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FABRICATION AND ASSEMBLY OF THE ERDA/NASA 100-KILOWATT EXPERIMENTAL WIND TURBINE

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16. Abstract

As part of the Energy Research and Development Administration (ERDA) wind-energy program, NASA Lewis Research Center has designed and built an experimental 100-kW wind turbine at Sandusky, Ohio. The two-bladed turbine drives a synchronous alternator that generates its maximum output of 100 kW of electrical power in a 29-km/hr (18-mph) wind. The design and assembly of the wind turbine were performed at Lewis from components that were procured from industry. The machine was installed atop the tower on September 3, 1975.

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SUMMARY

Recent shortages in the supply of clean energy coupled with increasing costs of fuel have resulted in a national wind energy program under the direction of the Energy Research and Development Administration (ERDA). The program will determine the practicality of wind turbine generators. As part of this program, the NASA Lewis Research Center was assigned the responsibility of designing, fabricating, and installing a 100-kilowatt wind turbine at its Plum Brook Facility in Sandusky, Ohio. The entire effort was completed in 18 months.

The wind turbine consists of a two-bladed rotor turbine, a drive train assembly, a power unit structure, and a tower. The rotor turbine operates at 40 rpm; a gearbox increases the rotor speed to an alternator speed of 1800 rpm. The turbine generates 100 kilowatts of electrical power at a wind speed of 29 kilometers per hour (18 mph). The wind turbine weighs 18 140 kilograms (40 000 lb) and on the tower is 30. 84 meters (100 ft) above the ground.

Most of the wind turbine components were procured from private industry. Component and subassembly testing were conducted at various steps in the first-stage assembly process at Lewis. The second stage of the assembly and checkout were conducted at Plum Brook on a service stand at the base of the tower.

The wind turbine was placed on top of the 30. 48-meter (100-ft) tower on September 3, 1975. The first major power to be generated was 80 kilowatts at a rotor speed of 30 rpm on October 23, 1975. The design power output (100 kW) at design speed (40 rpm) was first achieved on December 19, 1975.

INTRODUCTION

Recent shortages in the supply of clean energy, coupled with increasing costs of fuel, have forced the nation to reassess all forms of energy, including wind power, to determine their practicality. The national wind energy program, which originated at the National Science Foundation and is now directed by the Energy Research and Development Administration (ERDA), includes research and development on the many applications and concepts of wind-energy systems.

As a part of this program, which emphasized large, horizontal axis machines (ref. 1), Lewis was assigned the responsibility of designing and constructing a wind turbine generator large enough to assess the technological requirements and engineering problems of large wind turbine generators yet small enough to enable us to use, where possible, catalog components, thereby keeping the cost of the program down. To meet these requirements, Lewis designed and constructed a 100-kilowatt wind turbine at their Plum Brook Facility in Sandusky, Ohio. The entire project, from start to final assembly, was accomplished in 18 months. This report describes that activity.

The design and assembly of the wind turbine was conducted at Lewis with the fabrication of major parts and the final assembly performed by private industries. Typical examples of major components that were made to our specifications by private companies are the metal blades, obtained from the Lockheed Company of Burbank, California, and the tower, obtained from the Norris Brothers of Cleveland, Ohio. Other major components, such as the gearbox, generator, and main bearings required no special design or manufacture and were purchased from various industry catalogues.

All parts with the exception of the tower were delivered to Lewis and assembled into larger components. These components were then tested before their integration into the next assembly stage. Major assemblies such as the rotor, transmission train, housing, and tower were then delivered to the Plum Brook site. Assembly of the wind turbine was performed on a service stand at the base of the tower, which simulated the upper tower interface. Final assembly was performed by a 59 968-kilogram (65-ton) crane which lifted the entire machine (including blades, drive transmission, and yaw system) and placed it on top of the tower.

This report describes the wind turbine, the fabrication of the major components, and the assembly of these components. The report concludes with a description of the final lift and the installation of the wind turbine on the tower.

WIND TURBINE DESCRIPTION

The design of the 100-kilowatt wind turbine, including the preparation of all necessary drawings, was performed by Lewis. Details of the design have been described in three previously published reports (refs. 1 to 3). The wind turbine consists of the rotor turbine, drive train assembly, bed plate, yaw assembly, and tower (figs. 1 and 2). The rotor turbine operates at 40 rpm, generating 100 kilowatts of electrical power in a 29-kilometer-per-hour (18-mph) wind. The hub and blades are connected to a low-speed shaft (40 rpm), which drives a gearbox. In the gearbox the shaft speed is increased from 40 rpm to 1800 rpm. A high-speed shaft connects the gearbox to the 100-kilowatt alternator. This entire assembly, weighing 18 140 kilograms (40 000 lb), is located on top of a 30.48-meter (100-ft) tower.

Blades. - The rotor uses two metal blades, each 19.05 meters (62.5 ft) long and weighing 907.2 kilograms (2000 lb) (fig. 3). The blades are designed to provide 133 kilowatts of power in a 11.2-kilometer-per-hour (18-mph) wind when rotating at 40 rpm. They have an NACA 23 000 airfoil and are tapered with a 34° nonlinear twist.

Hub. - The hub connects the blade to the low-speed shaft. It also houses the mechanical gears, blade holders, and bearings for pitch changing the blades (fig. 4). The hub is of the fixed type; that is, it is bolted rigidly onto the main low-speed shaft with the blade fixed to the hub and allowing only the pitch change degree of freedom.

Pitch-change assembly. - The pitch change assembly consists of a hydraulic pump, a pressure control valve, an actuator, and gears for the rotational movement of the blades. The torque to change the blade pitch is provided by a rack and pinion actuator that turns a master gear, which in turn rotates the blades through bevel gears bolted to the blade spindle. The hydraulic pump is mounted separately on the structure, and the hydraulic fluid brought into the into the shaft by way of a rotating seal (fig. 2).

Transmission train assembly. - The torque is transmitted from the hub to the alternator through a 45:1 ratio gearbox (fig. 2). The hub transmits the high torque and low speed to the gearbox by means of a large, low-speed shaft. Out of the gearbox a high-speed shaft transmits the low torque and high-speed to the alternator through a belt and pulley drive. The entire assembly is supported on a bed-plate and enclosed in a fiberglass cylinder housing for protection.

Yaw assembly. - The yaw assembly consists of a large gear bearing assembly that is capable of rotating (yawing) the entire machine on top of the tower. The yaw rate is 1/6 rpm and is operational even when the machine is not generating power. Figure 2 shows the yaw assembly with the machine mounted on it.

Tower. - The tower is 30.48 meters (100 ft) tall constructed of steel with both pinned and welded joints and is anchored to a tension pile concrete foundation (fig. 5). The weight of the tower is 18 140 kilograms (44 000 lb) without the ladders and platforms and 25 401 kilogram (56 000 lb) with these accessories.

Controls. - The wind turbine will generate approximately 100 kilowatts of power at wind velocities of 29 kilometers per hour (18 mph) and greater. Between 12.9 and 29 kilometers per hour (8 and 18 mph) the electrical power is generated as a function of the wind velocity (fig. 6). At wind above 29 kilometers per hour (18 mph), the rotor blades increase pitch, thus spilling the wind and insuring that the power developed does not exceed 100 kilowatts. Below 12.9 and above 64 kilometers per hour (below 8 and above 40 mph) the turbine blades are placed in a feather position, and the machine is shut down. The rotor is maintained at a constant 40 rpm with rotor speed as the feedback control signal (fig. 7).

FABRICATION AND PROCUREMENT OF COMPONENTS

Most of the parts that made up the 100-kilowatt wind turbine were procured from industry. The following sections describe the major catalog or noncatalog parts.

Noncatalog Components

Most of the rotor assembly was unavailable as a catalog purchase. This included the two blades, hub, blade holders and the pitch change gears. The blades (fig. 3) were made to Lewis specifications by the Lockheed Company of Burbank, California. Three blades were purchased (one spare) along with a design task to perform structural static and dynamic analyses (ref. 4). The blades were delivered to Cleveland in a trailer designed and built for the specific purpose of transporting the blades over this long distance (fig. 8).

The blades are attached to the hub through a blade spindle and blade holder (fig. 4). The forging for a blade spindle is shown in figure 9(a). To meet the program schedule, a solid billet rather than a pierced billet was procured. The blade holder forgings are shown in figure 10(a). They too were solid rather than pierced billets. Figures 9(b) and 10(b) show the blade spindle and blade holder after machining.

The hub was the largest component of the rotor to be machined. It was procured as a solid billet (to meet schedule requirements) and machined. Figure 11(a) shows the solid billet, and figure 11(b) shows the billet after machining. Using a forging was preferred over a welded structure as most of the welds would have occurred in high stress areas. Other large components for which forgings were purchased and furnished to a contractor for machining were the pitch change gears and the main shaft forgings. The gear blanks are shown in figure 12, and the main shaft forging before and after machining is shown in figure 13.

Two large fabricated structures were procured as noncatalog components. They are the tower and yaw cone. The tower was designed by Lewis and fabricated by Norris Brothers of Cleveland, Ohio. It was delivered to Plum Brook in two sections (fig. 14).

The first (lower) section was installed on the concrete foundation. A crane placed the top section on the four legs of the lower section, and the two sections were then welded together. The lower portion of the tower has all pinned joints, and the upper portion has welded joints.

The cone (fig. 15), which provides the yaw capability of the machine is a welded structure of rolled plates. Its upper face interfaces with the yaw gear, and the lower face interfaces with the top of the tower. At this interface care was taken during design to insure that the bolt circle of the cone matched the bolt circle of the tower.

