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INSTALLATION AND INITIAL OPERATION OF A 4100 WATT WIND TURBINE

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SUMMARY

The objective was to gain some early, practical experience in the wind power field by purchasing and operating a commercial wind turbine. The purpose of this report is to describe that wind turbine activity, its controls, the machine installation, the initial operation, and the results obtained.

As part of a joint ERDA-NASA Lewis Research Center wind power program, the largest commercially available wind turbine has been installed at the NASA Plum Brook Station near Sandusky, Ohio.

The rotor has two blades and measures 30 feet, 2 inches (9.2 m) from tip to tip. In a 16.8 miles per hour (7.5 m/sec) wind, it rotates at 150 rpm to generate 4100 watts. The 50-hertz power was dissipated in a resistance load bank in our test.

The 75-foot-high tower which supports the wind turbine is pivoted so the machine can be lowered for inspection, servicing, and, possibly replacement by machines of other designs as part of a program of supporting research and technology in wind power.

As of November 10, 1975, the wind turbine completed 211 days of unattended operation. This experience has demonstrated that the blade pitching mechanism, which is designed to regulate speed by going into stall at higher speeds, can regulate speed to ±3 percent or better. It was discovered, however, that some brief but severe increases in wind speed will apparently cause enough of the blade to stall that normal operating speed cannot be maintained under load. There have been no signs of any problems resulting from rapid yawing while the two-bladed rotor was turning, even during wind speeds over 50 miles per hour and wind gusts up to 90 miles per hour. It was observed that the weather tower instruments, although located only 350 feet away from the wind turbine, do not always indicate either the wind speed or wind direction that the wind turbine is experiencing. The natural frequency of the wind-turbine tower was observed to be 22 radians per second, which is close to the desired, calculated value of 24.6 radians per second.

INTRODUCTION

The use of windmills to harness the potential power in the wind dates back for centuries. Wind turbines have also been used in this century to generate electric power but these machines have fallen somewhat into disfavor due to the development of more economical means of obtaining electric power. Fossil fuels, hydro, and nuclear sources have become the common power sources. Recent events, however, have led to renewed interest in the pollution-free, no-cost-but-intermittent fuel called wind.

In 1973, the National Science Foundation (NSF) was given responsibility for a national program to develop wind energy systems. NASA Lewis Research Center (NASA Lewis) was asked by NSF to assist in this program by providing project management for the design and fabrication of large, experimental wind turbine generators, and for the necessary supporting research and technology for this endeavor. This NSF responsibility was transferred to the Energy Research and Development Administration (ERDA) in January 1975, with NASA Lewis continuing on in its role of assistance.

A site for erection of the first large wind turbine was chosen to be at the NASA Lewis Plum Brook Station near Sandusky, Ohio. This 100 kilowatt wind turbine was to be placed atop a 100-foot tower. Its 125-foot-diameter blades are designed to generate up to 100 kilowatts in an 18 miles per hour wind.

To obtain early and practical experience in the wind power field, the largest commercially available wind turbine was also purchased for installation and testing by NASA Lewis. This 4.1 kilowatt wind turbine, which is the subject of this report, was placed at this same site, 750 feet away from the location for the 100 kilowatt wind turbine and 350 feet away from a weather tower which measures the wind speed and direction. This report describes the 4.1 kilowatt wind turbine, the electric controls and load bank, the pivoted tower, and the results obtained during the initial operation of this wind turbine, including an unexpected phenomenon resulting from the blade pitch/speed control.

DESCRIPTION OF THE 4.1 KILOWATT WIND TURBINE

This wind turbine (fig. 1) is the largest that is commercially available.* It is rated at 4.1 kilowatt in a wind of 16.8 miles per hour (7.5 m/sec). Its two blades cover a span of 30 feet, 2 inches (9.2 m) tip to tip. They are made of extruded aluminum and are hollow, untapered, and untwisted. The blade contour is a "Gottingen Number 548" (fig. 2). The blade pitch is controlled by the centrifugal force acting on weighted rods attached to the base of the blades (see fig. 3). An unusual feature of the design is that the rotor speed is limited by pitching the blade into stall instead of into a feathered position. The resulting tendency for large blade deflections in a high wind is counteracted to a large

*Manufactured by Aerowatt, Paris, France; available in U.S. through the American outlet - Automatic Power Div. of Pennwalt Corp., Houston, Tex.

extent by supporting cables running from the spinner nose back to the midsection of the blades. The nominal rotor speed of 150 rpm is increased by a gearbox to 3000 rpm to drive the 50 hertz alternator which is mounted in the tail section. This three phase, permanent magnet alternator is "delta" connected, and is rated at 220 volts at 10.8 amperes.

As the wind starts to blow, the rotor will start to turn at a wind speed of about 3 meters per second (6.6 mph). At this time, the blade is still in its starting pitch of 20 degrees (see fig. 4). As the rotor speed increases, the pitch is gradually reduced until, at a speed of 30 rpm, which is 20 percent of design rotor speed of 150 rpm, the pitch is at $1^{o}10'$. The pitch remains at this setting until the design rotor speed is reached at a wind speed of 16.8 miles per hour (7.5 m/sec). At wind speeds greater than this, the blade is rotated into and out of stalling pitch to maintain design rotor speed within 3 percent. The blades are supported by cables at near midspan to reduce deflection and high stresses at the blade root.

The wind turbine is free to rotate about its vertical axis, as guided by its high tail and the aerodynamic force of the wind. It is understood that the tail was put in this unusual location to take it out of a region of backwash and turbulence.

DESCRIPTION OF ELECTRIC CONTROLS AND LOAD BANK

The output of the wind turbine alternator is carried by three wires down through the tower and then by way of a trench to the control room. At this point, it is connected to the electric control package.

Figure 5 shows the schematic of the electric controls which connect and disconnect the load bank (shown in fig. 6) to the wind turbine. Figure 7 is a photograph showing the control box on the left and the load bank on the right.

The load is initially disconnected from the wind turbine. When the wind drives the unloaded wind turbine up to full speed (50 Hz output), the frequency sensor then causes the load to be connected to the wind turbine. If the wind is not sufficient to drive the wind turbine at the set load, the rotor will slow until the output frequency drops to 38 hertz. At this point the frequency sensor causes the load to be disconnected from the wind turbine. This cycle is repeated until: (1) the load is reduced to match available wind speed, (2) the wind speed increases sufficiently to match the load, or (3) the wind speed drops until it cannot drive the wind turbine to full speed. These two frequency set points can be varied as desired. The lower set point was chosen to avoid excessive excitation of the tower natural frequency which occurs when the electrical frequency is 35 hertz. This corresponds to a main shaft speed of 1.75 revolutions per second and an excitation frequency at 2 per revolution of 3.5 cycles per second.

Included in the control box is a voltmeter and an ammeter which can be switched to read voltage and current for any one phase at a time. There is also a wattmeter to read the total output power being generated, a meter to read accumulated watt-hours, and a frequency meter. For those situations when it is desired to slow the wind turbine, there is a switch provided to manually actuate the load connection relay to add load and slow the rotor down.

As shown in figure 6, the load bank originally consisted of a delta connected set of resistances. Each leg of the delta consisted of two parallel strip heaters at 57.6 ohms each and a wire-wound potentiometer of 0 to 25 ohms. This provided a load range of 2700 to 5000 watts. After a period of operation, it became apparent that substantial operating time was being lost because the wind speed was too low to sustain operation at the 2700 watt minimum load. It was decided to modify the load bank to provide capability for operation at a lower range whenever wind speeds were low. Two 96-ohm parallel strip heaters were added in series with each of the wires leading to the load bank. This changed the load capability to a range of 735 to 840 watts. This modification can be bypassed at will to restore the load bank to its original configuration.

DESCRIPTION OF PIVOTED TOWER

The 75-foot tower* (fig. 8) has two major sections. The lower, supporting section is made up of two vertical 18-inch-diameter tubes, spaced apart to make room for the main tower section to stand in between them. The main tower section is a 24-inch-diameter tube with a flange on top for mounting the wind turbine, a pivot at the 35-foot elevation to allow it to tilt down (see fig. 9) for servicing the wind turbine, and a bottom section filled with concrete to balance the weight of the top section and the wind turbine. Resting on a concrete foundation, the lower section is held in position by four $1\frac{1}{4}$-inch-diameter guy rods running from large concrete anchor blocks to the top of the lower section.

The upper, pivoted section is held in place by the pivot, by bolted brackets located just below the pivot and also near the bottom (see fig. fig. 10), and by four more $1\frac{1}{4}$-inch-diameter guy rods attached to the tower at the 59-foot elevation and to other large concrete anchor blocks. Access to the pivot and to the upper bolted bracket is provided by a ladder leading to a platform at the 29-foot elevation.

Located 36 feet away is a $13\frac{1}{2}$-foot-high service stand. When the main

*The tower was designed, fabricated, and installed by the Automatic Power Division of Pennwalt Corp. The associated service stand, all concrete foundations, and the electrical cable installation to the controls and load bank were designed by Lewis Research Center personnel, with fabrication and installation provided by local contractors.

tower section is pivoted down, the wind turbine comes to rest on top of a 3-foot-high platform on the service stand (figs. 11 and 12). At this point, the wind turbine can be inspected and serviced. The main tower is pivoted down by releasing the guy rods and bolted brackets and operating a 5-ton capacity winch (fig. 13), which is connected to the upper portion of the tower by a 1/2-inch-diameter wire rope.

The service stand is designed to allow the wind turbine to be placed in either of two positions. With the blades and spinner over the stand, the blade pitch mechanism can be reached. With the blades and spinner in the other direction, the blades hang over the edge of the stand and can be rotated to check for tracking and balance.

The rotating blades of a wind turbine impart an excitation force to the supporting tower at a frequency equal to once per revolution and twice per revolution. If the tower natural frequency happens to coincide with either of these frequencies, severe vibration could lead to fatigue and ultimately failure of the tower. To avoid this problem, the contractor decided to design the tower and its guys so that the natural frequency of the tower was between the two blade excitation frequencies. This required the use of a relatively large tower cross section and the use of solid guy rods instead of wire cable. The natural frequency of the final tower design was calculated by the contractor to be 24.6 radians per second. This value is almost exactly midway between the blade exciting frequencies of 15.7 radians per second and 31.4 radians per second.

RESULTS

The 4.1 kilowatt wind turbine was installed and put into operation early in December 1974. As usual, this was a windy month and the machine generated full power immediately. The pitch change mechanism worked smoothly and accurately, maintaining frequency to ±3 percent, better than the specified ±5 percent. Yawing was smooth and responsive to changes in wind direction even at very low wind speeds. The controls functioned as designed to connect and disconnect the load bank at the designated frequency switch settings. An initial overheating of the generator was eliminated by providing for a substantial flow of outside air from below the tail, through the generator and out a weatherproof vent in the top of the main housing. This also provided a bonus benefit of substantial cooling for the gearbox, thus extending its life expectancy.

To date, the wind turbine has operated satisfactorily at loads up to 4.1 kilowatts at ambient temperatures up to 70° F, has withstood winds over 50 miles per hour and gusts estimated at 90 miles per hour.

It is not possible to determine exactly the wind speed required for a given wind turbine power output since the wind is constantly varying, the wind sensor is located some distance away (350 ft), and the load is not able to be rapidly matched to available power. It is possible, however, to estimate wind speed versus power output within 1 or 2 miles per hour. The data indicates that a load setting of 735 watts requires an average wind speed of about 9 miles per hour, 2700 watts about 14 miles per hour, and 4100 watts about 17 miles per hour.

Figure 14 shows a trace of wind speed and the corresponding generator frequency. The wind speed is generally in the range of 15 to 30 miles per hour and the wind turbine shows good speed regulation, holding steady at 50 to 52 hertz. The load at this time was 2700 watts. The traces also show that at wind speeds below 15 miles per hour, the load is slightly too high as is indicated by the temporary drop in frequency at the points indicated.

Figure 15 shows a normal line current trace. The load is set at 2700 watts, and the current is holding between 7.0 and 7.2 amperes.

Figure 16 shows the effect of marginal wind velocity. The line current rises to a normal 7.0 to 7.2 amperes at the 2700-watt setting, but the wind is not sufficient to hold the wind turbine at full speed. However, as the speed drops, the current and the voltage also drop and the power dissipated in the fixed resistance of the load bank drops to balance the wind power available. As a result, the frequency is still high enough to prevent the load from being disconnected. The two points where the current drops to zero indicates short intervals when the wind speed drops even lower and is no longer even marginal.

