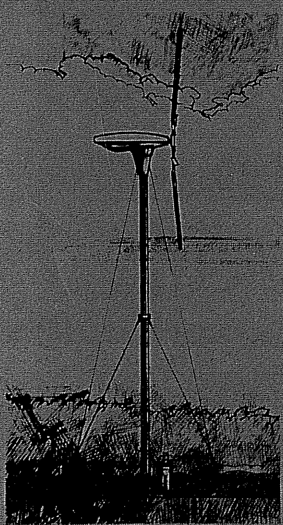
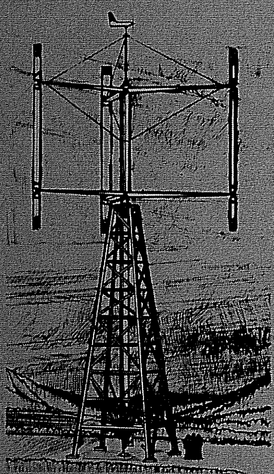
RFP-3304
UC-60

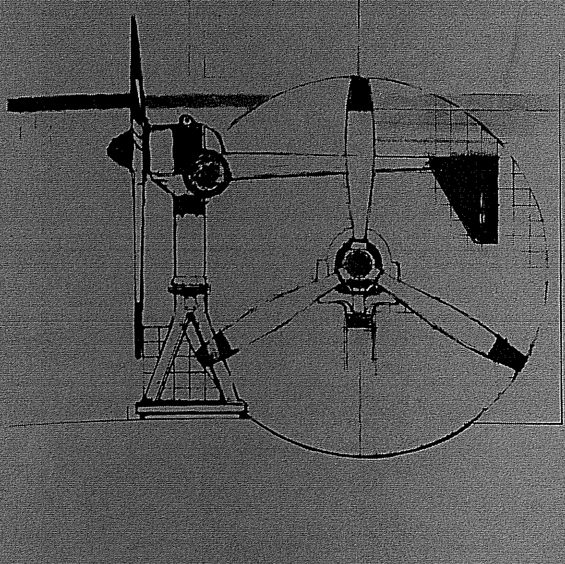
McDONNELL 40 kW GIROMILL WIND SYSTEM

Phase II
Fabrication and Test

JUNE 1980







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Prepared for
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Rocky Flats Plant
Wind Systems Program
P.O. Box 464
Golden, CO 80402

Subcontract No. PF-64100

As a Part of the
UNITED STATES DEPARTMENT OF ENERGY
WIND ENERGY TECHNOLOGY DIVISION
FEDERAL WIND ENERGY PROGRAM

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ABSTRACT

This report summarizes the results of Phase II of a program to design and test a 40 kW vertical axis windmill called a "Giromill". Phase I of this program covered trade off studies, selection of configuration, and detail design of that configuration. In Phase II the unit was fabricated, erected, and tested. This program was conducted under contract PF64100F, awarded by the Rockwell International Energy Systems Group at Rocky Flats, Colorado, as part of the Department of Energy (DOE) small windmill development program.

McDonnell Aircraft Company (MCAIR) was prime contractor, with major assistance from Valley Industries through a subcontract and license agreement, and from McDonnell Douglas Electronics Division (MDEC) through an intercompany work order.

Mr. J. W. Anderson was Program Manager for MCAIR, Mr. William Duwe was Engineering Manager for Valley Industries, and Mr. Tom Schmidt was Engineering Manager for MDEC. The principal engineers for MCAIR were Messrs. Burt Birchfield, Bob Brulle, Howard Clark, and Willis Kunz; for Valley Industries, Mr. Jim Herr; and for MDEC, Messrs. Bob Udell and Jerry Swaitlowski.

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1. INTRODUCTION

The design, fabrication and test of a 40 kW Giromill was accomplished in two phases. A preferred configuration was selected and designed during Phase I. This was done from 15 September 1978 to 15 June 1979, as detailed in Reference 1.

This report details the building, erection, and test activities of Phase II from the start on 15 June 1979 through April 1981.

Fabrication was completed by January 1980. The fixed tower was erected in December 1979, and the complete assembly including the rotating tower, was erected in February 1980. First turn was accomplished on 5 March 1980, and checkout testing, including running at operational RPM, was completed on 14 March 1980. These first checkout tests were done at Valley Industries plant in Tallulah, Louisiana.

After the checkout tests were completed, the unit was disassembled and shipped to Rocky Flats. First turn at Rocky Flats was on 3 July 1980.

The Giromill is presently connected into the local utility grid and has produced 40 kW or more of electric power when operating and with adequate winds. Operational testing in the electrical mode is continuing and may be followed by testing in the mechanical mode.

2. DESIGN AND ASSEMBLY OVERVIEW

The contractual design requirements specified the development of a prototype Giromill having an electrical power output plus an adapter kit to convert the system to a mechanical power output. A stand alone capability requiring no external power was also required.

Design tasks included: (a) Trade-off Studies, (b) Design Criteria Development, (c) Detail Rotor Design, and (d) Detail Control System Design. Supporting studies were conducted in aerodynamics, performance, loads, structural dynamics, weights, failure modes and effects, and test instrumentation.

After design the unit was fabricated and assembled. McDonnell Aircraft Company (MCAIR) made the blades while Valley Industries made the remainder of the structure. McDonnell Douglas Electronics Company fabricated the controller and blade actuators.

2.1 <u>DESIGN TRADE STUDIES</u> - To arrive at the preferred Giromill configuration for detail design, a series of trade off studies was conducted covering geometry, control system, blade, support arms, rotating tower, and fixed tower. Geometric trade-offs considered number of blades, number of support arms, blade solidity, blade thickness, and rotor aspect ratio. Minimum system cost was an important selection criterion.

Figure 1 shows the selected configuration and Figure 2 shows the Giromill erected and running at Rocky Flats test center. The rotor has three blades and is 58 ft in diameter by 42 ft long. Each blade is supported by two support arms to give a minimum blade bending moment. The support arms are held up with streamlined cables. The rotating tower extends to ground level to reduce bearing side loads and to locate the transmission and generator near the ground for easy maintenance access. The fixed tower is a truss tower made of structural angles. A microprocessor controller drives electrical actuators that modulate the blades to maintain constant rotor RPM.

2.2 <u>DESIGN CRITERIA DEVELOPMENT</u> - The system specifications are presented in Figure 3. These specifications were related to design criteria for the various components. Included were operating loads, maximum storm loads, and snow and ice loads.

2.3 <u>DETAIL ROTOR DESIGN</u> - The rotor consists of a central steel tube rotating tower with three aluminum blades, each supported by two steel support arms. The support arms are pinned at the rotating tower and supported at the outboard end by streamlined steel cables. The rotating tower is supported by two bearings: one at the top of the fixed tower and another near the ground.

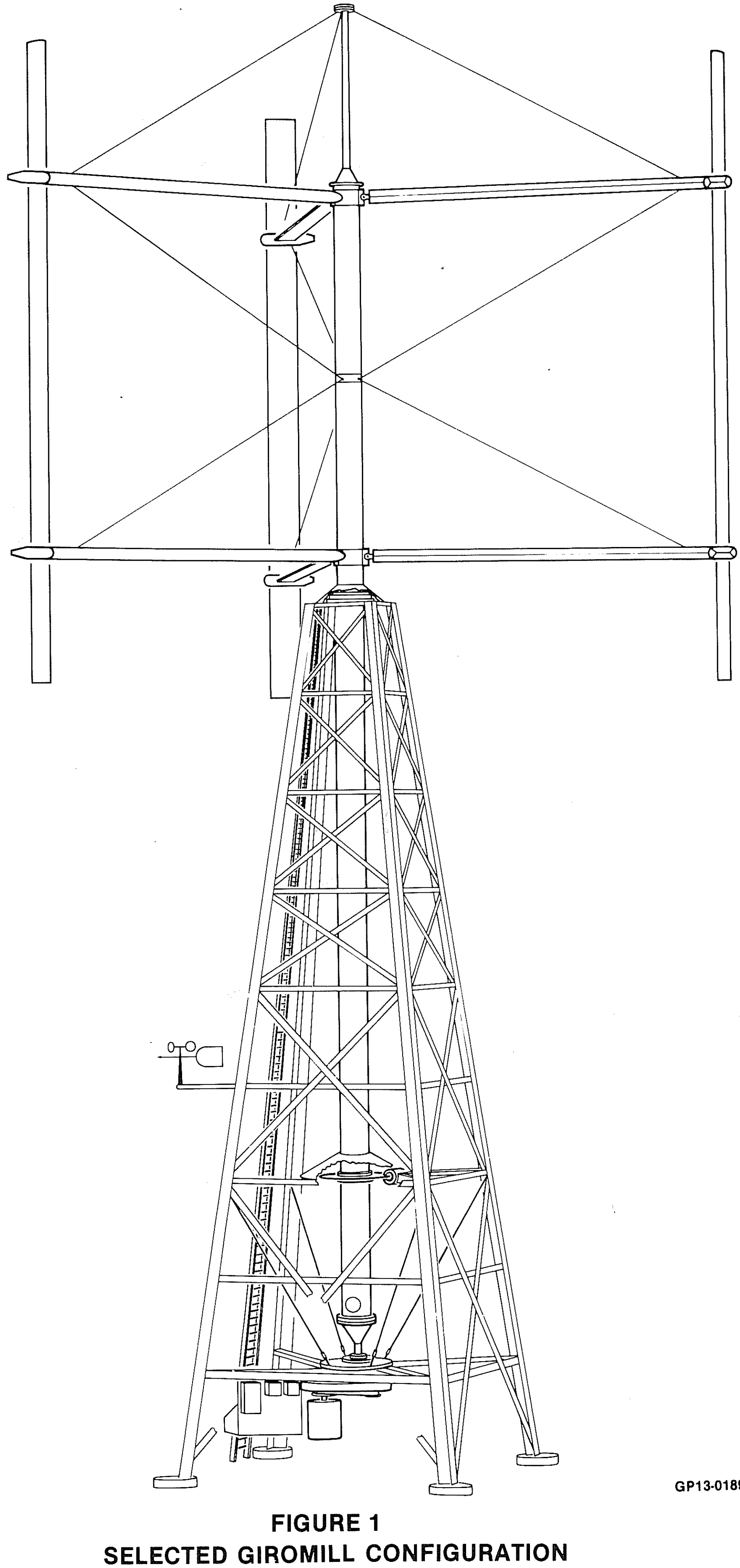

FIGURE 1
SELECTED GIROMILL CONFIGURATION

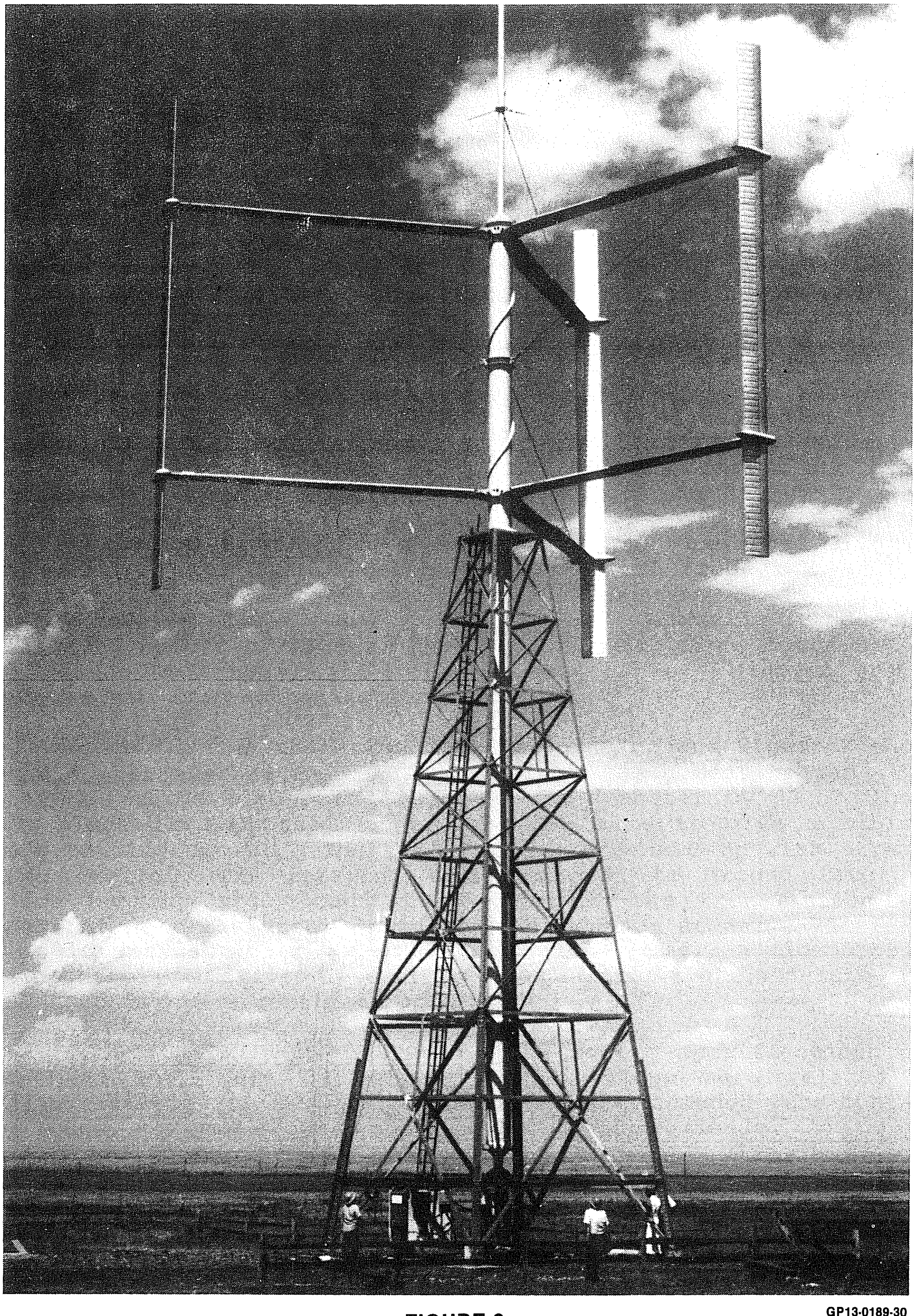

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FIGURE 2
GIROMILL AT ROCKY FLATS TEST CENTER

	ELECTRICAL	MECHANICAL
OUTPUT POWER MODE OPTIONS	40 kWMIN. IN 9 m/s (20 MPH) AT SEA LEVEL DENSITY. 60 Hz, POWER FACTOR OF 0.8 OR HIGHER 1. MATCH WITH EXISTING UTILITY GRID: 3-PHASE, 480 VOLT ±5% 2. INDEPENDENT OF UTILITY GRID: SINGLE MACHINE, 3-PHASE, 480 VOLT ±5% 3. INDEPENDENT OF UTILITY GRID: SINGLE MACHINE, 240 VOLT ±5% 4. 3-PHASE 480 VOLT ±5%, FOR TIE-IN OF TWO OR MORE MACHINES	40kW MINIMUM IN 9 m/s WIND HORIZONTAL SHAFT AT CONSTANT SPEED OF EITHER 440, 880, OR 1760 RPM. SHAFT SPEED NOT TO VARY MORE THAN ±1% FOR WIND SPEED GREATER THAN 9 m/s
HEIGHT	CENTERLINE OF ROTOR SWEPT AREA TO BE AT A HEIGHT OF 75 FT.	SAME
WIND RANGE		
CUT-IN	MINIMIZE WITH REGARDS TO ECONOMICS OF POWER PRODUCTION AND SYSTEM COST.	SAME
CUT-OUT*	27 m/s (60 MPH) MINIMUM. SELECTION OF A LOWER SPEED TO BETTER MEET PROGRAM OBJECTIVE OF LOW-COST POWER PRODUCTION MUST BE ADEQUATELY JUSTIFIED.	SAME
PEAK GUST PROTECTION	56 m/s (125 MPH) MINIMUM WITH A 1.5 SAFETY FACTOR	
CONTROLS		
START/STOP	AUTOMATIC	SAME
SHUTDOWN/CONTROL	AUTOMATIC FOR ROTOR OVERSPEED BACK-UP SHUTDOWN MECHANISM.	
OPERATION	AUTOMATIC CUT-IN, AND CUT-OUT AUTOMATIC RE-ENGAGE AS WINDS DROP BELOW CUT-OUT SPEED	
OUTPUT	AS REQUIRED TO PROVIDE PROPER OUTPUT POWER MODE	

*A cut-out wind speed of 40 mph was selected for the prototype.

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FIGURE 3
40 kW WIND CONVERSION SYSTEM SPECIFICATIONS

2.3.1 <u>Blade</u> - Each Giromill blade has an NACA 0018 shape and is a two-cell sheet metal airfoil consisting of a 0.16 inch leading edge skin, a 0.125 inch channel spar, and a 0.020 inch beaded trailing edge skin. A cross-section of the blade is shown in Figure 4. Blade bending, shear, and torsion are carried by the leading edge and spar. The beaded trailing edge structure acts as a truss member to transfer local air loads to the leading edge torque box.

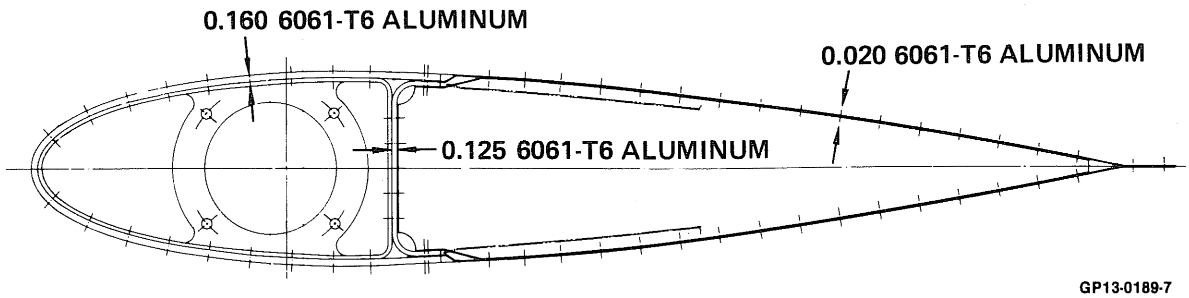


FIGURE 4
BLADE CROSS SECTION

The blade is attached to the rotor arm through a 4140 steel support tube fitting inserted into the end of each blade section. Blade bending is transferred to the tube by a coupling between two machined aluminum ribs. Torsion in the blade is transferred through bolts attaching the root rib to a flange on the support tube fitting.

2.3.2 <u>Support Arms</u> - The support arms are welded sheet steel construction, tapered and streamlined to minimize aerodynamic drag. The outboard half of the arms has a smaller cross section and is more streamlined. The outline of the support arms is shown in Figure 5. Attachment of the support arms to the rotating tower is shown in Figure 6. The streamlined wire braces are formed from 0.625 inch diameter stainless steel bar. Turnbuckles are used for rigging adjustments.

2.3.3 <u>Rotating Tower</u> - The rotating tower is made of flanged tubular sections which are bolted together. The middle sections are A36 steel tubing, 24 inch diameter by 0.250 inch wall thickness. Figure 7 illustrates the rotating tower.

2.4 <u>FIXED TOWER DESIGN</u> - The fixed tower is a truss type made of ASTM A36 structural steel angles. The joints are bolted. Figure 8 shows the fixed tower.

The upper bearing for the rotor is a sealed ball bearing. The inner bearing race is bolted to a flange on the rotating tower, as shown in Figure 9. The outer race is bolted to a steel ring for reinforcement. To provide a flexible mounting so that this bearing carries only radial loads, the bearing assembly is attached to the fixed tower with four thin sheets of steel.