Two more components of welded structure were the bedplate and service stand (figs. 16 and 17). The bedplate supports the entire machine on top of the tower. The alinement of the drive train is dependent on this structure and is thus considered a key component in the overall assembly of the wind turbine. The service stand was used for both subassembly procedures and for testing the machine at Cleveland and at the site at the base of the tower.

Catalog Components

The policy established early in the program was to use catalogue components wherever possible. Naturally, all of the fastening hardware met this requirement, but larger components such as the gearbox, generator, yaw gear and drive, blade bearings, mainshaft bearings, rotary actuator, and slip rings were also purchased directly from the manufacturers with no major modifications. These components are shown in figure 18.

WIND TURBINE ASSEMBLY

All wind turbine parts, except the tower, were delivered to Lewis for first-stage assembly. Figure 19 traces the flow of components through the two main assembly areas at Lewis: the test cell, where the drive train and yaw system were assembled and tested, and the aircraft hangar, where the blades and hub were assembled and where the large subassemblies were tested.

After the first-stage assembly and testing were completed, the wind turbine subassemblies were transferred to Plum Brook for the second stage. The flow chart in figure 20 traces the activities in the control room, tower, and service stand areas. The Plum Brook Facility contains over 32 square kilometers (8000 acres) of land with large open areas. Plum Brook has a clear view of the south-southwest prevailing winds in the summer and the north-northwest winds in the winter and is secure from trespassers and vandalism. A building located some 182.9 meters (600 ft) from the wind turbine site was adapted for the control room. Other structures at the site include a 61-meter (200-ft) meterological tower and a 4100-watt Aerowatt wind turbine (fig. 21).

First-Stage Assembly

The drive train components (minus the hub and blades) and the yaw components were assembled in one of the many large test cells at Lewis. After assembly the drive train was tested at the 40-rpm rotor speed (low-speed shaft) and 0- to 100-electrical-kilowatt load with a dynamometer driving the main, low-speed shaft where the hub would be mounted (fig. 22). The yaw assembly was tested in its normal operating mode using the yaw drive motors.

Drive train. - The parts of the drive train include the bedplate, gearbox, main shaft, alternator, pulleys, high-speed shaft, brake, and hydraulic pump. A no-load run-in test of the gearbox (fig. 23) was performed by its manufacturer before it was delivered to Lewis.

The bedplate was mounted directly on the floor of the cell and alined with the dynamometer. The gearbox, alternator, shafts, etc., were then attached to the bedplate and alined. The alternator was connected to the load bank, and the main shaft was coupled to the dynamometer-gearbox drive.

The hydraulic pump (fig. 24(a)) and its associated valves, piping, cooling fans, etc., were first given a 10-hour inspection test in the Lewis hydraulic laboratory. The pump was then moved to the test cell and installed on the bedplate (fig. 24(b)). No further testing was conducted on the pump because the hub and pitch change system, which includes the hydraulic pump, were to be tested later.

Yaw. - A service stand, which simulates the upper portion of the tower, was used as the fixture for the assembly of the yaw component. The large bull gear, drive shaft, gearbox, and motors were assembled and alined (fig. 25). The system was operated through the yaw controller (the electrical system that senses wind direction and operates the yaw motors to aline the machine with the wind) for 24 hours. This assembly, including the service stand, was then moved to the hangar.

Blade inspection. - Upon delivery the blades were dimensionally inspected. A blade holding fixture was used to support the blades in a cantilever postion to facilitate the inspection. The blades were then fitted to the spindle of the hub (fig. 26), and the coning and blade angles were checked to determine whether both blades would track the same when installed on the tower.

Blade and hub. - The pitch change gears, hydraulic actuator, and hub were assembled in the Lewis machine shop (fig. 27). A preliminary check was made of the assembly by applying an auxilliary hydraulic supply to the actuator. The system was then transferred to the hangar where the blades were pinned and bolted to the hub spindles. (See Blade inspection section.) The entire assembly was then operated, again with the auxilliary hydraulic supply, to check the operation of the pitch change gears with the blades mounted (fig. 28).

Housing. - The service stand (with the yaw assembly) were mounted to the floor of the hangar. The transmission train was then mounted to the yaw bull gear (fig. 29). The hub, including the pitch change actuator (but not the blades), was attached to the main shaft. The fiberglass housing was then fitted to the wind turbine assembly. (See fig. 30.)

Miscellaneous assembly and testing. - The end of the first-stage assembly provided an opportunity for conducting tests and adding brackets, wiring, and the plumbing of some of the systems. At this time the hub and pitch change system was tested. Also conducted at this stage was the blade pitch change inertia test. Dummy weights, which simulated the pitch change inertia of the blades, were mounted on each blade spindle where the blades are normally attached (fig. 31). The complete hydraulic pitch change system including the pump, plumbing, and actuator were operated using the dummy weights for blade inertia simulation. This test was the first operation of the complete hydraulic system.

Second-Stage Assembly

After all the assembly and testing were completed at Lewis, the machine was partially disassembled and delivered to the Plum Brook site as major subassemblies. These were the blades, the transmission train, the hub and pitch change gears, and the yaw and service-stand assembly. Other equipment such as the load bank, control panels, switch gear, and the PDP-8 computer for data acquisition were already at the site. As shown in figure 20, there were three major areas where second-stage assembly was conducted: the control room, the tower, and the service stand. The following is a description of the activities in these areas.

Tower. - The tower was delivered to the site in two sections (fig. 14) and assembled with a crane. Wiring terminations and the installation of a 450-kilogram (1/2 ton) lift were then performed to complete the major part of the installation.

After the service stand was delivered to the site, the yaw assembly, including the yaw cone, were removed from the service stand and lifted to the top of the 30.48-meter (100-ft) tower to check the bolt patterns and shaft alinements on the yaw drive shaft. This procedure avoided later problems when the entire machine including the yaw cone would be installed on top of the tower.

Service stand. - A foundation for the service stand was provided at the base of the tower. This fixture became a permanent installation at the site and will be used each time the wind turbine assembly is removed from the top of the tower (fig. 32).

After securing the stand to the foundation, the same electrical circuits that are provided at the top of the tower were wired to the assembly stand. The transmission train, hub and pitch change gears and housings were then assembled to the stand. All instrumentation was completed on the wind turbine including the installation of the multiplexers which are part of the data acquisition system.

The major test of the wind turbine on the assembly stand was the motoring of the transmission. Provisions had been made to allow operating the alternator as a motor to drive the transmission. This capability was used to repeat some of the tests conducted earlier, resulting in a final checkout of the system. It also was the first time the hydraulic system had been operated with the shaft rotating (thus checking the rotary seal). The final assembly step was to attach the blades to the hub and yaw the wind turbine (without rotation of the shaft) as a final test.

Control room. - The main electrical switch gear for the load banks, rpm controller for the rotor speed, and data acquisition equipment were installed in the control room (fig. 33). Duplicate cables were installed from the tower and assembly stand to the control room.

Final Assembly

On completion of the assembly of the wind turbine, preparations were initiated for lifting the entire wind turbine to the top of the 30.48-meter (100-ft) tower. A crane with a 54.7-meter (150-ft) long boom and a lifting capacity of 58 950 kilograms (65 tons), without the boom, and a crew of eight men were contracted for the lift. A spreader bar and cable had been designed, fabricated, and proof loaded by Lewis to twice the lifting weight (36 290 kg (80 000 lb)) for lifting the assembly. Four lifting lugs had been designed into the bedplate for the attachment points. Panels in the fiberglass housing were removed to allow cable access to the lifting lugs. Some adjustments had to be made in the transmission train for clearance of the cables.

Prelift. - All terminations for the electrical and control signal slip rings had been made through connectors. The assembly stand duplicated the top of the 30.48-meter (100-ft) tower, requiring only a reconnection at the top of the tower with identical connectors. The yaw drive-motor-gear box and drive shaft were installed on the 30.48-meter (100-ft) tower before the installation.

The cabling was then secured and the bolts removed at the yaw-cone - assembly-stand interface. Some care was taken to adjust the spreader bar cable lengths so that the center of gravity of the assembly when lifted was correct to maintain the machine in a horizontal position. The blades were feathered and the brake activated.

Lift. - The weather forecast had been monitored for two days before the day of the lift. It was desired that the winds not exceed 16 kilometers per hour (10 mph). Thus, the lift operation was scheduled for shortly after daybreak when the winds were the lowest. The actual lift was performed at midmorning with the winds still less than 8 kilometer per hour (5 mph) at the 27.4-meter (90-ft) level. Approximately 12 men on six tag lines steadied the machine as it was lifted from the assembly stand to the top of the tower (fig. 34). The brake was activated throughout the lift to prevent any rotation of the blades. The entire lift operation ran smoothly.

Postlift. - After the machine was placed on the tower, the yaw drive was assembled, the cabling was connected, and the yaw-cone - tower interface bolts were torqued. The electrical circuits were debugged and the yaw system made operational. The machine was not rotated that day because of the need for further debugging of data systems. The yaw system remained active, that is, the machine automatically oriented itself to the wind direction.

CONCLUDING REMARKS

A 100-kilowatt wind turbine has been designed, fabricated, and assembled. This wind turbine has a horizontal-axis, 38.1-meter (125-ft) diameter rotor with two blades, each weighting 907 kilograms (2000 lb). The rotor drives a 100-kilowatt synchronous alternator through a stepup gearbox. The assembly is installed on a 30.48-meter (100-ft) tower. The design and assembly was accomplished in an 18-month period. The fabrication of the major components was done by various private companies under contract to Lewis.