An unusual phenomenon noticed on a few occasions is illustrated by figure 17. While the wind turbine was operating normally at a power level of 2700 watts, the wind speed increased considerably. When it reached an average value a little over 40 miles per hour with gusting over 50 miles per hour, the wind turbine suddenly dropped in speed to about 40 rpm (an output frequency of about 13 Hz). With the frequency dropping below the 38 hertz lower set point, the load was automatically dropped. The frequency remained at about 13 hertz and the load remained disconnected as long as the winds were high, which was for several hours. Figure 18 shows the wind turbine picking up speed again and resuming normal operation. This appears to correspond with a brief drop in wind speed to about 12 miles per hour.

The most logical explanation for this phenomenon is that the rapid gusting over 50 miles per hour caused the entire blade to go into stall so badly that it could no longer supply the torque necessary to maintain rotation, even in the absence of any electrical load. With the blade velocity greatly reduced, the angle of attack became still greater and the stall condition even worse. It was not until the wind velocity became much lower that the angle of attack was low enough to create the lift necessary to start normal operation once more.

To verify this explanation, a preliminary analysis was made in which the torque and power available were calculated for the various wind speed, rotational speed, and blade pitch angle conditions (see fig. 2) which occur during normal operation. The results of these calculations are presented in figure 19.

The curves labeled "zero torque" in figure 19 outline the operating envelope for the 4.1 kilowatt wind turbine. At any point within these boundaries, the rotor torque is positive, or tends to increase the rotor speed, and outside these bounds the torque is negative, and tends to decrease the rotor speed. Also, the closed curve labeled 4.1 kilowatts is the boundary for conditions at which the turbine can produce 4.1 kilowatts or more.

The blade stall explanation given for the phenomenon depicted in figure 17 is verified by figure 19. For example, if a sustained gust over 40 miles per hour occurs during normal operation at 150 rpm, the rotor torque becomes negative and the rotor speed begins to decrease. Then, unless the high wind condition (over 40 mph) dies out quickly, the rotor will slow down and operation will then be limited to the area to the left of the near-vertical line labeled "zero torque" in figure 19. The rotor cannot speed up again until the wind speed decreases, and the line of operation can be held to that area between the two near-horizontal lines labeled "zero torque." This verifies the explanation given for the phenomenon shown in figure 18.

To further explain figure 19, a series of curves were produced which show what portion of the rotor blade is stalled and what portion produces the driving force for various conditions. The curves in figure 20 were calculated for a rotational speed of 150 rpm, pitch angle of -1.16°, and a range of wind speeds from 12 to 40 miles per hour. It can be shown by further analysis that at 150 rpm, there are two wind speeds at which the wind turbine can match a 4.1 kilowatt load. These are wind speeds of about 14 and 38 miles per hour. Between these two values, the net power available would be greater than 4.1 kilowatts.

The data obtained, and the experience accumulated during this initial operation has produced the following results and conclusions: A blade pitching mechanism, designed to regulate speed by going into stall at higher speeds, can regulate speed to ± 3 percent or better. Some brief but severe increases in wind speed will apparently cause enough of the blade to stall that normal operating speed cannot be maintained under load. There have been no signs of any problems resulting from rapid yawing while the two-bladed rotor was turning, even during wind speeds over 50 miles per hour and wind gusts up to 90 miles per hour. The weather tower instruments, although located only 350 feet away from the wind turbine, do not always indicate either the wind speed or wind direction that the wind turbine is experiencing. The natural frequency of the wind-turbine tower was 22 radians per second, which is close to the desired, calculated value of 24.6 radians per second.

CONCLUDING REMARKS

NASA Lewis Research Center has completed a 4.1 kilowatt wind turbine installation at the Plum Brook Station, 5 miles south of Sandusky, Ohio. This installation consists of a commercial wind turbine mounted atop a 75-foot pivoted tower, a load bank and associated controls, and a 13-foot service stand.

As of November 10, 1975, the wind turbine completed 211 days of unattended operation. This experience has demonstrated that the blade pitching mechanism, which is designed to regulate speed by going into stall at higher speeds, can regulate speed to ±3 percent or better. It was discovered, however, that some brief but severe increases in wind speed will apparently cause enough of the blade to stall that normal operating speed cannot be maintained under load. There have been no signs of any problems resulting from rapid yawing while the two-bladed rotor was turning, even during wind speeds over 50 miles per hour and wind gusts up to 90 miles per hour. It was observed that the weather tower instruments, although located only 350 feet away from the wind turbine, often do not indicate either the wind speed or wind direction that the wind turbine is experiencing. The natural frequency of the wind-turbine tower was observed to be 22 radians per second, which is close to the desired calculated value of 24.6 radians per second.

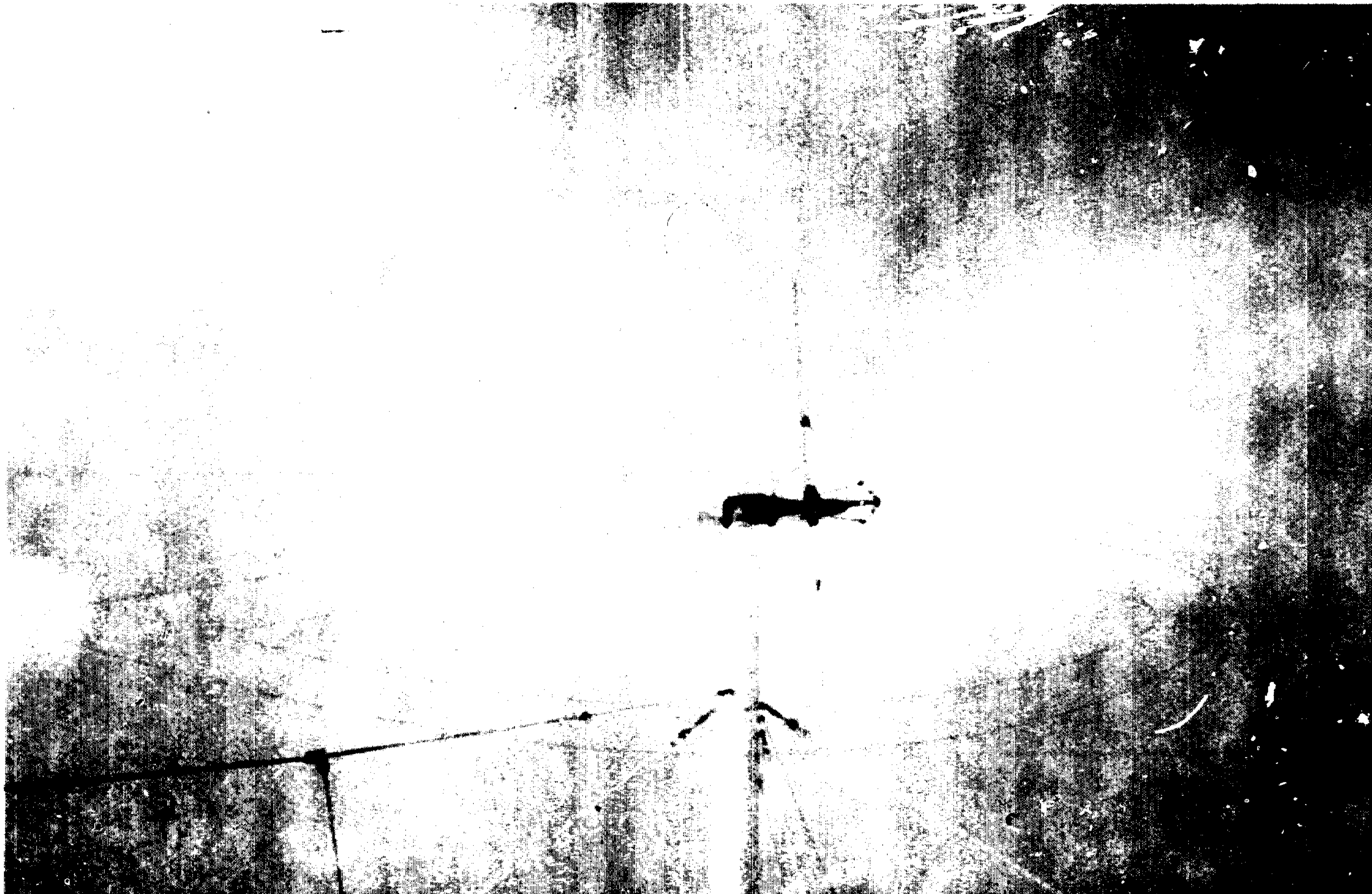

Figure 1. - The 4.1 KW aerowatt wind turbine.

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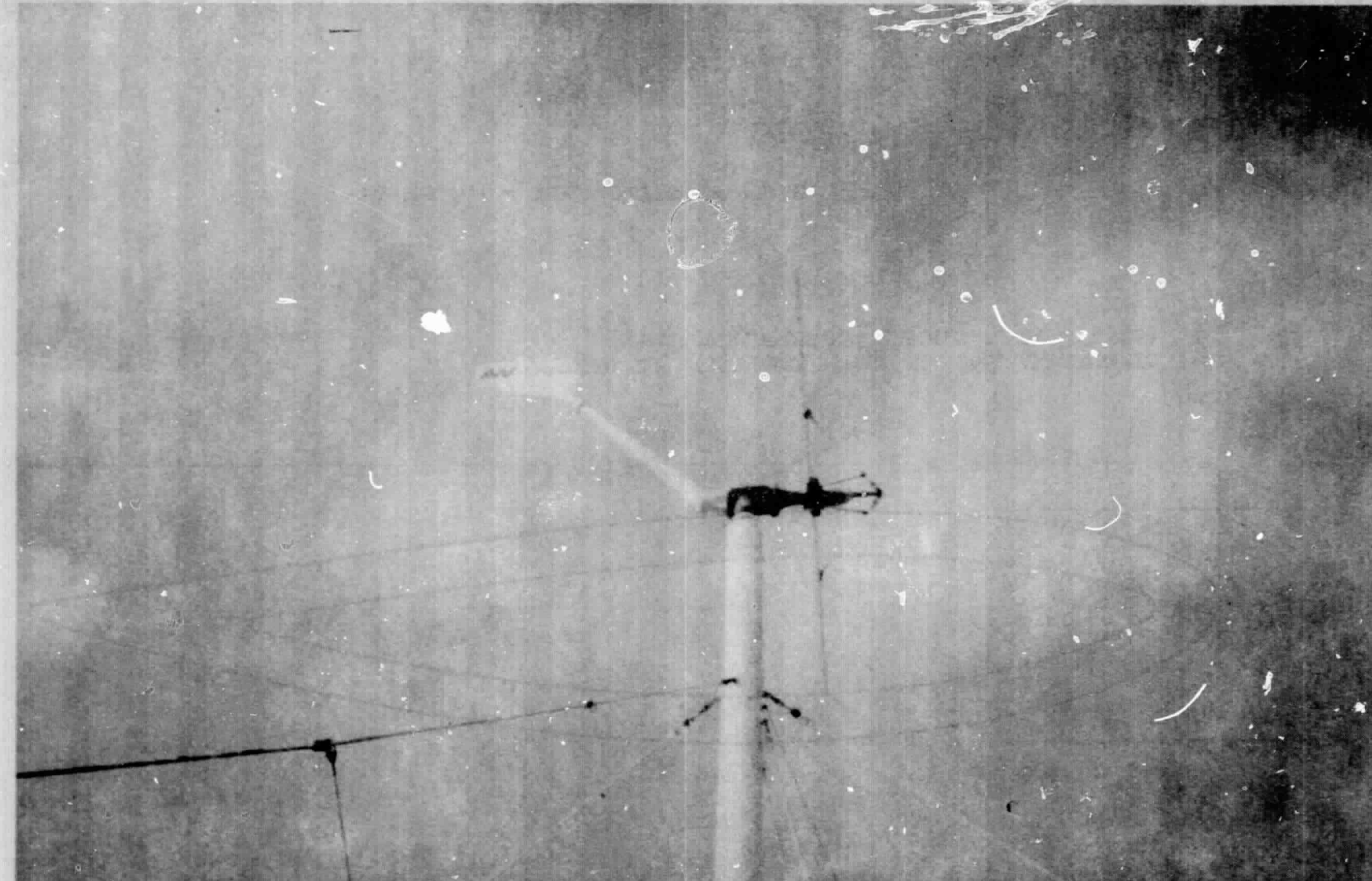
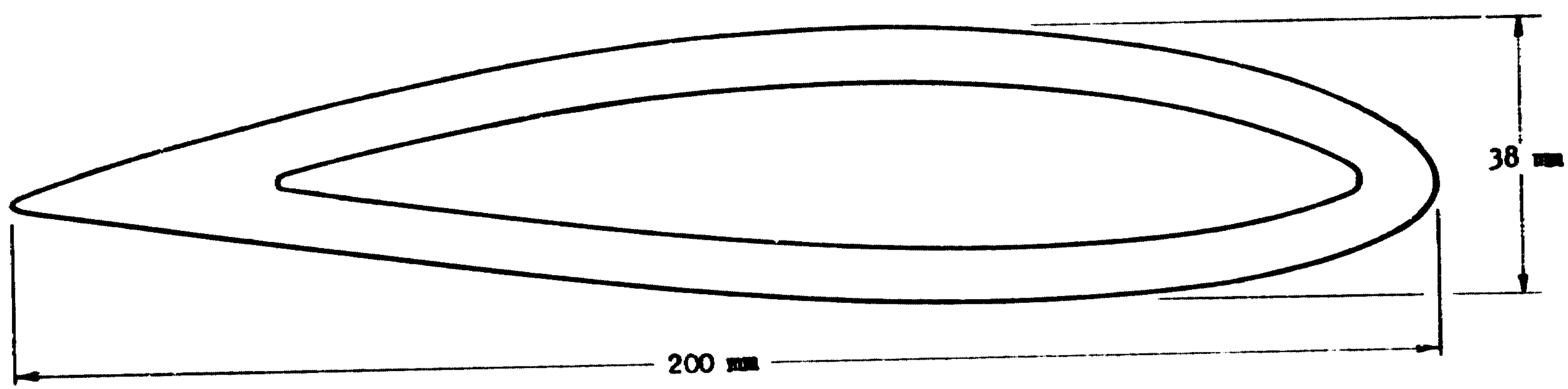


Figure 1. - The 4.1 KW aerowatt wind turbine.