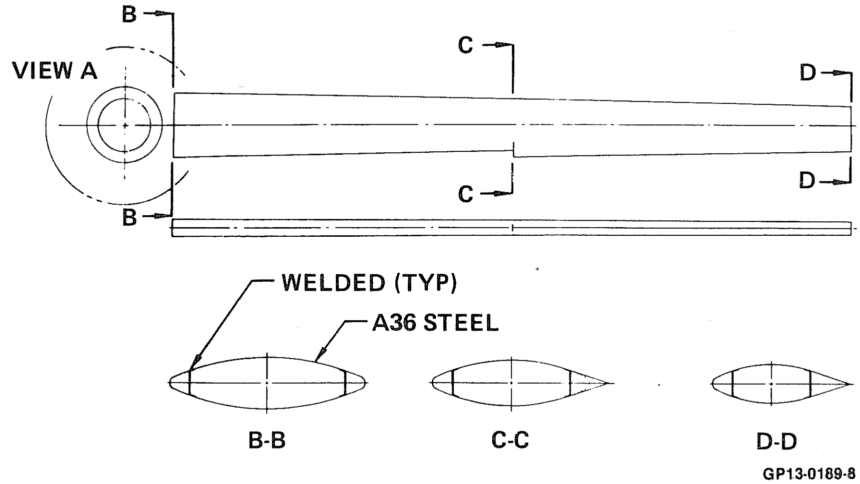
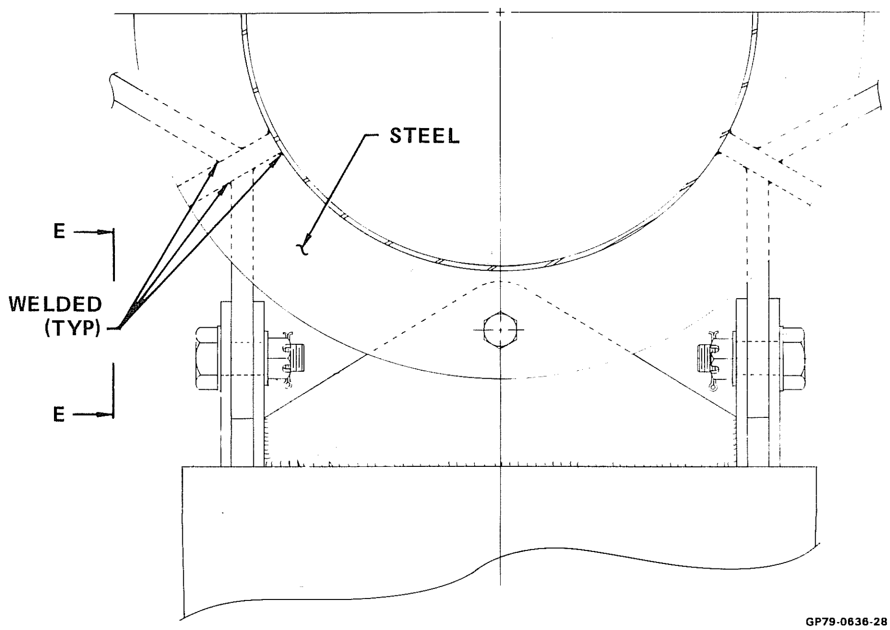


FIGURE 5
GENERAL ARRANGEMENT SUPPORT ARM



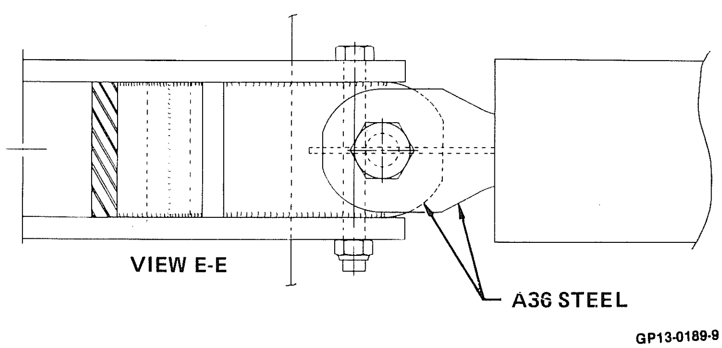


FIGURE 6
ARM/TOWER ATTACHMENT

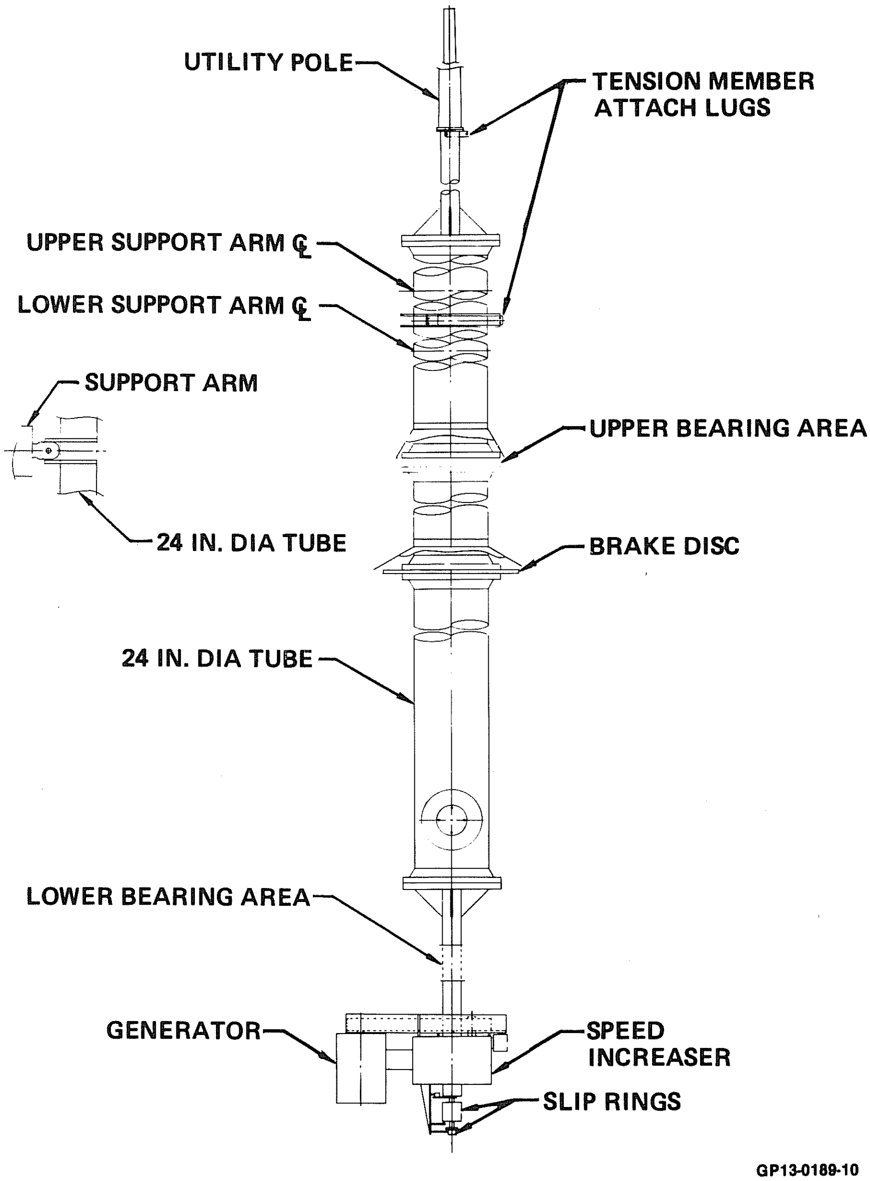


FIGURE 7
ROTATING TOWER

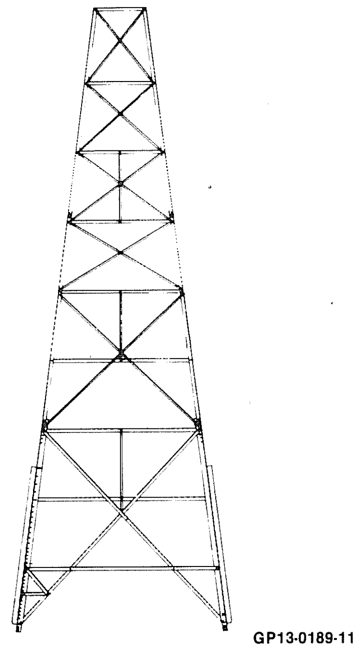


FIGURE 8
FIXED TOWER

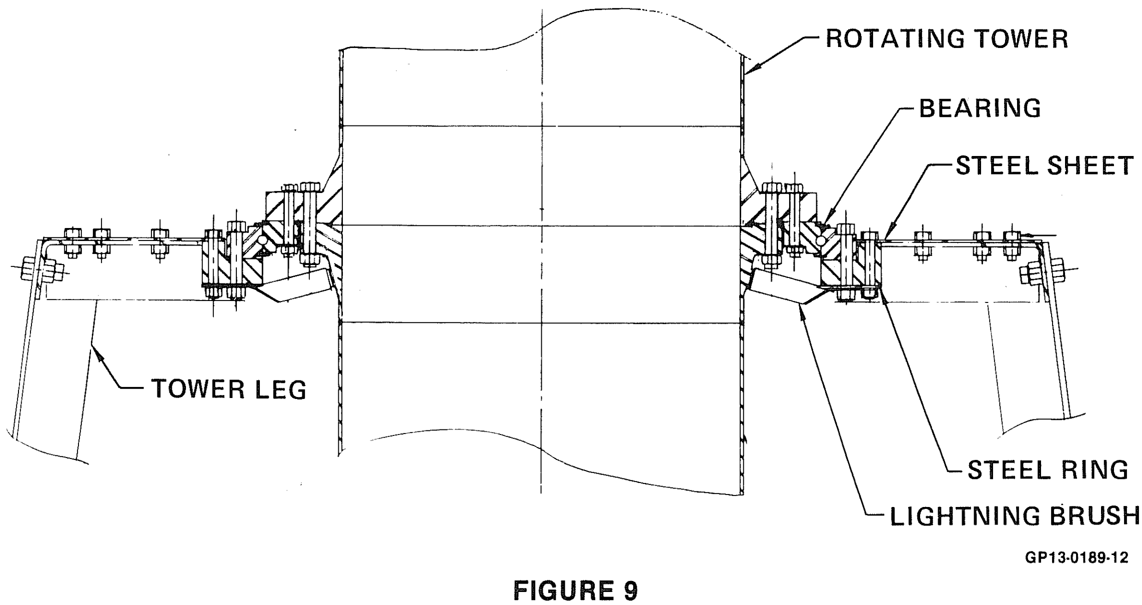


FIGURE 9
UPPER BEARING MOUNTING

A tapered roller bearing is used for the lower bearing (Figure 10). It is bolted to a plate that is suspended from the four tower legs by four tension members. Turnbuckles are used to adjust the length of the four members for proper rigging of the lower bearing, as shown in Figure 11. Four horizontal members attached to the tower legs take the side load on the bearing. This bearing carries the entire thrust load (weight) of the rotor and radial load.

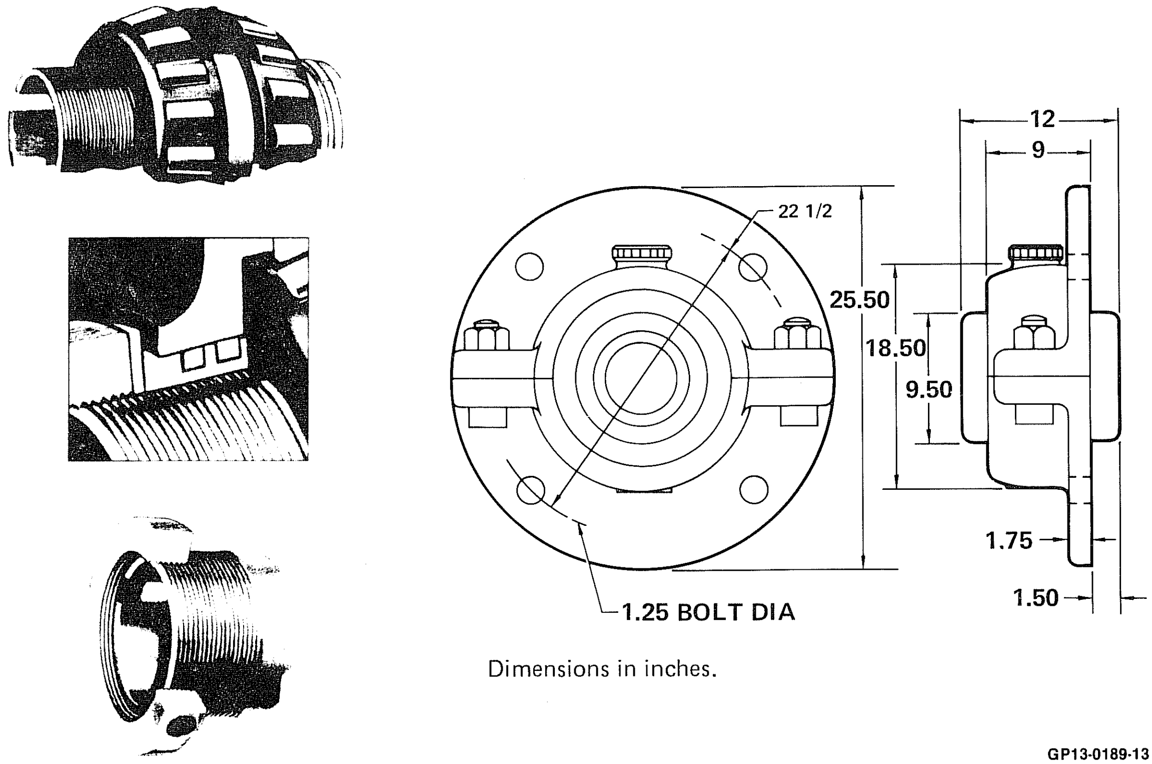


FIGURE 10
LOWER BEARING

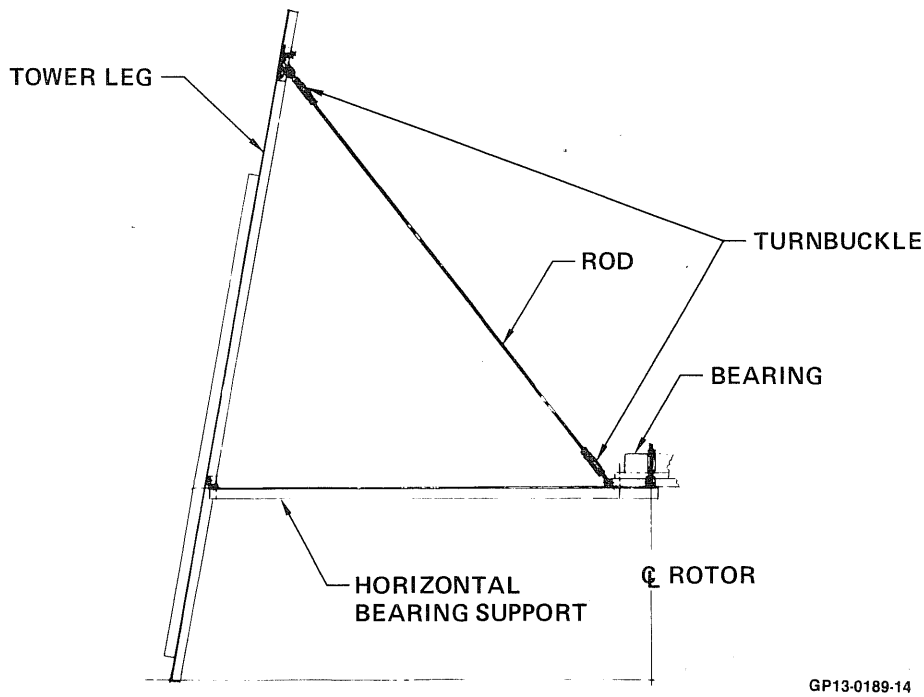


FIGURE 11
LOWER BEARING MOUNTING

A disc brake system is designed into the prototype for emergency situations. The brake disc is bolted between two flanges of the rotating tower. The caliper is actuated by internal springs and released by hydraulic pressure. In all normal operating and standby modes the caliper is in the released position making for a fail safe configuration.

The fixed tower has a spread foundation made up of four concrete piers. Figure 12 illustrates a typical pier. Two 1.5 inch diameter anchor rods extend out of each pier.

2.5 <u>CONTROL SYSTEM DESIGN</u> - The control system uses a microprocessor controller that sends commands to electric blade actuators. Constant RPM control is achieved by a proportional plus integral feedback on rotor RPM, summed with a measured blade speed command. The blade rock angle (relative pitch angle) commands generated by the control unit are transmitted to individual electrical blade actuators. Each actuator consists of an electric motor, power amplifier, and gear box. The actuator positions the blades according to the commands resulting from position feedback which is monitored by a potentiometer. This potentiometer is mounted in the actuator gear box and related to blade position through a separate set of gears.

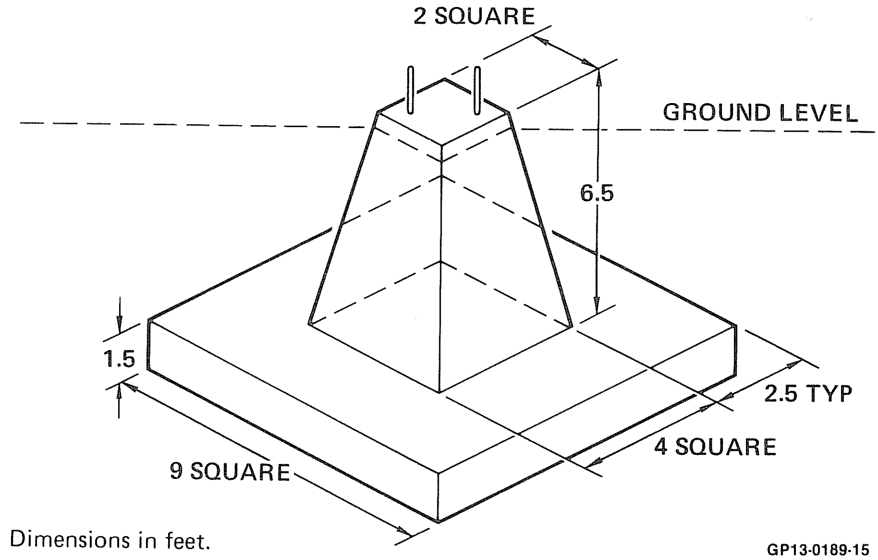


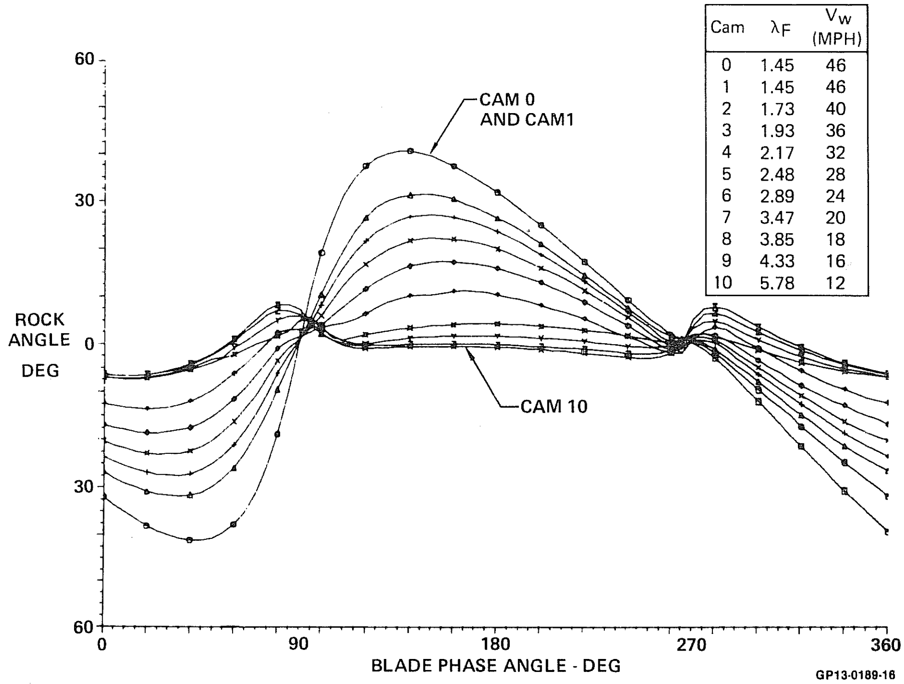
FIGURE 12
FOUNDATION PIER

The control system is housed in two enclosures: (1) control unit which contains the microprocessor and (2) control system power switching unit (CSPSU). These enclosures are mounted on the control panel at the base of the fixed tower.

The control unit utilizes a microprocessor in conjunction with three programmable read-only memories (PROMS) and associated interface circuits. The rock angle profiles, Figure 13, stored in the PROMS are used for commanding the blade actuator as a function of the blade phase angle, ψ, and rotor RPM. Self tests in the controller assure a fail-safe system.

The Giromill rock angle actuator is a self contained closed loop servomechanism which controls the angular position of the output shaft in response to a position signal. This servomechanism consists of an electronic control amplifier and a direct drive actuator powered by a dc motor operating from the 48 volt supply. An isometric view of the actuator is shown in Figure 14.

Power for the control system is generated by a 48 volt alternator, driven by a toothed belt from the main gear box at the bottom of the rotating tower. Four 12 volt batteries, mounted on the control panel, provide power for starting and standby.



Cam	λ_F	V_W (MPH)
0	1.45	46
1	1.45	46
2	1.73	40
3	1.93	36
4	2.17	32
5	2.48	28
6	2.89	24
7	3.47	20
8	3.85	18
9	4.33	16
10	5.78	12

FIGURE 13
PROGRAMMED ROCK ANGLE PROFILES

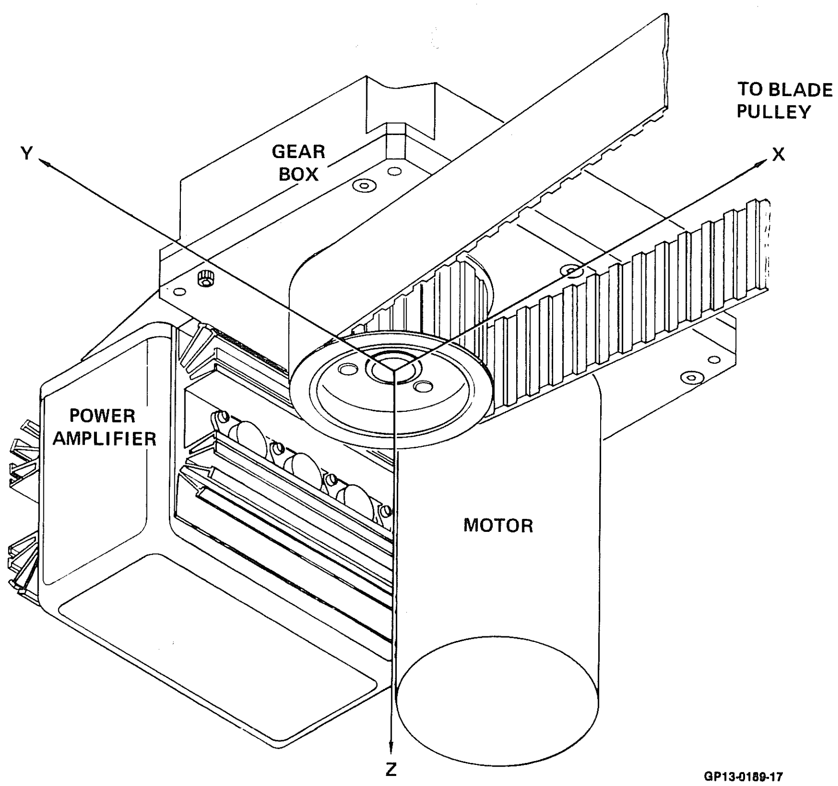


FIGURE 14
BLADE ACTUATOR ASSEMBLY

2.6 MECHANICAL AND ELECTRICAL OUTPUT POWER SYSTEM - A shaft-mounted helical gear box speed increaser, having a gear ratio of 24.3 to 1, is mounted on the lower end of the rotating tower. The output shaft of the gear box drives the generator through a toothed belt final stage for an overall increase of 54.675 to 1. For the electrical output design the generator speed is 1830 RPM. Figure 15 shows the electrical drive system assembly.