The components were delivered to Lewis where they were assembled into subassemblies. The second stage of the assembly was conducted on a service stand at the base of the tower at Plum Brook. For the final stage a 58 968-kilogram (65-ton) capacity crane lifted the wind turbine to the top of the tower. The lift and installation procedure was carried out with no problems. First major power generated was 80 kilowatts at a rotor speed of 30 rpm on October 23, 1975. Full design power of 100 kilowatts at 40 rpm was generated on December 19, 1975, in an 29 kilometer-per-hour (18-mph) wind.

Operation milestones - The following are the dates of the major milestones that have been achieved to date in the operation of the 100-kilowatt wind turbine.

September 3, 1975 - Installation of the wind turbine on the tower

September 6, 1975 - First startup and rotation of the rotor to 10 rpm with no electrical power generated.

October 23, 1975 - Rotation of rotor to 30 rpm with 80 kilowatts of electrical power generated

December 19, 1975 - Design operation at 40 rpm with 100 kilowatts of electrical power generated.

Lewis Research Center,
National Aernautics and Space Administration,
Cleveland, Ohio, March 8, 1976,
778-24.

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Figure 1. - ERDA-NASA 100-kilowatt experimental wind turbine.

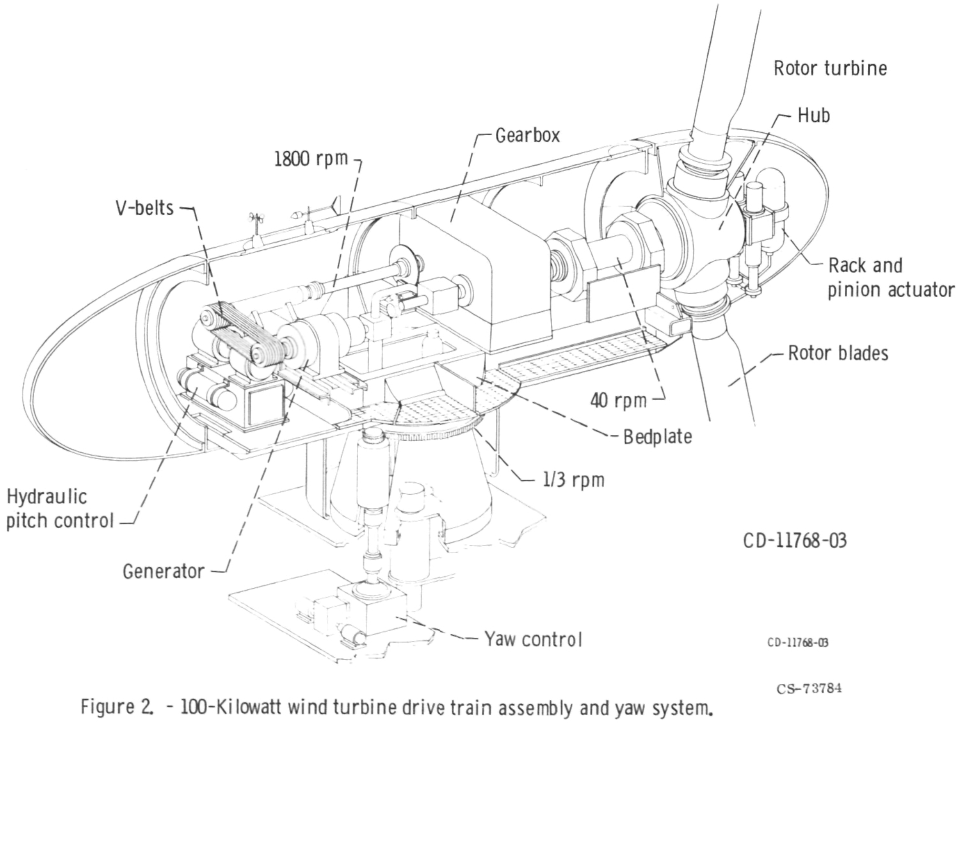


Figure 2. - 100-Kilowatt wind turbine drive train assembly and yaw system.

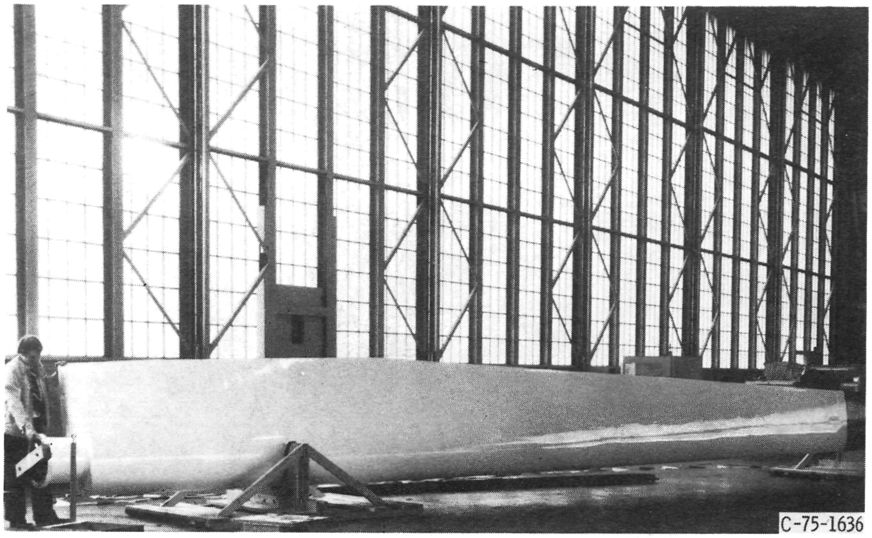


Figure 3. - Metal blades.

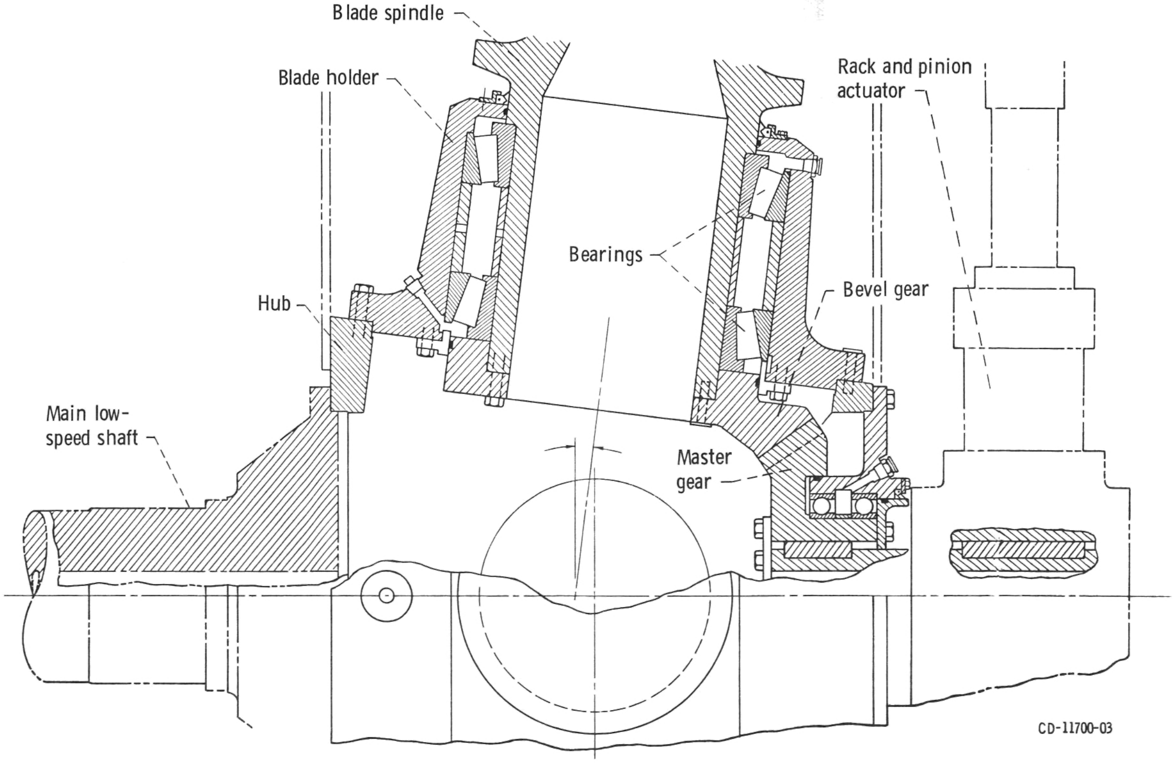


Figure 4. - Schematic of hub and pitch change assembly - fixed hub.

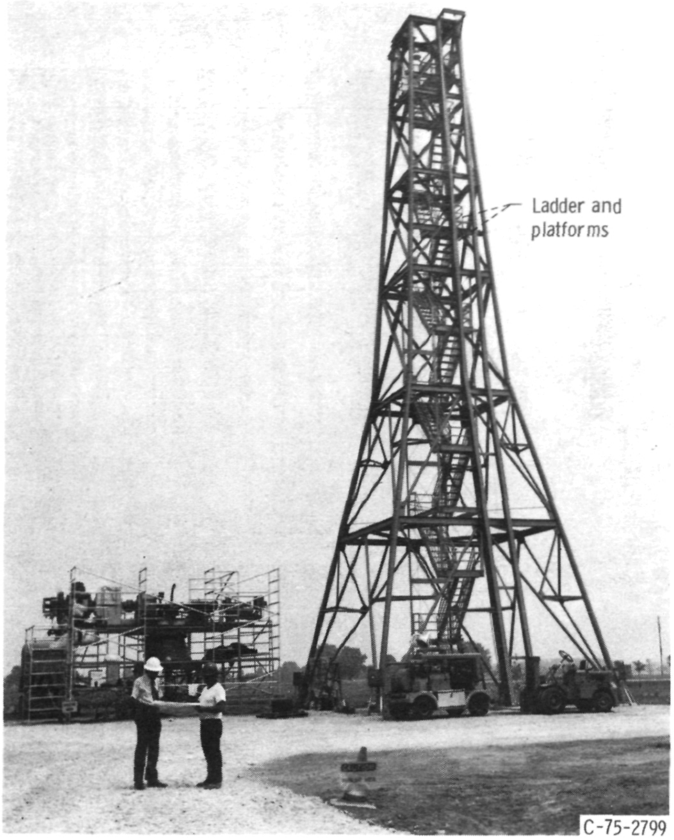


Figure 5. - 100-Kilowatt experimental wind turbine tower.