GOTTINGEN 548 (SEE NACA REPORT NO. 286, AERODYNAMIC CHARACTERISTICS OF AIRFOILS-V, DATED 1926)

FIGURE 2. - CROSS SECTION OF BLADE.

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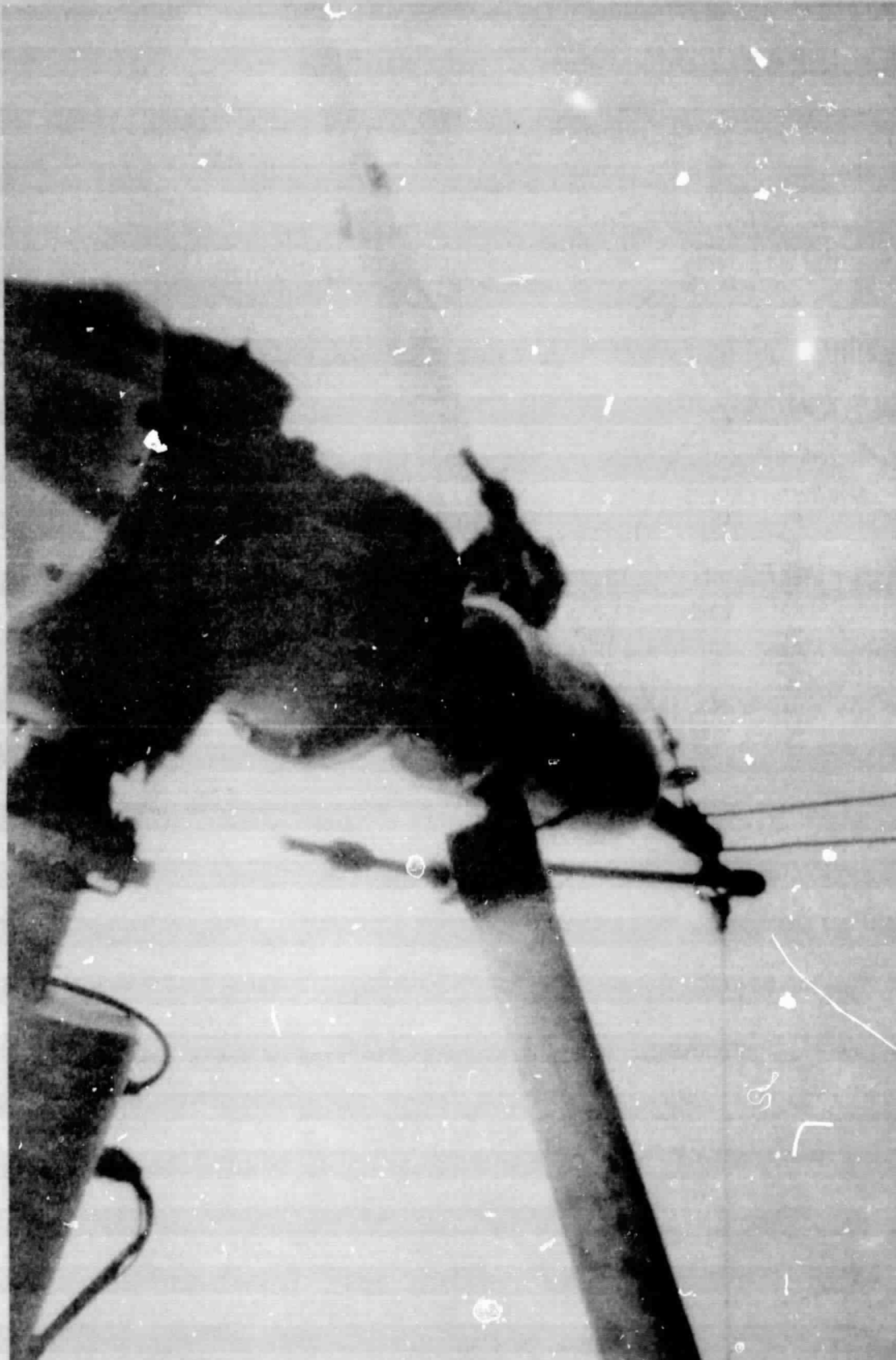

Figure 3. - Rotor assembly with pitch control weights.

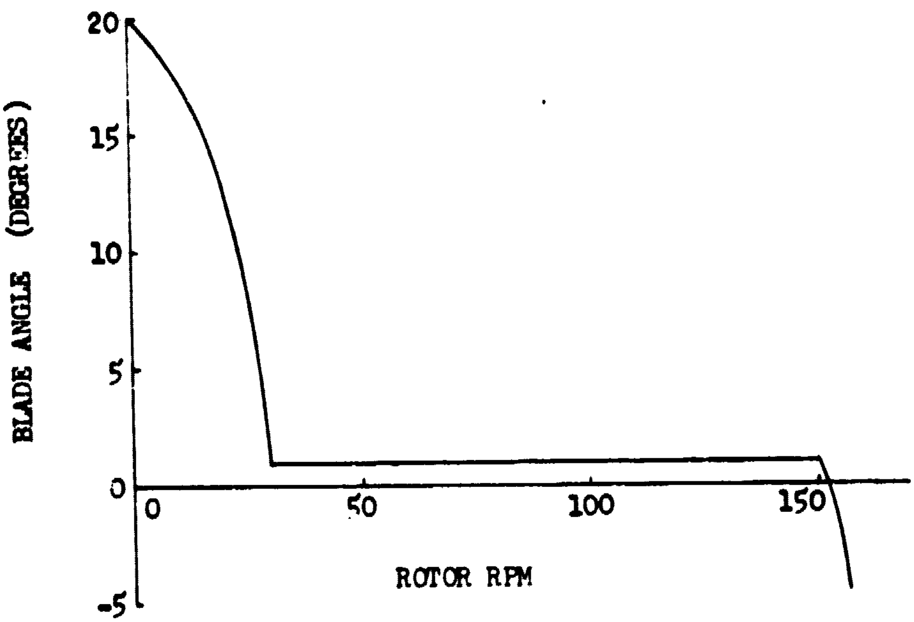

FIGURE 4. - BLADE ANGLE AS FUNCTION OF ROTOR RPM.

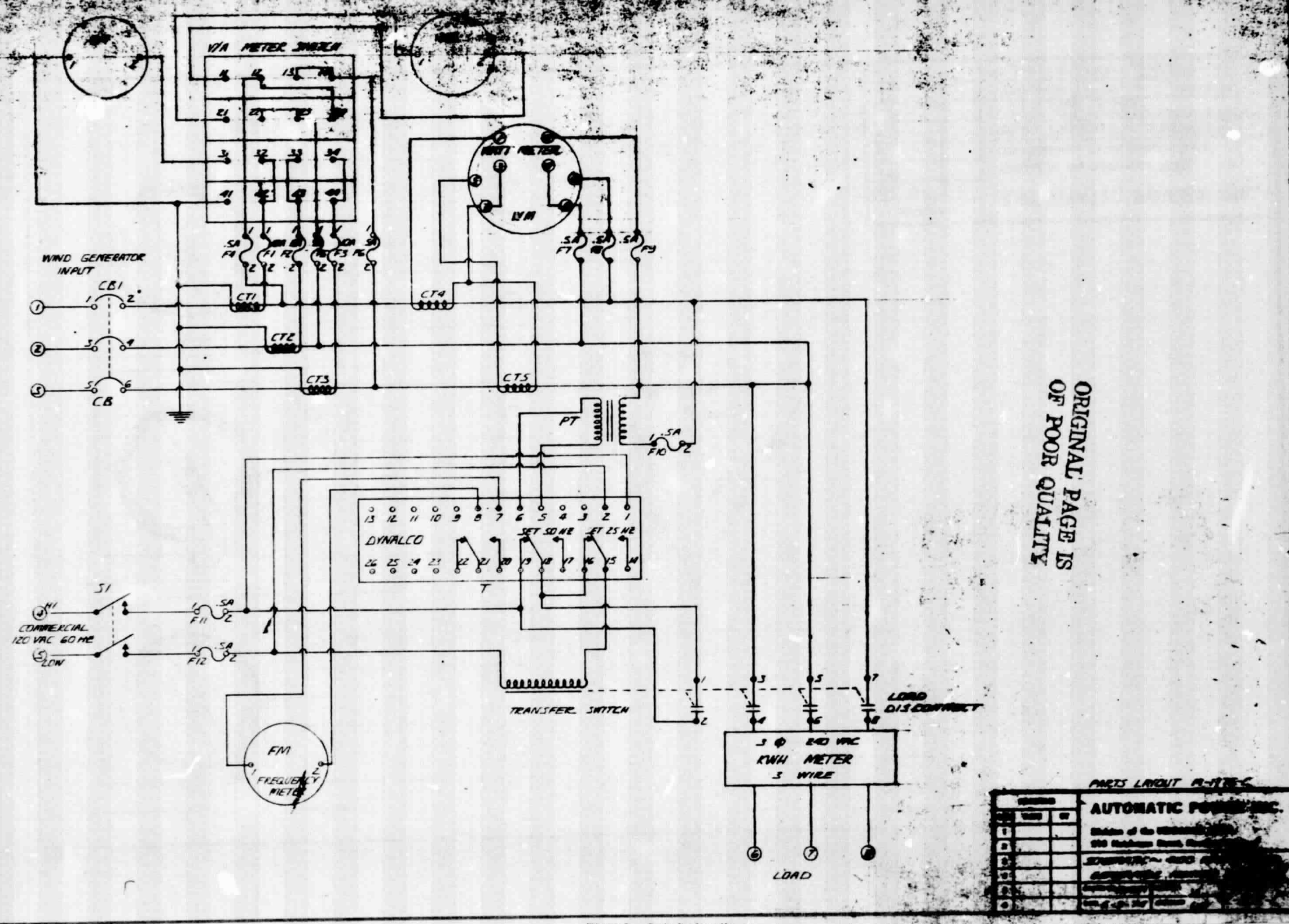

Figure 5. - Control schematic.

