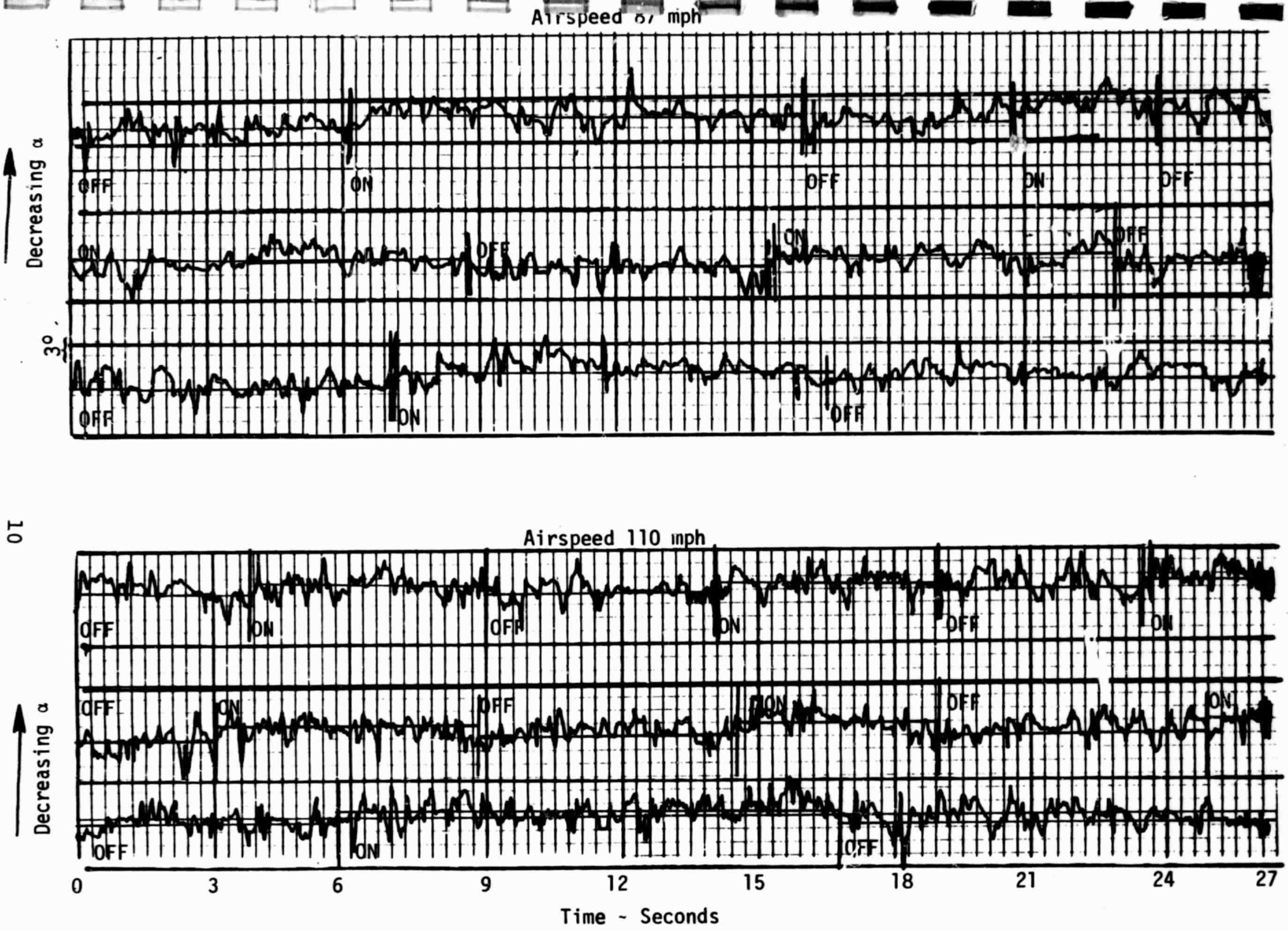

Figure 4. Angle of Attack measurements with and without Water Spray; 87 and 110 mph, 18° spray angle, 1000-1200 mm/hr Rain Rate.

