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CONTROLLED VELOCITY TESTING
OF THE
ASI/PINSON HIGH RELIABILITY WIND TURBINE GENERATOR

TN-80-13

Introduction:

Controlled Velocity Testing (CVT) is a testing technique designed to test a SWECS under a controlled wind regime for rapid determination of performance characteristics and parametric changes. The CVT program is carried out at the Department of Transportation (DOT) rail site at Pueblo, Colorado. The test site is a section of straight precision (Grade 7) track approximately 2.5 miles long. In order to undergo CVT, a SWECS is mounted on a stub tower and secured to the first of two flat cars and pushed by a high speed railroad engine. The SWECS is mounted on the forward section of the lead flat car, while an instrumentation van and a portable generator are mounted on the aft section of the second flat car (Figure 1). The second flat car also serves as a buffer to reduce turbulence between the locomotive and the SWECS.

Test Specimen:

Manufactured by Aerospace Systems, Inc. (ASI) of Burlington, Massachusetts, the ASI/Pinson High Reliability Wind Turbine Generator (WTG) is a vertical-axis, three-bladed, cyclicly variable pitch machine designed to produce 1 KW of electrical output at 9 m/s (20 mph). This government funded prototype incorporates a 2.4 m in height x 4.6 m in width (8 ft x 15 ft) diameter rotor with three constant chord, 8-ft long aluminum rotor blades. The blade pitch is controlled by control rods which are actuated by a tilt-cam assembly. A "V"-vane tail assembly connected to the tilt-cam assembly orients the cam (with respect to wind direction) and actuates the desired cyclical pitch, thereby providing the basic rpm control. The machine is designed to cut-in at 2.2 m/s (5 mph) and produce maximum output at 160 rpm.

Test Set-up and Instrumentation:

When undergoing CVT, the ASI/Pinson was mounted on a Rohn SSV-6 tower section that was stiffened to give an overall tower and WTG natural frequency of 8.9 Hz. Instrumentation provided by the manufacturer for CVT included strain gages on one blade, one strut, one "L"-link and the gearbox torque reaction bar, as well as a Trump-Ross Encoder for rpm, a yaw position potentiometer and a linear position potentiometer for measuring travel of the actuator lever arm(trip mechanism movement). Transducers for output current, voltage, power, wind velocity and direction were supplied by Rocky Flats. A ground speed instrumentation sensor was supplied by DOT. However, wiring errors, damaged wiring and lack of timely information on the range of measurement

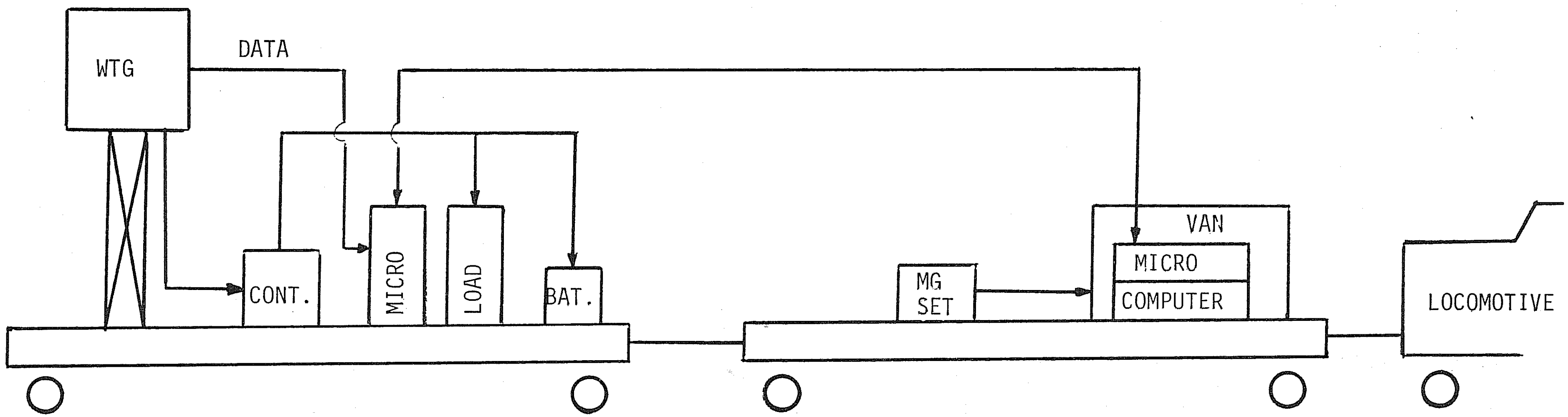

Figure 1
CVT Test Set-Up

from (ASI/Pinson) defeated the effort to calibrate the strain gages. The pulley attached to the actuator rod (used to drive the yaw position potentiometer) could not be kept tight, and the belt between this pulley and the potentiometer would not stay on. Also, the pulley attached to the main shaft, for the purpose of driving the rpm sensor, came loose and was cemented back into place. Based primarily on a rather tight test schedule, it was decided that data from these sensors (except rpm data) were not mandatory for the CVT tests.

Outputs of the active calibrated sensors were fed through signal conditioners to a microprocessor located in one of the instrumentation racks (flatcar #1). A second microprocessor was located in the instrumentation van (flatcar #2) and interfaced with a Hewlett-Packard 9845A desk top computer. Another instrumentation rack contained two programmable solid state loads (PS^2L) rated at 1 kW each. These were connected in parallel with a battery and were set to regulate at voltage levels above or below, or at the voltage level of, the battery.

Using the instrumentation and data acquisitions systems described above, plots of all data points collected for power/windspeed and rpm/windspeed were obtained from the HP 9845A within seconds of a run completion. A "Method of Bins" program, which averages all data points collected (one each second) at each unit of windspeed during a run, can be used to generate selected plots of power/windspeed, rpm/windspeed, Cp/windspeed, tip speed ratio/windspeed etc. within a few minutes of run completion.

Discussion of Results:

During CVT of the ASI/Pinson, test runs were made at three different sets of ground speed: 0 to 30 mph in 5 mph increments; slow, steady runs the full length of the track at 10, 15 and 20 mph to provide large amounts of data relative to cut-in velocity; and accelerations from 25-30 mph to 60 mph. Table I is a matrix of tests completed during CVT of the ASI/Pinson, including the corresponding wind speeds.