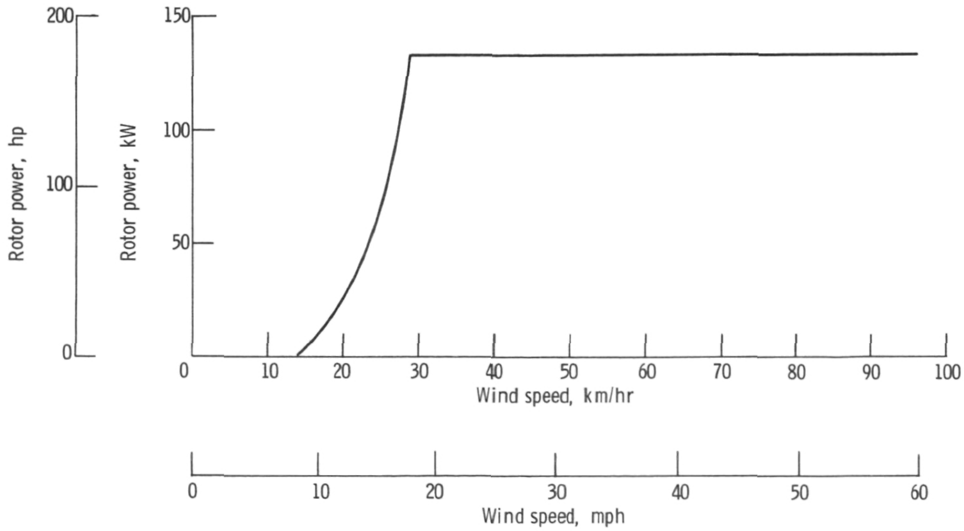


Figure 6. - Rotor power as function of wind velocity.

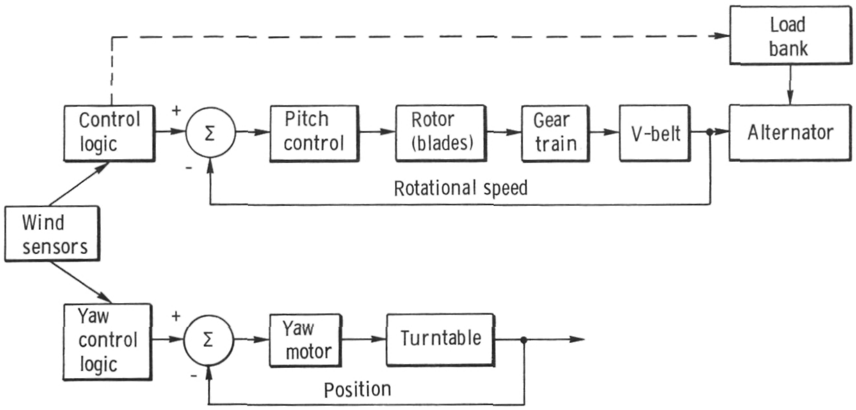
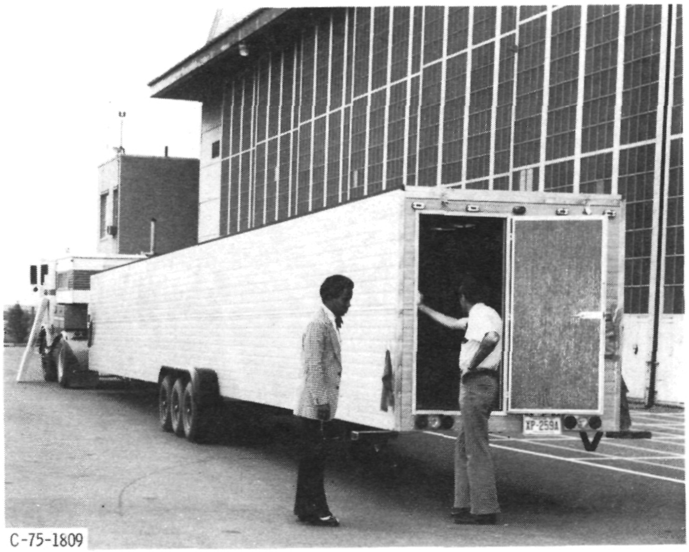
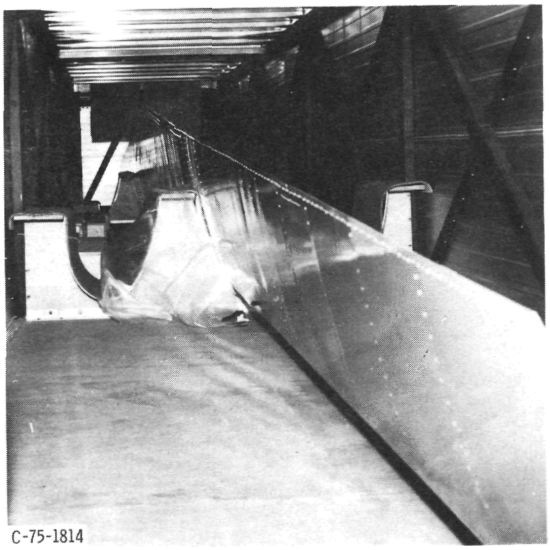


Figure 7. - Asynchronous (off-net) operation control block diagram.

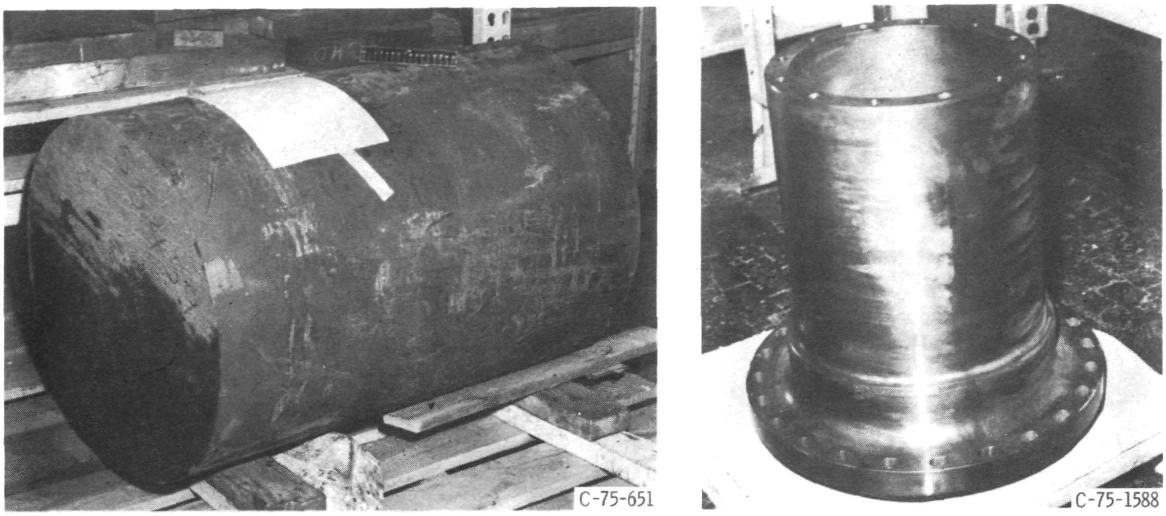


(a) Exterior.



(b) Interior.

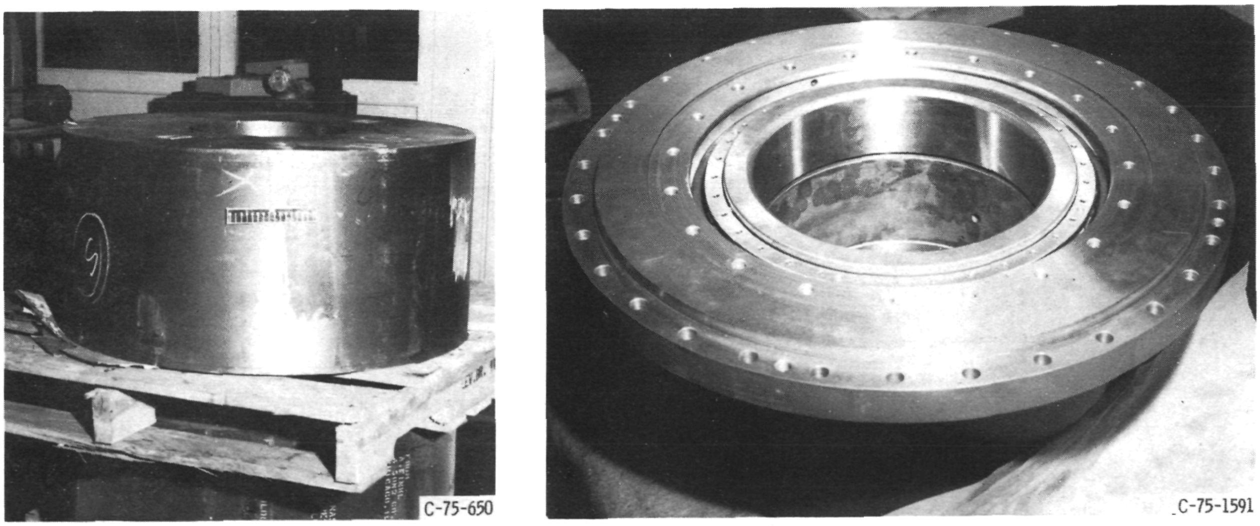
Figure 8. - Blade trailer.