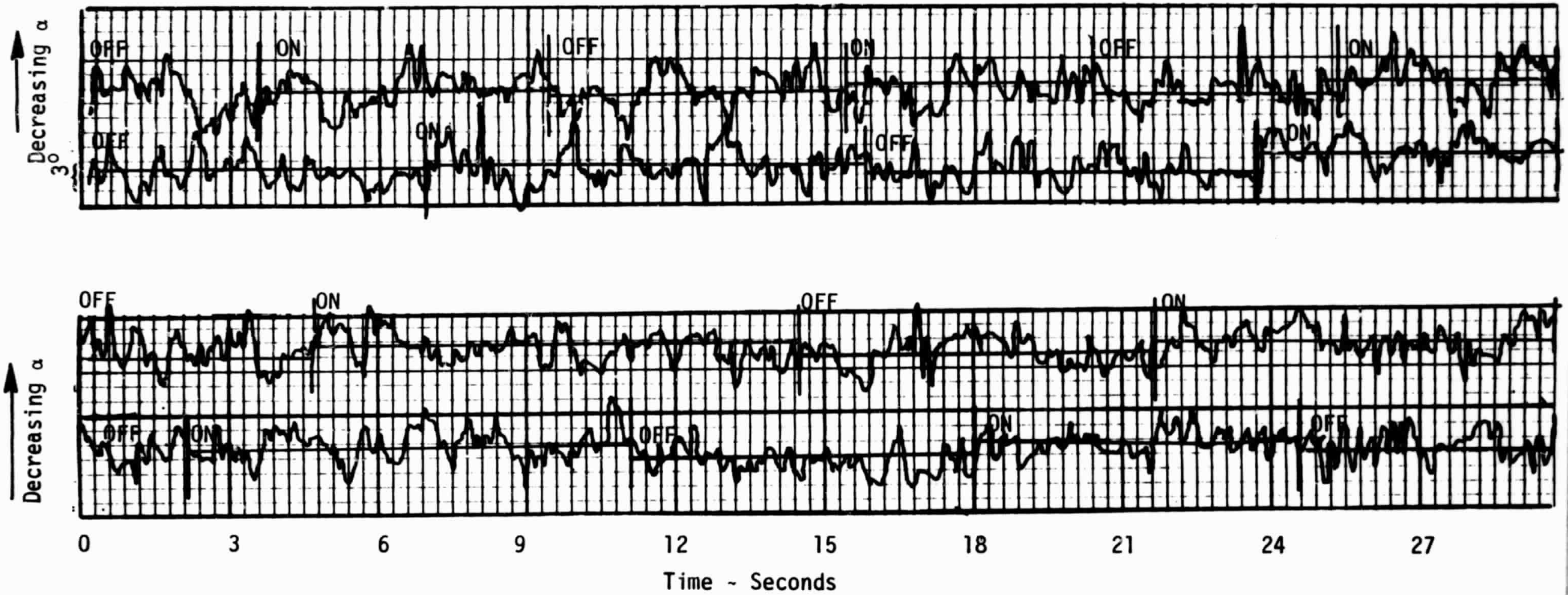

Figure 5. Angle of Attack measurement with and without Water Spray; 125 mph, 18° spray angle, 1000-1200 mm/hr Rain Rate.

natural heavy rain condition) causes a slight bias in the measurement of the angle of attack but the magnitude of this bias is insufficient to produce serious consequences when using the measurement to warn a pilot of an approaching stall condition.

SECTION 2

INTERACTION BETWEEN WATER DROPS AND AIR STREAMS

2.1 INTRODUCTION

In conducting rain simulation tests in a wind tunnel it must be assured that any aerodynamic performance modification that is observed is an actual rain induced aerodynamic effect and not an artificial effect resulting from techniques used to simulate rain. At least two potential sources of non-aerodynamically produced effects must be considered. If a water spray is introduced into a wind tunnel at an initial velocity considerably different than that of the prevailing airstream, then sufficient distance must be allowed so that the water drops accelerate to nearly the velocity of the air stream at the point where the model is mounted in the tunnel. Accelerating the droplets to the tunnel airspeed removes momentum from the air and thus decreases the airflow velocity. Since lift and drag measurements are proportional to the square of velocity a small decrease in airspeed could produce a significant loss in measured lift. A 5% loss in airspeed, for example, would result in a 10% loss in the measured lift coefficient. Another potential problem results in the use of pitot static probes to measure pressure and velocity within the tunnel test section. Since rain simulation in a wind tunnel has almost never been performed in the past, any performance deteoriation of pitot static probes in a rain environment has not been measured. Pitot static probes used on aircraft for measuring indicated airspeed are equipped with a drain to prevent water from clogging the entry ports. However, the accuracy of even these systems when immersed in a heavy rain environment has yet to be established. An experimental test program was conducted to quantitatively measure the magnitude of any significant effects produced by each of the potential problems described.

2.1.1 Test 1. Performance of Pitot Static Probes in a Water Spray

The purpose of this test was to establish if a pitot static probe can be used to accurately measure airflow velocities in a water spray. The pitot tube had a 1/8"diameter orifice at the stagnation point and eight 0.0040 in. diameter static pressure holes equally spaced 2 1/2 inches behind the stagnation point. The pitot tube was <u>not</u> equipped with a drain. Such a drain is however, usually present on aircraft pitot tubes. The pitot tube was placed in the center of the test section attached to an overhead track outside the tunnel that allowed scanning of the test section horizontally from one side of the tunnel to the other side. The total allowable scanning distance was 28". Only a 4" region adjacent to each side wall was inaccessable by scanning. Three types of tests were conducted. The first test series consisted of fixing the location of the pitot tube in the center of the test section and introducing a water spray (that simulated a given rainrate) into the center section of the tunnel. The water spray covered an area of the tunnel 20" x 20". The pressure of the water spray was chosen so that the water drop velocity essentially equalled the air velocity in the test section. Thus no significant variation of air velocity was expected to result due to momentum transfer between the water and the air even though a velocity differential existed in the upstream inlet part of the tunnel.* Pitot static probe measurements were recorded both with and without the influence of the water spray. On and off cycling of the water spray at approximately 10 to 15 second intervals was used to establish any deteriorated performance of the pitot static probe.