When CVT of the ASI/Pinson began, immediate attempts were made to adjust the cut-out point to the recommended 160 rpm. Several runs were made after adjusting the trip mechanism between each run. However, results were not consistent (i.e., they did not always reflect the direction of the adjustment). During one run, an overspeed condition caused the rotor to reach 235 rpm, and several rivets that tie the blade skin to the extruded leading edge "popped"

TABLE I

TESTS COMPLETED MATRIX

TASKS		Wind Speed (mph)		
		0 to 30	10, 15, 20	30 to 60
Tail Alignment	- Wind velocity at which tail aligns with wind direction	✓	✓ (10,15 only)	X
Rotor Start	- Wind velocity at which rotor starts to turn	✓	✓ (10,15 only)	X
Cut-In	- Wind velocity at which cut-in occurs	✓	✓ (10,15 only)	X
Cut-Out	- Wind velocity at which WTG shuts down	X	X	✓
Power Curve	- Plot output power vs. wind speed	✓	✓	✓
Load Variation	- Power curve with varying load voltages	✓	✓	✓
Improve Startup	- Minor changes made in configuration to lower cut-in velocity	✓	✓	X

PROBLEM AREAS

Problems Encountered	Solutions
One airfoil of the tail assembly damaged during shipment to DOT.	Local sheet metal shop made satisfactory repairs. It is believed there was no effect on machine performance.
Two welds on tail boom found to be cracked.	Welded locally.
Tachometer pulley loose on output shaft of gear box.	No apparent way to fix mechanically. Cemented the bushing, pulley shaft and face to gearbox shaft with Duco Cement - it worked.
Yaw pulley loose on actuator rod. Up-down movement caused drive belt to jump off pulleys.	Unable to fix this one. Tested without it. No tracking error data available.
Two of the three bolts in the swivel body and nut in swivel-end of actuator lever found loose.	Retightened.
Rotor oversped during two runs.	Reason traced to tail assembly airfoils rotating on single attach point resulting in much less lift. Sheet metal straps added to prevent rotation.
Rivets popped and skin peeled on two blades.	Blades repaired locally.
Locknut on top of swivel came loose. Resulted in shortened travel of actuator rod and did not allow mechanism to reach full run position.	Locknut retightened.
Power curves consistently indicated output in excess of 2 kW.	Instrumentation and calibration checked. No clear answer as yet. Natural Power, Inc. is investigating. A dynamometer test is planned at WSTC to investigate this area.

TABLE II (Cont.)

PROBLEM AREAS

Problems Encountered	Solutions
Drawings or manual do not contain information on hookup of linear pot to measure activator rod travel.	Unable to obtain information for ASI/Pinson, fabbed a jury rig.
Damaged strain gauges, wiring errors and lack of firm information on calibration range.	Unable to resolve in time for CVT. No data collected.

out of blades 2 and 3. Figure 2 reflects power data generated during this time frame. Data collection continued beyond the maximum rpm and power points through shutdown and almost to complete stop. It is felt that high centrifugal and aerodynamic loads caused the rivet failures, and an investigation is planned to establish the pull strengths of the rivets. After new rivets were installed, another test was made to verify the cut-out point. This test run resulted in the same overspeed condition and the test was stopped.

Examination revealed that the airfoils on the "V"-vane tail assembly had rotated about their single attachment point to the tail boom. The trailing edges had moved approximately 4 inches apart, in comparison to a starting point of less than 1/4" apart. This movement decreased the angle of attack and amount of lift required to actuate the trip mechanism for shutdown. Figure 3 presents rpm data generated just prior to discovery of the airfoil rotation with critical points noted. Figure 3 plainly shows the trip mechanism starting to shut down at a windspeed of approximately 18 m/s (40 mph). Then, the airfoils apparently rotated and allowed the rotor to run up to 235 rpm in approximately 10 seconds. The test run was stopped at this point.

Repair was initiated consisting of two 2" sheet metal straps extending between the two airfoils and across the boom. One strap was located just ahead of the attachment point, the other at the trailing edge. The airfoils were rotated such that the trailing edges were nearly touching.

After making several additional test runs with the modification, it was evident that the cut-out rpm was now far too low, although the cut-out wind speed was normal (Figure 4). A number of trip mechanism adjustments produced no improvement. A close examination of the trip mechanism revealed that the locknut holding the threaded rod (bolt) in the actuator rod swivel had worked loose. This shortened the stroke of the actuator rod and the remainder of the trip mechanism. The locknut was tightened and a few more runs were made to locate the cut-out point. In this configuration, the machine would go into a deep stall and nearly stop rotating. Power and rpm data reflected in Figures 5 and 6, respectively, were generated after tightening the loose swivel locknut. These data reflect a significantly high cut-in wind speed (10 m/s) and low cut-out wind speed (15 m/s).