(a) Forging.

(b) Machined.

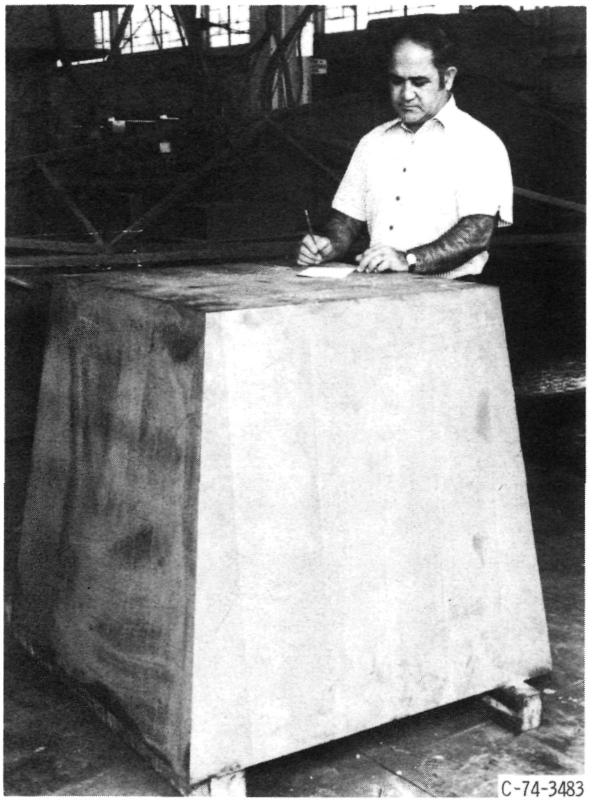
Figure 9. - Blade spindle.

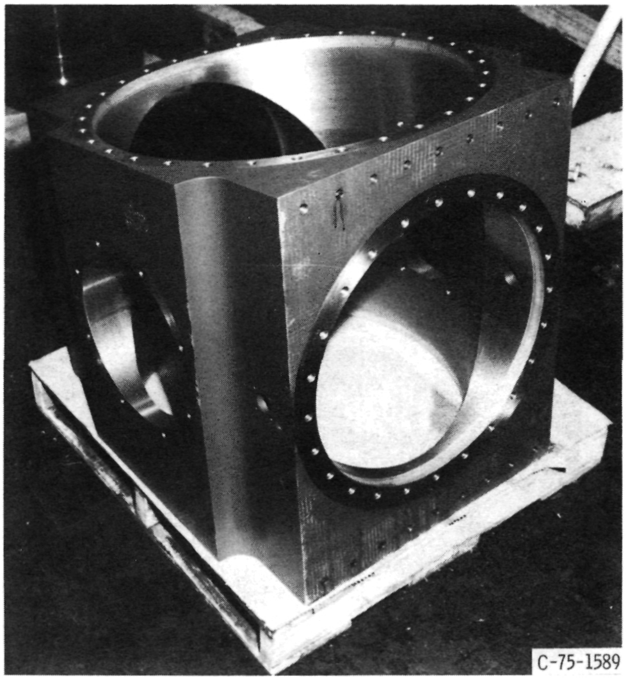


(a) Forging.

(b) Machined.

Figure 10. - Blade holder.





(a) Forging.

(b) Machined.

Figure 11. Main hub.

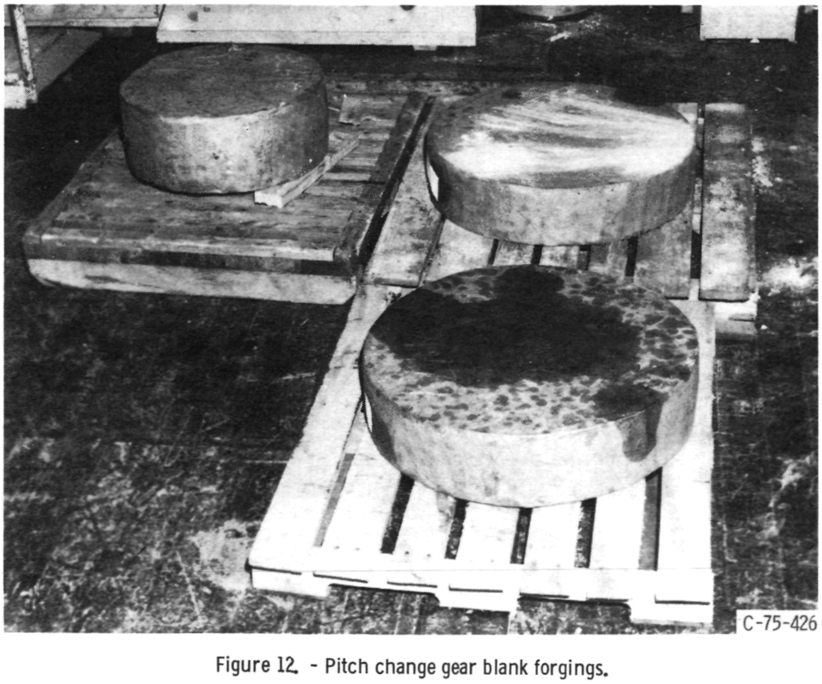
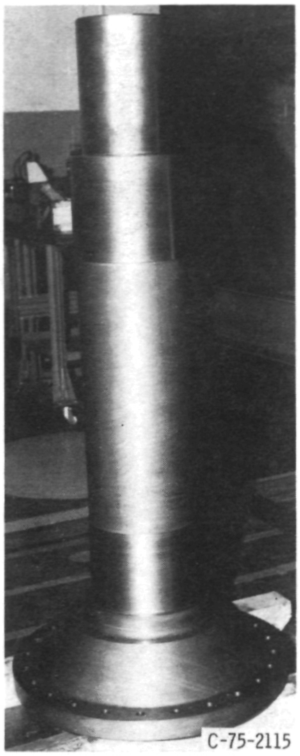


Figure 12. - Pitch change gear blank forgings.

(a) Forging.



(b) Machined.

Figure 13. - Main shaft.

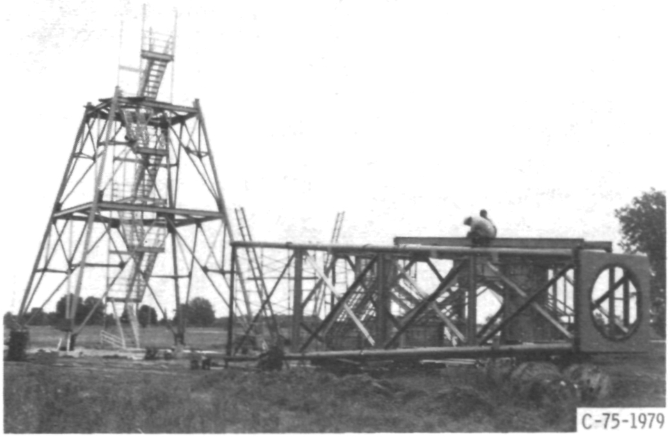


Figure 14. - Tower at site.

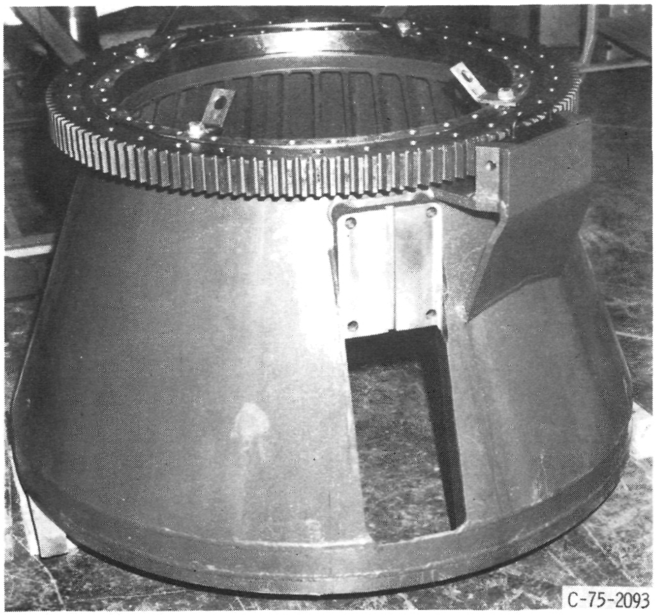
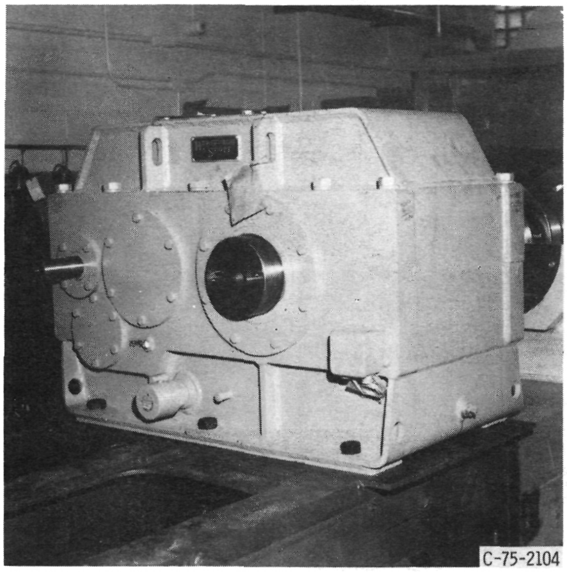


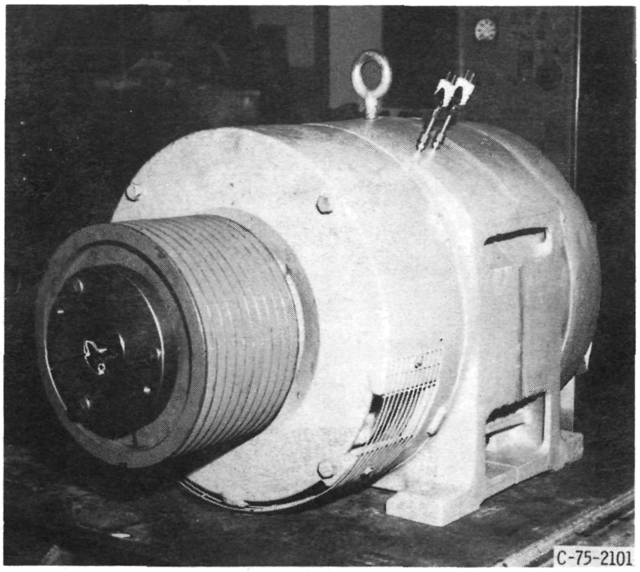
Figure 15. - Yaw cone and gear assembly.