An induction generator is used to feed 480 volt, 3 phase, 60 Hz power into a large utility grid. A magnetic contactor, controlled from the control system through a relay, is used to connect the Giromill to the utility grid.

The mechanical output kit converts the Giromill from an electrical output to a 1760 RPM mechanical output through a horizontal shaft. A right angle gear box and mounting bracket replaces the electrical generator.

2.7 PERFORMANCE - Performance calculations were made employing the Larsen Cyclogiro Performance Computer Program. Figure 16 shows the overall performance computed for blades being modulated to give constant effective angles of attack ${}_e$. The maximum predicted Cp is approximately 0.5 and occurs at an ${}_e$ = 9° at a blade speed ratio λ= 3.4. The cyclogiro performance program does not account for aerodynamic loss due to blade damping. This loss in Cp was computed separately and is shown in Figure 16. Note that its effect is predominate at the higher blade speed ratios and is negligible at blade speed ratios less than 3.5.

Also shown in Figure 16 are lines of constant rotor power (10 kW to 50 kW) and the performance point for the rock angle cam in discrete winds from 12 to 40 MPH (circled points). These points show what cam or rock angle profile would be required to achieve that particular performance at the specified wind speed. The double dashed lines emanating downward from these discrete wind points show how the power coefficient varies when that constant blade rock angle profile is maintained. For example, modulating the blades along a profile defined by cam 6.5 (λ = 3.15 see Figure 13) or 22 MPH wind speed cam, would result in a Cp of .385 at λ= 3.15. Maintaining this same blade modulation as the blade speed ratio was increased would result in the Cp decrease shown by the double dashed line leading downward and to the right. The fixed cam Cp variations from 22 MPH to 40 MPH are shown. The Cp variations for fixed cam modulations from 20 MPH down to 12 MPH are not shown since they lie very close to the dashed line obtained by correcting for aerodynamic damping.

To achieve an output of 40 kW from an electrical generator requires the rotor to have an output of about 50 kW. The 50 kW line therefore shows the rock angle variation needed for constant power above a wind speed of 20 MPH.

2.8 ASSEMBLY AND CHECKOUT - The unit was assembled and checked out at the Valley Industries Plant at Tallulah, La. After checkout it was disassembled and shipped to Rocky Flats.

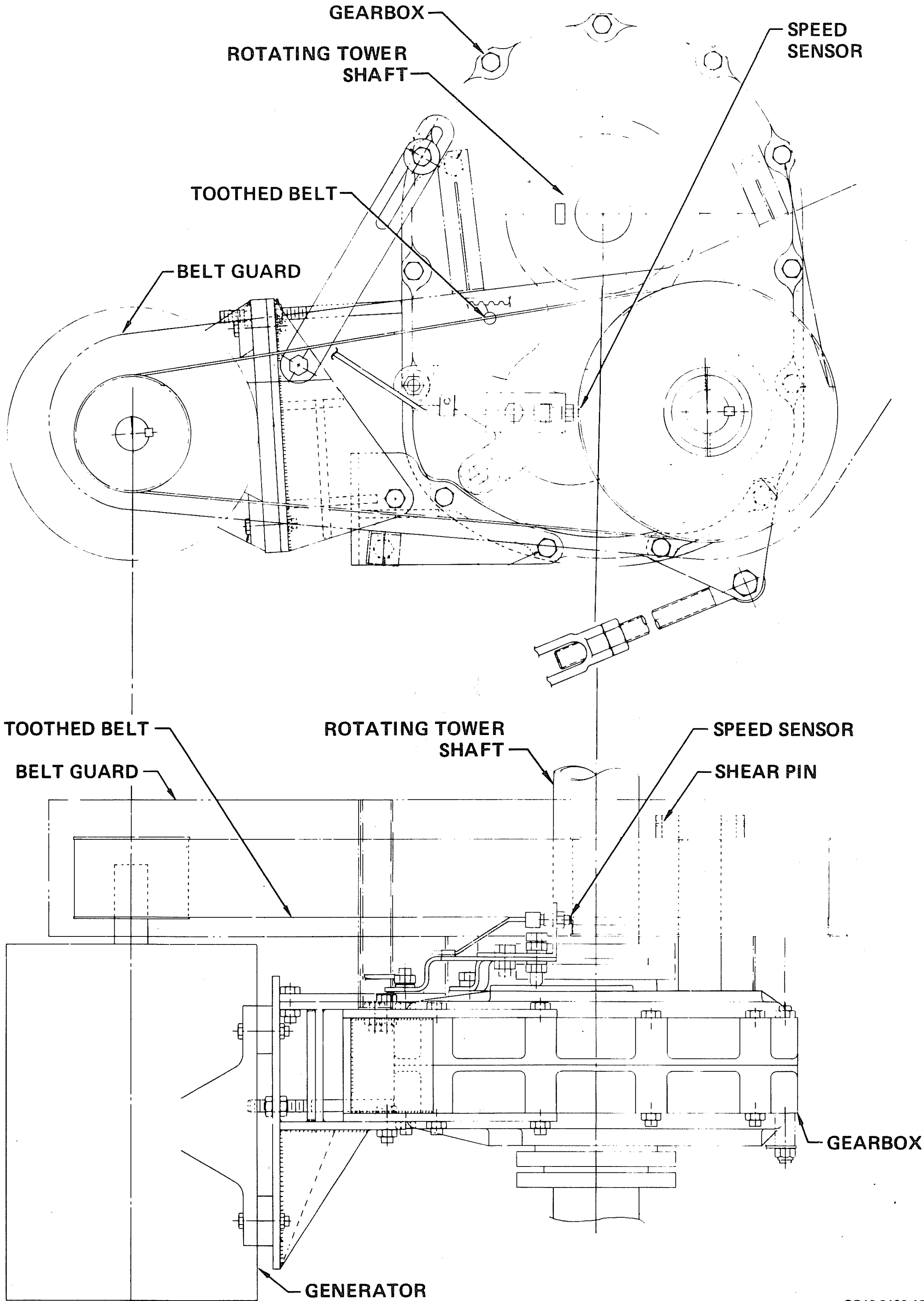


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FIGURE 15
ELECTRICAL DRIVE SYSTEM

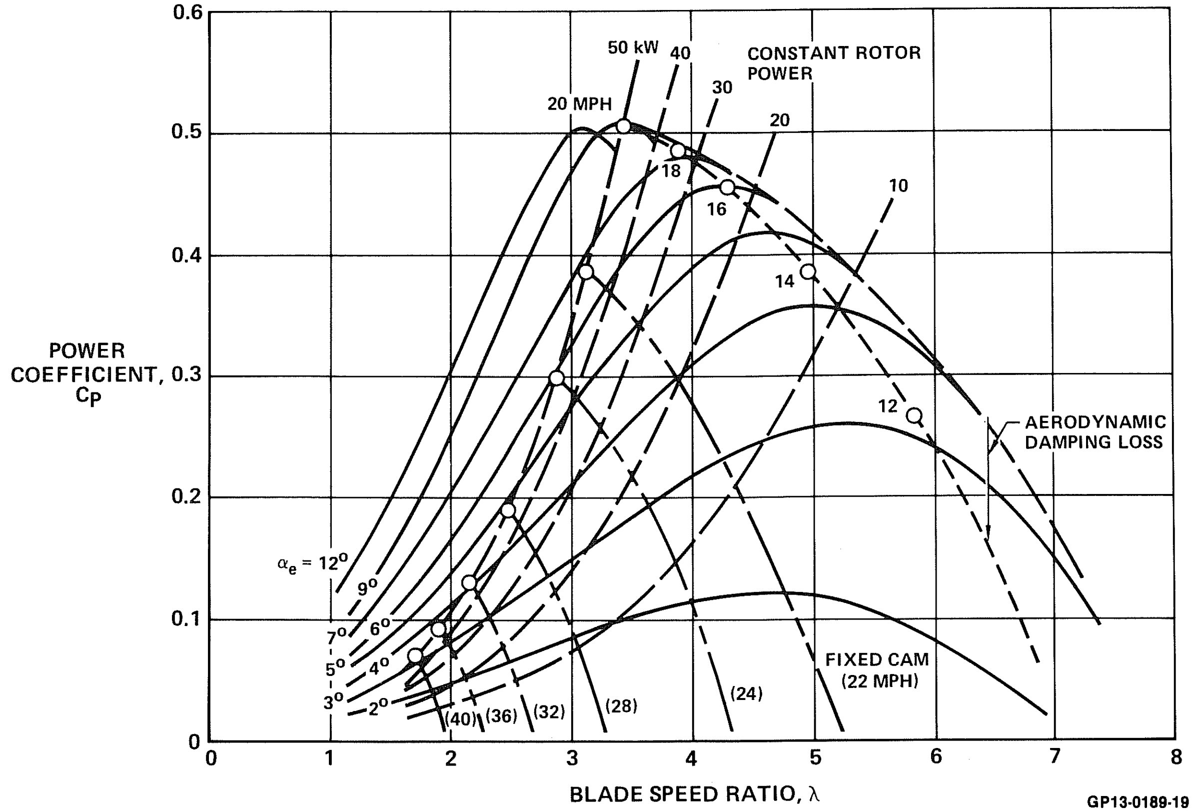

FIGURE 16
GIROMILL CONTROL PERFORMANCE

Pictures of the unit assembly at Tallulah are shown in Figures 17 through 23. These pictures illustrate the key assembly steps as follows:

1. Lower portion of the fixed tower was first erected.

2. Upper portion of the fixed tower was assembled and then raised and attached to the lower part.

3. A subassembly of the lower main bearing with the lower portion of the rotating tower and speed increaser/ generator was completed and then this assembly was attached to the fixed tower.

4. Installation of the remaining portion of the lower rotating tower and upper main bearing was then completed. At Tallulah the rotating tower was eased through the side of the fixed tower where several members had been removed. At Rocky Flats the tower was lowered through the top.