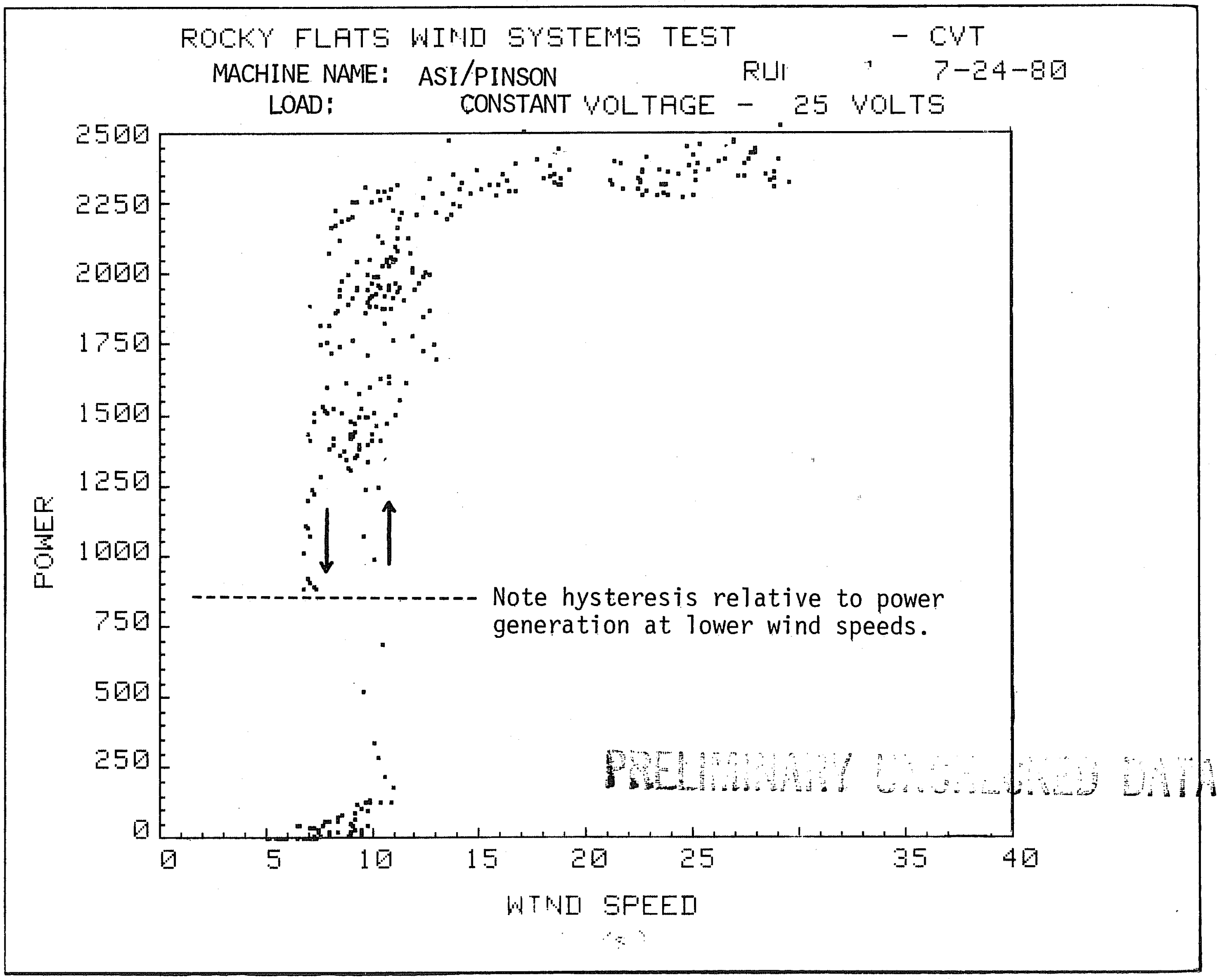

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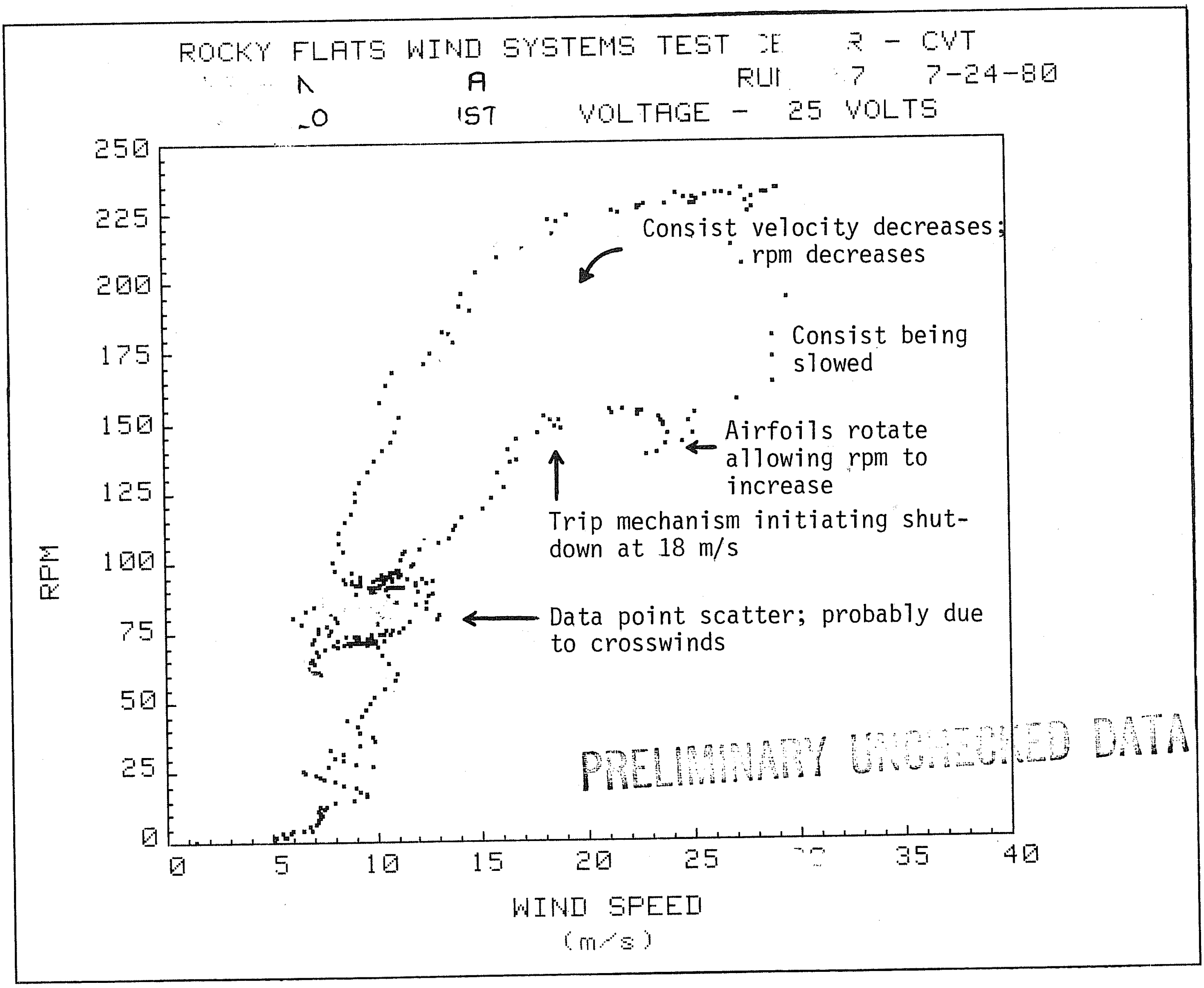
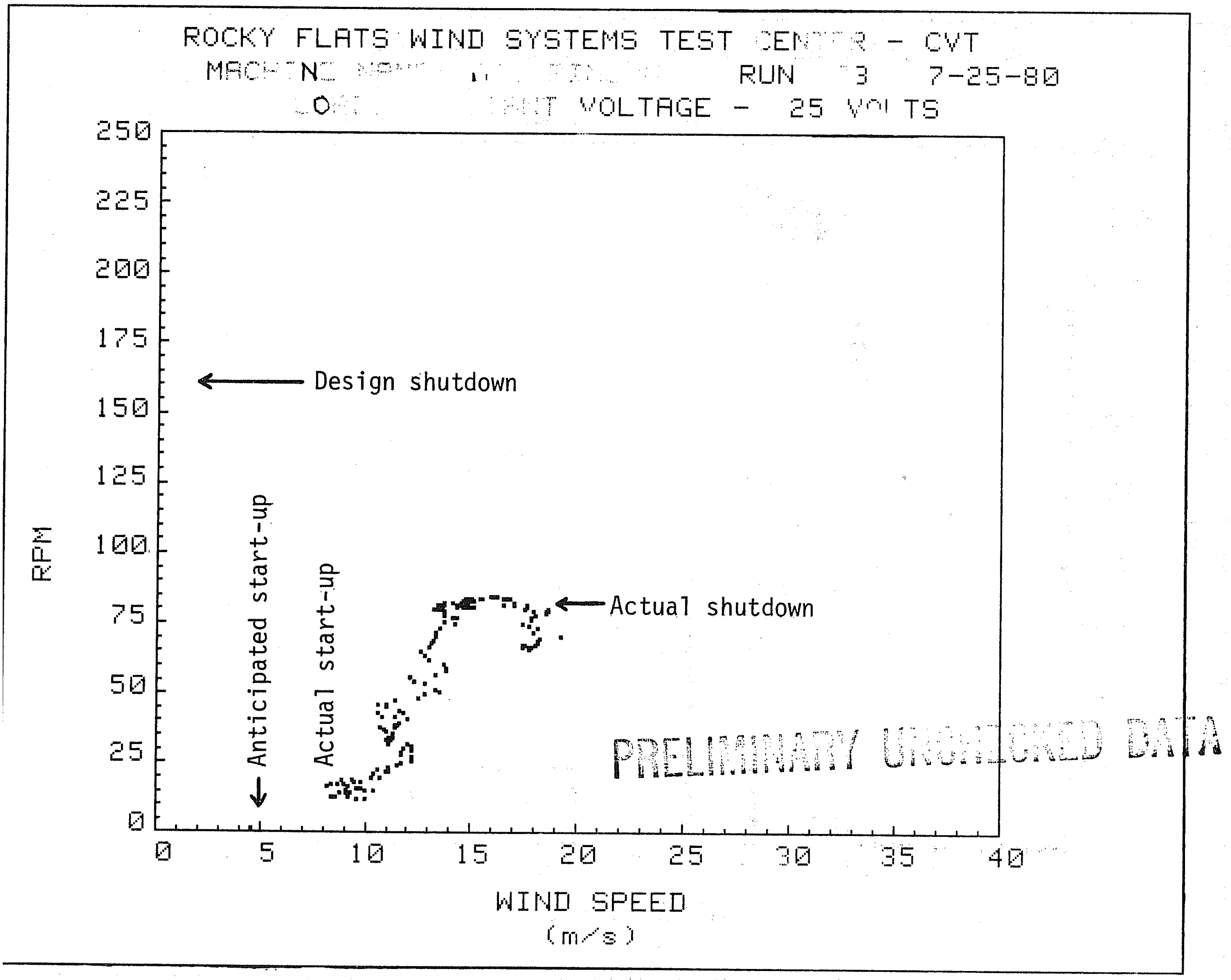
FIGURE 2