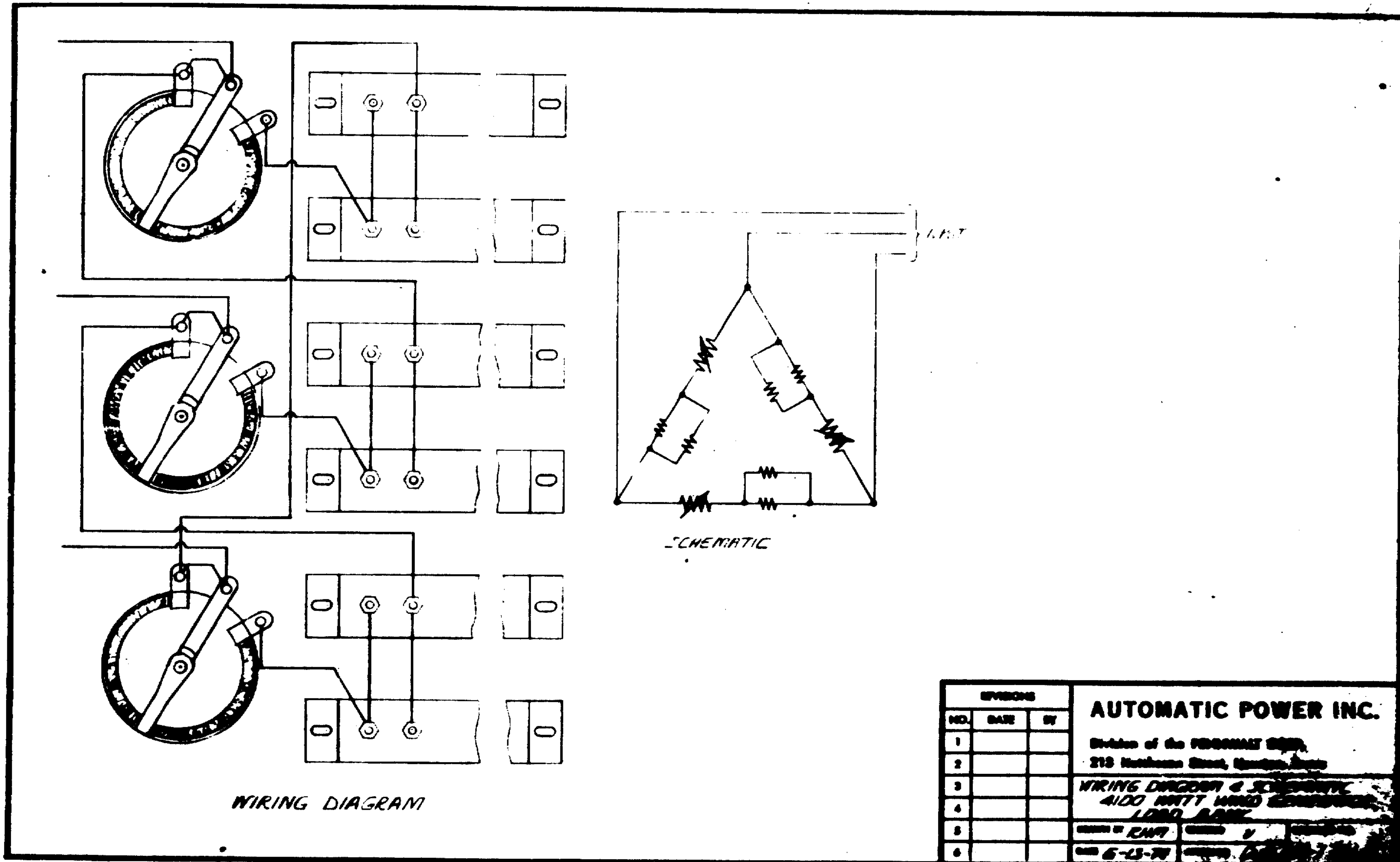

Figure 6. - Load bank schematic.

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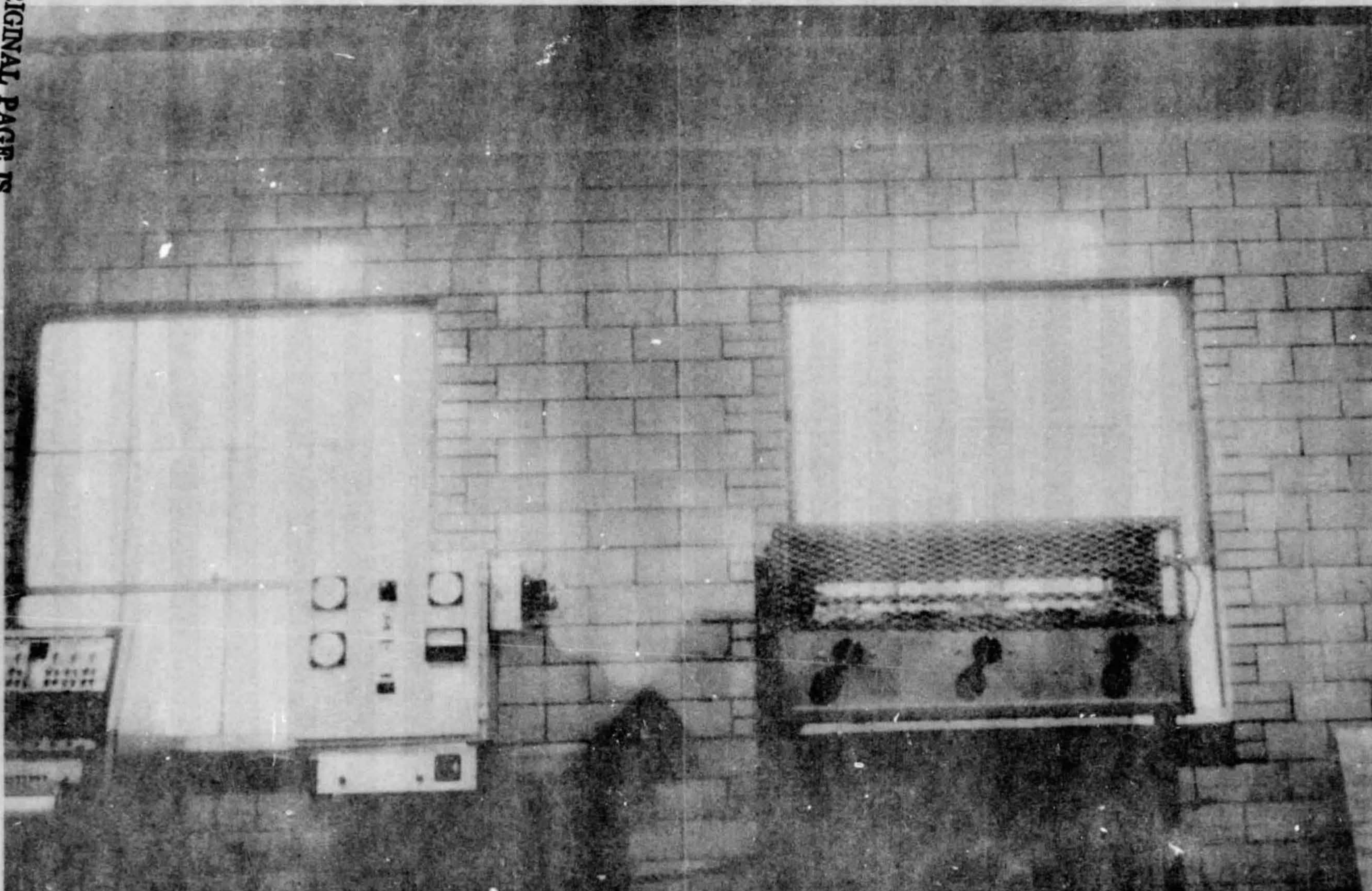

Figure 7. - Control box and load bank.

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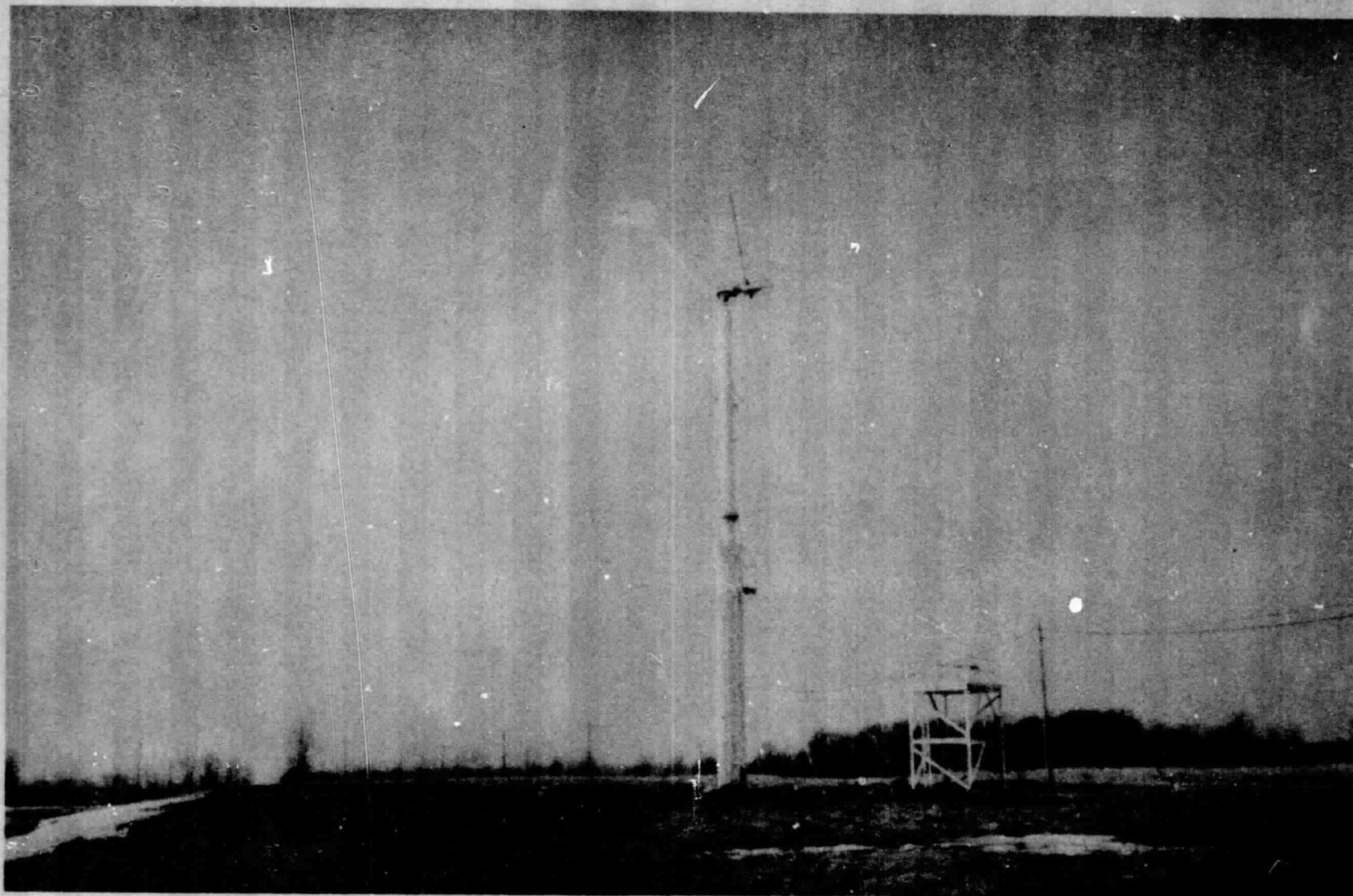

Figure 8. - The 75-foot tower with the wind turbine in place.

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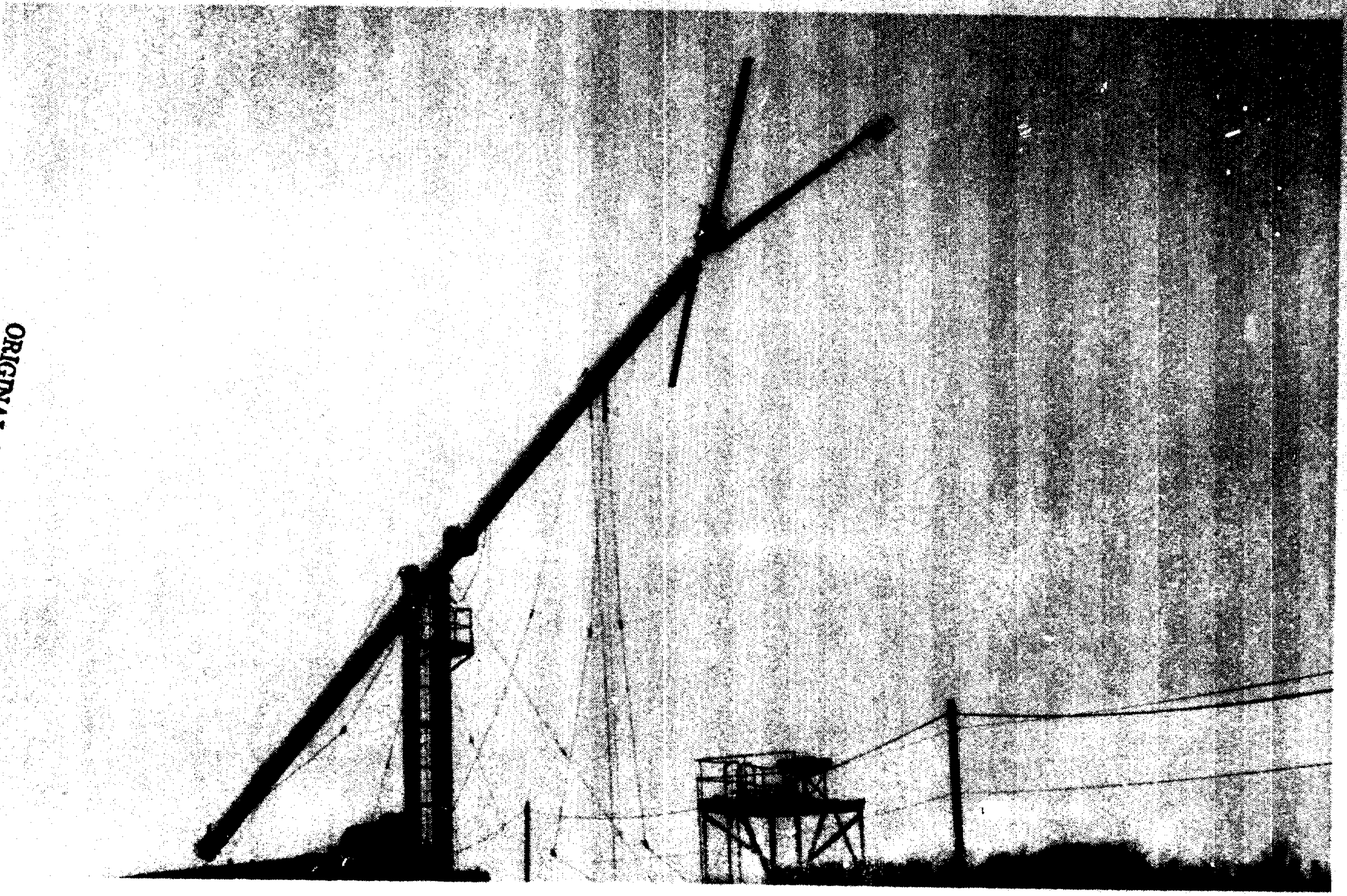

Figure 9. - Tower being lowered.