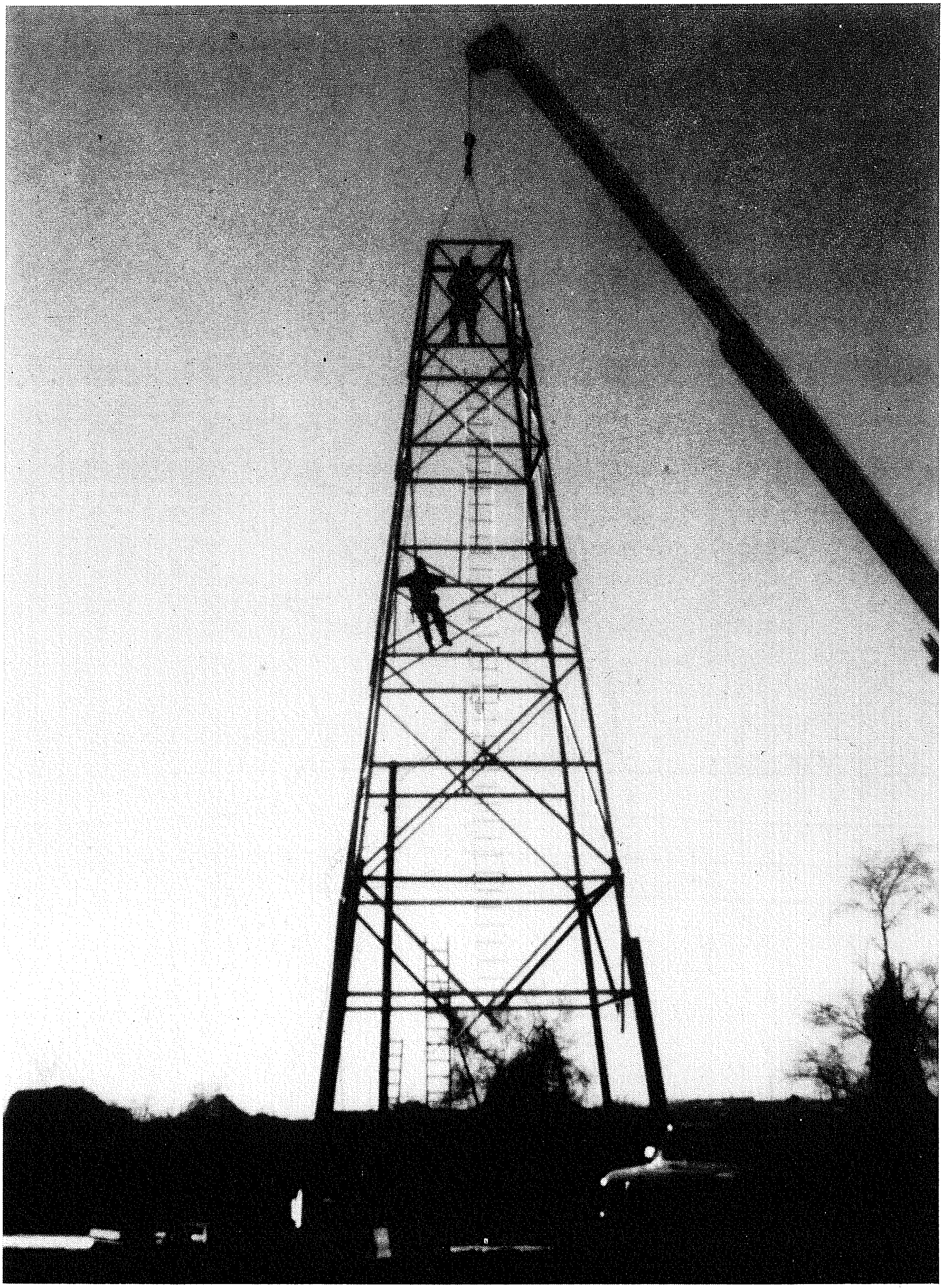

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FIGURE 17
FIXED TOWER AFTER INSTALLING THE UPPER SECTION

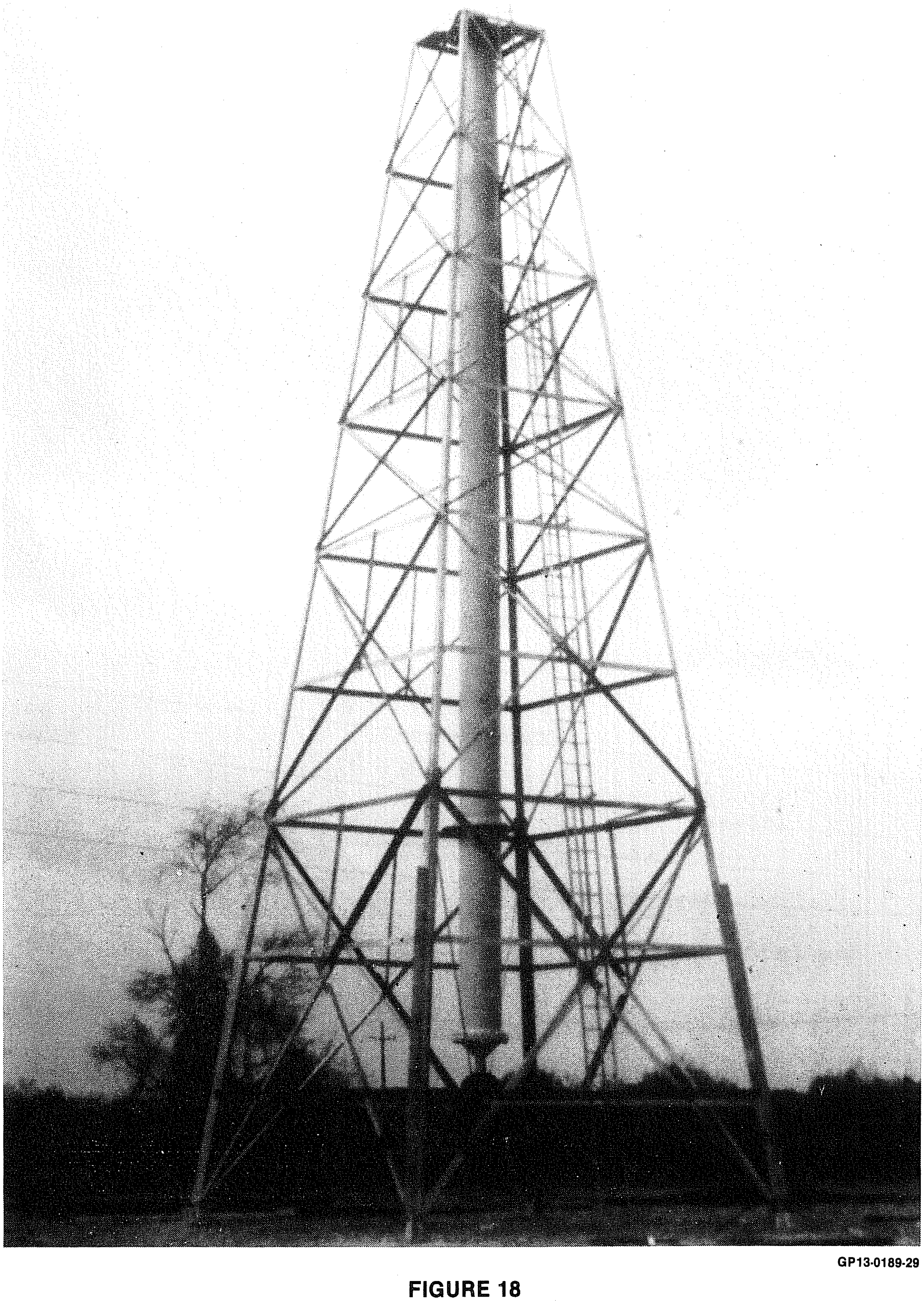

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FIGURE 18
FIXED TOWER WITH LOWER SECTION OF ROTATING TOWER

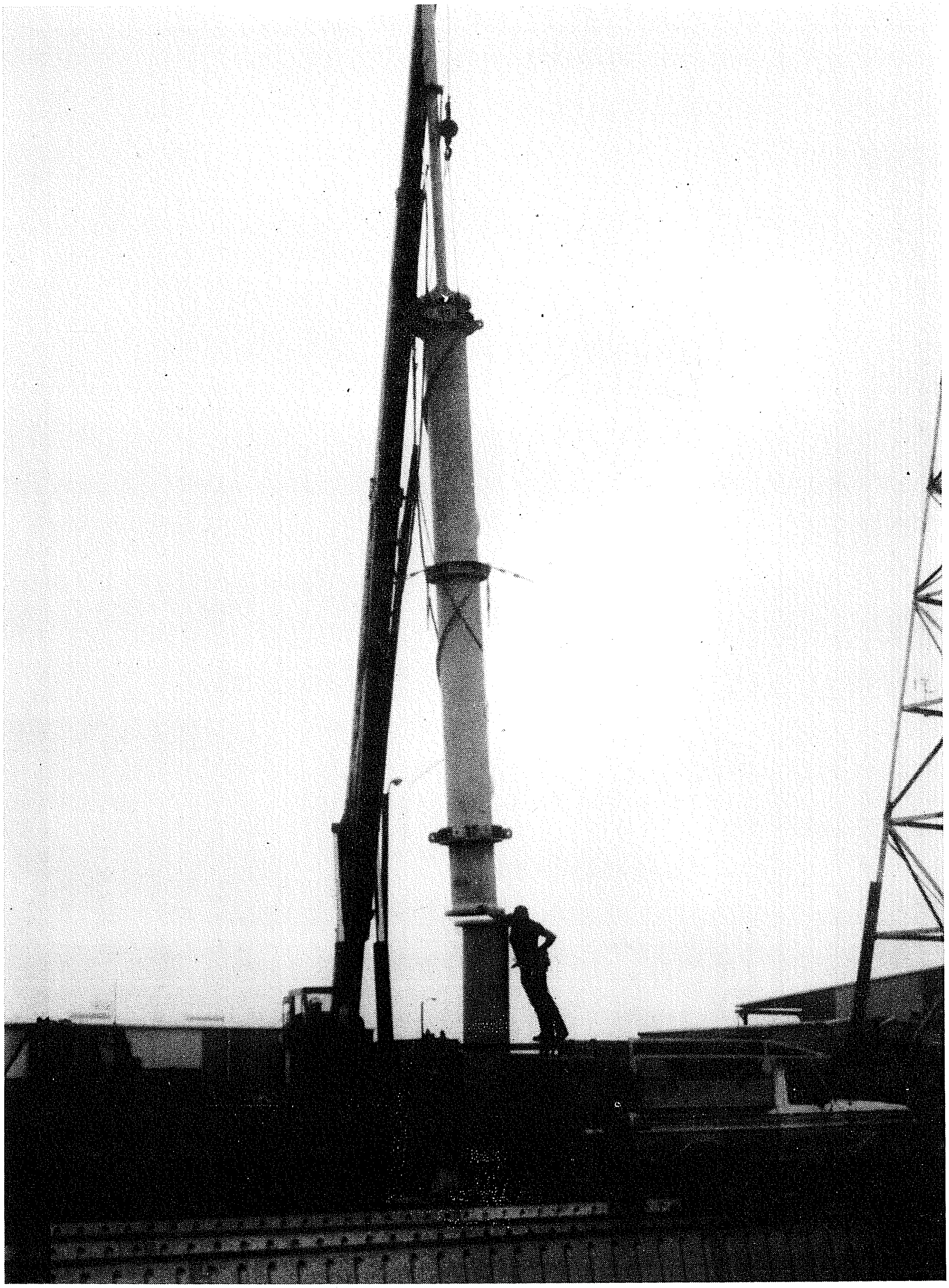

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FIGURE 19
ATTACHMENT OF ROTOR TO ASSEMBLY STAND

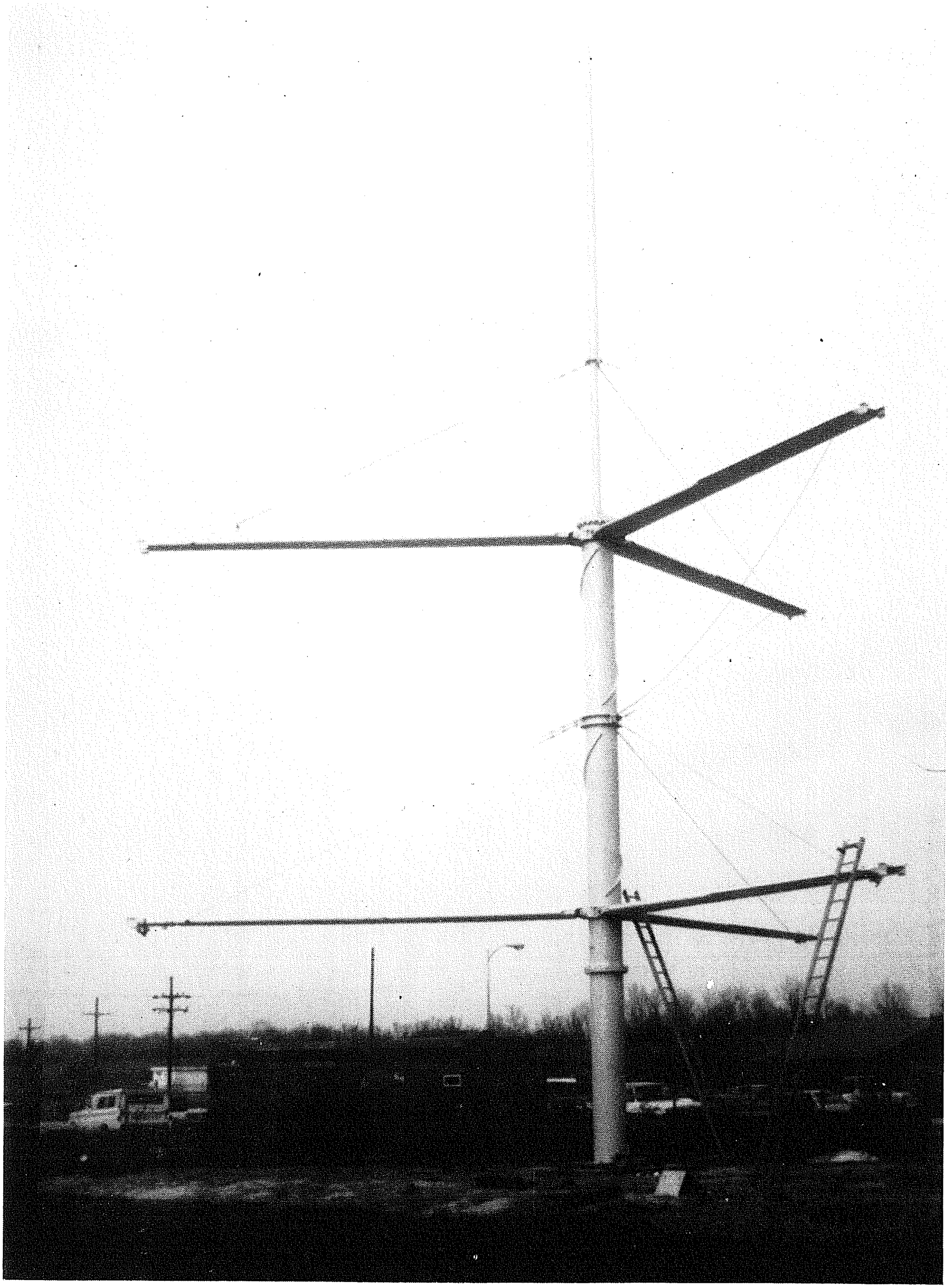

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FIGURE 20
ROTOR ASSEMBLY

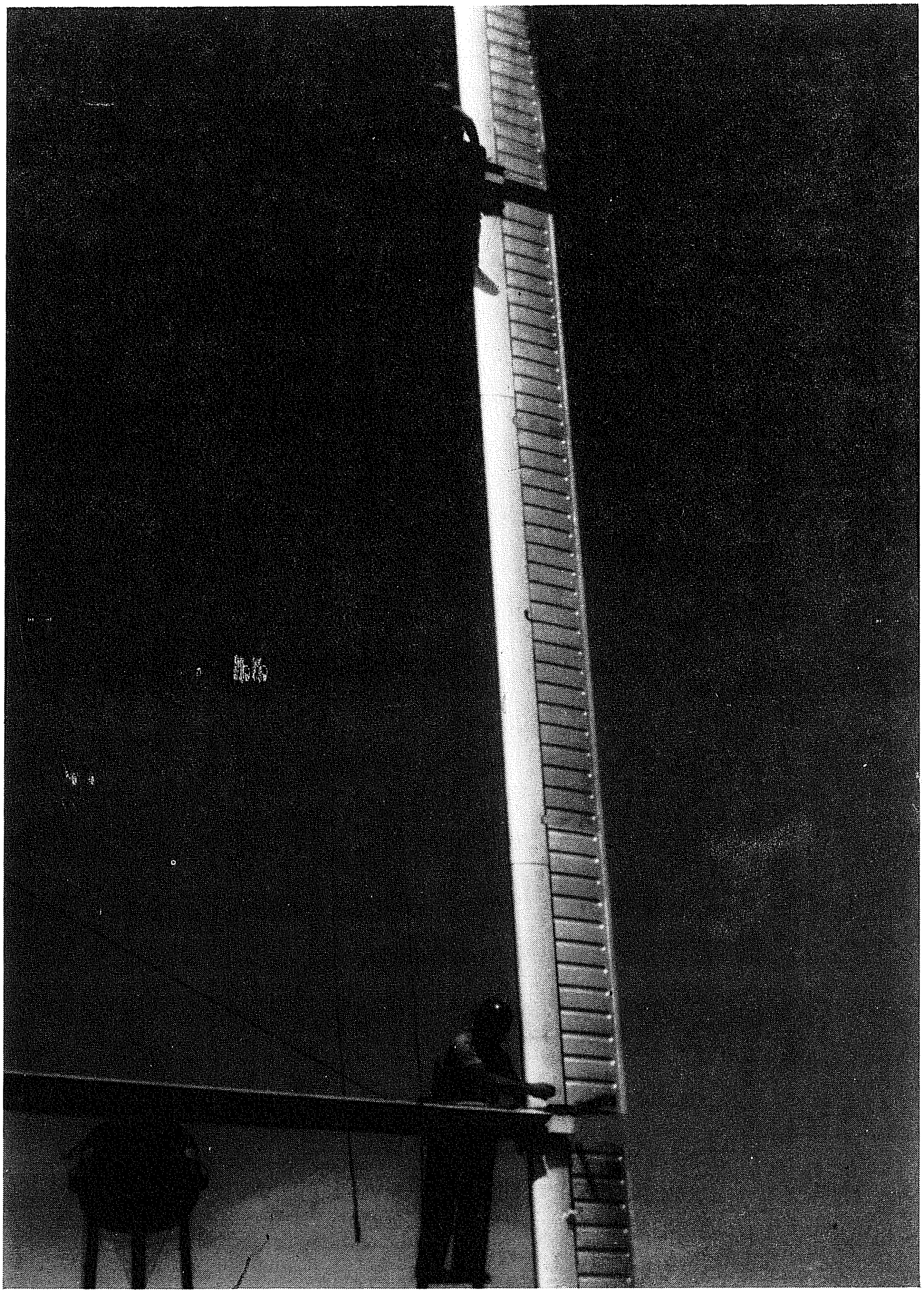

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FIGURE 21
ALIGNING BLADE WITH SUPPORT ARMS

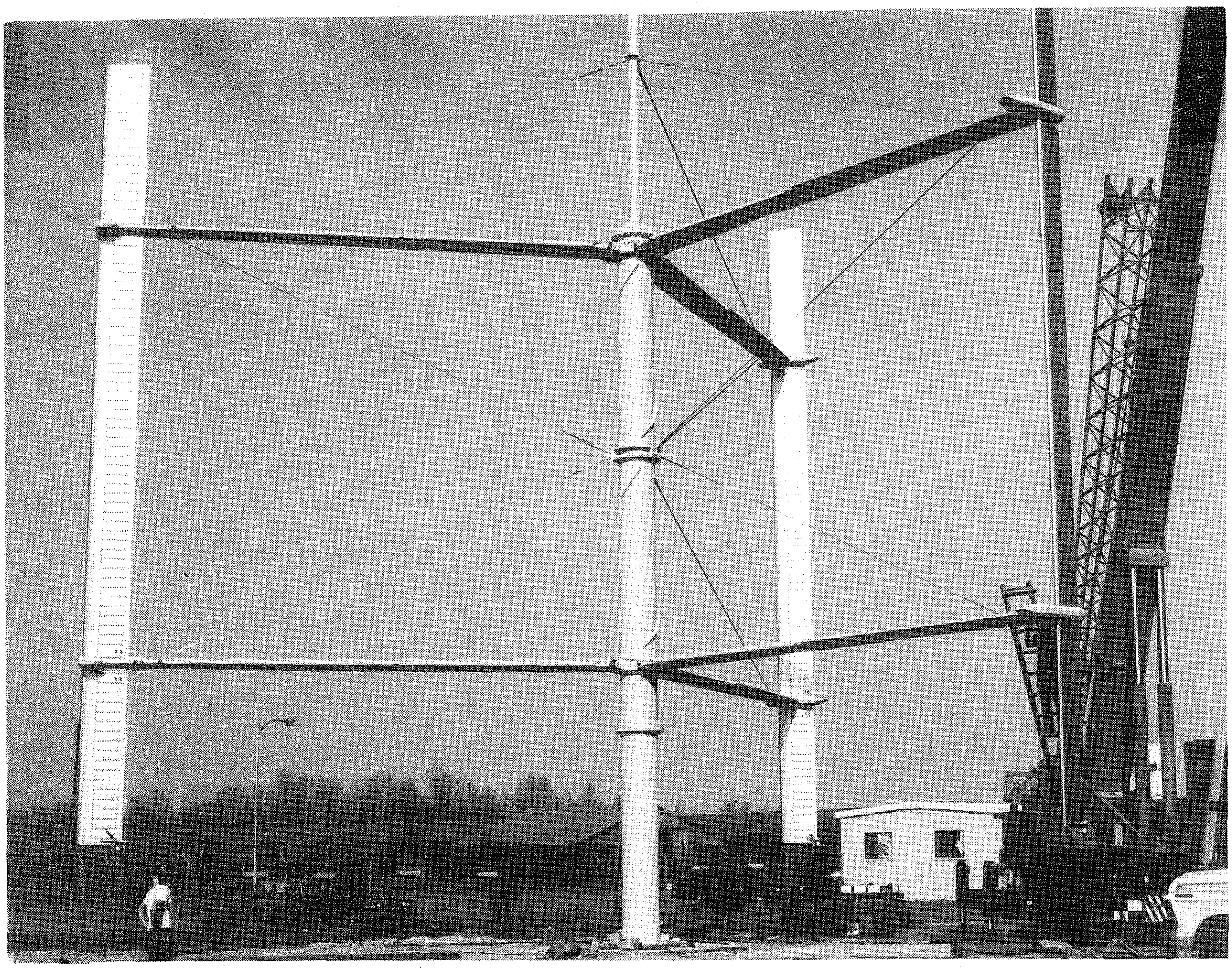

FIGURE 22
ROTOR ON ASSEMBLY STAND

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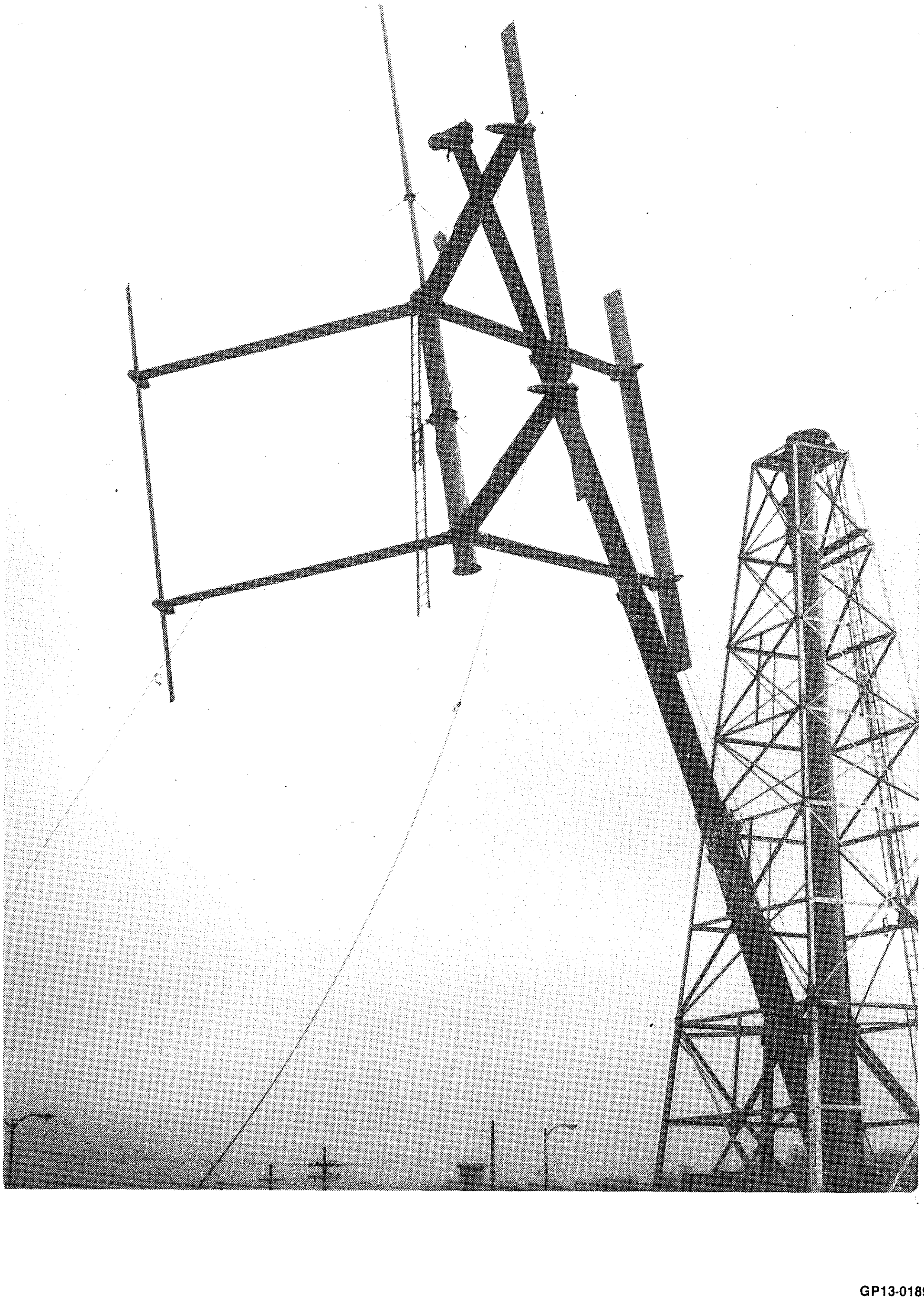

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FIGURE 23
LIFTING ROTOR ASSEMBLY TO FIXED TOWER

5. The rotating tower was then rigged to be vertical and turn smoothly by adjustment of the lower bearing tension members and alignment of the lower bearing.

6. Rotor assembly stand was then erected.

7. Upper rotating tower was assembled and placed on assembly stand.

8. The lower and then the upper support arms were attached to the rotating tower.

9. The blades were installed and the entire rotor rigged for level support arms orientation and free turning of the blades.

10. Blade actuators were installed and temporary wiring connected running from the controller to the actuators.

11. Actuator and control unit checkout was then completed.

12. Rotor was lifted and attached on top of the fixed tower.

13. All other parts were installed and all wiring connected.

14. The unit was then certified for final checkout and running.

System checkout was accomplished without connecting the generator to the grid. The unit was therefore forced to run at zero power output. It did it very well, stabilizing at synchronous RPM even with moderate wind gusts. A picture of the unit running at Tallulah is shown in Figure 24. About one week of testing was accomplished prior to shipment to Rocky Flats.

2.9 <u>ORGANIZATION AND SCHEDULE</u> - Figure 25 presents the key member organization and Figure 26 shows the schedule for accomplishing the effort.

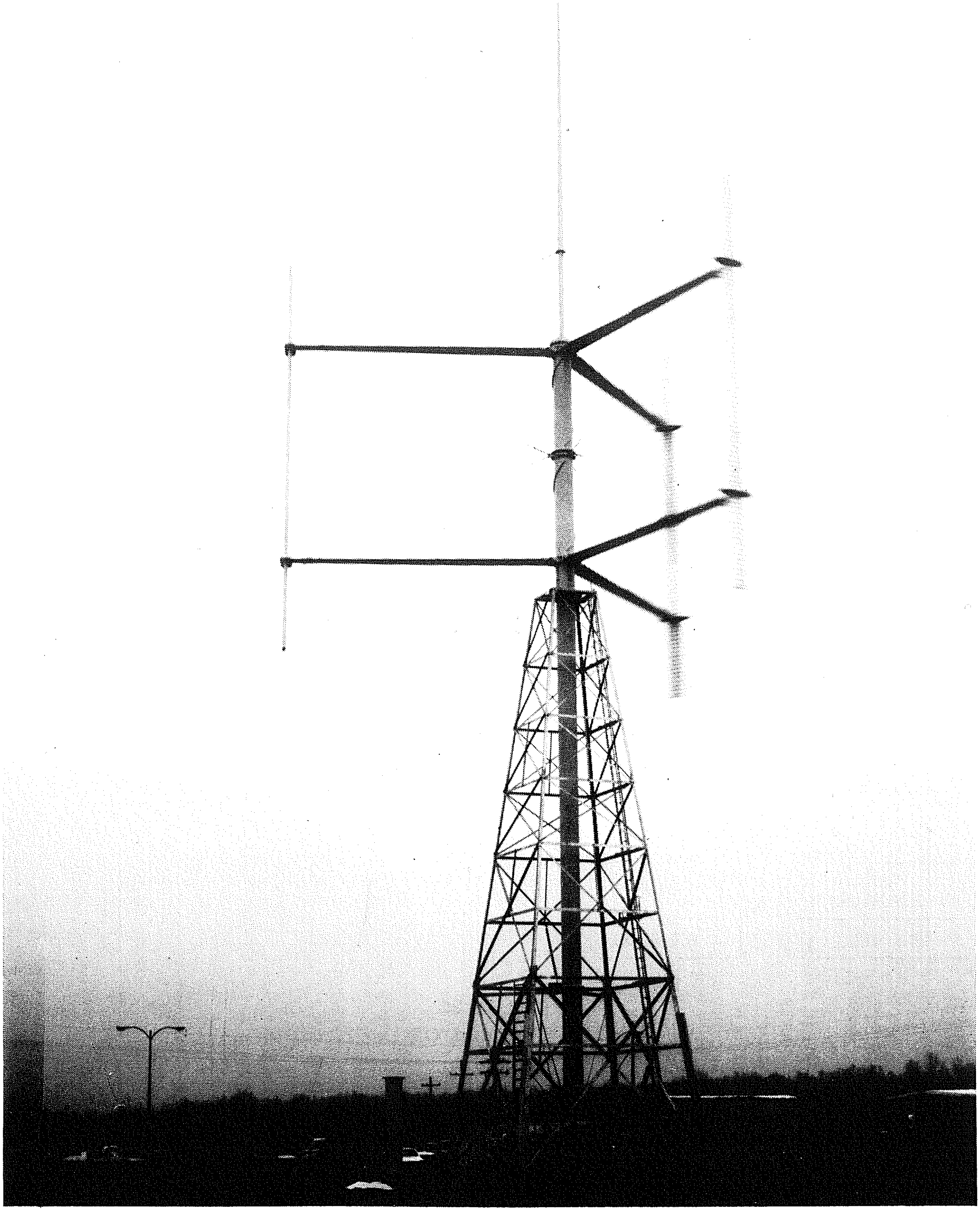

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FIGURE 24
GIROMILL OPERATING CHECKOUT