OVERSPEED CONDITION



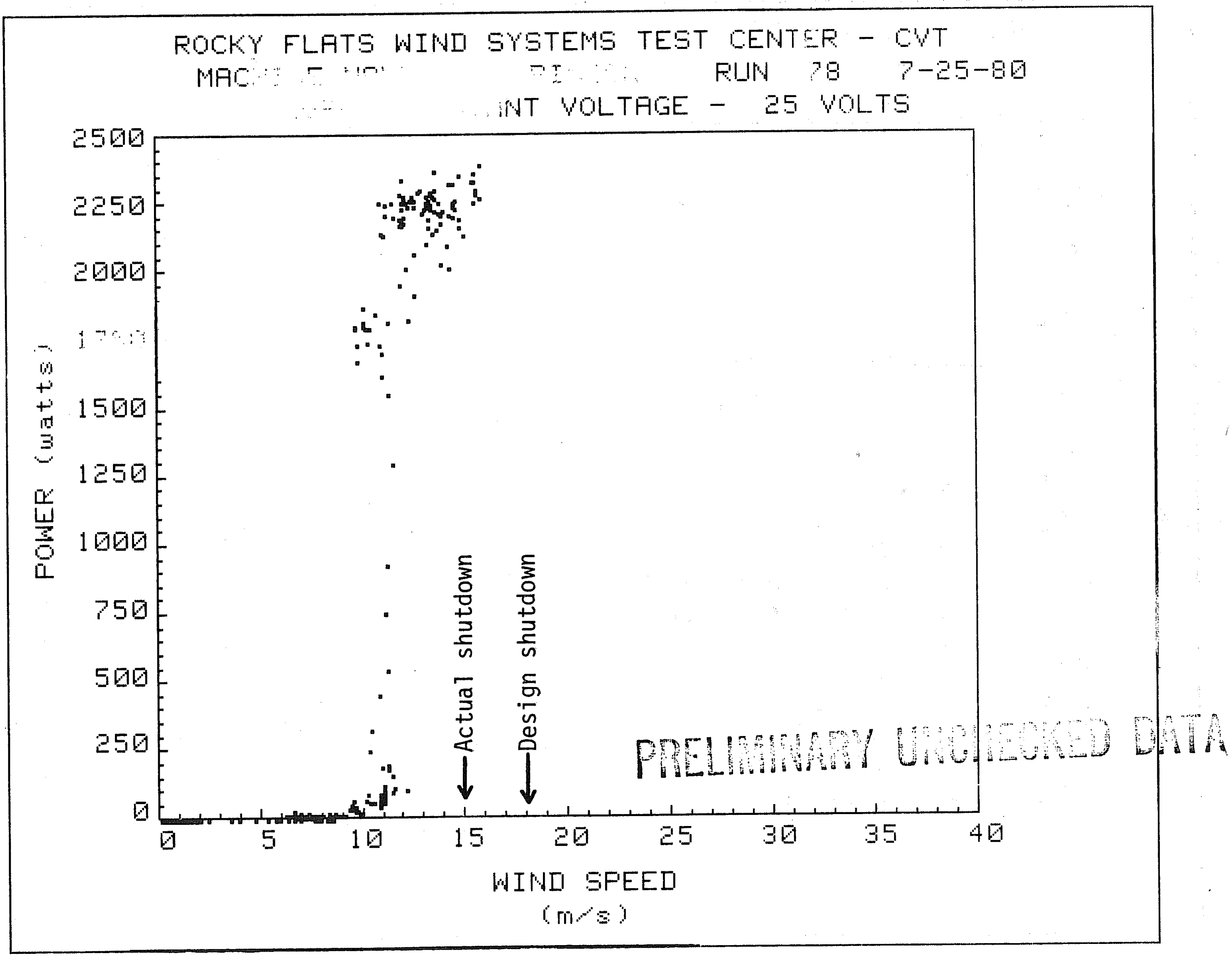
TOTAL DATA PO

FIGURE 3
OVERSPEED CONDITION



TOTAL DATA POINTS

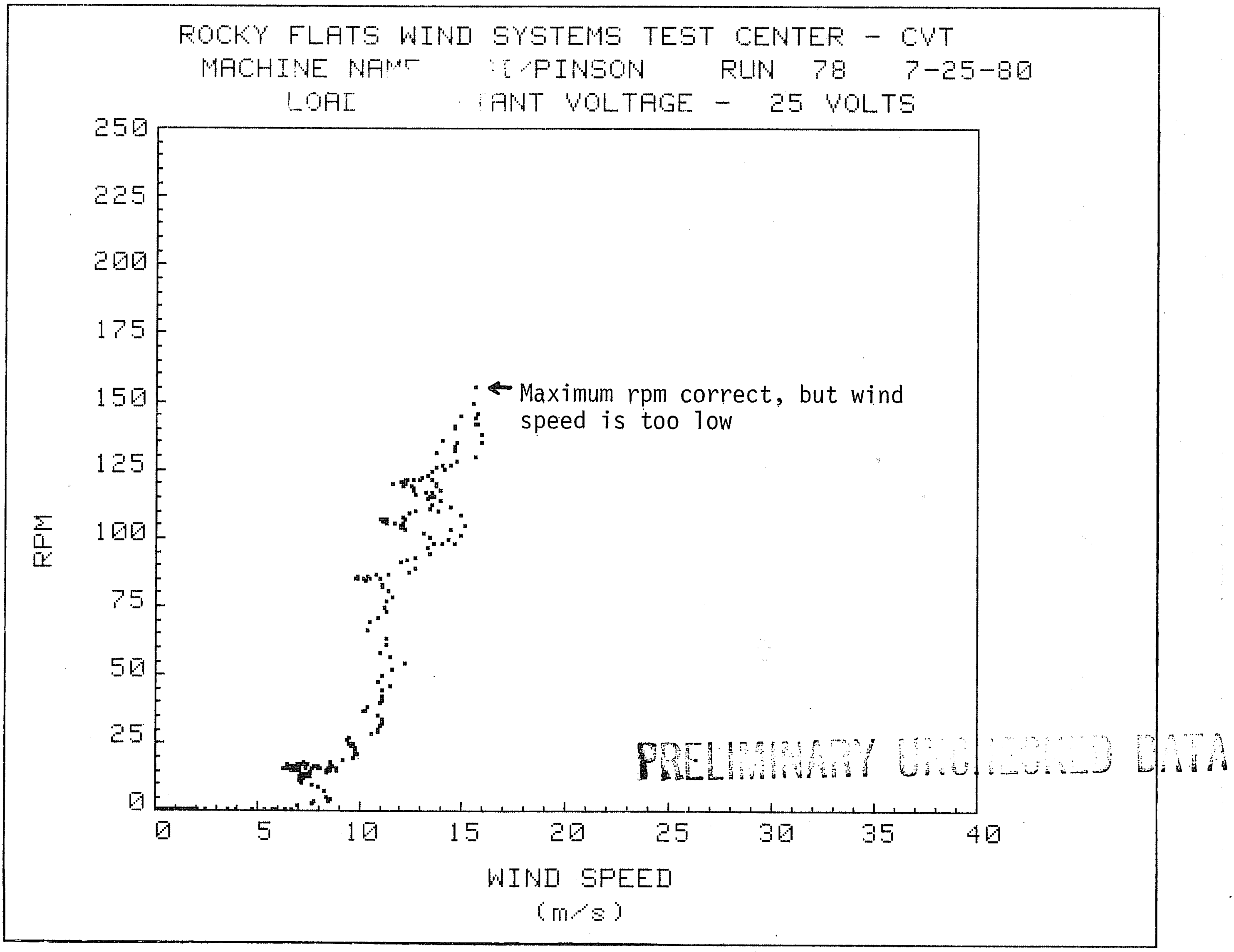
FIGURE 4
EARLY SHUTDOWN



TOTAL DATA POI

FIGURE 5

TRIP MECHANISM STROKE NORMALIZED



TOTAL DATA POINT

FIGURE 6

TRIP MECHANISM STROKE NORMALIZED

The tail was again modified to allow a 2" separation between the airfoil trailing edges (roughly the mid-point of the previous configurations). Several more runs and one additional adjustment of the trip mechanism indicated the WTG was then operating normally and further testing could be performed. Figures 7 and 8 contain data generated during testing in this configuration with the trip mechanism adjusted for shutdown at an rpm of just under 160. Note that the WTG restarted after shutdown. This configuration was kept for the remainder of the tests, and cut-in and cut-out were re-checked and re-verified. Figures 9 through 12 are plots of data generated on the same run as Figures 7 and 8 after using the "Method of Bins." These data (Figures 9 through 12) indicate that shutdown occurs at the proper rpm, but just above a wind velocity of 13.4 m/s (30 mph). Design shutdown wind velocity is approximately 17.9 m/s (40 mph). Also note that maximum Cp and power do not occur at the same wind speed. This could indicate an improper match between the rotor and load. Table II is a summary of all problem areas encountered during CVT of the ASI/Pinson.

Although a major objective of CVT on the ASI/Pinson was to obtain power curves, it is also important to remember that considerable effort was expended to improve performance and perform adjustments in an attempt to achieve the optimum configuration of the WTG. Testing at three different positions of the airfoils of the tail assembly, while not pre-planned, provided valuable data relative to shutdown rpm and wind velocity. The collective pitch adjustment was changed late in the testing period to increase the angle of attack in an effort to improve start-up. Unfortunately, the effects of this change were clouded by changes in performance induced by the trip mechanism stroke being shortened when the locknut came loose. As part of the CVT Test Plan, load voltage settings were also varied from 22 to 25 volts. Results of these varied settings showed that power output increased from approximately 2050 watts at 22 volts to approximately 2350 watts at 25 volts. In addition, a number of configuration changes for improving start-up were suggested by the ASI representative visiting the facility. The changes were tried but did not materially improve start-up. It should also be noted that a Pinson representative paid a visit to the WSTC prior to shipment of the machine to DOT. The WTG was judged to be properly "tuned" per manufacturer's specifications and ready for test.