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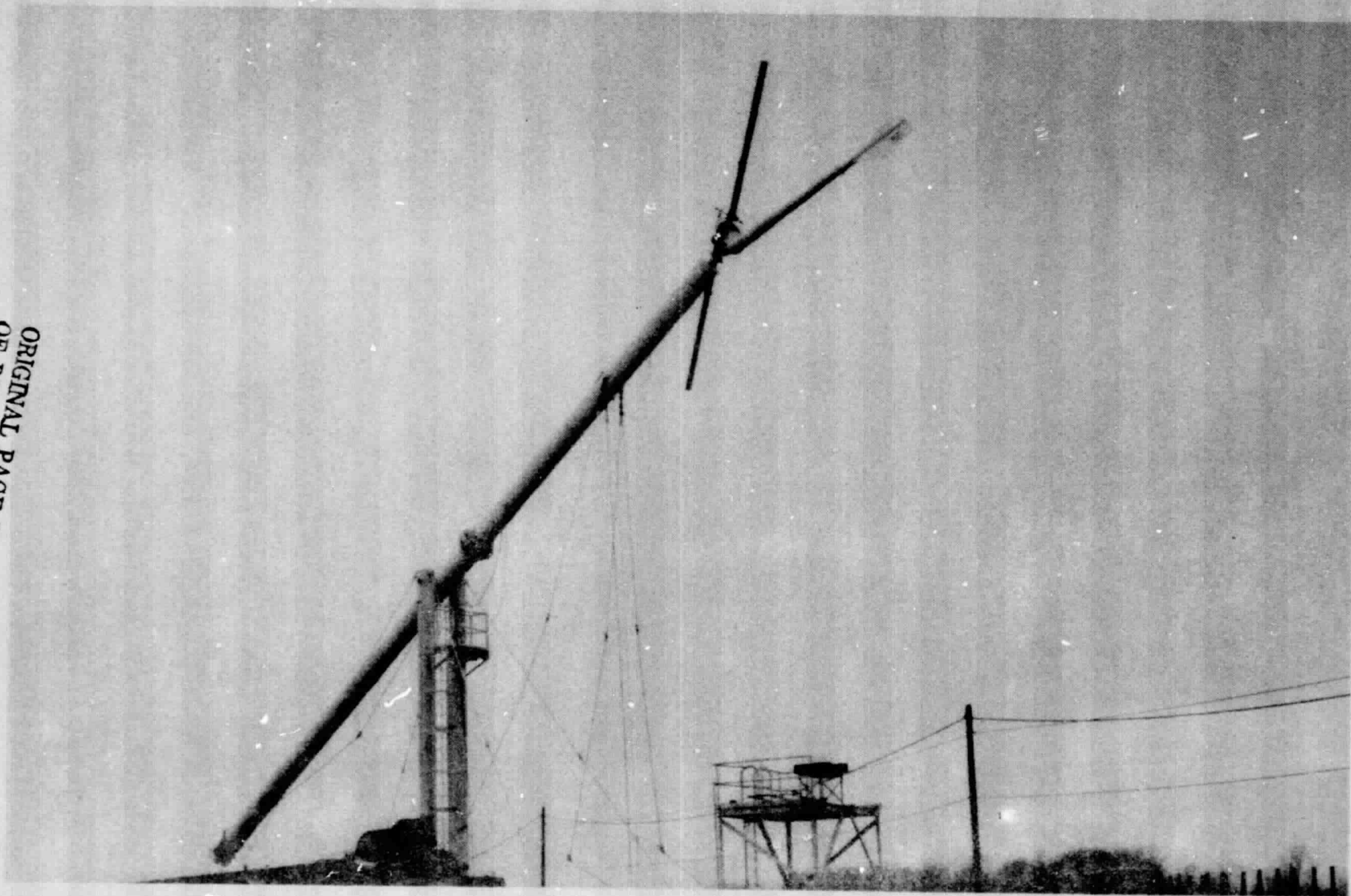

Figure 9. - Tower being lowered.

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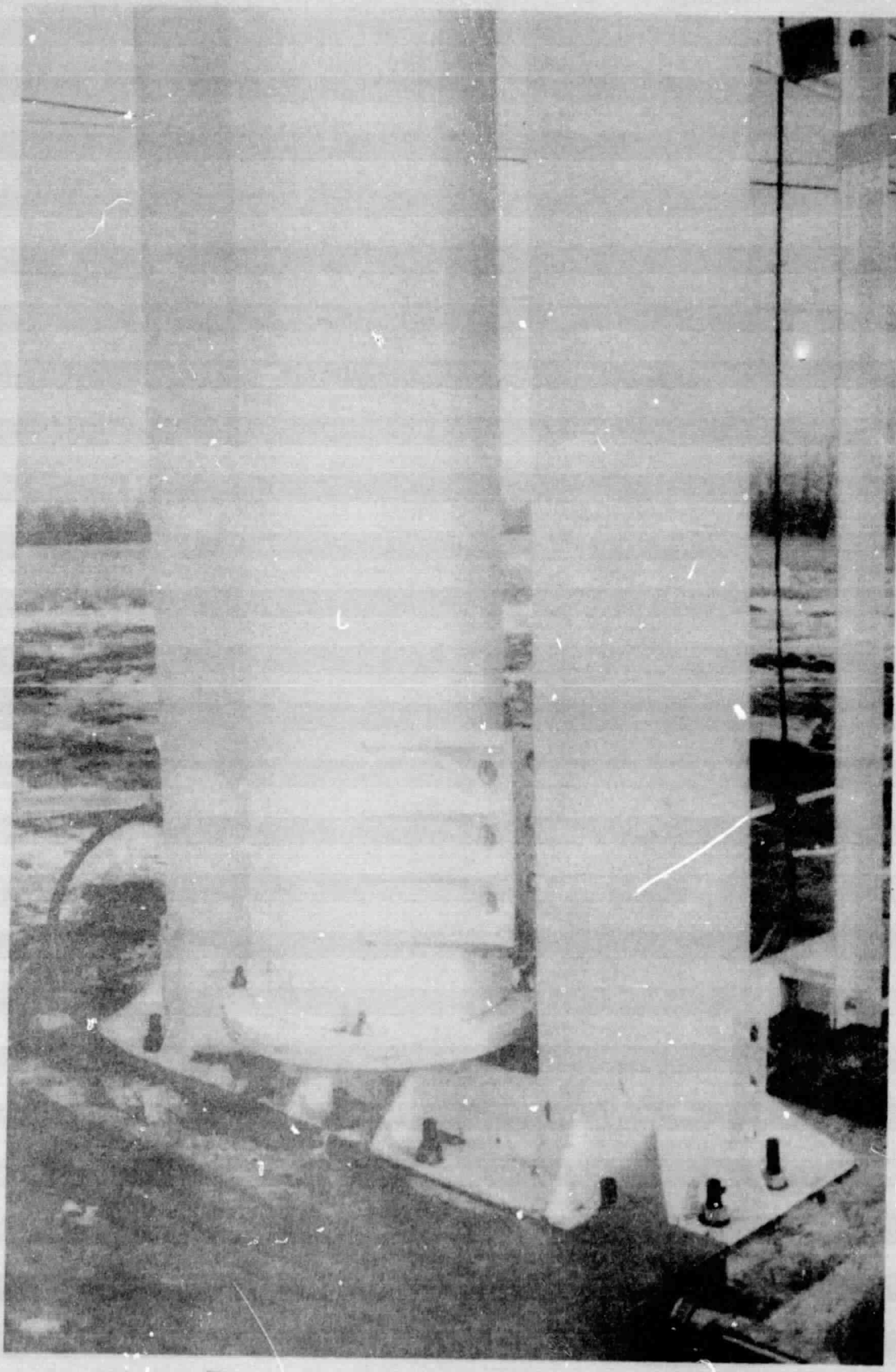

Figure 10. - Bolted brackets at tower base.

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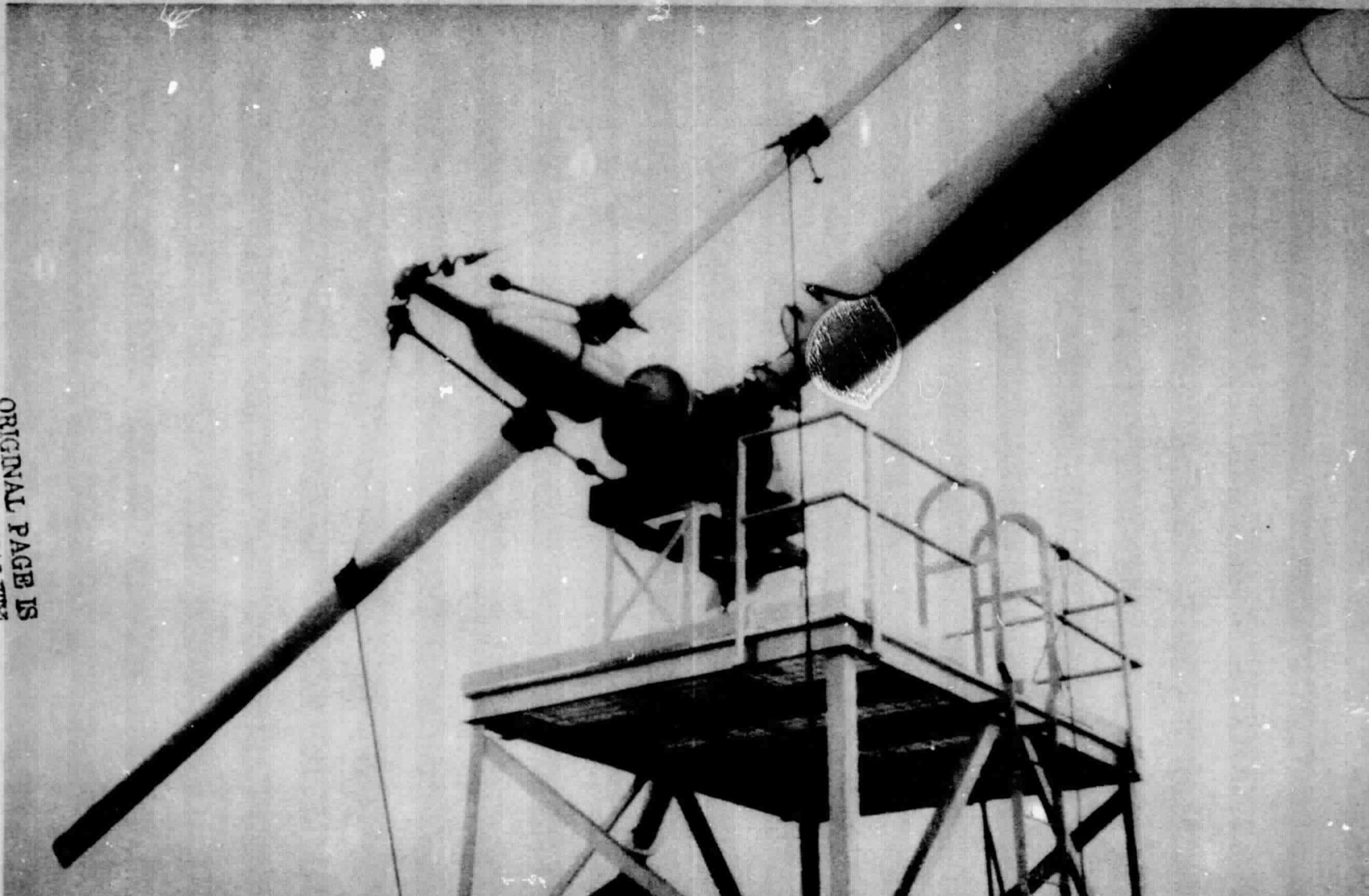

Figure 11. - Wind turbine resting on service stand-rotor end.