Figure 16. - Bed plate.

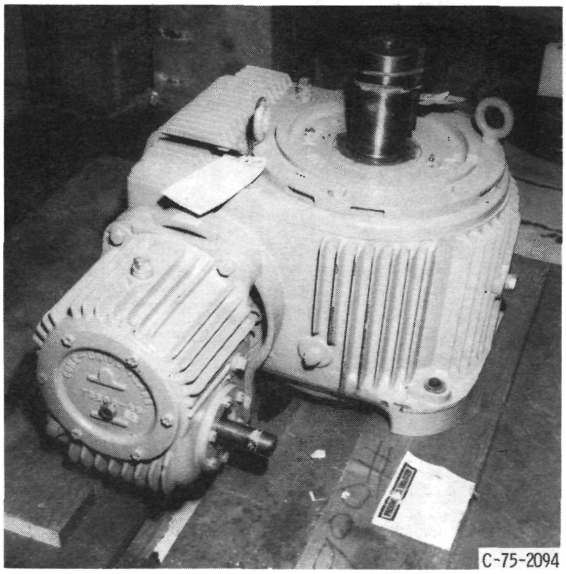
Figure 17. - Service stand.



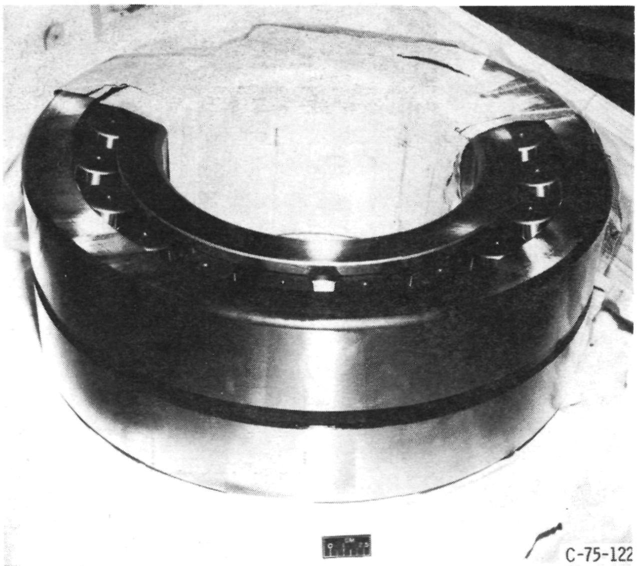
(a) Gearbox.



(b) Generator.

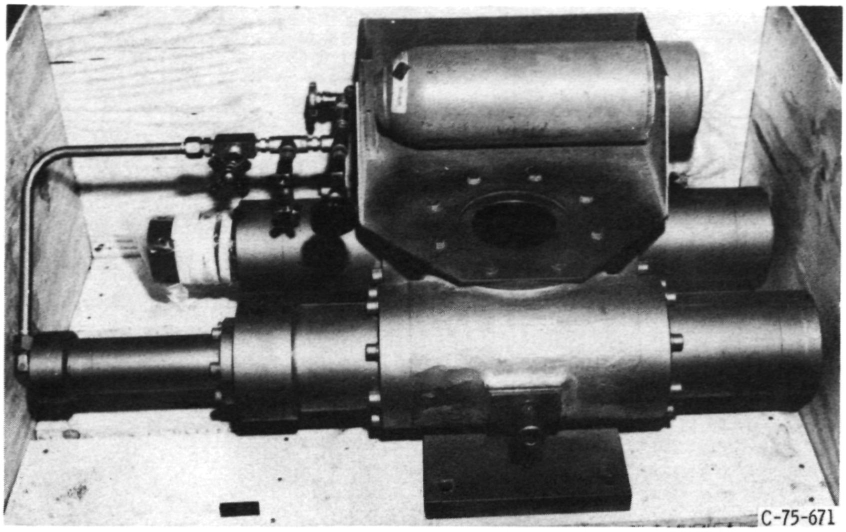


(c) Yaw motor and gearbox.

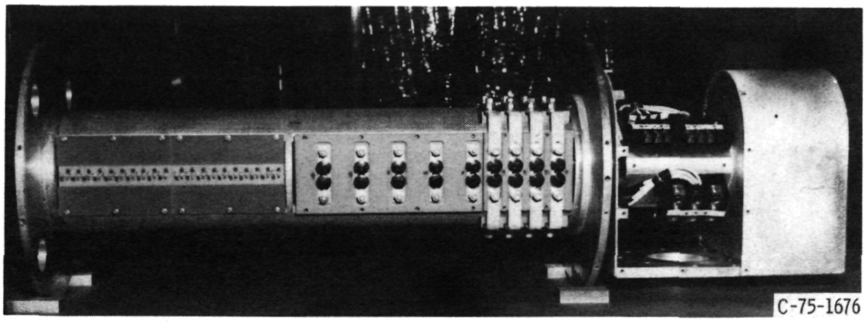


(d) Main shaft bearings.

Figure 18. - Some large catalog components.



(e) Rotary actuator.



(f) Slip ring.

Figure 18. - Concluded.

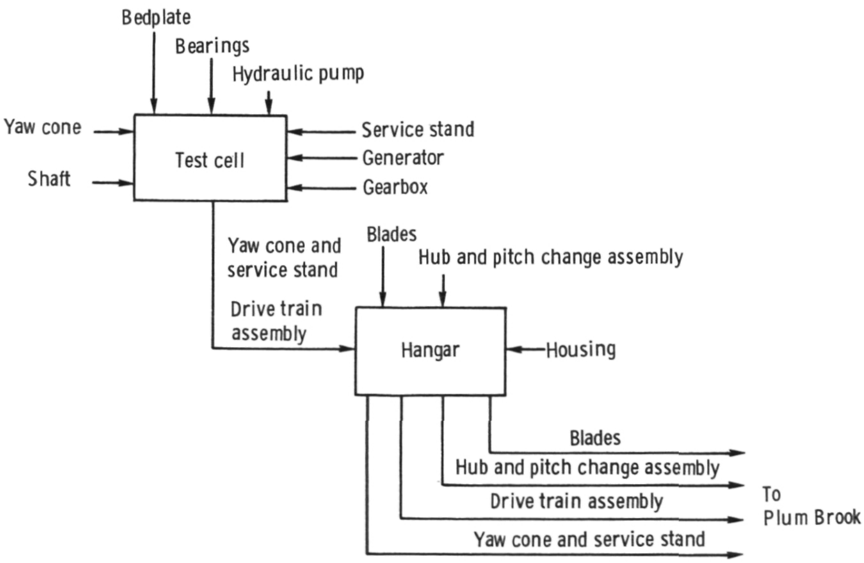


Figure 19. - Flow chart for first-stage assembly at Lewis.

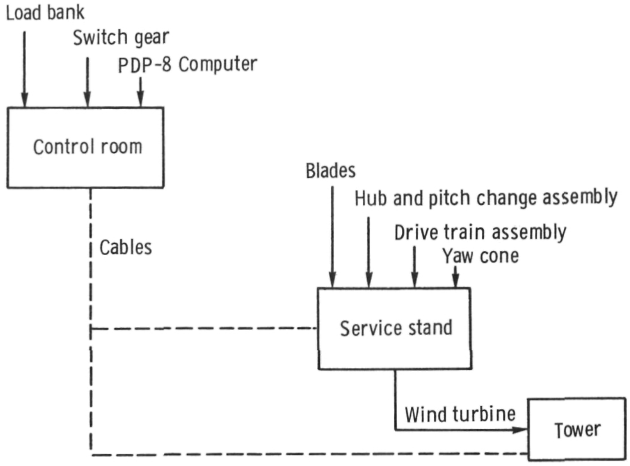


Figure 20. - Flow chart of second and final assembly stages at site.

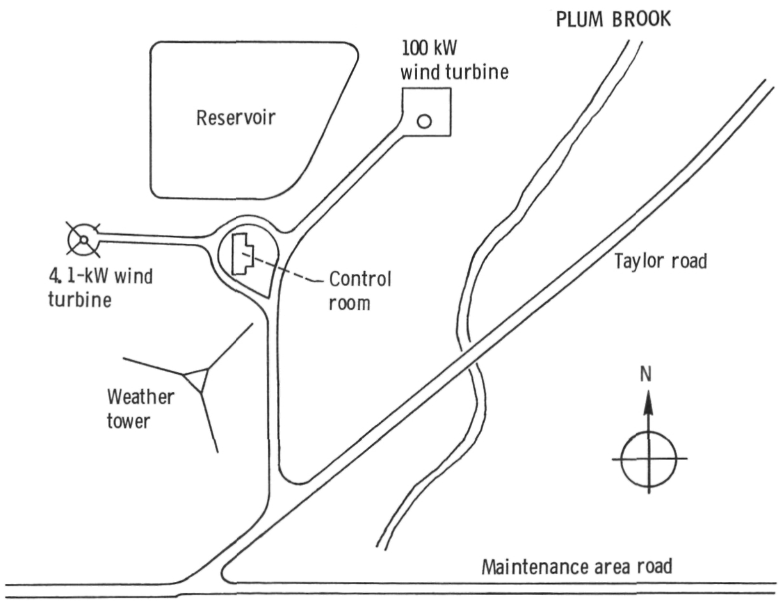


Figure 21. - Site layout.