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*This assumption is verified by test results presented in Section 2.1.3.

Figure 6 shows results for test runs at an airspeed of 87 mph and a rainrate simulation of 125 mm/hour. The smallest (vertical) scale increment on the graph paper corresponds to a velocity increment of 2 mph. On and off cycle times are indicated on the figure by a vertical line through the trace. No discernable change in velocity measurements could be correlated to the presence or absence of the water spray. Occasionally a longer period drift occurred in the trace which likely can be related to fluctuating engine rpm and thus fan blade speed. Other test conditions at higher air speeds produced the same results. No significant clogging of the pitot tube with water accumulation inhibited accurate measurements. Thus these first tests concluded that the pitot tube measures accurate air velocity in a simulated rain environment at least up to a rainrate of 125 mm/hr. As a corroborating type experiment a second test series was conducted. In this case a water spray was introduced into the tunnel and the pitot tube was scanned horizontally across the tunnel test section into and out of the spray. The 20" x 20" coverage region of the tunnel allowed for the pitot tube to be exposed to the spray in the center regions of the tunnel while not exposed on the extremities. An initial scan with no water spray was used to establish the turbulence level and velocity distribution along the path of the pitot tube. Figure 7 shows selected results from this test series. Again no consistent change in the pitot tube velocity measurements can be related to the presence or absence of the water spray. The less turbulent velocity structure in the central region of the test section is an intrinsic tunnel property and occurs even without the presence of water. Next, a variation of the above procedure was conducted by changing the water pressure on the spray and thus the spray velocity in the test section. The water velocity was varied from as low as 35 mph up to 130 mph while the test section air speed was maintained constant at 87 mph. The purpose