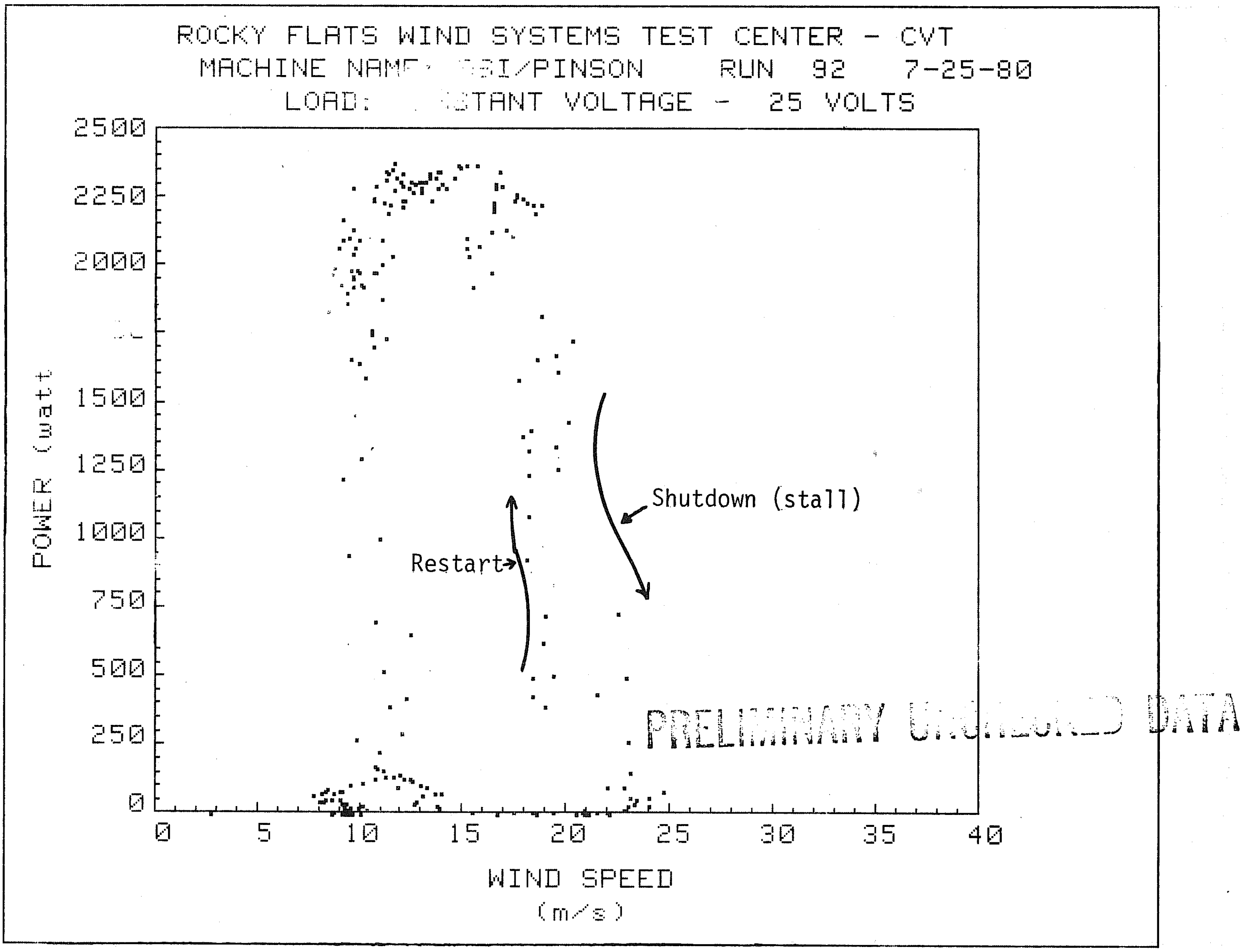


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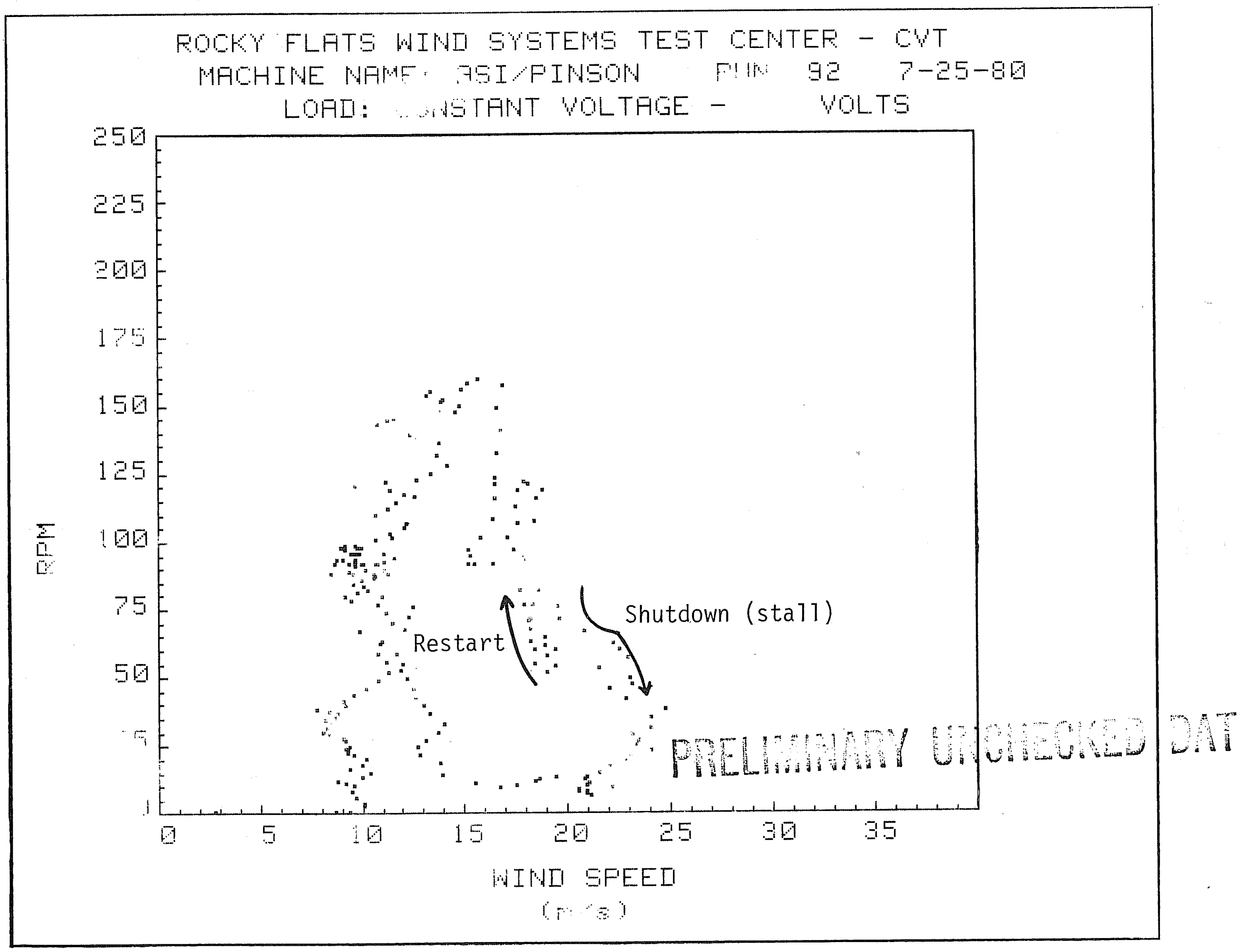
FIGURE 7

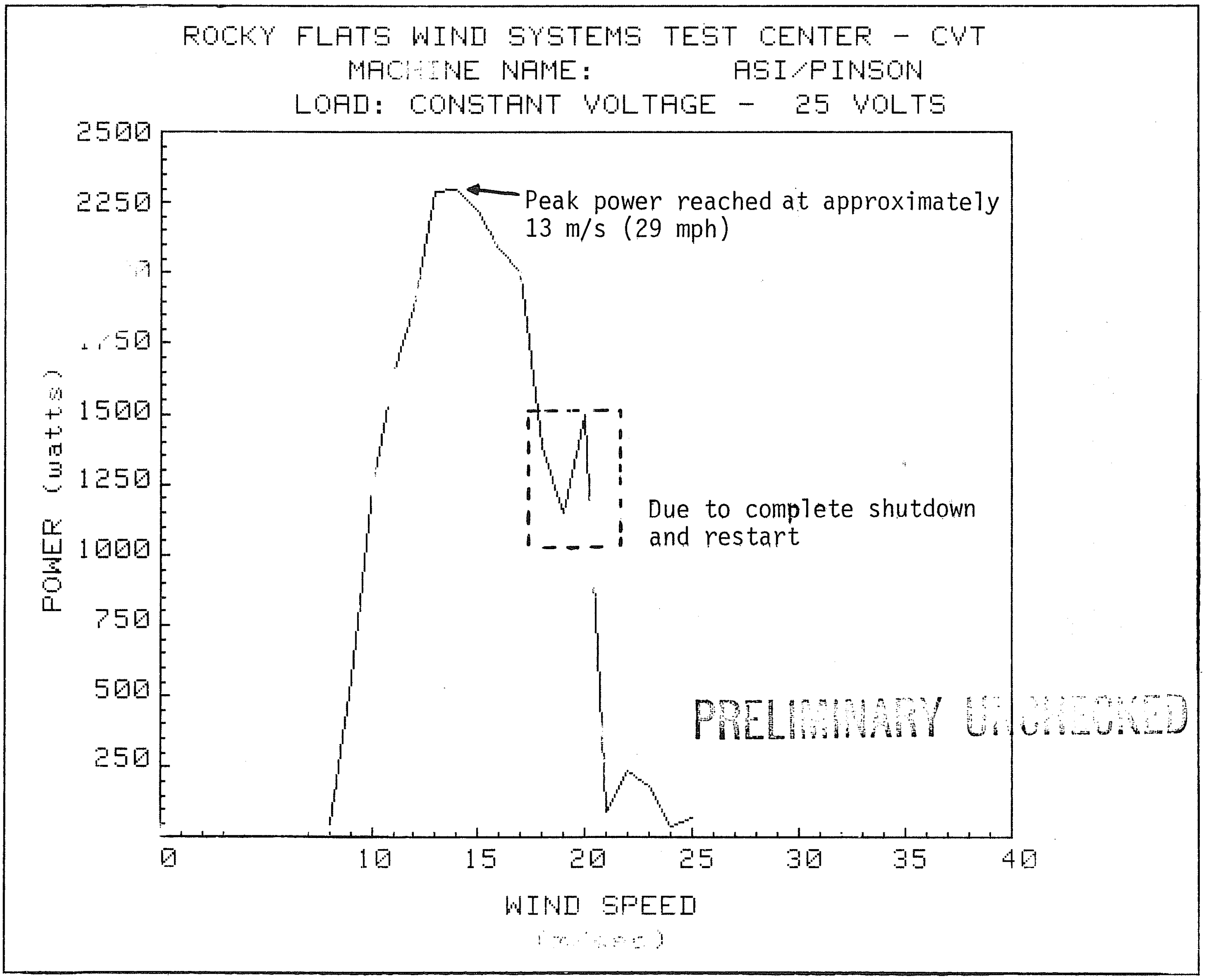
WTG NORMAL - RPM REGULATED ABOVE SHUTDOWN



TOTAL DATA POIN

FIGURE 8

WTG NORMAL - RPM REGULATED ABOVE SHUTDOWN



TOTAL DAT

184

FIGURE 9

RUN 92 AFTER USING "METHOD OF BINS"