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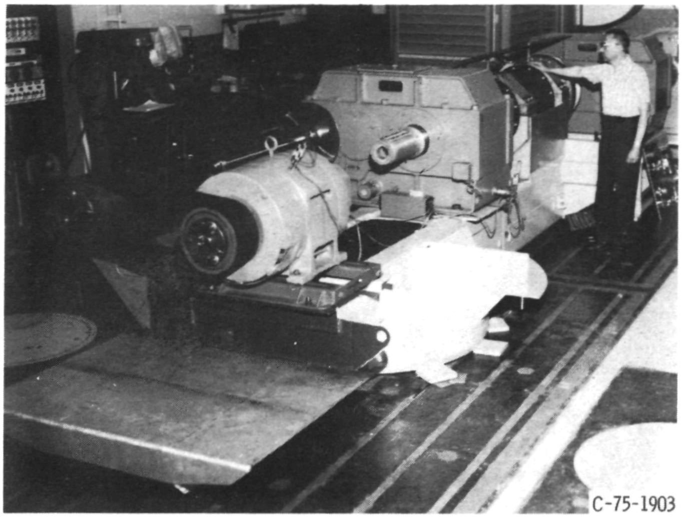


Figure 22. - Drive train assembly.

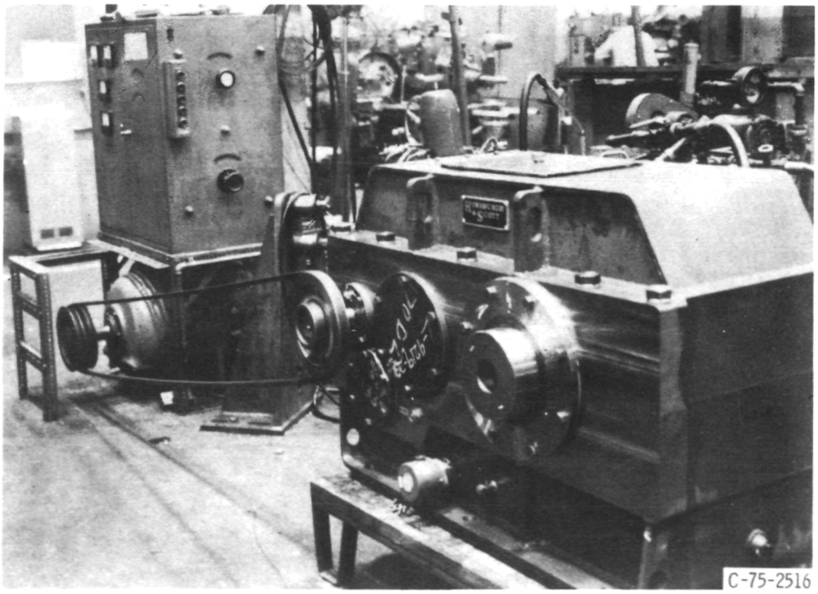
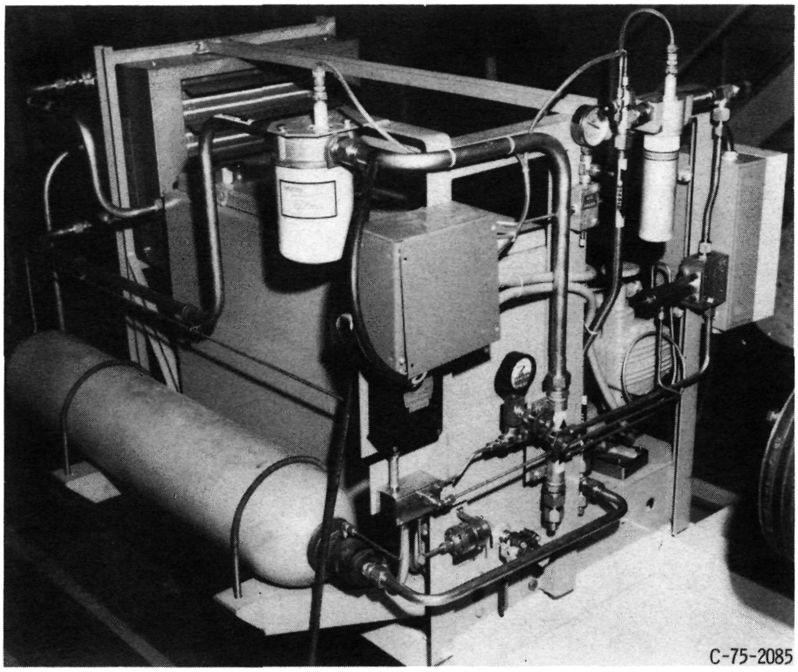
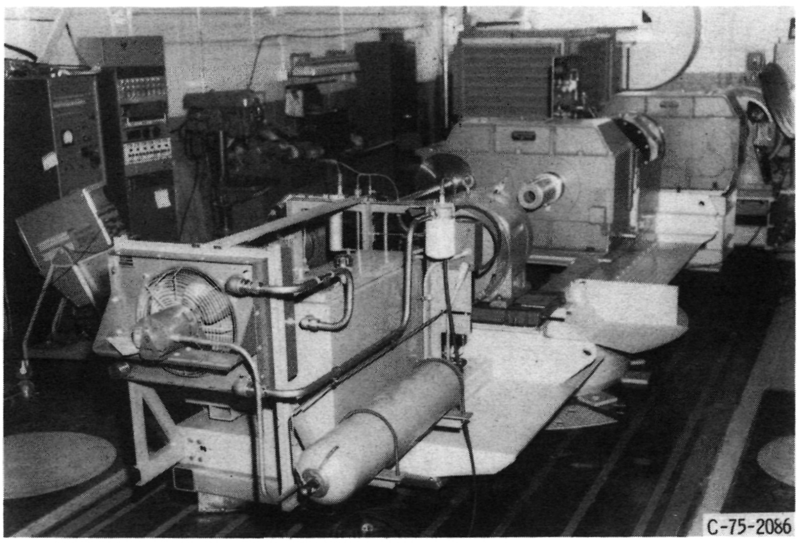


Figure 23. - Run-in test of gearbox.



(a) In Lewis hydraulic laboratory.



(b) Installed on bedplate.

Figure 24. - Hydraulic pump.

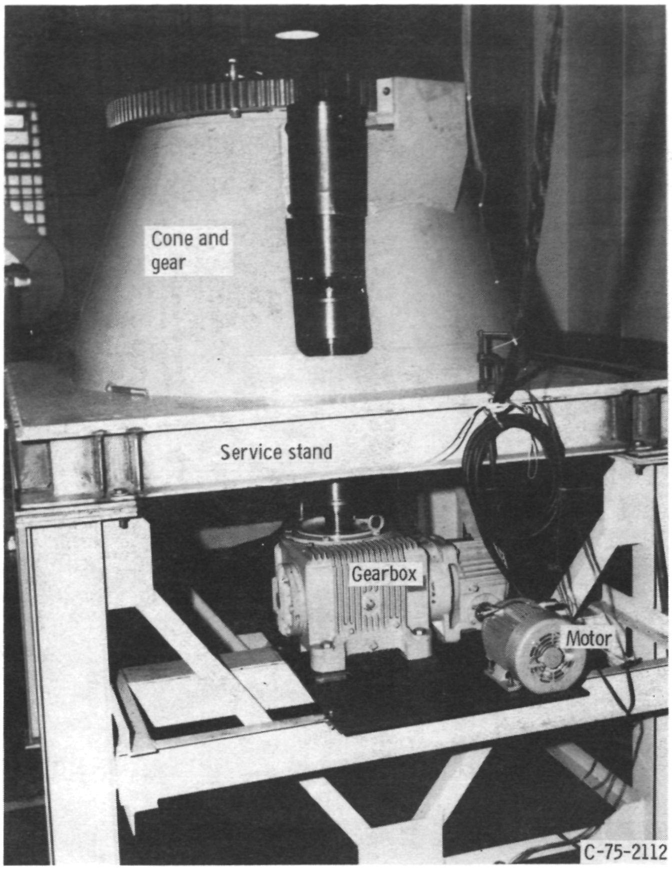


Figure 25. - Yaw assembly.

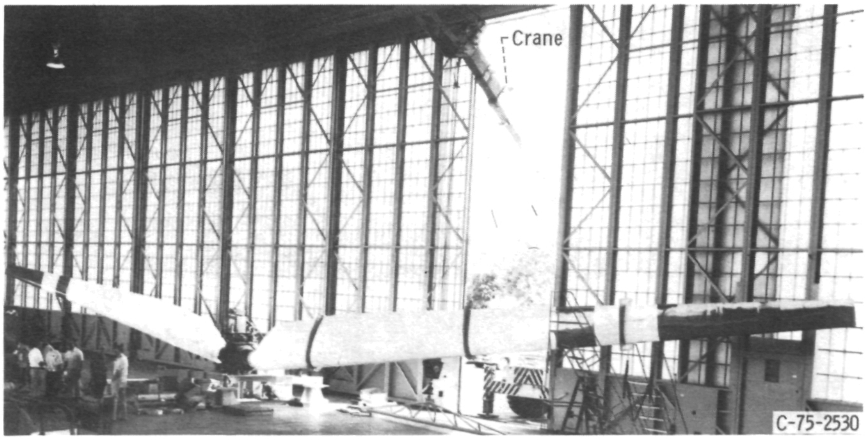


Figure 26. - Blades fitted to hub.