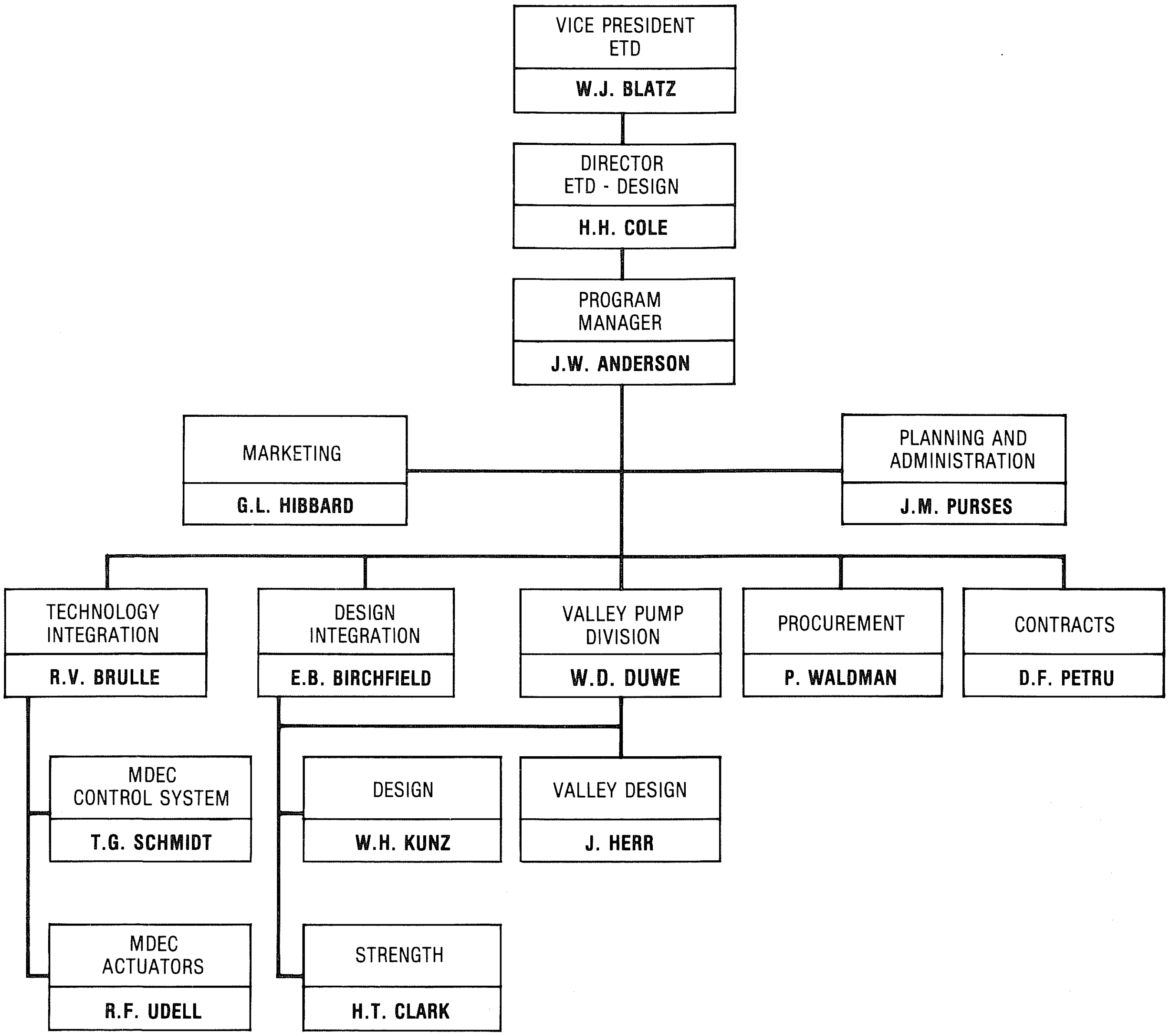

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FIGURE 25
MCAIR 40 kW GIROMILL ORGANIZATION

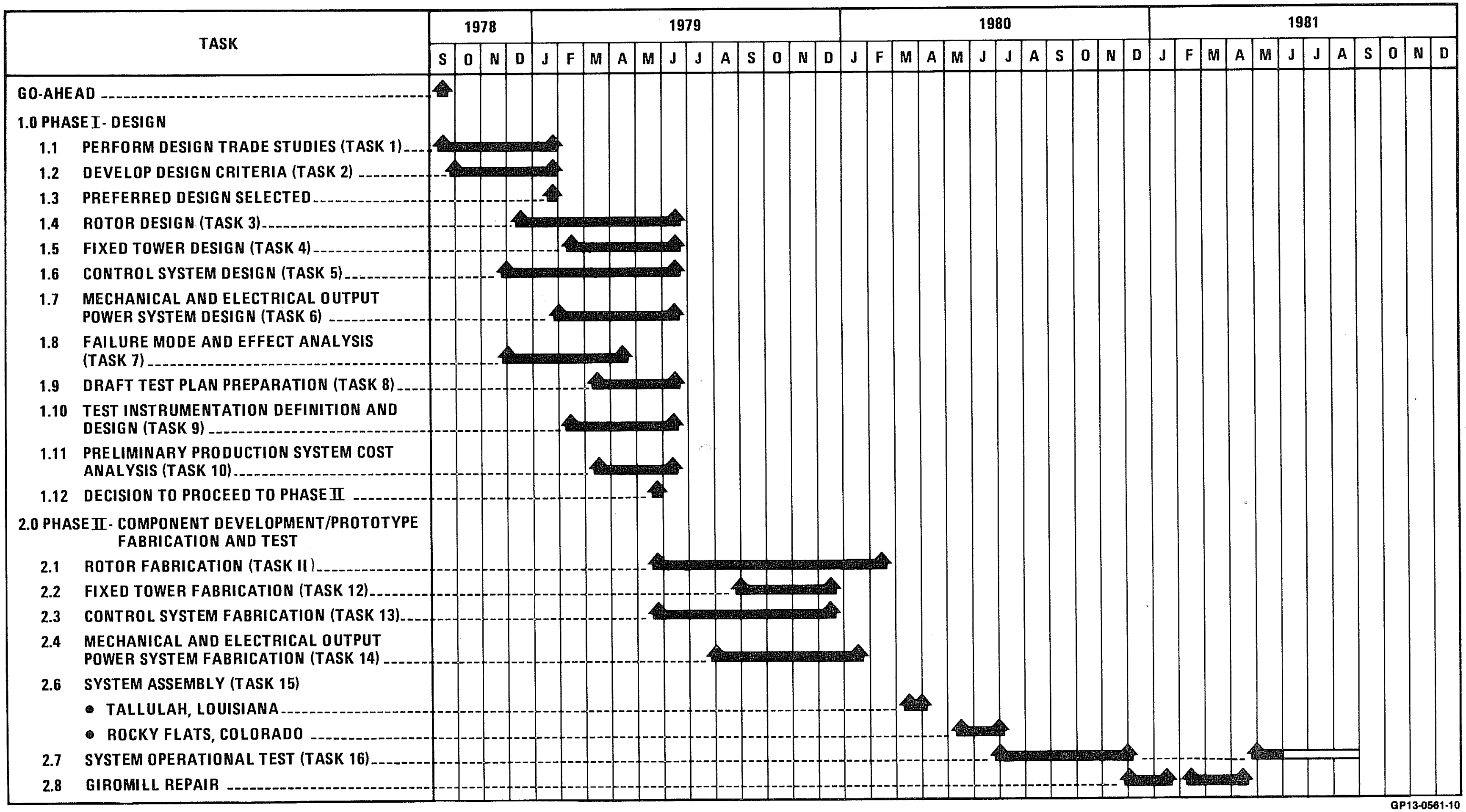

FIGURE 26
40 kW GIROMILL DEVELOPMENT SCHEDULE

3. FABRICATION DESCRIPTION

3.1 <u>BLADES</u> - The blades were fabricated in three sections; upper, middle and lower. The upper and lower sections are identical. The same method of fabrication was used for each section. The assembly tooling is shown in Figure 27. The primary assembly tooling (right side of figure) consists primarily of seven yoke fittings which support the total blade assembly and insure proper alignment of the three blade sections.

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FIGURE 27
ASSEMBLY TOOLING FOR GIROMILL BLADES

The first part placed in the yoke fixture was the leading edge skin. Machined ribs were then riveted to the leading edge skin with the connecting torque tubes inserted through the ribs to maintain alignment. Spars and trailing edge skins were then concurrently riveted to the leading edge skin. A second set of yoke fixtures, shown in the middle of the figure, were used for aligning the trailing edge tab prior to riveting the two trailing edge skins together, through the tab, and thus closing up the blade structure. Finally, the formed sheet metal ribs at the end of each blade section were riveted to the trailing edge skin and spar.

3.2 <u>SUPPORT ARMS</u> - The support arms were assembled in the fixture shown in Figure 28. Initially the two spars were placed in the fixture and bolted to the root fittings which attach the support arm to the rotating tower. The root fittings were pinned to the assembly fixture. The trailing and leading edge sections were then welded to the spar caps. Internal ribs and other miscellaneous fittings were welded next. Miscellaneous fittings included the in-plane attach lugs located at mid-span, the box structure used for attaching the streamlined struts to the support arm, and the blade bearing support plate. The cover skins were then tack welded to the spar caps, one side being completely tack welded before tack welding of the remaining skin commenced. Completion of the skin-to-spar welds was done very carefully by intermittently filling in the weld beads between the original tack welds to minimize warpage due to heating. A pair of support arms were then placed in a separate fixture and strain relieved. The strain relief fixture is an open box structure consisting primarily of two large I-beams, connected by six spacer bars on top and bottom. Strain relieving was done according to PW-39, Section I of the ASME Boiler and Pressure Vessel Code. The heat-up and cool-down rates used are tabulated in Figure 29.

3.3 <u>FIXED AND ROTATING TOWERS</u> - The fixed tower was fabricated by the Delta Steel Company of Jackson, Mississippi. This tower is a standard size used for many other purposes throughout the country. The pieces are standard steel angles cut to length on an automated sawing machine. Holes for connecting fasteners are automatically punched by numerically controlled machines.

The rotating tower was fabricated in five sections by the Custom Machine Company of Monroe, Louisiana. All sections were standard size commercially available pipes. Flanges were welded to the pipes to permit bolting sections together. The three mid-sections were 1/4-inch thick, 24-inch diameter pipes with standard weld-neck flanges welded to each end. These butt-weld joints were ground flush for maximum fatigue life. After welding and strain relieving, the mating flange faces were machined to insure flatness and alignment when assembled. Rings were fusion welded to the pipes to provide attachment structure for the support arms and streamlined struts.

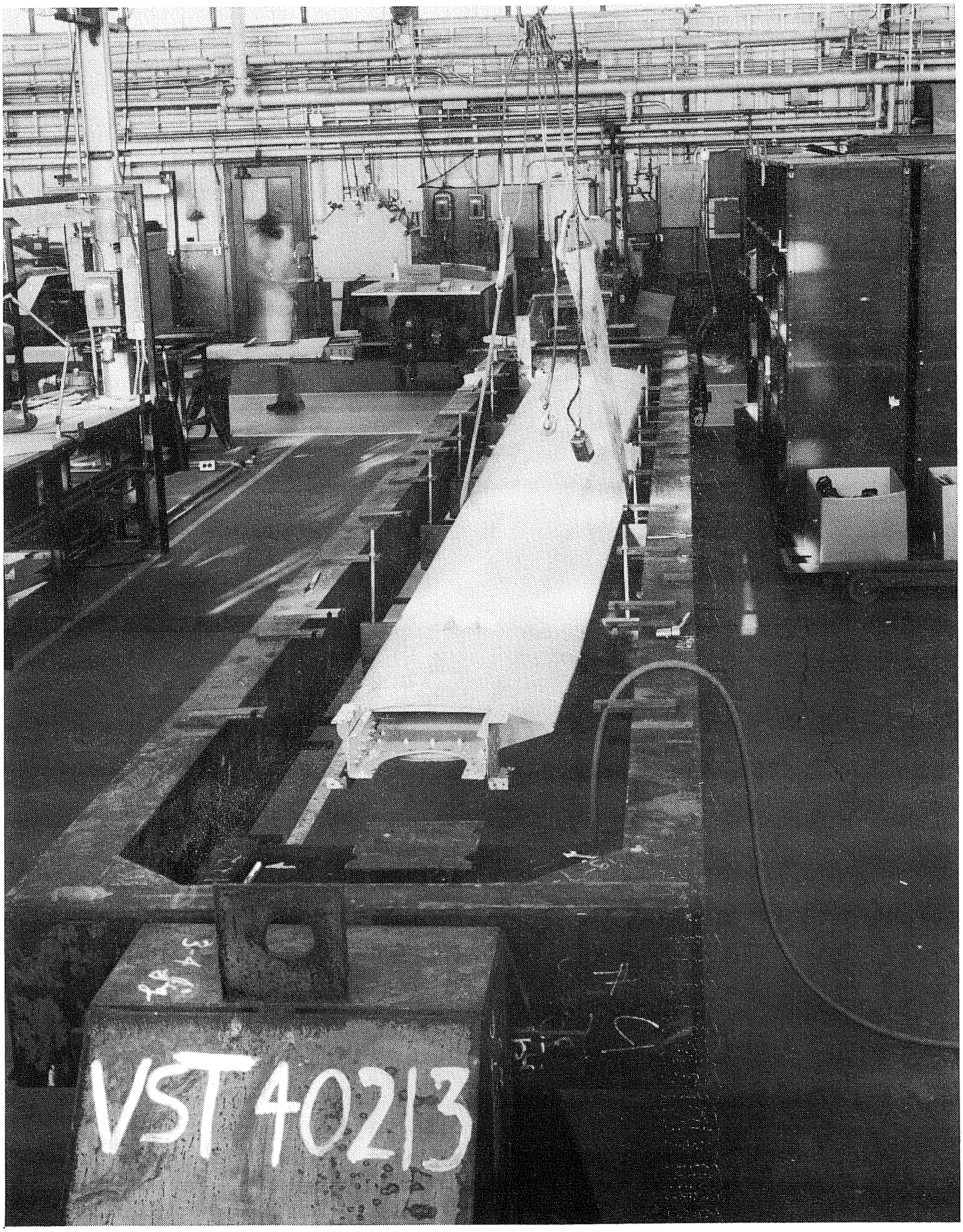

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FIGURE 28
SUPPORT ARM ASSEMBLY FIXTURE

STEP	INSTRUCTION	TEMPERATURE (^oF)
1	PREHEAT SLOWLY	0 - 600
2	HEAT-UP RATE NO FASTER THAN 50^{o}F/HOUR	600 - 925
3	HOLD FOR TEN HOURS	925 ± 25
4	COOL-DOWN RATE NO FASTER THAN 50^{o}F/HOUR	925 - 600
5	COOLING IN STILL AIR	600 - AMBIENT

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FIGURE 29
STRAIN RELIEF CYCLE FOR SUPPORT ARMS

Upper and lower sections were much smaller pipes than used in the mid-sections and therefore required large adapter plates as well as gusset plates welded to the pipe ends. Simple shop tooling was used to insure perpendicularity of the plates with the pipe centerline. Post-weld heat treatment was in accordance with PW-39, Section I of the ASME Boiler and Pressure Vessel Code.

4. PHASE II - DESIGN CHANGES

During the fabrication of the various components and the testing of the Giromill, some desirable design changes in the configuration described in the Phase I report (Reference 1) became apparent and the drawings, delivered at final design review, were changed accordingly. In addition, continued control system analysis finalized the controller gains and other constants.

4.1 DESIGN CHANGE DESCRIPTIONS

Support Arms - Fabrication of the support arms revealed that the sheet metal skins tended to "oil can" while being welded. To alleviate this, additional support arm ribs were welded to the skins. Six additional ribs per support arm were used.

The rib locations are shown on Valley Industries Drawing 40213. The various rib shapes are shown on Valley Drawings 40520 through 40531 for the upper and lower support arms. The only difference between the upper and lower support arm ribs is a slot in the lower arm that fits around the pipe carrying the actuator wiring.

In addition to installing additional support arm ribs, the forming of the upper and lower support arm skins was simplified. Initially, the skins were to be rolled into their streamlined shape. However, this was determined to be expensive and time consuming. Instead, the skins were braked at seven places to form the moldline. Each discrete bend subtended an angle of approximately 7 degrees. The effect on aerodynamic drag was considered negligible. Valley Drawing 40213 was changed to reflect this revision.

Rotating Tower - Strength and dynamics calculations were based on using a 24 inch diameter by 3/16 inch wall thickness pipe for the rotating tower. This was thought to be a standard off-the-shelf pipe. However, we found it required a special order. Rather than incur an extra cost and time delay an available 24 inch diameter by 1/4 inch wall thickness pipe was procured. Strength and structural dynamics checks of the greater thickness tower were completed. They indicated a greater structural safety margin and a more favorable structural frequency. This change is reflected in Valley Drawing 40119.

Control Panel - A five foot square panel made from 1/4 inch steel plate is used to mount the controller unit, CSPSU, and generator contactor boxes. This panel is attached to one of the horizontal torque members used between the lower main rotor bearing and the fixed tower corner members. It was noted that this panel swayed quite a bit when it was windy. Therefore, an additional brace was installed. This change is reflected in Valley Drawing 40340.

A voltage regulator assembly box was added to the panel, when it was determined that an integral regulator was not available for the battery charging alternator. This change, along with the voltage regulator wiring diagram, are shown in Valley Drawing 40340.

Blade Support Tube - The blade support tube connects the blade center section with an end section, either upper or lower, and mounts the blade bearing that is connected to the support arm. This tube must react to large loads and hence is made from high strength steel. A 4130 steel was specified for this part. However, it was unavailable in the form required. To prevent a program delay, 4140 material billets were procured. This material has slightly better strength properties. The change is shown in MCAIR Drawing 71A090151.

Blade Shims - When assembling the Giromill it was determined that tolerances could add up and cause the blades to rub against the support arm fairings. To increase the clearance, blade shims were made to fit between the blade support tube mounting flange and the blade rib, as shown in Figure 30. Shims having a thickness of 3/16 or 1/4 inch were used as required to provide clearance. MCAIR Drawing 71A090101 shows that change.

Control System - At the completion of Phase I, the final control system constants had not been determined. The final values are tabulated in Figure 31. Figure 32 presents these gains and other constants as used in the control system simulation program. This is an updated version of Figure 108 of Reference 1, the Phase I Final Report.

Several control system modifications were also done as a result of the operating tests completed. These are discussed in Section 6.3.3.

Blade Bearing Lightning Protection - A lightning strike could pit the surface of the blade bearing. Therefore, protection was provided by mounting a grounded pole on top of the rotating tower. The pole height was selected to provide a cone-shaped protection zone over the blades.

The lightning pole attachment failed during Giromill operation damaging a blade and two support arms (See Section 6.3.1). Because of this carbon brushes with high copper content were installed to shunt the current around the bearing. The brush installation is shown on MCAIR Drawing 71A090101. Removal of the lightning protection pole is reflected in Valley Drawing 40102.

4.2 DRAWING SUMMARY - Figures 33 through 36 summarize the pertinent drawings completed by the four plants associated with building the Giromill. These drawings contain the various modifications described in Section 4.1, as well as corrective actions, dictated by the testing, which are covered in Section 6.0.