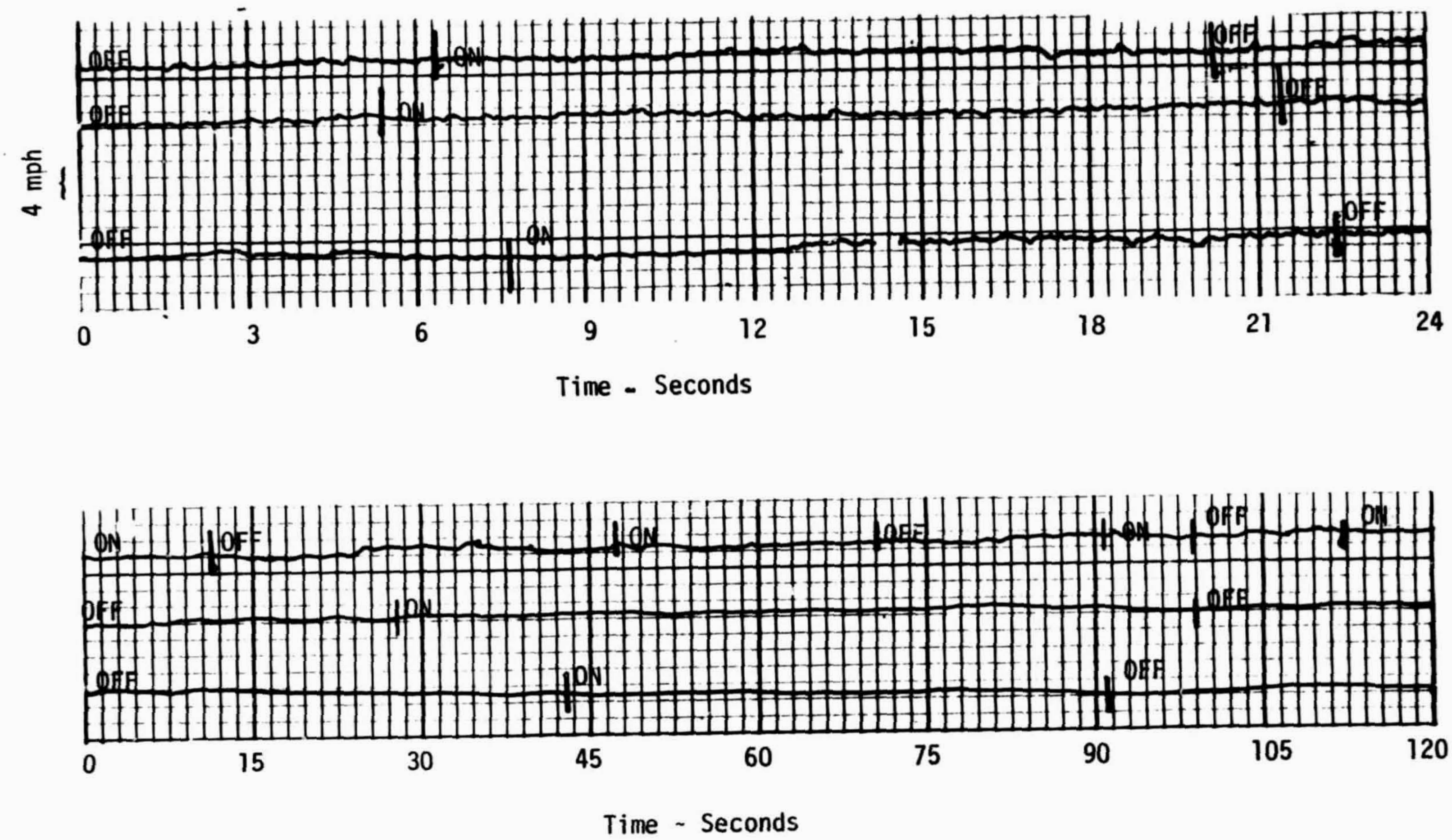

Figure 6. Velocity measured by Pitot Probe in and out of water spray; 87 mph Air Velocity, 125 mm/hr Rain Rate.

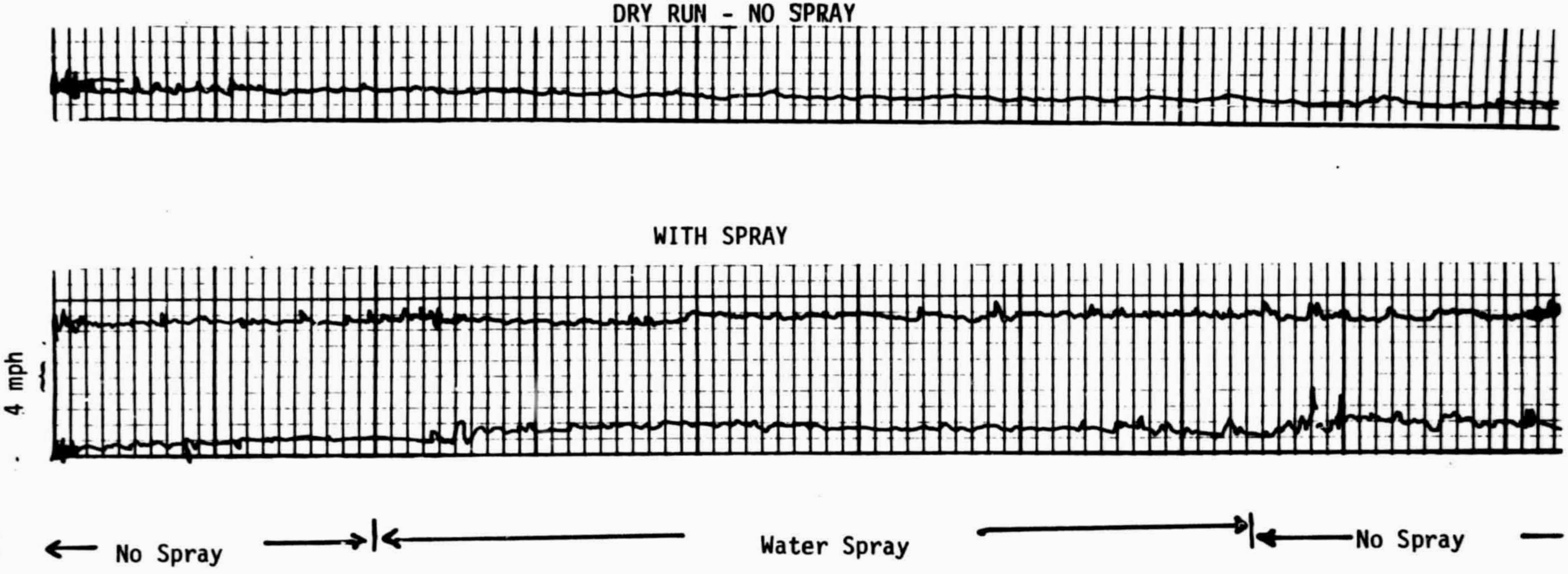

Figure 7. Velocity measured by Pitot Tube scanning across test section through spray area; 87 mph Air Velocity, 125 mm/hr Rain Rate.

of this test was to establish if water droplets impacting the pitot tube at a velocity unequal to the air velocity affected the pitot probe measurement. Several of these sample test runs are shown on Figure 8. In many of these scans, spikes in the trace were observed which most certainly resulted when a water drop directly impacted a critical location on the pitot tube. These spikes always showed a significant positive excursion in the velocity profile measurement. Even in cases when the water velocity was much less than the air velocity a positive velocity excursion occurred. The equivalent rainrate simulated by varying the water velocity varied from 50 mm/hr to 180 mm/hr. Thus these tests tend to confirm that over the range of rainrates simulated and air velocities tested, the pitot tube measures accurate velocity profiles with the only adverse performance being an occasional spike in the trace when a water droplet directly impacts a critical location on the pitot tube.