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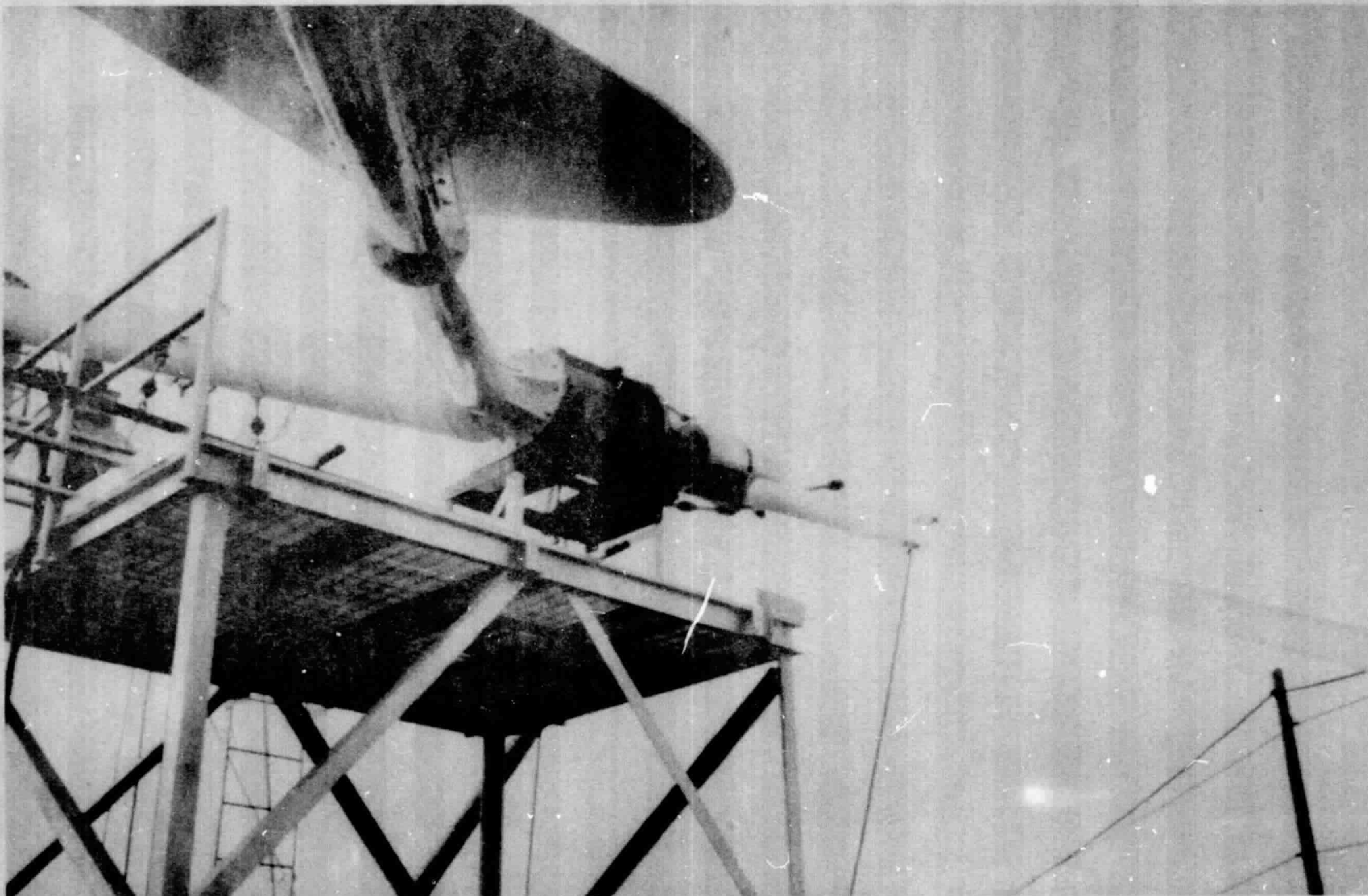

Figure 12. - Wind turbine resting on service stand-tail end.

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Figure 13. - The 5-ton winch.

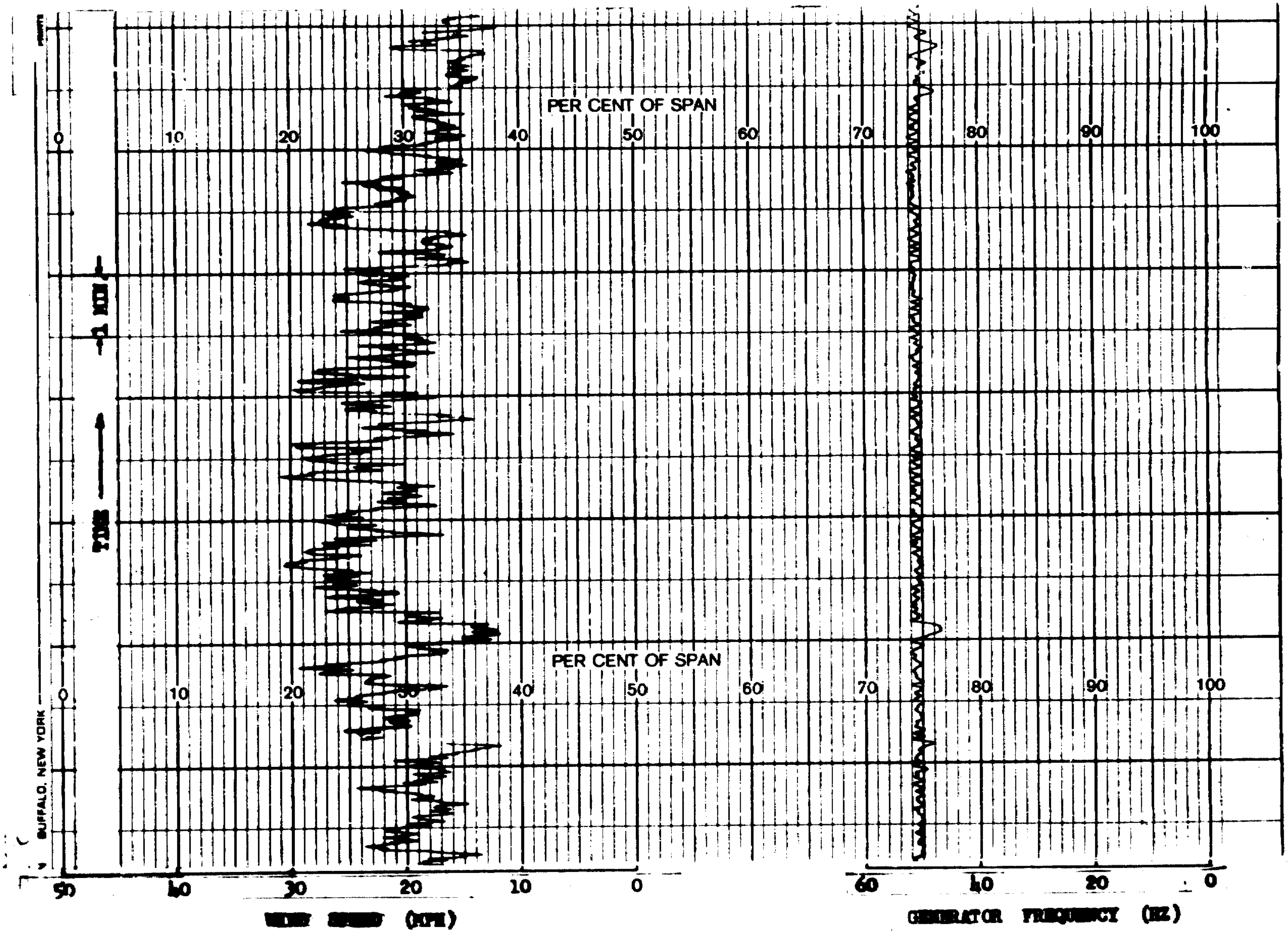


FIGURE 14. - WIND SPEED AND GENERATOR FREQUENCY.

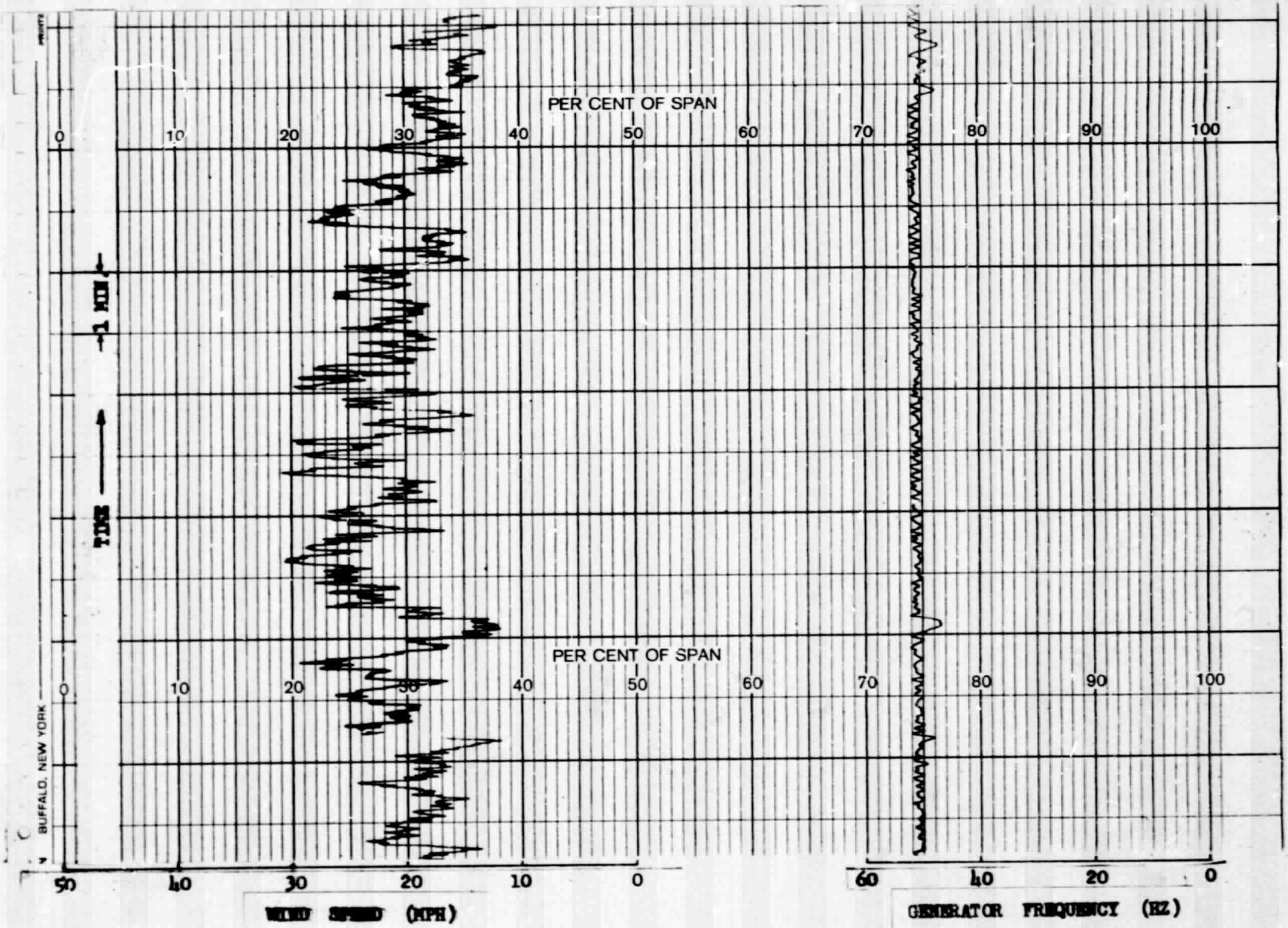
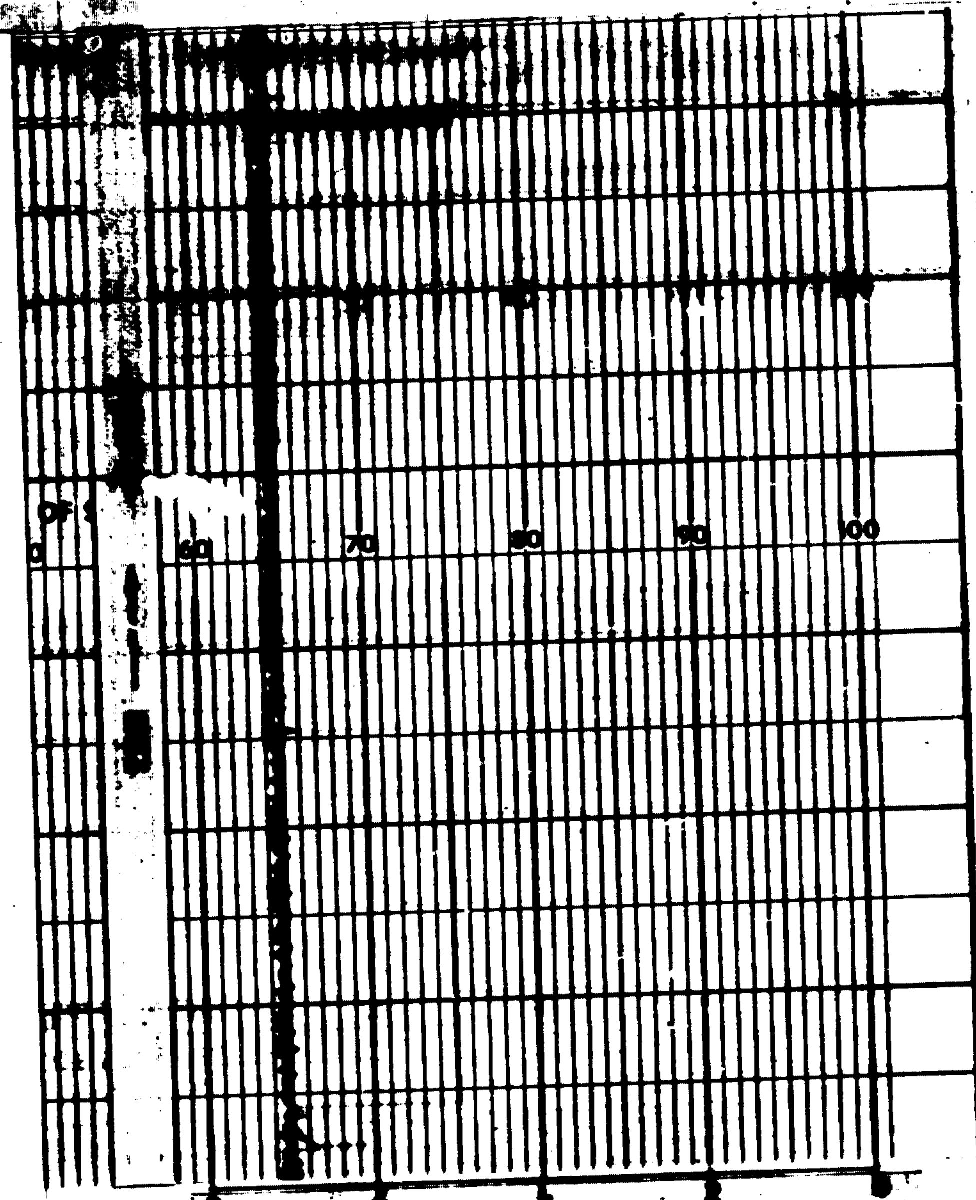