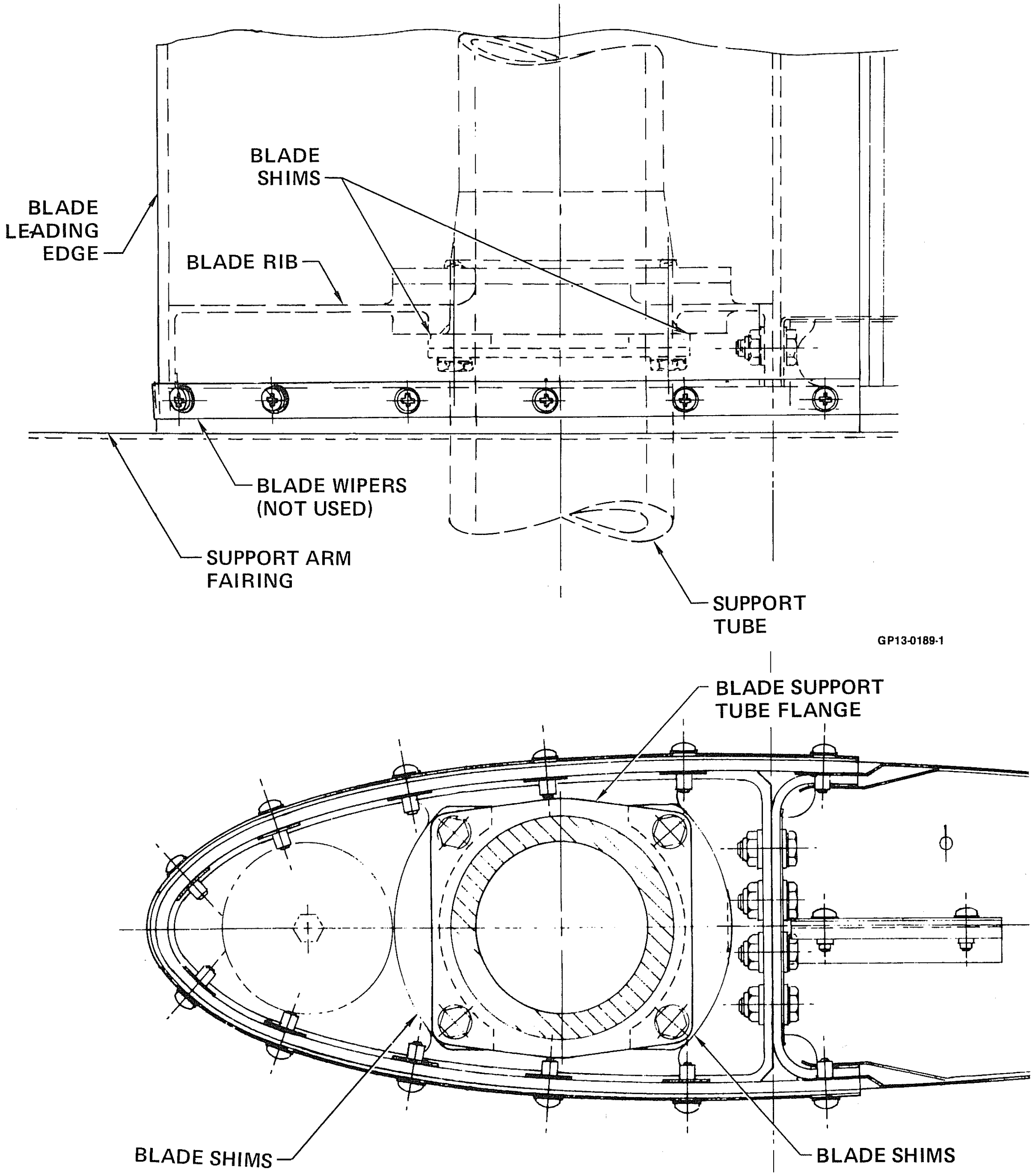

FIGURE 30
BLADE SHIMS FOR CLEARANCE

PARAMETER	VALUE
CONTROL SYSTEM GAINS (CAM UNITS PER UNIT PERIOD)	
START UP GAIN (K_1 x K_4)	–3.662
OPERATING INTEGRAL GAIN (K_2 x K_4)	–17.395
OPERATING PROPORTIONAL GAIN (K_3 x K_4)	–234.375 ($29.98 \leq$ RPM < 32.66) –585.9375 (RPM ≥ 32.66)
BLADE SPEED RATIO GAIN (K_5) (CAM UNITS PER UNIT BLADE SPEED	0.5
LIMIT CAM VALUES (λ_F) AS A FUNCTION OF WIND VELOCITY (h = 75 FT FOR STANDARD SEA LEVEL CONDITIONS)	
V_W GREATER THAN 19 MPH	$\lambda_F = 3.47$
V_W GREATER THAN 17 MPH	$\lambda_F = 3.85$
V_W GREATER THAN 14 MPH	$\lambda_F = 4.33$
V_W GREATER THAN 10 MPH	$\lambda_F = 5.78$
CAM BIAS VALUE (λCM_0)	0.8
LIMIT CAM VALUES (BLADE SPEED RATIO)	
CAM 0 (AND CAM 1)	1.45
CAM 10	5.78
OPERATING WIND SPEED, Vw (ONE MINUTE AVERAGE VALUE RELATED TO h = 75 FT FOR STANDARD SEA LEVEL CONDITIONS)	10 MPH $\leq$ Vw $\leq$ 40 MPH
START UP WIND SPEED (h = 75 FT FOR STANDARD SEA LEVEL CONDITIONS)	
LOW WIND	ONE MINUTE ABOVE 13 MPH LESS ANY TIME BELOW 10 MPH
HIGH WIND	ONE MINUTE BELOW 37 MPH LESS ANY TIME ABOVE 40 MPH
ROTOR RPM DISCRETES	
CONSTANT CAM START UP	TO 7.17 RPM
OPEN LOOP START UP USING K_1 K_4 GAINS	TO 29.98 RPM
GENERATOR CUT IN/CUT OUT	32.92 RPM
NOMINAL	33.5 RPM
OVERSPEED	33.83 RPM
MAXIMUM NUMBER OF OVERSPEED CUT-OFFS WITHIN AN OPERATING PERIOD	5
ROCK ANGLE COMMAND LEAD ANGLE AT OPERATING RPM	15 DEG

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FIGURE 31
GIROMILL CONTROL SYSTEM CONSTANTS

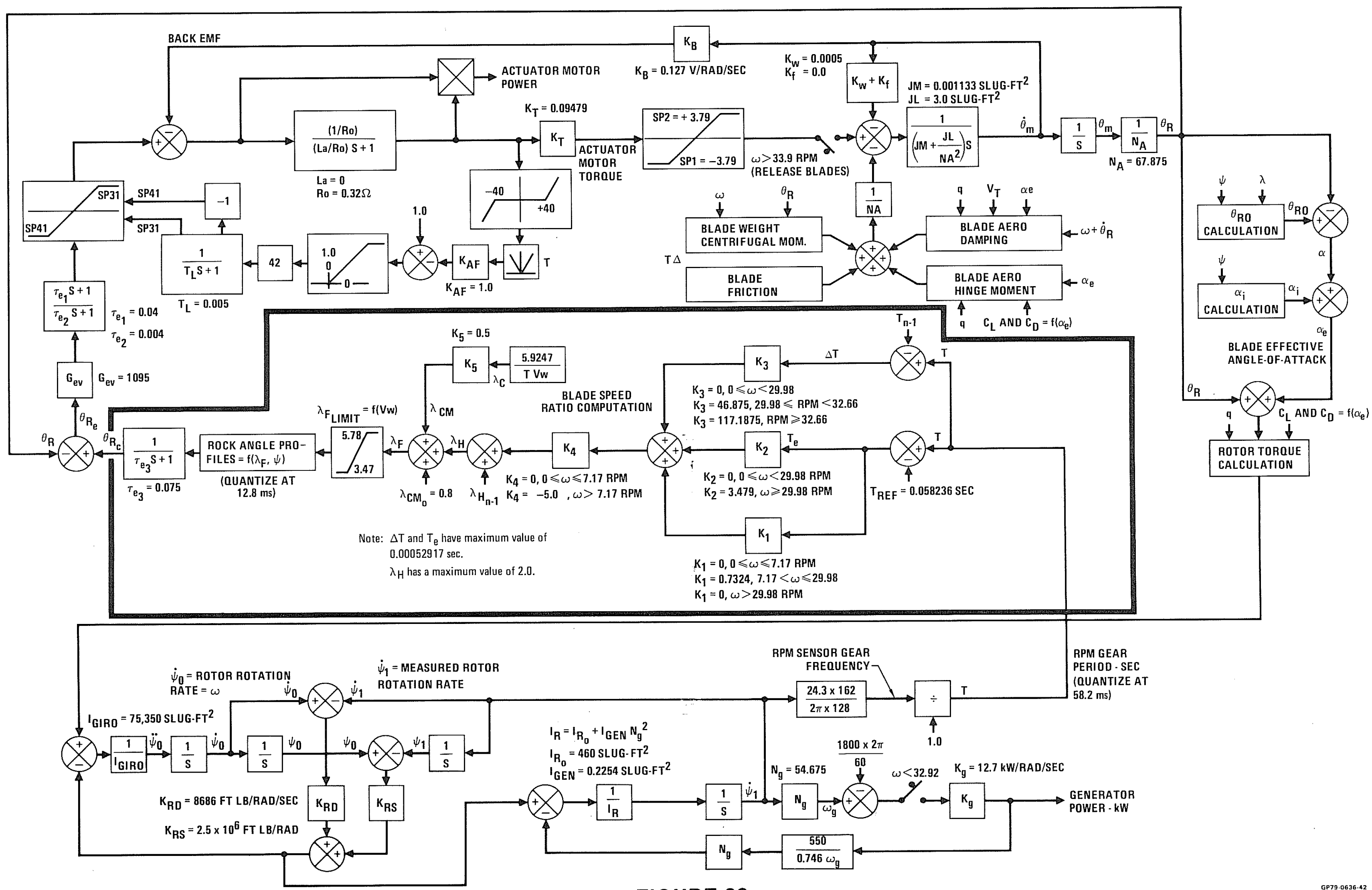

FIGURE 32
GIROMILL CONTROL SYSTEM CSMP SIMULATION-CONTROLLER

DRAWING NUMBER	REVISION	TITLE
71A090000		Giromill Structural Arrangement
71A090101		Blade Top Assembly
71A090120	A	Blade Assembly
70A090121		Blade Leading Edge
70A90122	A	Blade Trailing Edge
71A090123		Blade Channel
71A090124	A	Blade Rib Leading Edge Machining
71A090125	A	Blade Rib Formed Trailing Edge
71A090150	A	Support Tube Assembly
71A090151	A	Support Tube Machining
71A090160	A	Support Tube Rings
71A090170		Bearing Support Upper
71A090171	A	Bearing Support Lower
71A090180	A	Sprocket Blade Drive
71A090190		Ballast, Fixed
71A090191		Ballast, Adjustable
71B090200		Bearing, Roller, Self Alignment - Spec. Control Drawing
71B090205		Belt Drive - Spec. Control Drawing
71A090211		Supports - Fairing
71A090212		Skins, Fairing - Leading Edge and Actuator Cover
71A090213		Skins, Fairing - Hub and Trailing Edge
71A090214		Seals - Blade Wiper
71T090000		Test Instrumentation - Giromill Blade

FIGURE 33
MCAIR BLADE DRAWINGS

DRAWING NUMBER	REVISION	TITLE
J40000	B1	40KW Giromill
D40001	-	Foundation
J40003	A1	Fixed Tower Assembly
D40052	B1	Lower Bearing to Fixed Tower Intf/Assy
D40102	B1	Rotating Tower Assembly
D40186	B1	Rotating Tower Assembly
D40186	B1	Mechanical Drive System Assembly
D40205	B1	Electric Drive System Assembly
D40213	B1	Upper and Lower Support Arms
D40253	B1	Brake System and Assembly
D40301	A1	Speed Sensor Assembly
D40340	C1	Wire Assembly Interface
D40387	A1	Control System Gen. Drive Assembly
D40389	B1	Control System Slip Ring Assembly
D40392	B1	Upper Bearing to Fixed Tower intf/Assy
B40401	-	Electrical Power System Design 1
A40423	-	Wind Speed and Direction Sensor Assembly
D40502	-	Rotor Assembly Fixture Foundation
D40503	-	Rotor Assembly Fixture

FIGURE 34
VALLEY TOP ASSEMBLY DRAWINGS

DRAWING NUMBER	REVISION	TITLE
H05G0075	A	Control Unit - Giromill
PLH05G0075	A	Parts List
H05G0084	A	Power Switching Unit
PLH05G0084	A	Parts List
H06G1863	A	Circuit Card Assembly Logic - A1
PLH06G1863	A	Parts List
H06G1864	A	Electronic Component Assembly
PLH06G1864	A	Parts List
H08G1735		Wiring Diagram - Giromill Control System
H09G2325	A	Schematic Diagram - Giromill Control Unit
H09G2326		Schematic Diagram - CSPSU
H11G0264		Envelope Drawing, Control Unit
H11G0266	A	Envelope Drawing, CSPSU
H14G3393	A	Cable Assy, Special Purpose, Electrical
PLH14G3393	A	Parts List
S52H0059		Housing - Giromill Control Unit
S52H0060	A	Housing Giromill CSPSU
S76M0109	A	Plate, Mounting Component
S76M0110		Plate, Mounting Component
S76M0119		Plate Mounting, Transistor
S76B0065	A	Plate, Identification
S76B0064	A	Plate, Identification
H12G0867		Acceptance Test Procedure - Control Unit - Giromill P/N H05G0075
H12G0868		Acceptance Test Procedure - Power Switching Unit - Giromill P/N H05G0084
H77D0014		Microcircuit Specification Giromill Control Unit

FIGURE 35
GIROMILL CONTROL SYSTEM DRAWINGS

DRAWING NUMBER	REVISION	TITLE
7010A	6	Servomechanism - Giromill Blade Control
7010A0001	6	Servomechanism - Giromill Blade Control
7010-0002	4	Housing - Cover
7010-0003	5	Housing - Main
7010-0004	2	Gear - Spur
7010-0005	2	Gearshaft, Spur
7010-0006	3	Gearshaft, Spur
7010-0007	1	Gear, Spur
7010-0008	2	Gear Cluster, Helical
7010-0009	2	Gear, Helical
7010-0010	2	Pin, Hollow
7010-0011	2	Cover, Access
7010-0012	1	Cover, Access
7010-0013	1	Cover, Access
7010-0014	1	Plate, Mounting Potentiometer
7010-0015	2	Base, Amplifier
7010-0016	2	Cover, Amplifier
7010-0017	1	Heat Sink, Electrical Electronic Equipment
7010-0018	1	Gasket
7010-0019	1	Spacer
7010-0020	2	Guide - Card
7010-0021	1	Bushing
7010-0022	1	Insulator
7010-0023	2	Motor Assembly
7010-0024	1	Potentiometer Assembly
7010-0025	2	Motor, Direct Current
7010-0026	1	Terminal
7010-0027	2	Diagram, Schematic Electrical
7010-0028	2	Terminal, Electrical
7010-0029	2	Printed Circuit Board Envelope

FIGURE 36
GIROMILL ACTUATOR DRAWINGS

DRAWING NUMBER	REVISION	TITLE
7010-0030	1	Clamp, Loop
7010-0031	2	Diagram, Connections, Interconnect Board
7010-0032	1	Screw, Machine
7010-0033	2	Printed Circuit Board Assembly Amplifier
7010-0034	2	Printed Circuit Board Assembly Driver
7010-0036	1	Bracket, Mounting Capacitor
7010-0037	1	Bracket, Mounting Capacitor
7010-0038	1	Screw, Machine
7010-0039	1	Shield-Electromagnetic Interference
7010-0040	1	Spacer - EMI Shield
7010-0041	1	Potentiometer
7010-0042	1	Shield - Electromagnetic Interference
7010-0043	1	Shield - Electromagnetic Interference
7010-0044	1	Armature Assembly
7010-0045	1	Art Work - Interconnect Board, Back Side
7010-0046	1	Art Work - Interconnect Board, Component Side
7010-0047	1	Interconnect Board Assembly
7010-0048	1	Interconnect Board
6917-0002	3	Schematic, Servo Driver Board
PL 7010-0033-01	3	Parts List - Printed Circuit Board Assembly Amplifier
PL 7010-0034-01	3	Parts List - Printed Circuit Board Assembly Driver
PL 7010A001-01	7	Parts List - Servomechanism - Giromill Blade Control
PL 7010-0047-01	1	Parts List - Interconnect Board Assembly
PL 7010-0023-01	1	Parts List - Motor Assembly
PL 7010-0024-01	1	Parts List Potentiometer Assembly
ATP7010A	1	Acceptance Test Procedure

FIGURE 36 (Continued)
GIROMILL ACTUATOR DRAWINGS

5. UPDATE OF MANUFACTURING COST ESTIMATES

5.1 PROTOTYPE COST ESTIMATES - The preliminary estimates of production costs, itemized in Section 15 of Reference 1, are still valid, except for the support arms. The estimates are for the use of the Giromill as an electric power generator tied into an electric utility grid. The basic ground rules under which the estimates were made and an itemized list of the estimates are shown in Figures 37 and 38. Learning curves applied to direct labor and quantity discounts for vendor items, specified in Reference 1 for various components, remain unchanged.

The prototype cost estimates shown in Figure 38 are higher than for units designed for production. For a prototype design many parts are designed for expediency, i.e., the quickest and least expensive method for one unit rather than for several units in a long production run. For example, the blades were made from formed sheet metal parts, joined by rivets, because this is the least expensive method for a single unit. For long production runs, an extruded leading edge shape would be more economical. The initial tooling cost and long lead time for such a part, however, made it an impractical choice for the prototype design.

5.2 PRODUCTION DESIGN CONSIDERATIONS - The cost of the support arms exceeded original estimates because of difficulties encountered during manufacturing and because the large number of small pieces fabricated and welded on assembly were more labor intensive than anticipated. In a company sponsored effort, several of the more expensive components, including the support arms, are being reviewed for possible cost saving changes to be incorporated into a production design. Several of the proposed cost reducing designs are discussed in the following paragraphs.

Blades - The production version of the blades would have an extruded leading edge section to replace the sheet metal leading edge and spar. The trailing edge would be either injection molded plastic sections or formed aluminum much like the present configuration. Ribs are no longer needed since blade bending is transferred to the support tubes through socket action in the leading edge extrusion.

The blade support tubes were redesigned to utilize standard size pipes and thereby eliminate costly machining operations.

Support Arms - The current design is made from many formed and welded parts. It would be replaced by a standard steel pipe with fittings welded to the root end for attaching to the rotating tower, and to the tip for mounting the blades and actuator. A simple aerodynamic fairing would be welded to the outer one-half of the support arm to reduce drag. The effect on cost estimates of this design on 1000th unit cost is shown in Figure 38.

- ALL COSTS IN 1977 DOLLARS
- COSTS INCLUDE G&A AND PROFIT
- MARKETING AND TRANSPORTATION COSTS NOT INCLUDED
- FOUNDATION AND ERECTION COSTS NOT INCLUDED
- COMMERCIAL STEEL FABRICATORS TO BUILD ENTIRE UNIT
- RDT&E AND TOOLING COSTS NOT INCLUDED
- ROTOR CENTERLINE PLACED TO PROVIDE A 30-FOOT GROUND CLEARANCE
- CUT-OUT WIND VELOCITY IS 40 MPH. ALL OTHER REQUIREMENTS ARE AS SPECIFIED IN REFERENCE 2
- APPROPRIATE LEARNING CURVE APPLIED FOR EACH COMPONENT PART OF GIROMILL

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FIGURE 37
GROUND RULES FOR ESTIMATING COST OF 1,000th UNIT

	1st UNIT	1000th UNIT	1000th UNIT (1)
FIXED TOWER	$ 5,961	$ 3,636	
ROTATING TOWER	11,686	4,006	
SUPPORT ARMS	28,541	9,878	3,980
STREAMLINE RODS	1,556	467	
BLADES	13,693	4,944	
UPPER BEARING	878	263	
LOWER BEARING	1,624	487	
CONTROL SYSTEM	7,039	4,084	
SPEED INCREASER	3,810	1,143	
MAIN DRIVE PULLEY	559	167	
MAIN GENERATOR PULLEY	194	58	
MAIN DRIVE BELT	89	27	
INDUCTION GENERATOR	1,060	318	
ELECTRIC COMPONENTS	369	111	
TOTAL MATERIAL, LABOR, OVERHEAD	$77,059	$29,589	$23,691
G&A (7%)	5,394	2,071	1,658
PROFIT (10%)	8,245	3,166	2,535
TOTAL	$90,698	$34,826	$27,884
DOLLARS/KILOWATT (41.7 kW)	$ 2,175	$ 835	$ 669

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(1) Redesigned support arms

FIGURE 38
GIROMILL BUDGETARY COST ESTIMATE
1977 Dollars

Control System Modifications - In the cost estimate for the controller presented in the Phase I report, it was assumed that a circuit board would replace the wired-up board of the prototype unit. The same assumption was made in the cost estimate of the production version. Additional control modifications would consist of eliminating the batteries and charging alternator for machines tied into the grid. The controller and actuators would use grid power. This means that these would have to be redesigned for grid power. However, analysis shows the changes would not appreciably affect the presently estimated controller and actuator costs.

General Cost Reduction - In addition to the redesign of various components for production, other changes are also being considered. Analysis to date has shown that a two bladed rotor, with the same solidity and RPM as the present rotor, would be more cost effective than the current 3-bladed rotor. Cost is reduced by eliminating two support arms, one blade, and one actuator.

Many of the structural components were designed by stiffness requirements to provide satisfactory vibration, flutter, and structural response characteristics. Because this provided additional margins of safety for structural considerations, the machine could be uprated to a higher capacity output with little or no structural changes. Initial indications are that the rating could be as high as 60 kW in a 23 mph wind. Both cost of energy and cost per kilowatt installed would therefore be decreased.

6. TESTING

The control system, the controller, and actuators, were subjected to a series of bench acceptance tests prior to the installation of the units in the Giromill. The Giromill system was also put through an acceptance test prior to delivery to Rocky Flats.

Testing at Rocky Flats commenced with first turn without the generator connected in July 1980. Development problems and lack of wind delayed first turn with the generator connected to the grid until September. The unit went to unattended operation in November. Over the Thanksgiving holiday, while running unattended, the lightning pole fell, damaging a blade and two support arms. The rotor was removed from the tower and placed on the rotor assembly fixture. The damaged blade and support arms were then removed for repair. Over the Christmas holiday, the assembly fixture stand pulled out of the concrete in a high wind, and the remaining blades and support arms were damaged. The unit was repaired, reassembled, and put back in operation in April 1981.

Development and data collection problems and the inconsistency of the wind have combined to limit the amount of data collected. To date not enough consistent data has been obtained to define the performance of the unit. Also, the mechanical drive system has not yet been tried.

6.1 <u>CONTROL SYSTEM ACCEPTANCE TESTS</u> - Control system acceptance tests were done in two phases. The first phase was acceptance of the controller unit; the second was acceptance of the actuators as they were driven by the controller. Both of these acceptance tests were conducted at MDEC - Grand Rapids Division.

The controller acceptance test procedure was conducted on 10 October 1979. It was conducted per the procedures outlined in MDEC drawing H12G9867. No major discrepancies were found.

The actuator acceptance tests along with integrated controller/actuator tests were conducted on 12 December 1979. The actuator acceptance tests were conducted according to MDEC-GR drawing ATP7010A. No major discrepancies in actuator operation were found from these tests. However, some electronic adjustments were made that smoothed out the actuator running and decreased the power required. The biggest was an electronics revision of the second order rock angle command filter time constants of 0.035 and 0.040 to 0.055 and 0.020. This reduced the actuator power required by half, through elimination of high current spikes.