A third test series was conducted to establish limiting conditions for pitot tube performance in a water spray. In these tests the tube nozzle was not vibrated. Thus a stream of water originating from the tube was directly aimed at the pitot probe (107 inches downstream) in the test section. At the location of the pitot tube the water spray had diffused to cover an area approximately 3" x 3". At a test section water speed and air speed of 87 mph this corresponds to a rainrate simulation of 2200 mm/hr, a rate exceeding the measured one minute world record (1875 mm/hr in Unionville, MD). By varying the water velocity in the test section from 35 mph to 130 mph, the rainrate that was simulated ranged from 1200 to 3200 mm/hr. Selected results from this test series are shown in Figure 9. In this test series the pitot tube was scanned across the test section, being exposed to the water stream only over the three inch distance in the center of the tunnel. In all tests conducted, when the pitot tube was immersed in the stream, a large increase in pitot tube measured

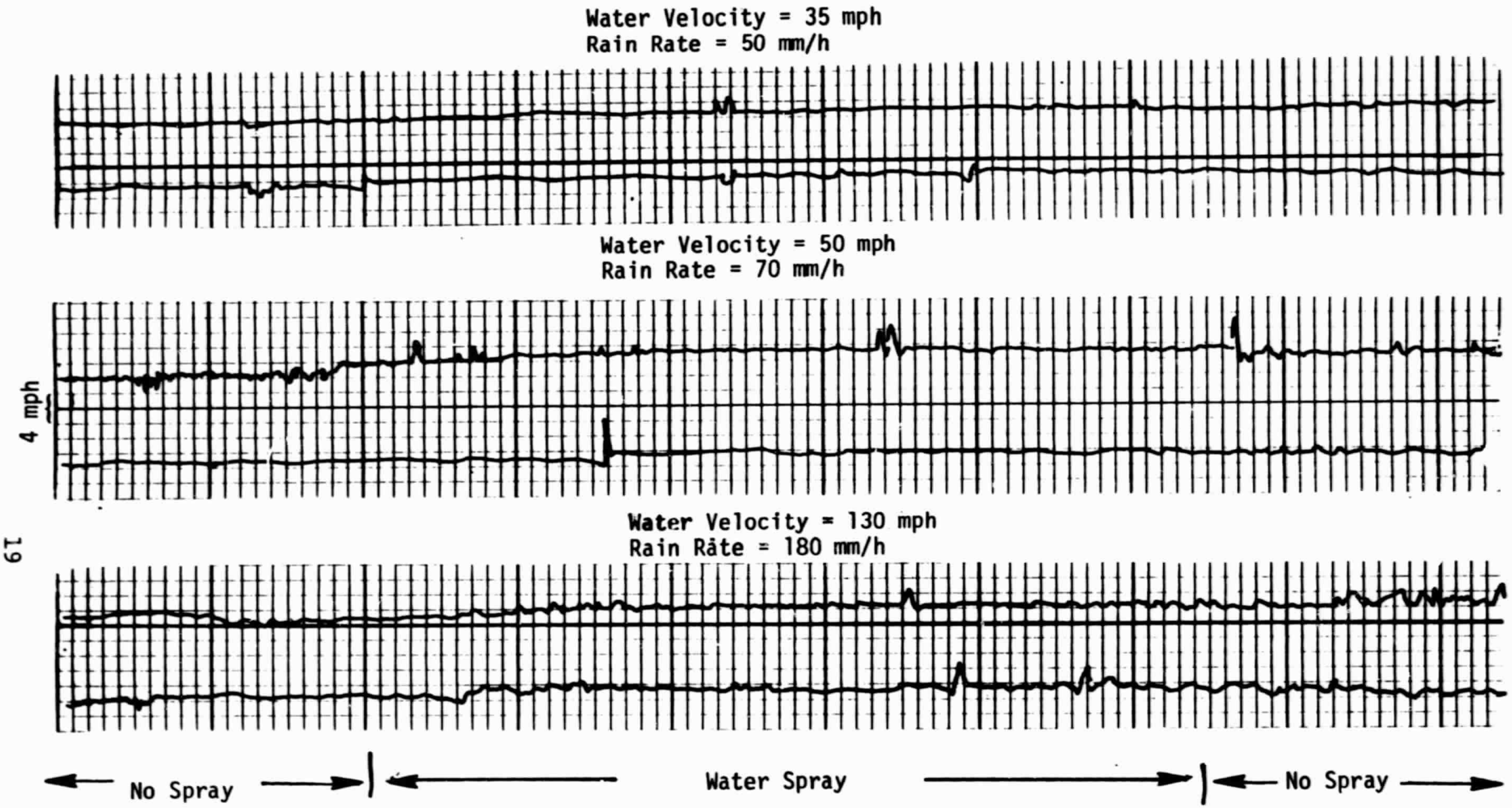

Figure 8. Velocity measured by Pitot Tube scanning across test section through Spray area; 87 mph Air Velocity, 35-130 mph Water Velocity, 50-180 mm/hr Rain Rate.