FIGURE 14. - WIND SPEED AND GENERATOR FREQUENCY.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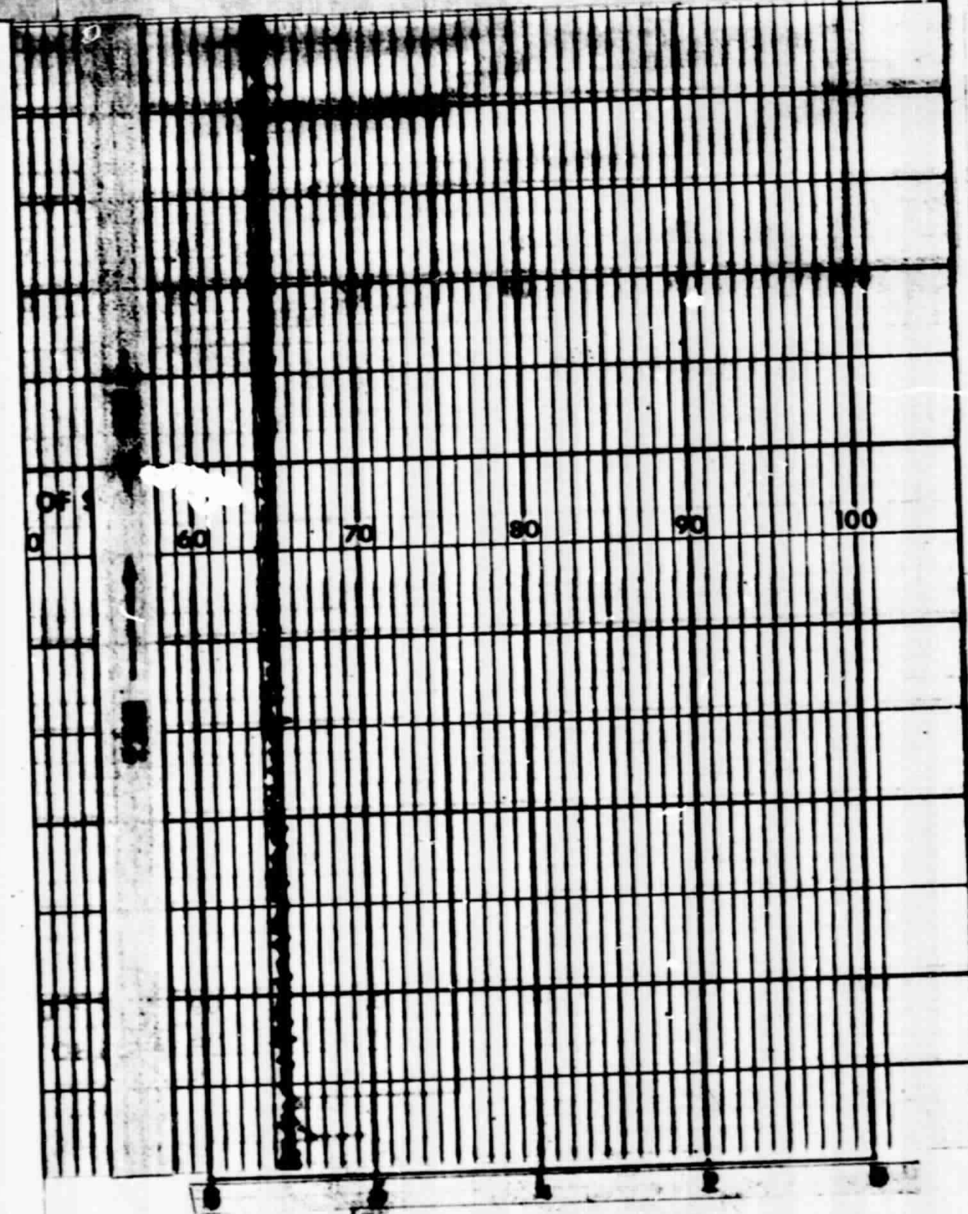

FIGURE 15. - LINE CURRENT

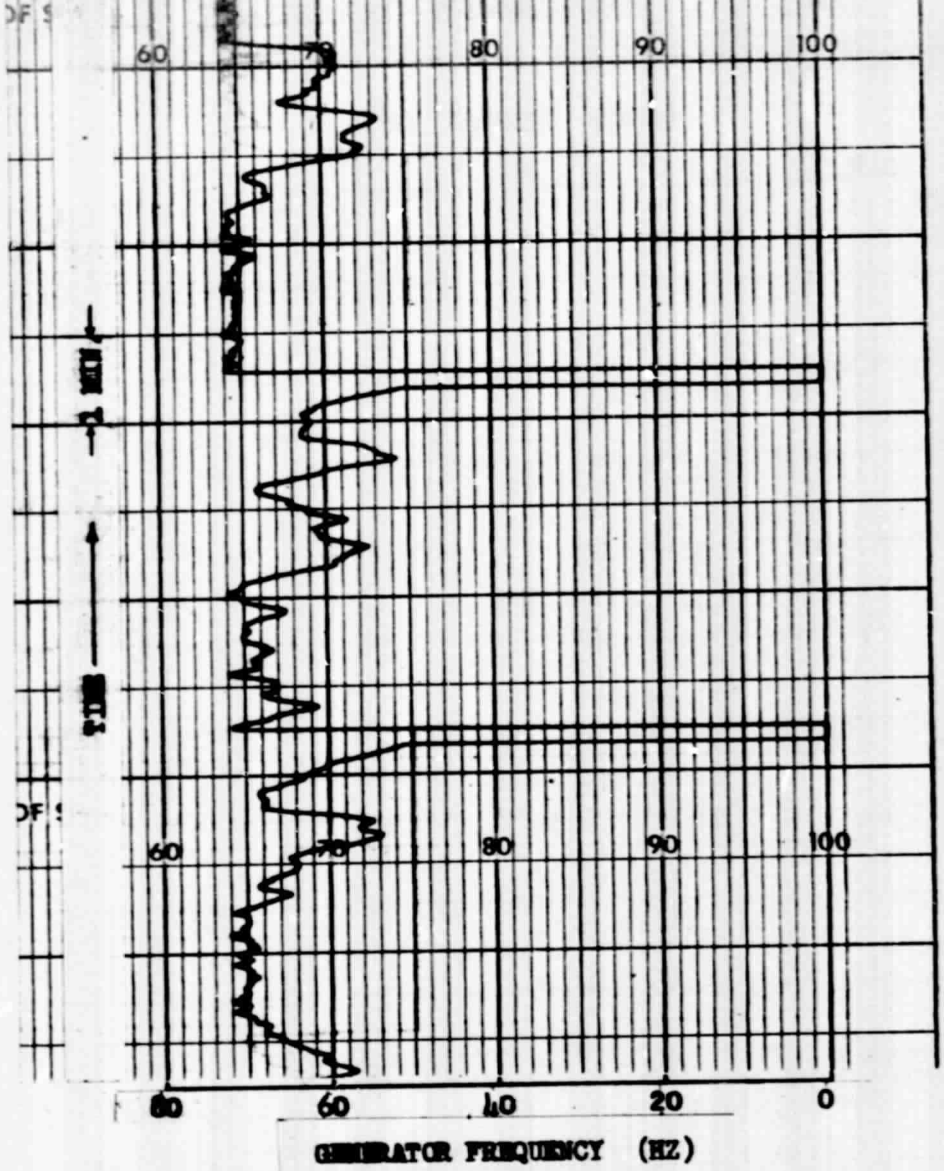

FIGURE 16. - GENERATOR FREQUENCY

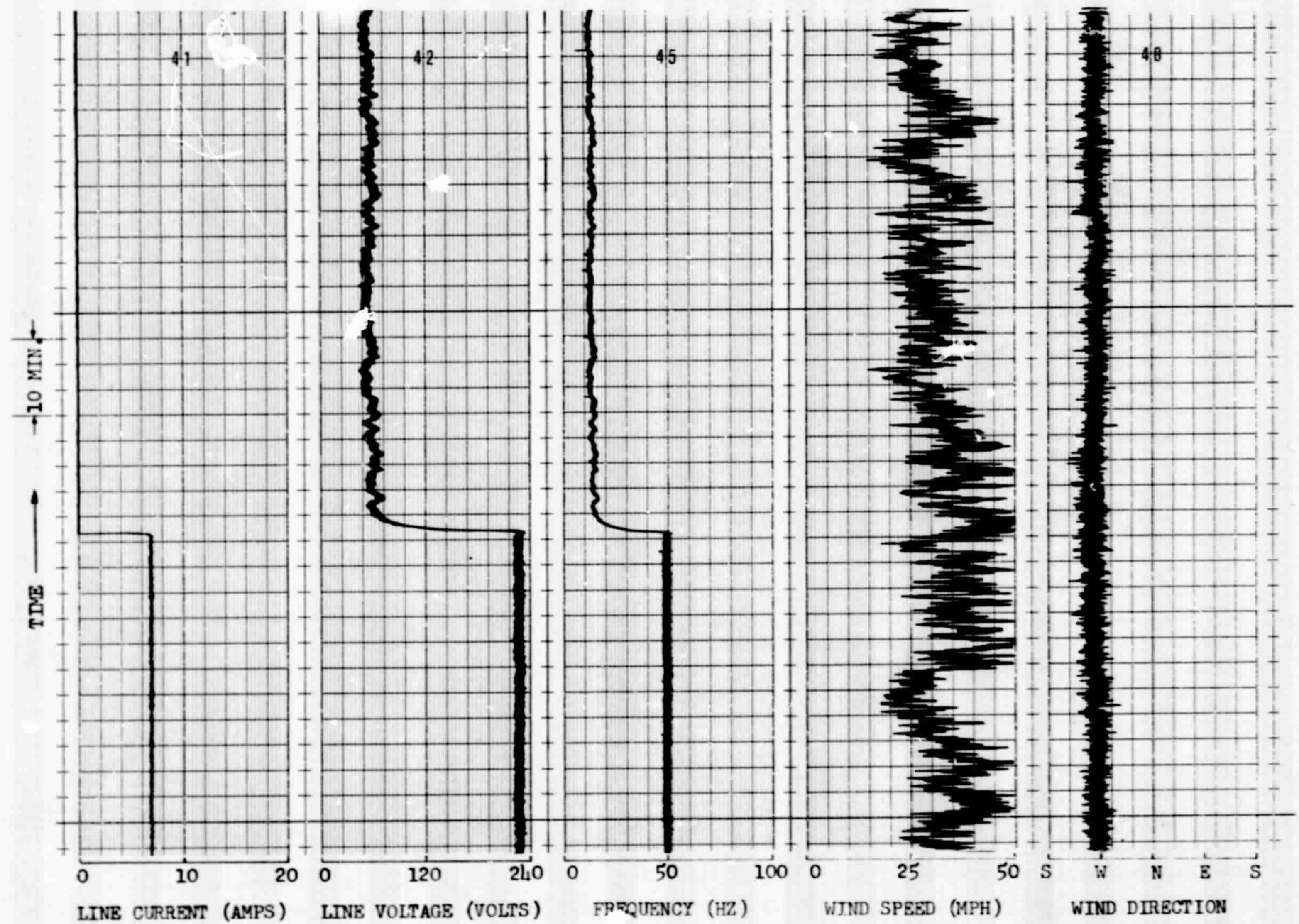

FIGURE 17. - CURRENT, VOLTAGE, FREQUENCY, WIND SPEED AND DIRECTION.