The controller unit and actuators were shipped to Valley Industries Plant in Tallulah, La., on 19 December 1979.

6.2 GIROMILL SYSTEM ACCEPTANCE TESTS - The Giromill was erected and subjected to a series of acceptance tests at the Valley Industries Plant at Tallulah, La. It was structurally completed and fully erected on 25 February 1980. Control system and instrumentation wiring, alignments, and non-rotor rotating tests of the control system were completed by 27 February. Emergency brake hydraulic problems delayed first start-up until 5 March. The 40 kW generator was not connected to the local utility grid for these tests. Since only a limited amount of testing was going to be done at Tallulah, it was not cost effective to spend the man-hours and money to run a special grid connect line to the unit.

Instrumentation consisted of a 12 channel Honeywell Visicorder, digital RPM indicator, and a wind speed and direction indicator. Basically the three blade rock angle commands, the three blade actuator feedback values, and the two tower accelerometer values were always recorded. Additional parameters were recorded as necessary depending on the test. The vibration sensor cut-off located on the top of the fixed tower was set at 1.0 g.

For first start the control system was configured to give a blade modulation profile corresponding to cam 0 (see Figure 13). This modulation profile will normally limit rotor RPM to about 20 in a 20 MPH wind. The winds were from the NNW at 10-15 MPH. The Giromill ran up to about 15 RPM in 30 seconds. After it ran for about 60 seconds, power to the actuators was cut and the Giromill coasted to a stop. Several similar runs were completed to check the emergency brake system and battery charging alternator. Run 6 was configured to give normal operation and develop full RPM. The Giromill came up to speed and operated exactly as programmed. Full operational RPM was maintained without even having the generator connected.

Approximately 30 additional runs were completed over the next several days to check out the various systems.

From 11 March through 13 March 1980, the Giromill was demonstrated to be in compliance with the checkout requirements. Authority to ship the Giromill to Rocky Flats was received on 13 March 1980.

6.3 OPERATIONAL TEST - The Giromill was erected and functionally checked at Rocky Flats during May and June 1980. First turn without the generator being connected was accomplished on 3 July 1980. Various problems, mostly with the actuators and grid connect electrical system, and lack of wind delayed first turn with grid connect to 15 September 1980.

This section summarizes the problems and corrective actions taken during the tests at Rocky Flats.

6.3.1 Structural

Blade Seals - To prevent an aerodynamic performance loss due to air flow between the blade sections separated by the support arms, blade seals were designed and fabricated. Wipers were installed on the blades that rubbed over the fiberglass support arm fairings. Due to construction tolerances and blade deflections under load, the wiping surfaces were not always perfectly aligned. This caused several of the blade wipers to bind and create high friction. For the prototype Giromill, all blade wipers were removed before beginning operational testing. In addition, blade shims were installed to increase the clearance between blade and fairing (see Section 4.1).

It has been estimated that a performance degradation of 10% could result from not having seals between blade sections. To evaluate the seals' effect, simple temporary seals made from tape should be installed and the performance compared.

Blade Alignment - Self-aligning bearings are used to allow for blade deflections caused by manufacturing tolerances and blade loads. The largest contributor to the possible misalignment of a blade is the deviation of the radial centerlines between the upper and lower support arms. This deviation will cause a blade to be off vertical.

Analyses were performed to establish the allowable tolerance of this deviation by determining the effect of this condition on performance and system dynamics. For centerline deviations causing a one or two degree blade misalignment, no detrimental effects could be calculated. It was therefore decided that the total allowable angular tolerance between support arm centerlines would be arbitrarily specified to lie just within the bearing misalignment capability. Since for all practical purposes, the angular tolerance between the support arm centerlines is dominant, that tolerance should be less than the 1.0 degree bearing misalignment capability.

When the Giromill was assembled, it was visibly noted that Blade 3 was not vertical. Measurement showed it was off by 0.75 degrees, which is within the tolerance specified. However, because of the visible nature of this deviation, production Giromills should attempt to hold the upper and lower support arm centerline tolerance closer.

Battery Charging Alternator Attachment Bracket - The battery charging alternator is mounted on two brackets attached to the speed increaser. Two slots in each bracket allow for alternator drive belt adjustment. These slots are 5/16 inch wide. The bolts through the slots are 1/4 inch. The resultant freeplay allows the alternator to tilt, loosening the belt and causing it to ride on the pulley rim.

A permanent fix is to make the bracket slots 1/4 inch wide. A temporary fix was made by shimming the alternator to prevent it from tilting.

Lightning Rod Structural Failure - A standard 30 foot commercial utility light pole was mounted on top of the rotating tower to provide lightning protection for the blade bearings by providing a 90° (included angle) cone of protection. The pole specification required it be fastened with four 3/4 inch bolts and double washers. When the pole was delivered it was found to contain four 1-1/4 inch holes in the mounting flange. Spacers were made that had a 3/4 hole and fit snugly into the 1-1/4 inch mounting holes. The pole was mounted on top of the rotating tower using 3/4 inch bolts through the spacers, and fastened with one washer and nut per bolt.

As mentioned, while the Giromill was running unattended over the Thanksgiving holiday, the lightning pole came off, damaging one blade and two support arms.

The rotor was removed from the tower and placed on the assembly fixture. The damaged blade and support arms were then removed.

A visual inspection revealed that the nuts had pulled through the washers, allowing the bolts, nuts, and spacers to pass through the holes in the base of the pole and remain with the rotating tower as shown in Figure 39. The washers were partially extruded into the pole base holes, as shown in Figure 40, indicating that the washers failed in shear. In addition, paint was chipped along the weld line attaching the pole tube to the base plate indicating possible high oscillatory loads.

The pole was analyzed as a cantilever beam, fixed at the root by four 3/4 inch bolts. Bending loads on the pole were assumed to be caused by air drag (W) on the pole. Air drag load was calculated by the formula:

$$W = C_d \, q \, S$$

where W = total air drag load on the pole

C_d = drag coefficient for a cylinder conservatively assumed to be 1.2)

q = pressure loading in pounds per square foot

$= V_w^2/295$ (V_w = velocity of wind in knots = $\frac{\text{mph}}{1.15}$)

S = planform area of pole

In order to analyze the failure of the washers, bolt loads were calculated for several wind velocities up to 125 MPH. The bolt pattern at the pole-to-tower interface and a cross-section through an attach bolt is shown in Figure 41. Bolts were assumed to react to the pole root bending moment as a couple between bolts at diagonally opposite corners. Figure 42 lists, for each incremental wind velocity, the total drag load, root bending moment on the pole, and the maximum individual bolt load.

Bending and shear stresses on the washer are plotted versus wind velocity in Figure 43. Stresses were calculated assuming that the washer was divided into six equal segments, each segment being fixed at its intersection with the edge of the nut face. Thickness of the washer used in the analysis was scaled from an actual part. Bending of each segment was caused by an upward force on the washer applied by the pole base as shown in Figure 41.

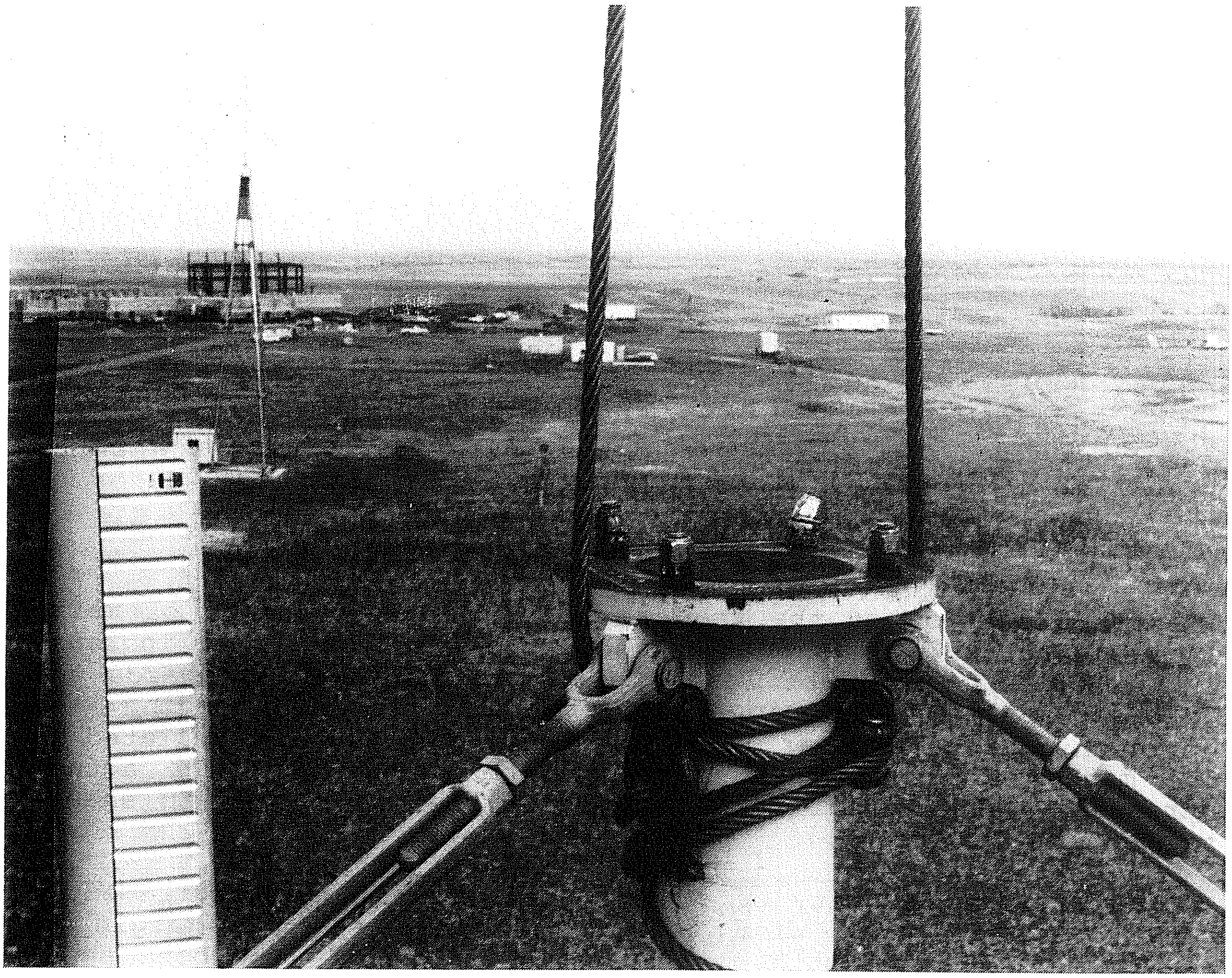

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FIGURE 39
LIGHTNING POLE-TO-ROTATING TOWER INTERFACE JOINT

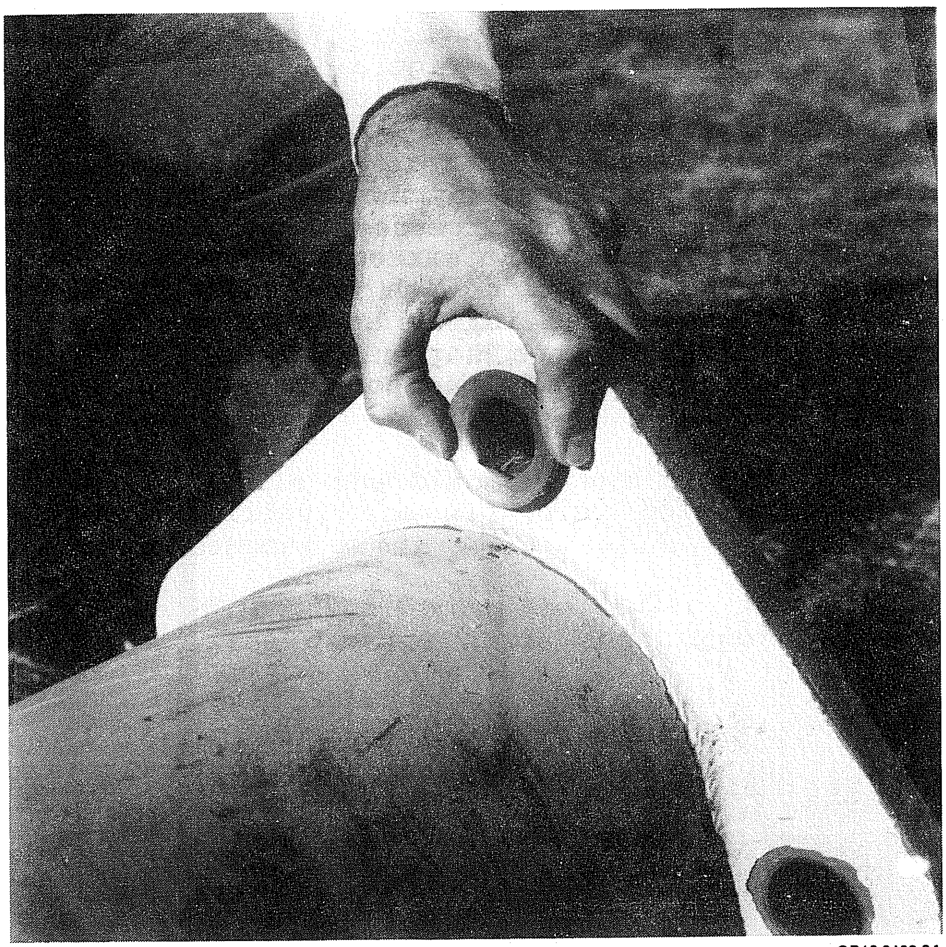

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FIGURE 40
WASHER PARTIALLY EXTRUDED INTO HOLE

The location of the load is based on measurements of markings on the failed washer. As the washer deflects under increasing load, this point of load application would move towards the bolt centerline, reducing the eccentricity for bending and approaching a pure shear loading. Bending stresses calculated in the manner described will therefore be higher than the actual stresses. (The actual failure mode of the washer was in shear, as shown in Figure 40.)

At a wind velocity of 40 mph, the Giromill is programmed to shut down. At this wind velocity, there is ample margin of safety on yield strength, as shown in Figure 42, for both shear and bending. A positive margin of safety exists on yield strengths for bending up to a wind velocity of 60 MPH. A positive margin of safety exists on yield strength for shear stresses up to a wind velocity of 130 MPH.

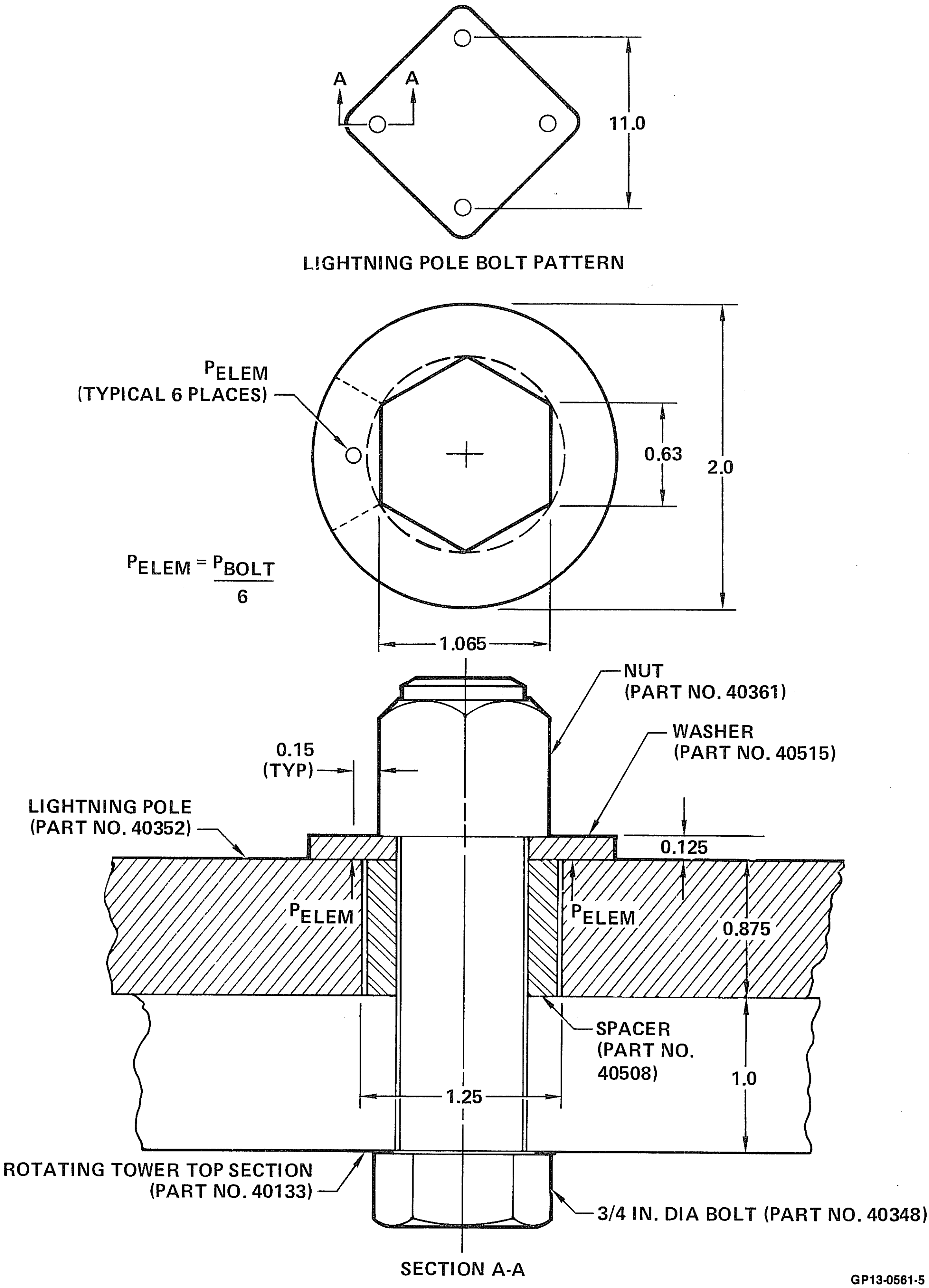

FIGURE 41
LIGHTNING POLE-TO-ROTATING TOWER INTERFACE GEOMETRY

V_{WIND} (MPH)	W (LB)	M_{ROOT} (IN. LB)	P_{BOLT} (LB)
20	18	2,767	252
40	71	11,072	1,007
60	159	24,913	2,265
80	283	44,290	4,026
100	442	69,205	6,291
125	691	108,133	9,830

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FIGURE 42
LIMIT LOADS ON LIGHTNING POLE vs WIND VELOCITY

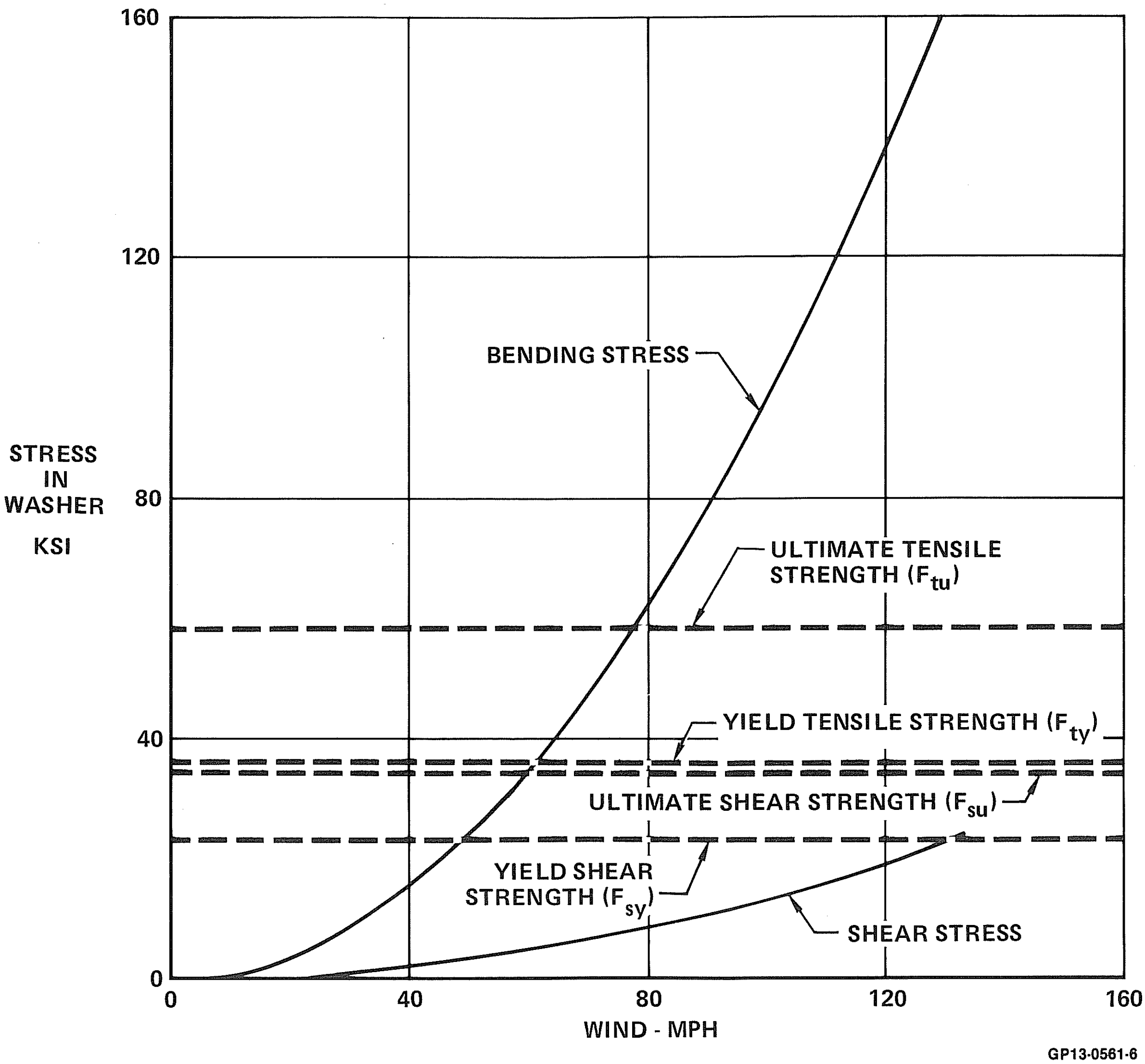

FIGURE 43
WASHER BENDING AND SHEAR STRESS

The location of the pole on the ground after the accident indicated that the attach bolts failed while the Giromill was running. The wind speed at the time of failure was probably 40-45 MPH (possibly 5 MPH over cut-off speed). Since considerable margins of safety exist for the joint at this wind velocity, it is speculated that dynamic forces added to the wind drag loads on the pole to cause failure. These forces could have resulted from a soft spring constant of the joint, from a loose joint at the pole base caused by bending of the washers from previous high wind loads, from spacers too long to allow proper seating of nuts, or from insufficient torque on the nuts.