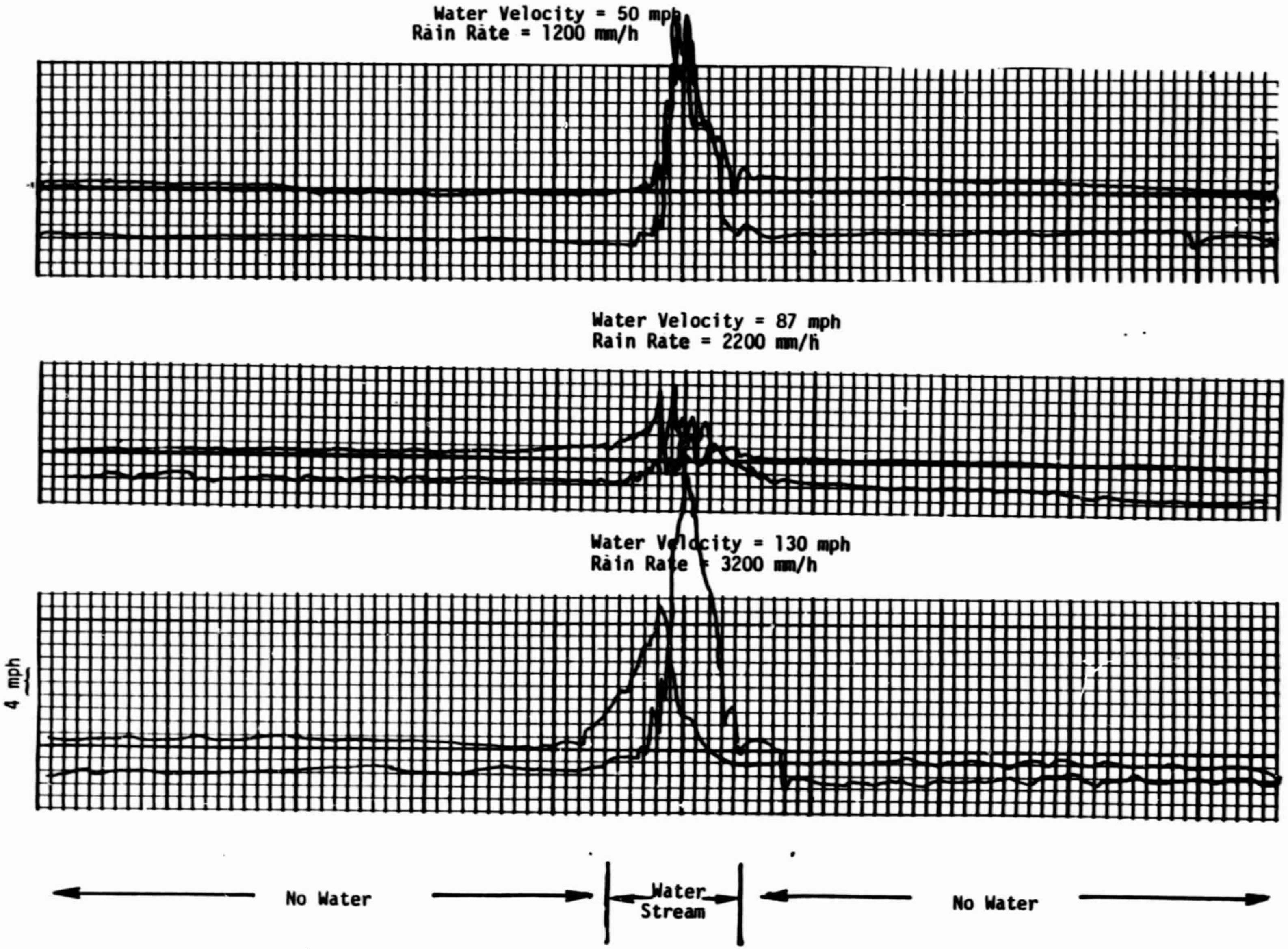

Figure 9. Velocity measured by Pitot Probe scanning across test section through water stream; 87 mph Air Velocity, 1200-3200 mm/hr Rain Rates.

air velocity occurred. The velocity increase occurred even when the water velocity was less than the 87 mph tunnel air velocity. Under most conditions the pitot tube measured a fictitious velocity sometimes exceeding the true velocity by 30 mph. It is unknown why a positive velocity increase always occurred. Perhaps an acoustic wave induced the pressure change. On occasions the pitot tube became saturated with water and when exiting the water stream a biased velocity measurement was retained. The water was then removed from the pitot tube before proceeding with the next test. This test series confirms that under the most severe of water spray impact conditions (far exceeding those likely to be encountered by an aircraft in nature) a pitot tube will measure biased velocities on the high side but if the tube does not clog with water it will return to accurate readings when removed from the spray. Under severe rainrates encountered in nature, no significant performance penalties should result with pitot tube measurements.

2.1.2 Test 2. Evaluation of Fan Performance with Water Spray in Tunnel

In the UDRI Environmental Wind/Rain Tunnel an axial vane fan powers the airflow directly through the test section, through the fan, and out to the exterior. Exposure of the fan to large amounts of water could effect the blade performance causing lift lost, increased drag, and decreased fan efficiency. To ensure that any measured performance deterioration in the tunnel is not the result of decreased fan efficiency experimental tests were conducted to uncover this problem if it existed.