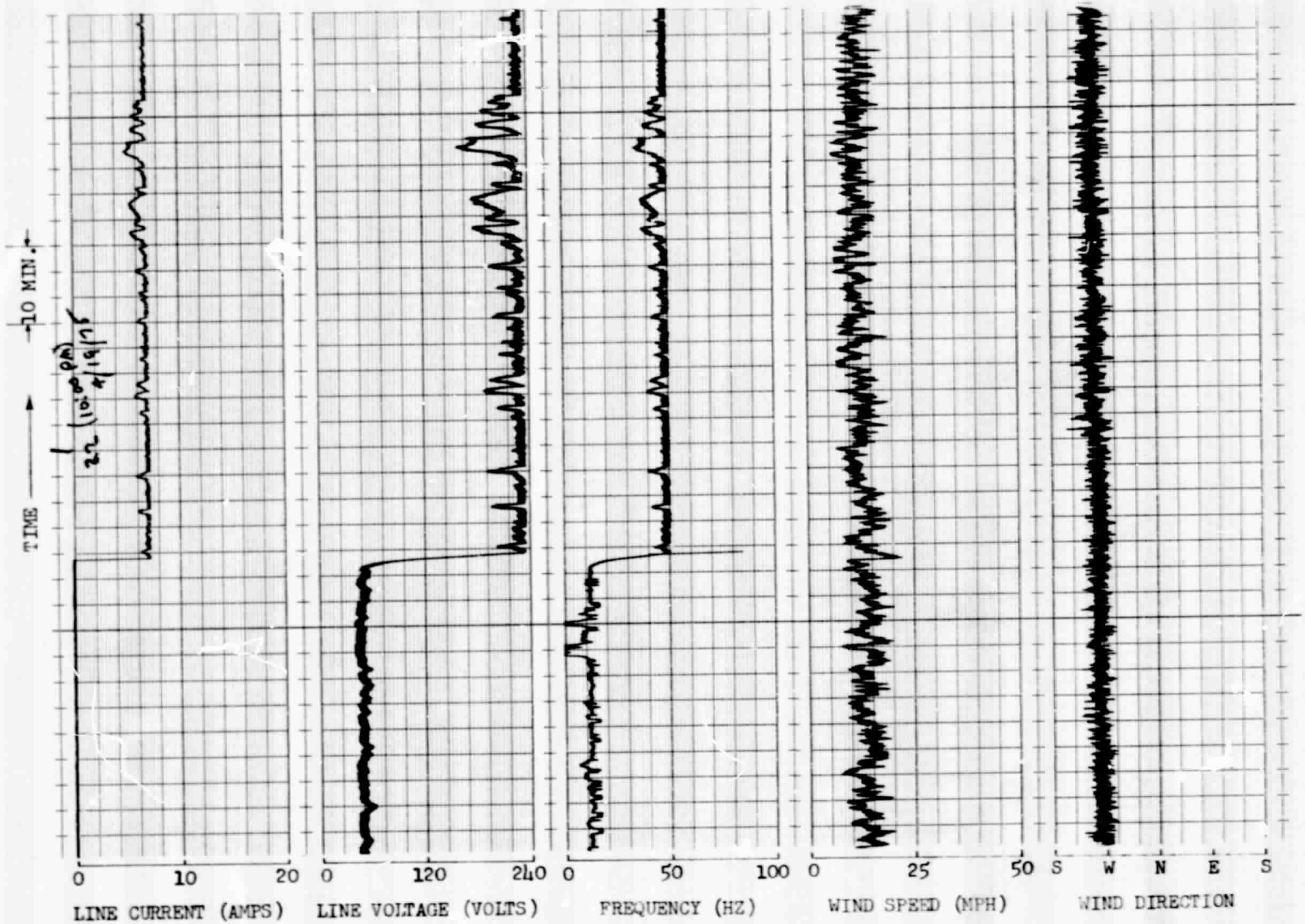

FIGURE 18. - CURRENT, VOLTAGE, FREQUENCY, WIND SPEED AND DIRECTION.

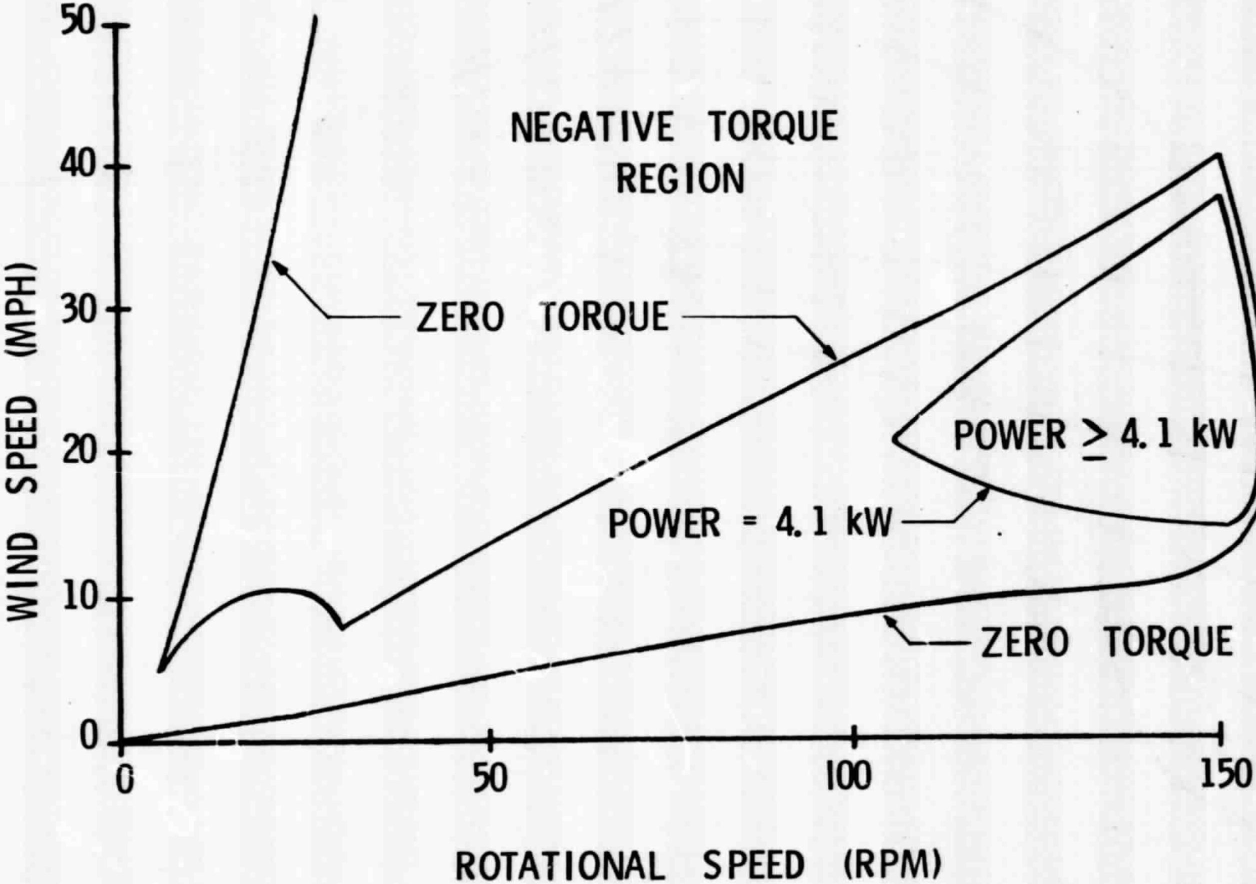

FIGURE 19.- 4.1 WIND TURBINE OPERATING ENVELOPE

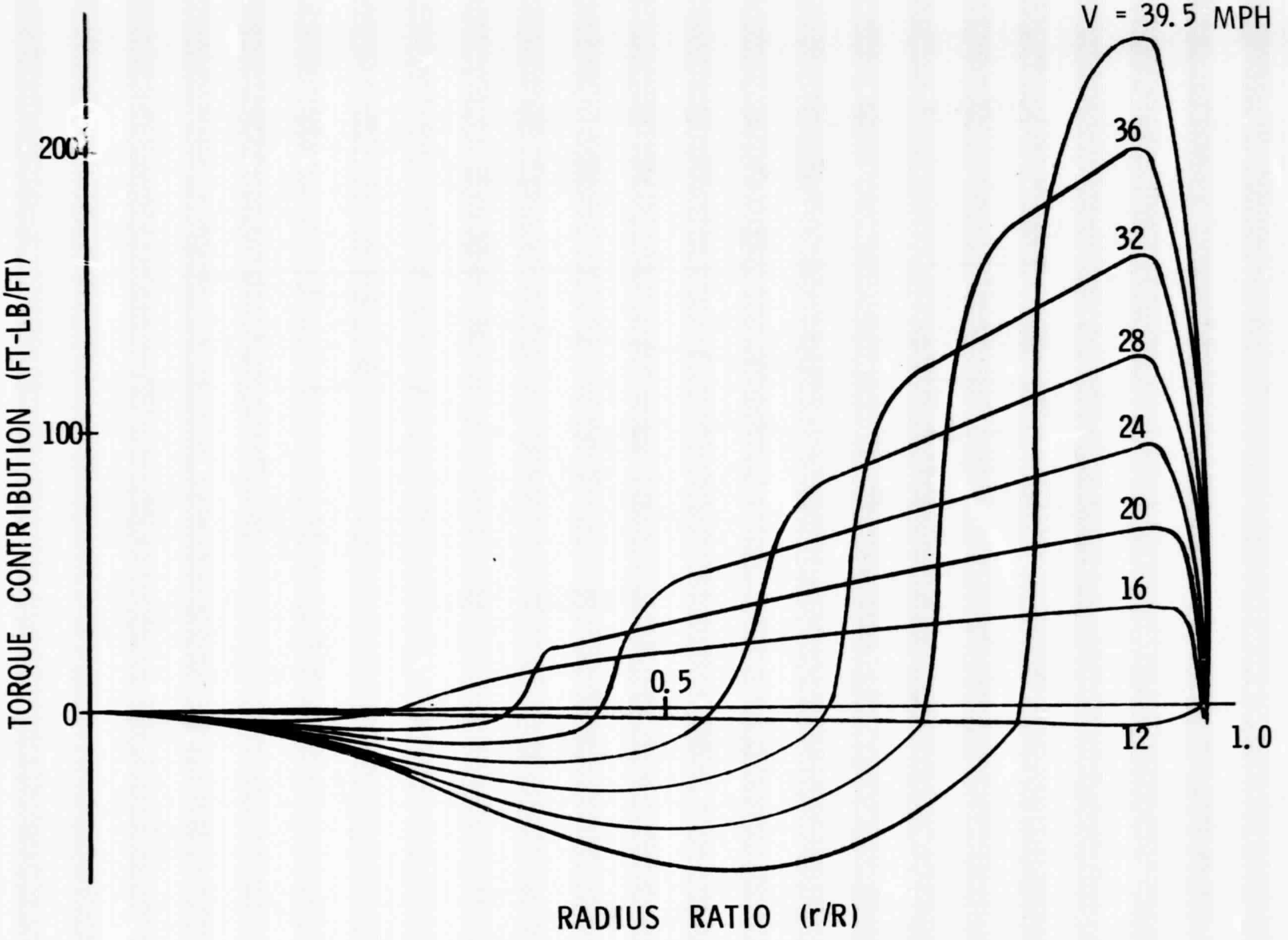

FIGURE 20.- SECTIONAL TORQUE FOR VARIOUS WIND SPEEDS