If the joint at the root was indeed loose or essentially a soft spring, additional forces on the joint could be caused by the rotating motion of the pole in a deflected position.

Based on the preceding analysis and the uncertainty of dynamic loadings in addition to static wind loadings, it was decided to eliminate the need for a lightning arrestor pole. This was accomplished by installing carbon brushes on the upper support arm at the blade support tube. This provides a grounding path for lightning current from the blade through the support arm.

6.3.2 Mechanical

Manual Brake Control - An emergency brake is provided consisting of a caliper acting on a brake disc attached to the rotating tower. The caliper is kept open by hydraulic pressure so that any power loss actuates the brake.

During Giromill checkout it became apparent that many times we wanted to shut the Giromill off without also actuating the brake. Therefore, a manual brake switch was mounted in the contactor enclosure. This switch, when connected to the brake control connector, bypassed normal controller control for the brake and allowed manual control. This device worked very well for the variety of testing that had to be done.

Actuator Pulley Loss - The actuators are connected to the blades by a toothed belt and pulley system. When the Giromill is running, the blade is continually being cycled back and forth by the actuator. This cyclic motion has resulted in the actuator pulleys coming loose and falling off. These pulleys are held on by a taper lock and keyway. The taper lock specification requires torquing the set screws to 175 in-lb while tapping the taper lock. To obtain the torque value is difficult, since the actuator will turn while the screws are being tightened. A strap wrench, that fits around the pulley, was used to hold the actuator while tightening the set screws.

Actuator Belt Slipping - Once during checkout it was noticed that two blades were not correctly aligned, in that a zero rock angle command did not result in the blade being at zero. Checking revealed that the toothed blade actuator belts had slipped several teeth. This was attributed to belt stretch and the inability to tension the belt correctly.

The belt specification indicates that when the belt is first installed it will stretch somewhat, and should be retightened after a few days. This should become a standard operating procedure.

To enable measurement of belt tension a belt access hole was drilled in the support arm, as shown in Figure 44. This hole is located near the belt mid span, and by inserting a 1/4 inch rod through the hole, belt tension and deflection can be measured using a belt tension tester such as is shown on Page 30-55, Reference 3. The force and deflection as measured by the tester should be 10 lbs for 0.44 inches deflection. This should give 500 lb tension in the belt.

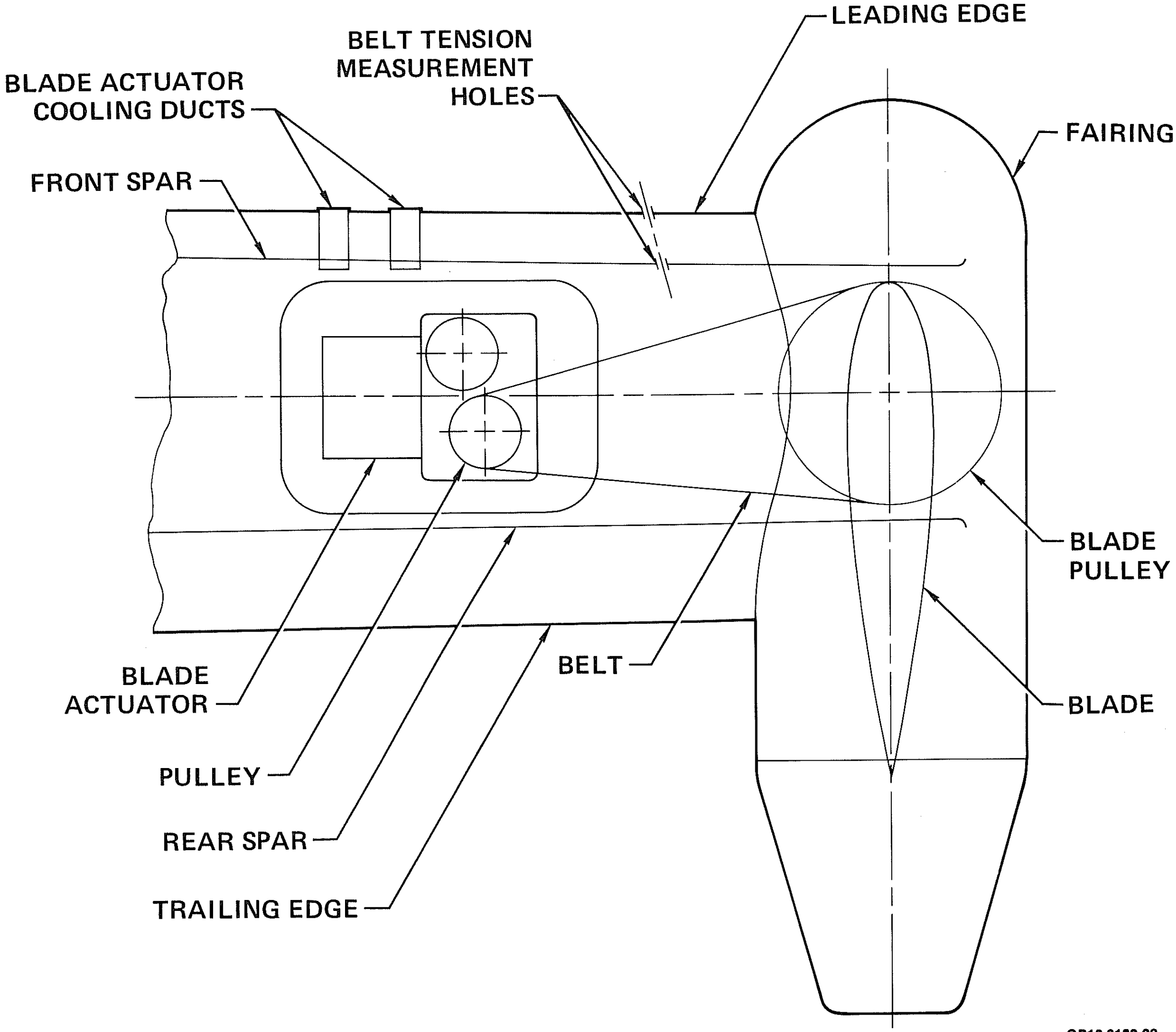

FIGURE 44
BLADE ACTUATOR BELT TENSION MEASURING ACCESS HOLE

6.3.3 Control System

Actuator Gear Box Oil Seepage - On inspection of the parts after they had been shipped to Rocky Flats, one blade actuator showed evidence of leaking oil. Disassembly showed that the oil had leaked past the motor oil seal. All actuators were modified by adding another motor oil seal and providing an external drain hole between the two seals.

After running about one month, oil leakage from the actuators was again noted. This was found to be coming through the gear case mating seal. The g loads at the actuator were sufficient to exude oil through the porous seal. The fix was to install non-porous seals in all actuators.

Inadvertent Controller Shutdowns - The first several weeks of normal running were plagued by a controller command shutdown caused by having the controller/actuator self-check tolerance too tight. This self-check of the controller/actuator electronics is provided to shut down the Giromill immediately whenever an anomaly is detected, preventing a dangerous situation from developing. This is part of the failure detection system programmed in the controller.

The shutdown problem was attributed to the self-check on how well the actual rock angle was following the commanded value. The shutdown occurred whenever a near-zero rock angle was commanded for an appreciable portion of the blade orbit. The checking logic and the tolerances were modified to eliminate this problem. The other failure detection functions worked as planned and on several occasions shut down the Giromill when a failure occurred.

In addition, the controller logic was changed to keep the controller on whenever a no-go shutdown occurred. This allowed diagnostic checks to be run to isolate the particular self-check that had caused the Giromill shutdown.

Also some minor changes in the initial controller turn-on diagnostic were made. These changes resulted in a more orderly computation scheme.

Wind Direction Time Constant Reduction - Initially a filter having a time constant of 500 ms was used in the wind direction controller circuit. This filter caused the rock angle commands to be erratic when the wind was from the direction where the 3° wind direction sensor potentiometer dead band was located. The fix was to essentially eliminate the time constant filter circuit, changing it to a 2.2 ms value. This solved the erratic rock angle commands problem. However, the long term effect on actuator life due to following all rapid wind direction fluctuations will have to be determined.

An alternate way of correcting the erratic rock angle commands would be to install a wind direction sensor having dual potentiometers. No dead zone would therefore exist.

Controller Processor Phase Sequence - Start-up in a low wind was found sometimes to take more than the 120 seconds allocated. Also when coasting down from an overspeed or aborted start, weathervaneing friction was sometimes sufficient to keep the rotor turning about 15 to 16 RPM. This was especially true if the wind was about 9 MPH. To maintain better control of the operation, values of the phase sequences were modified as shown in Figure 45.

PHASE	RPM RANGE	ACTUATOR POWER	GRID CONNECT	NEXT PHASE	CONDITIONS FOR GOING TO NEXT PHASE	TIME LIMIT	SHUTDOWN CONDITIONS
0	–	OFF	NO	1	PROCESSOR POWER TURN ON	–	–
1	–	OFF	NO	2	INITIALIZE COMPLETE AND SELF-TEST GO	–	SELF TEST FAILURE
2	$\omega < 7$ RPM	ON	NO	2A	ROTOR HAS FORWARD ROTATION	120 SEC	TIME LIMIT
2A	$\omega < 7$ RPM	ON	NO	3	FIRST RPM SENSOR FLAG		TIME LIMIT
3	$\omega < 32.95$ RPM	ON	NO	6 4	TIME LIMIT $\omega \geqslant 32.92$ RPM	240 SEC (1)	RPM FROM RPM SENSOR $\neq$ RPM FROM ROTOR ANGLE POT
4	$32.92 \leqslant \omega \leqslant 33.83$	ON	YES	3 5	$\omega < 32.92$ RPM $\omega > 33.83$ RPM	NO LIMIT	RPM SENSOR FLAG PERIOD > 64 MILLISECONDS
5	$33.83 \geqslant \omega \geqslant 32.92$	OFF	YES	6	$\omega < 32.92$ RPM	60 SEC	TIME LIMIT
6	$32.92 > \omega \geqslant 15$ RPM	OFF	NO	3	$\omega < 19.7$ RPM(3)	10 MIN (2)	TIME LIMIT OR PHASE 6 → PHASE 3 LOOP COUNT > 5

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(1) Was 120 sec
(2) Was 60 sec
(3) Was 15 rpm

FIGURE 45
GIROMILL CONTROL SYSTEM - PROCESSOR
Phase Sequence

Control System Power Supply - Two failures of the control system power supply were experienced. The first was diagnosed as a short in the power input circuit. The second was a loss of the 5 vdc output circuit.

Since both of the failures were different, and no evidence of external causes existed, they were attributed to quality control in power supply manufacture. No Giromill changes were made.

Battery Charging Alternator Marginal - Continuous running of the Giromill resulted in a slow discharge of the batteries. It appeared that the brake solenoids and actuators are pulling more power than calculated, and that the alternator output is slightly low. This resulted in a discharge of the batteries and eventual shutdown of the Giromill.

The production fix will be to install a larger alternator for stand-alone Giromill systems, and use a grid driven power supply (eliminate batteries and alternator) system connected to the power grid.

A temporory fix was made to the unit at Rocky Flats by installing battery chargers to supplement the present alternator.

Actuator Power Transistor Failures - Several power transistors, located on a heat sink attached to the actuator amplifier case, failed during the test. Most of these failures were in conjunction with other failures or anomalies. Power transistor failures were evident after an actuator motor had jammed due to a magnet chip breaking off. Another case of power transistor failure was when a motor short occurred, probably caused by pulling on the wires when replacing the actuator gear case gasket. Another occurred on the actuator where the blade belt had slipped three cogs, which could have created large actuator loads.

There were other power transistor failures where no cause was evident. Analysis has indicated that the actuator electronics may be experiencing a low voltage, causing loss of electronic control. Low voltage can occur when the actuator motors draw a high current, causing a large voltage drop through the power slip rings.

The actuators and wiring were modified so as to have a separate power line to the actuator electronics not affected by the motor current variations. This is expected to eliminate the power transistor failures. Verification of this fix has not been completed at this writing.

Premature Overspeed Shutdown - When first running the Giromill with the generator connected to the grid, the controller would sometimes shut down the Giromill, signalling an overspeed condition when none had occurred. Analysis showed that drive train flexibility could cause an occasional overspeed indication. This is because the speed increaser/generator drive sprocket is used to get an RPM indication by relating to the time to count 125 teeth of the sprocket.

The fix was to program that five consecutive indications had to be present to trigger an overspeed shutdown. Since an RPM measurement is obtained every 0.058 second (at synchronous RPM), this means a delay of only 0.24 second in initiating a shutdown in event of an actual overspeed. During this time the rotor RPM would increase 0.3 RPM, calculated assuming the existence of maximum rotor torque and no generator load. This much increase does not create a critical situation.

6.3.4 Electric Generation

Grid Connect Relay Chatter - During first attempts to connect the generator to the grid, a grid connect relay chatter occurred. This in turn caused the controller to sense an error signal, shutting off the Giromill. The chatter was attributed to the sensitivity of the RPM measurement and the fact that there was no RPM tolerance between grid connect and disconnect.

A temporary fix was to install a time delay relay which prevented grid disconnect for 1.5 seconds after disconnect command. The final fix was to essentially incorporate that time delay in the controller program. This solved the grid connect relay chatter, but does allow the generator to drive the rotor for that short time.

Generator Circuit Breaker Tripping - At times the grid connect contactor heaters will trip. This causes power to drop off line. It occurs when the wind is marginal and the generator is being cut in and out intermittently. The power surges due to inrush currents eventually trip the heater.

This problem was corrected by installing slightly larger heaters and setting them to reset automatically after a three minute cooling period.

6.4 PERFORMANCE - The Giromill has been operated successfully by producing full power and feeding it into the utility grid. Blade modulation, the key to the Giromill concept, has worked as planned. A constant rotor RPM is maintainable even in a gusty wind with or without the generator connected to the utility grid. However, only a limited amount of performance data has been collected due to a variety of events. The damage due to the lightning rod failure and ensuing repair time consumed the greater portion of the windy season at Rocky Flats. Other data was lost when the grid connect heaters tripped and the Giromill ran unconnected to the grid. Still other times the data collection system was down when the Giromill was running.

The data collected is plotted in Figure 46. This is binsed data of several hours of continuous running. The data were corrected to sea level conditions.

The data indicate that the prototype performance is lower than predicted. This reduction of performance is related to the increase in rotor drag due to: (1) The blade seals not installed which effectively decrease blade aspect ratio increasing induced drag (see Section 6.3.1), (2) One-half inch wide gaps existing between the support arms and blade fairings due to manufacturing deviations (see Section 4.1), and (3) The blade fairings are not streamlined to account for the flow angularity changes around the blade orbit. They should be shaped disk-like rather than rectangular to prevent blade/support arm juncture interference drag.

Correcting these design deficiencies should raise the performance to near the predicted level.

An attractive alternate method of running the Giromill was demonstrated. The control system was temporarily configured to hold the blades at a rock angle of zero when the RPM reached synchronous speed. This essentially converted the Giromill to run in the Darrieus mode after it had started using the normal Giromill blade modulation. The unit ran very smoothly in the Darrieus mode. Unfortunately the data acquisition system was not operating at the time (had been hit by lightning), so performance in this mode is not available at this time. Further testing in this mode is recommended to explore its possible advantages.

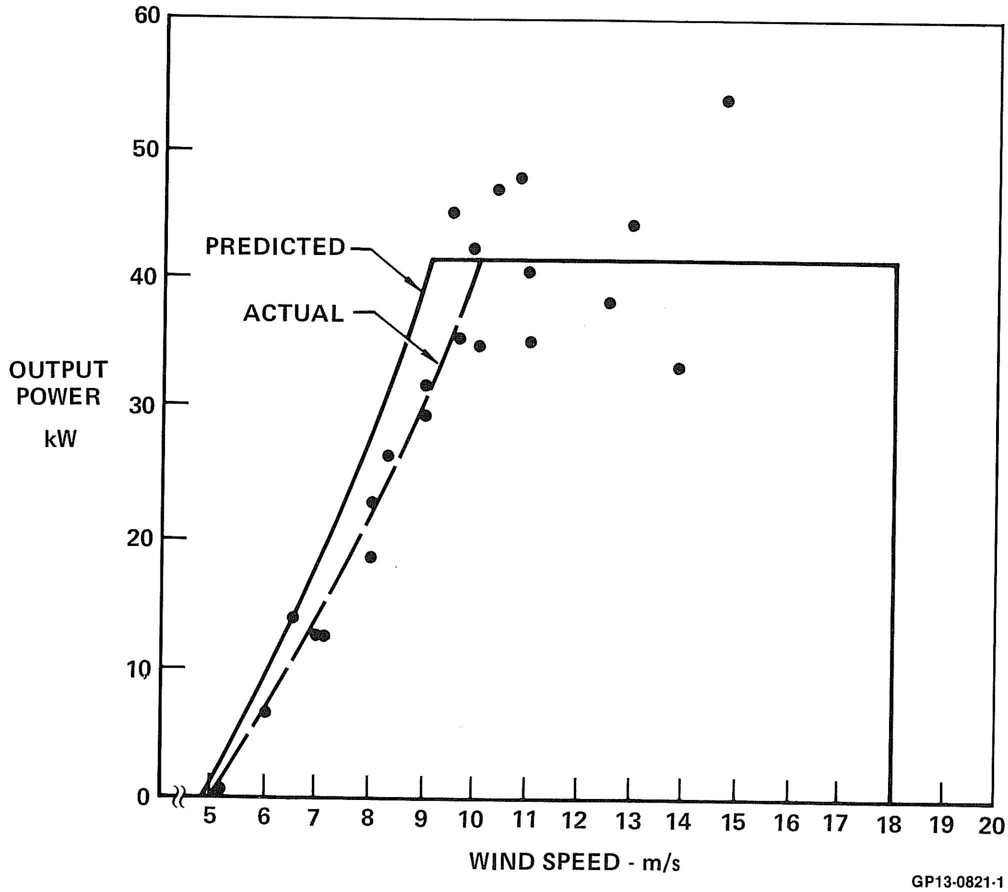

FIGURE 46
GIROMILL PERFORMANCE
Rocky Flats Binsed Data Corrected to Sea Level

7. CONCLUSIONS & RECOMMENDATIONS

7.1 CONCLUSIONS

- A prototype 40 kW Giromill was designed, constructed, and operated successfully by generating 40 kW or more power for a utility grid.
- The Giromill blade modulation scheme works as planned. It is able to maintain a constant rotor RPM in a gusty wind with or without the generator connected to the utility grid.
- The unit runs smoothly. Very little vibration is evident during normal operation under all wind conditions.
- The Giromill has operated as expected, however, performance is lower than predicted due to poor design and fabrication of the blade/support arm fairings.
- Satisfactory blade actuator reliability has not been achieved.
- Controller-commanded shutdown due to failure detection was successfully demonstrated.
- Aerodynamic blade noise is minimal. The loudest noise while running comes from the generator drive belt.
- The fixed blade (Darrieus) mode has been successfully demonstrated. This hybrid operation has advantages that should be explored.
- Mechanical drive remains to be tested.
- No problems have been encountered which might preclude the future development of the Giromill concept.

7.2 RECOMMENDATIONS

On the basis of the tests conducted to date, the following recommendations for further testing or follow-on effort are made.

- Extensive testing using the fixed blade mode should be conducted. The advantages of reduced blade actuator duty cycle, and possible blade positioning to control power output should be investigated.
- The noisy generator drive belt should be replaced by a direct gear drive making the machine very quiet.

7. CONCLUSIONS & RECOMMENDATIONS (Continued)

- More and better instrumentation should be installed to verify theoretical analyses of the system structure and dynamics.
- The blade actuators reliability should be increased.
- Uprating present 40 kW unit to approximately 60 kW should be investigated.
- A two-bladed unit should be investigated.

8. REFERENCES

1. Anderson, J. W., et al, "Development of a 40 kW Giromill, Phase I," Volume II - Design and Analysis, DOE Report RFP-3032/64100/3533/79-17-2, August 1979.

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