The test series which served to establish pitot tube performance also was useful to address the fan efficiency problem. The tests consisted of introducing a water spray into the tunnel and cycling the spray on and off to determine if any change of velocity in the test sections could be correlated to the presence of water. Since a pitot tube was used to measure the velocity, any velocity change might be attributable to either a change in blade efficiency or water spray effects on the pitot tube. However as previously seen in Section 2.1.1 and Figure 6 no change in air velocity in the test section could be related to the presence of the water spray. Thus from this series it is possible to also conclude that no decrease in the performance of the fan results from the interaction of the water spray with the fan blades.

2.1.3 Test 3. Momentum Transfer Between Slow Moving Water Stream and Air

Having established the satisfactory performance of both the tunnel fan blades and the pitotstatic probe in an airstream with a water spray present, tests were then conducted to determine if airflow changes could result from introducing a waterspray at a velocity very much different from the air velocity and allowing the airstream to accelerate the water spray. Test were conducted with the tunnel test section airspeed velocity fixed at 87 m/hr. The non-dimensional velocity profile of the air in the contraction inlet to the tunnel, based upon the area ratio, from the spray system to the test section can be seen in Figure 2. From previous results in the UDRI Environmental Wind/Rain Tunnel it is know that water exiting the nozzle at a higher velocity than the ambient air slows only slightly between the nozzle and the test section in the available distance of 108 inches (See Reference 1). For this reason the water velocity can be considered constant throughout the tunnel inlet and the test section . Air velocity surveys were conducted horizontally across the test sections, into and out of the water spray to determine if the drag of the water drops signficantly affected the local airspeed. Any difference in air velocity in the water spray from that outside the spray would reflect a momentum transfer from water to the air.

Using the local contraction ratio to estimate the air velocity at various location in the inlet, an expression for the average velocity difference between the water spray velocity and the air velocity (from the location of spray nozzle to the pitot tube location in the test section) was derived. This expression in approximate form is given by

$$\bar{\Delta} V = V_W - .38\ V_T$$

where

V_W is the water spray exit velocity considered constant throughout the inlet and test section, and

V_T is the air stream velocity in the test section.

If the water velocity is matched to the test section air velocity ($V_W = V_T$) then the average velocity differential through the inlet is $\overline{\Delta V} = .62\ V_T$. Consequently, if a water stream is penetrating the air stream then the water stream on an average is flowing 62% faster than the air stream through the inlet region even though the velocities are matched at the test section. Considerable momentum transfer is thus possible. Table 1 shows the average velocity differential for the conditions under which experimental tests were performed. Note that even under the condition when water velocity is much less than the test section air velocity, the average water velocity still exceeds the average air velocity throughout the inlet. Mathematical analysis of the momentum transfer process is complicated by the fact that the spray pattern expands with distance from the nozzle. At the nozzle exit, where the velocity differential is greatest, the volume of air being affected is very small. Whereas, where the water spray has expanded to a larger coverage area the velocity differential is less but a larger volume of air is being affected. Consequently, the greatest momentum transfer is expected to occur in the central part of the

TABLE 1

Experimental Test Conditions

Test Section Air Velocity MPH	Water Velocity MPH	Average Velocity Difference ΔV MPH	Rain Rate mm/hr	Spray Coverage (test section)
87	35	2	195	14"x14"
87	50	17	275	14"x14"
87	87	54	500	14"x14"
87	120	87	600	14"x14"
87	145	112	800	14"x14"
87	87	54	700	12"x12"

spray with less momentum transfer occurring towards the exterior of the spray pattern. The experimental test results confirm this supposition. Figure 10 shows sample results from several test cases at an airspeed of 87 m/h with various water spray velocities. When the water velocity was small, 35-50 mph, the velocity scan across the tunnel test section shows no discernable variations of velocity at any test section tunnel location. Even when the water velocity was matched with its test section air velocity at 87 mph, no velocity variation was observed. However, as the water exit velocity was increased above 90 mph, the center regions of the spray show a somewhat higher air velocity than the exterior locations. The maximum velocity increase in the center of the spray was about 2 mph. As the water exit velocity increases even further to 145 mph, representing a rainrate of 800 mm/hr, the velocity increase in the central region of the spray was approximately 3 mph greater than the air stream velocity unaffected by the water spray. These results tend to indicate that the drag force exerted by the drops on the air stream has some affect in changing the local air flow velocity in the test section. Under the test conditions simulated in the UDRI Environmental Wind/Rain Tunnel, the change of air velocity resulting from this momentum transfer is small, but could be significant if very exacting test conditions are required. Because in the UDRI tunnel the water velocity is introduced into the tunnel at a velocity higher than the surrounding air, the momentum transfer will always result in an increase in the test section air velocity. Thus if aerodynamic measurements were being made a positive lift increase would be observed. In tests at which air velocity and water velocity are matched in the test section at say 87 mph no velocity change was observed - even at a rainrate of 700 mm/hr. The application of these results to other wind tunnels with spray bars should dictate however, that the momentum transfer factor must be taken into consideration. Of