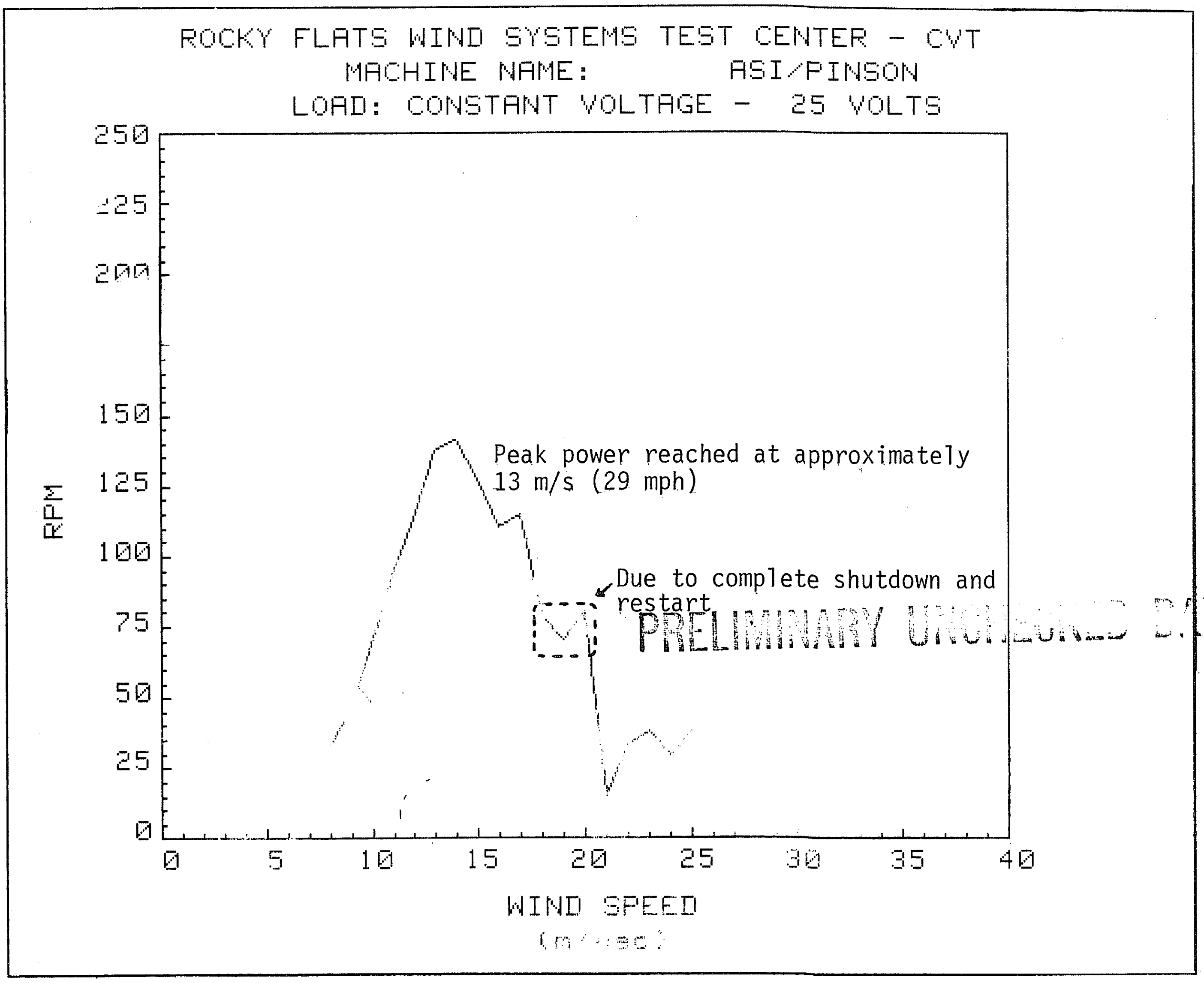


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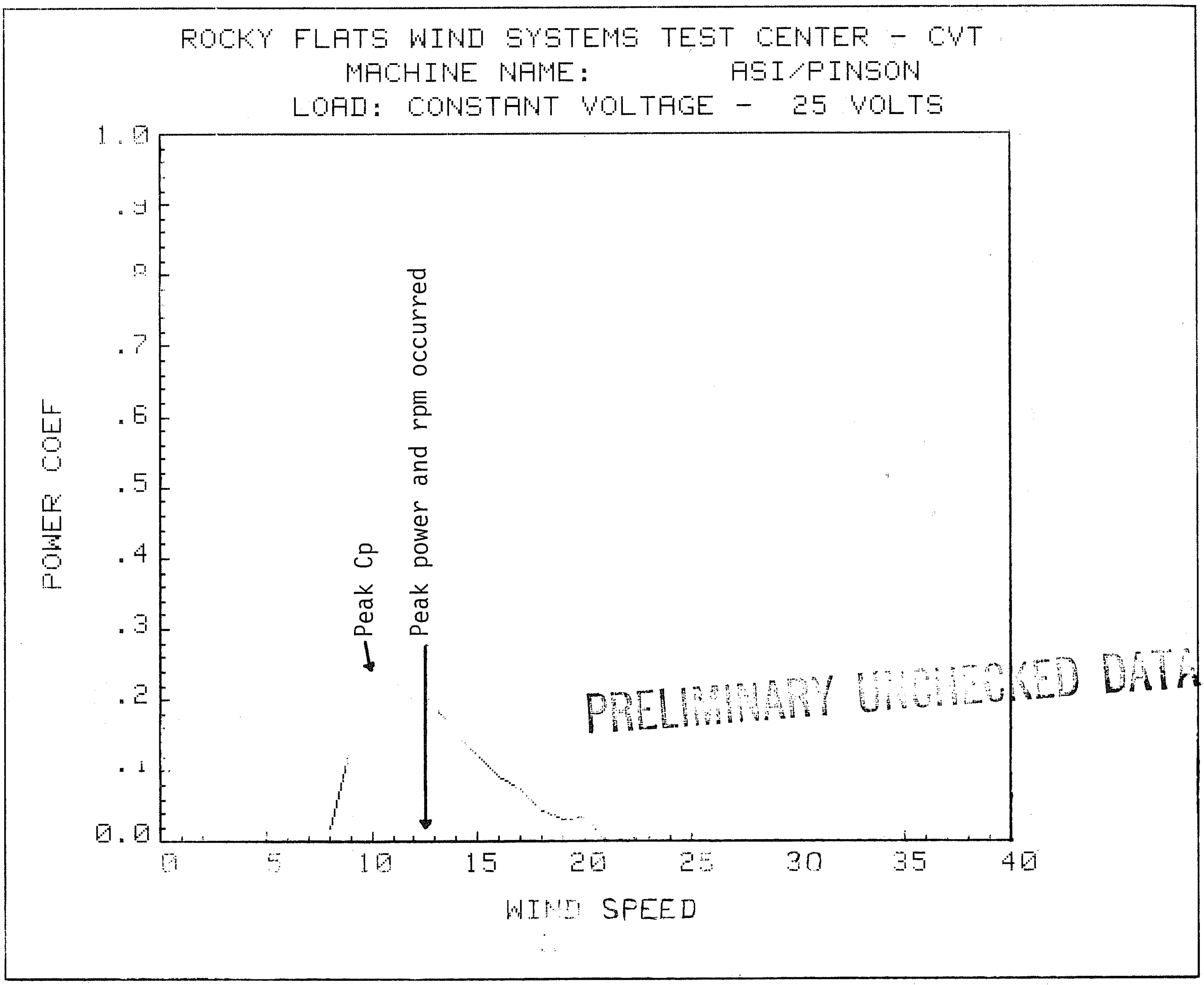
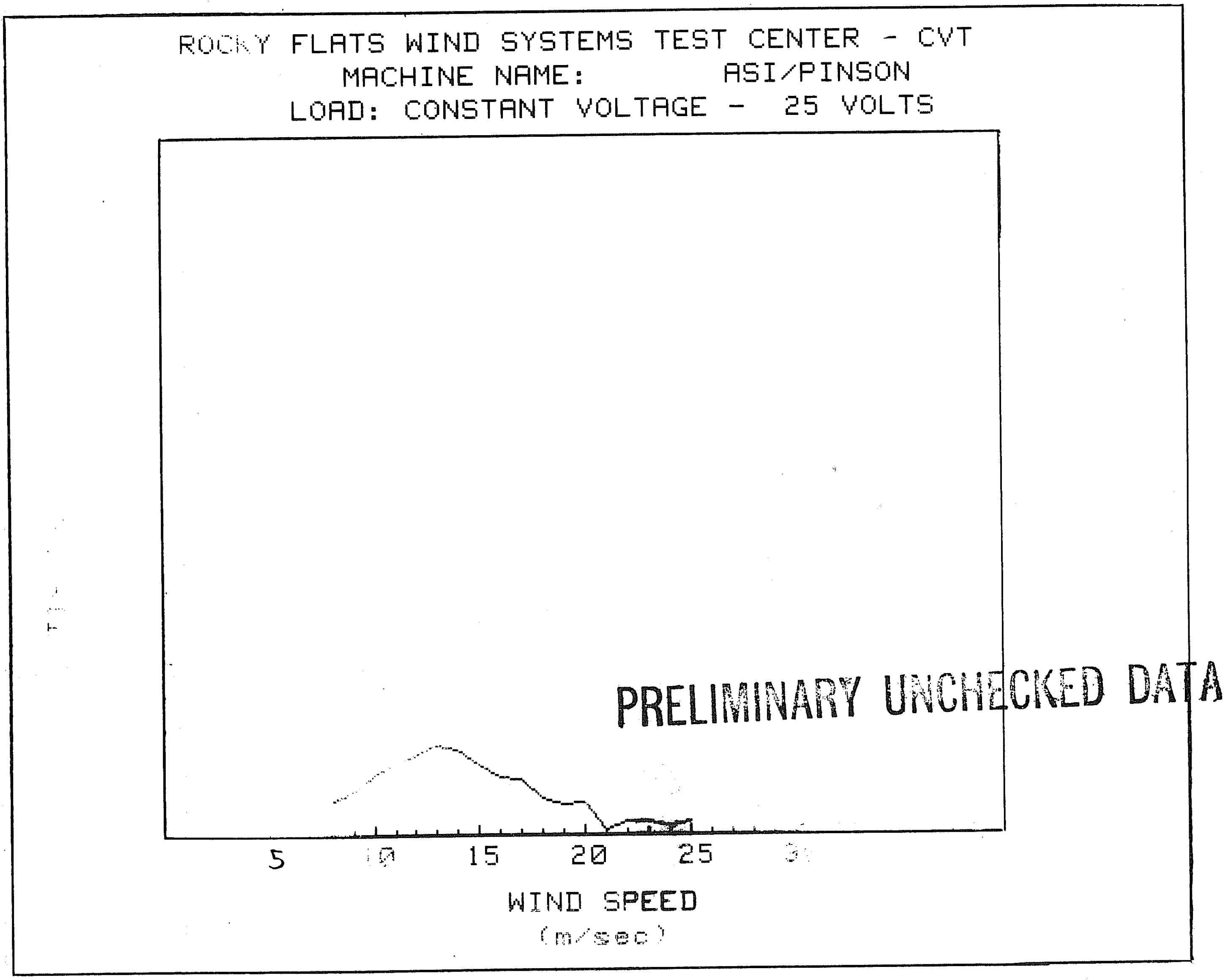
FIGURE 10

RUN 92 AFTER USING "METHOD OF BINS"



TOTAL

FIGURE 11
RUN 92 AFTER USING "METHOD OF BINS"



TOTAL

FIGURE 12
RUN 92 AFTER USING "METHOD OF BINS"

CONCLUSIONS/RECOMMENDATIONS:

Although a "tight" test schedule prohibited extensive parameter testing after the ASI/Pinson began operating normally, it is felt that CVT produced a great deal of useful data in a very short time period. A number of problems were discovered and corrective actions were either taken or defined which should have future value to both Rocky Flats and the manufacturer. Despite the fact that the optimum WTG control configuration was not defined, definite improvements were made. The test methodology clearly could be employed to define such optimum configurations in a time and cost effective manner. Conclusions and recommendations derived from CVT are summarized in the following paragraphs.

Of the design specifications that could be evaluated by CVT, quantitative data indicated the machine failed to meet specifications in three areas:

- Although the maximum output of the ASI/Pinson was measured to be in excess of 2 kW at 13 m/s (29 mph), the output at the machine's rated wind speed (9 m/s - 20 mph) was only 600 watts. The high maximum power output will be investigated through dynamometer testing at RF.
- Design specifications of the machine call for a cut-in wind speed of 2.2 m/s (5 mph). However, the cut-in wind speed measured by CVT was in excess of 7 m/s (16 mph).
- The cut-out wind speed of the WTG was determined to be less than the design specification of 17.9 m/s (40 mph).

Qualitative data generated from CVT showed that the ASI/Pinson would not perform up to design specifications under atmospheric test conditions due to the following problems:

- The angle of attack of the tail assembly airfoils was not originally, and may not yet be, set to the otpimum point. It is believed that this problem contributed significantly to the low cut-out wind speed (see above).
- The method of attaching the airfoils to the tail boom is inadequate. Once the optimum angle of attack is determined (see the preceding problem), a positive method of attaching the tail assembly airfoils to the tail boom must be developed in order to retain the optimum point.
- The attachment of the swivel-to-actuator rod (used to pitch the blades) is not adequate or reliable.

In relation to the instrumentation provided for CVT by the manufacturer, the following problems were discovered:

- The method of attaching the tachometer pulley to the drive shaft is not adequate.
- The method of attaching the yaw pulley to the actuator rod is not reliable and must be improved.
- No means of attaching the linear potentiometer (for measuring actuator rod travel) was provided.