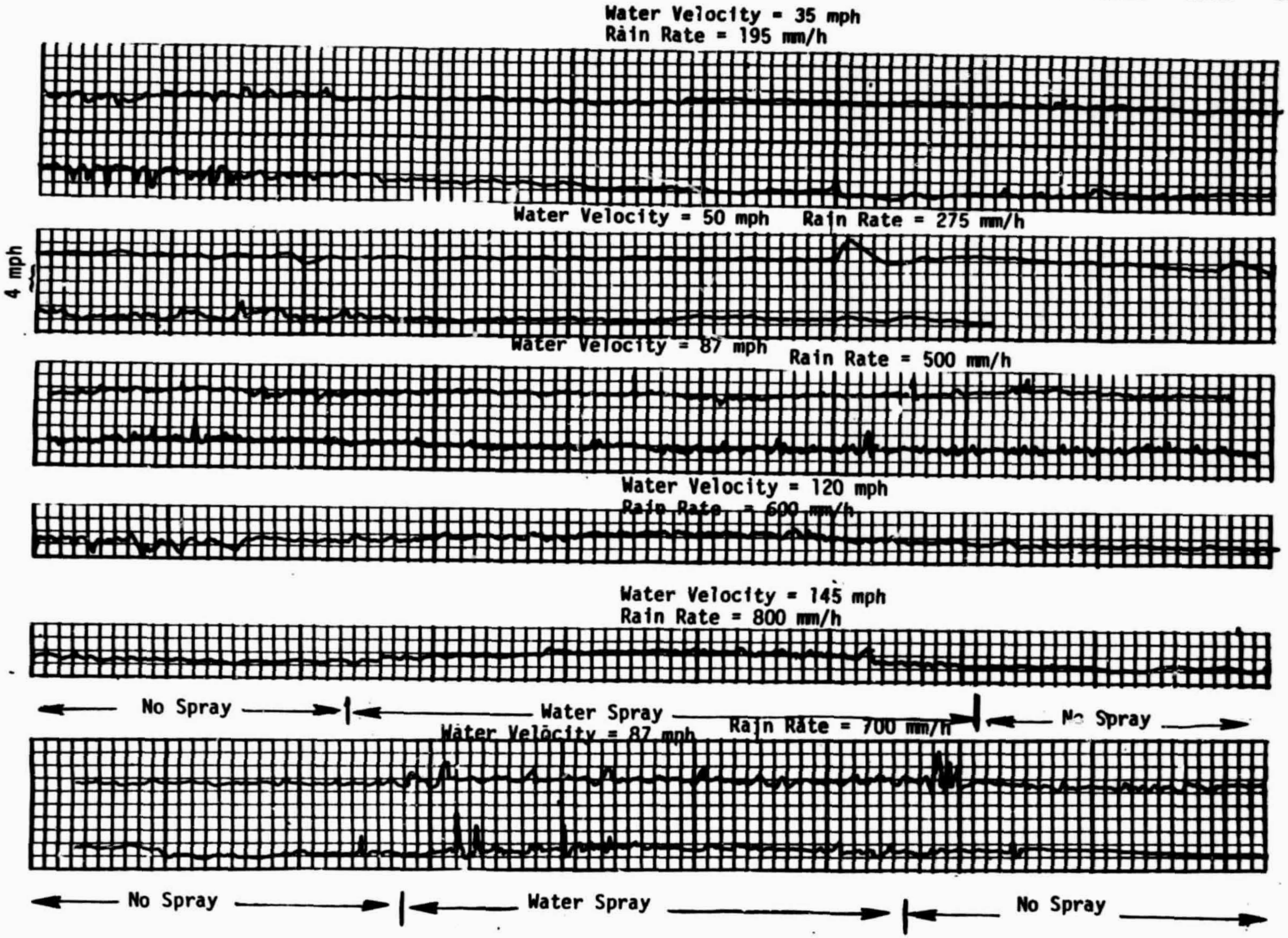

Figure 10. Velocity measured by Pitot tube scanning across test section through Spray area; 87 mph Air Velocity, 35-145 mph Water Velocity, 195-800 mm/hr Rain Rate.

special significance would be tunnels in which the water spray is introduced at a very low velocity and given sufficient distance to accelerate to near air velocity in the test section. Under such a condition, a measureable loss in air velocity may occur in the test section region exposed to the water spray. Special consideration should be given when simulating rainrates exceeding 500 mm/hr. It is recommended that a pitot tube be used to survey the velocity profile in the test section region of the tunnel both with and without the water spray present so that tunnel characteristics are accurately defined for the spray conditions under which tests are to be conducted.

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1. Luers, James K. and Fiscus, Ira B., "Nozzle Tests for Simulating Heavy Rain in a Wind Tunnel," AFWAL-TR-83-3131, January 1984.