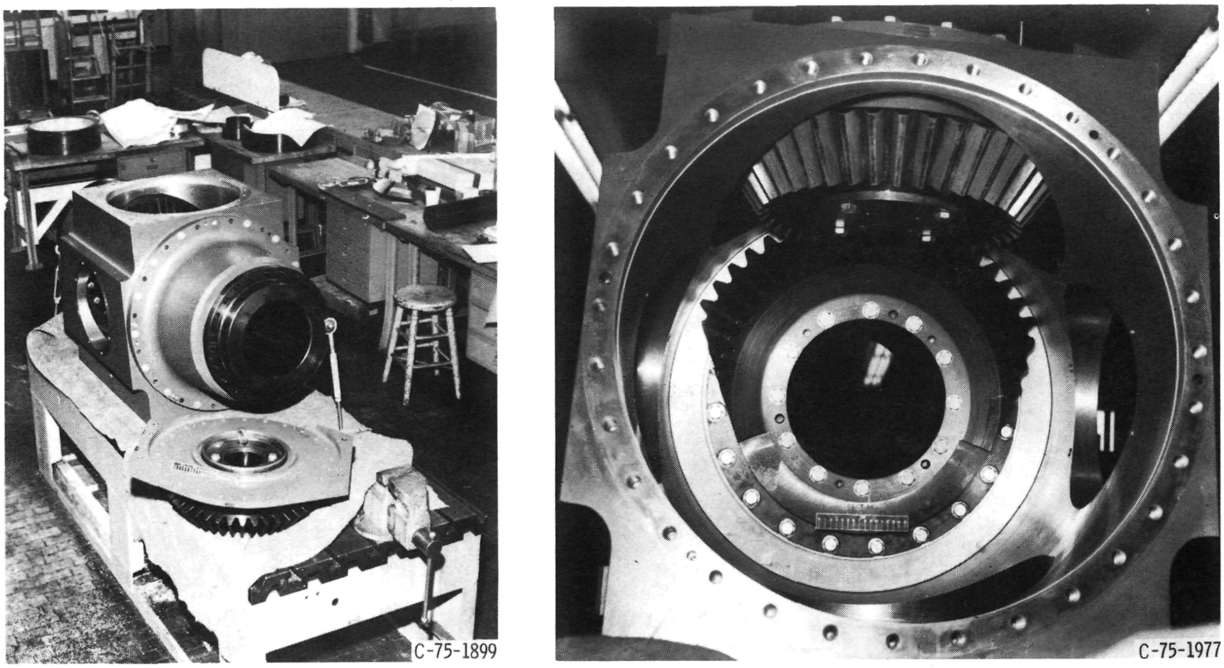


Figure 27. - Hub and pitch change gear assembly.

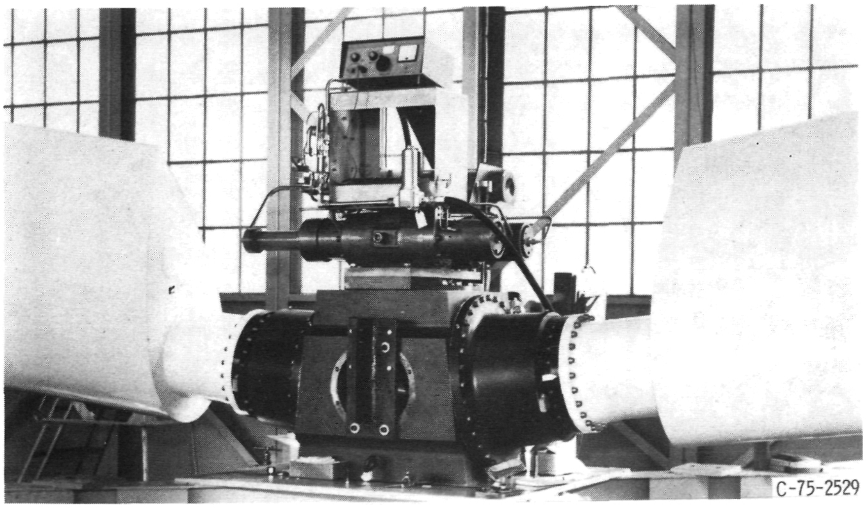


Figure 28. - Hub and pitch change with actuator.

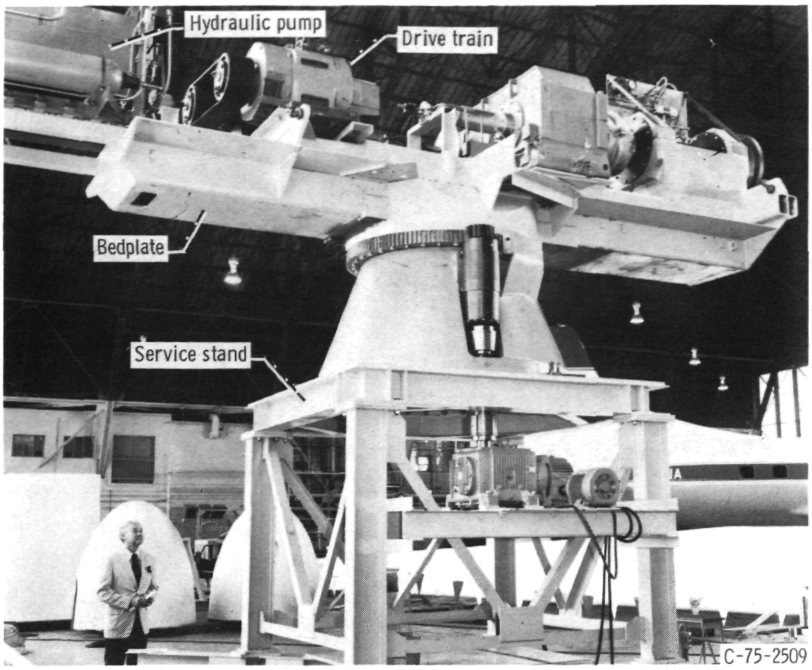


Figure 29. - Assembly in hangar on service stand.

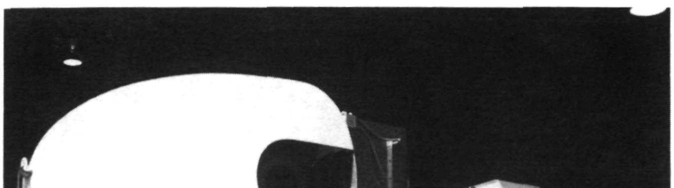


Figure 30. - Fitting fiberglass housing.

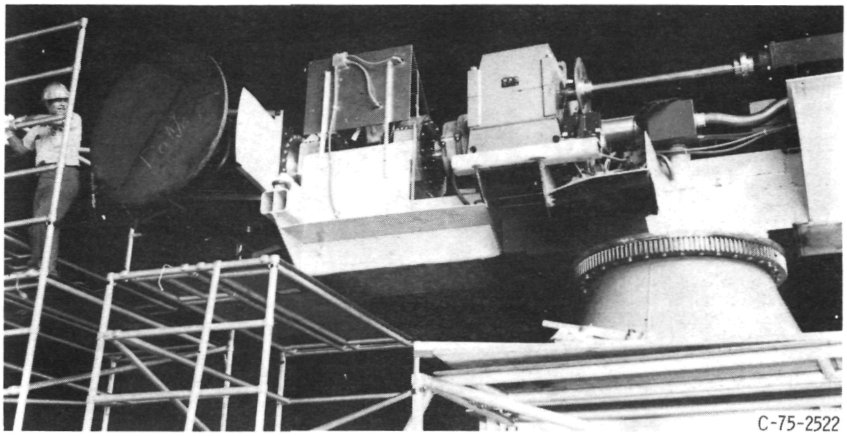


Figure 31. - Dummy weights for hydraulic pitch control test.

Figure 32. - Service stand.

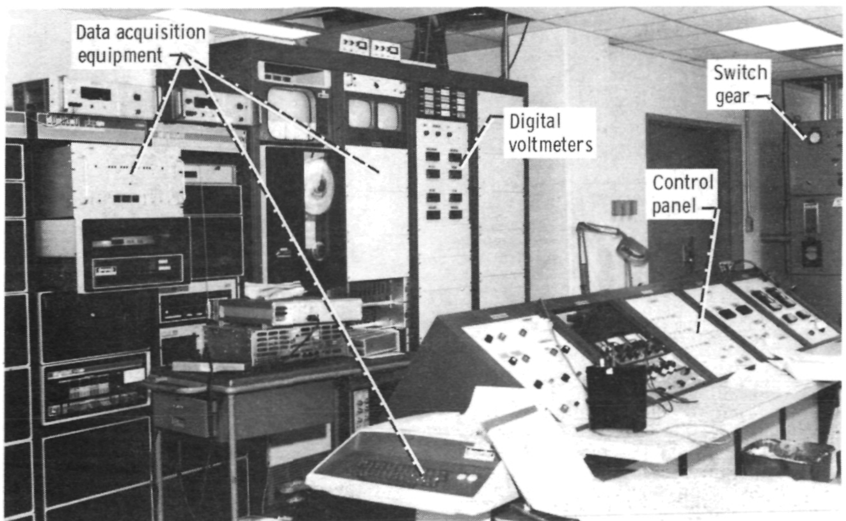


Figure 33. - Control room.

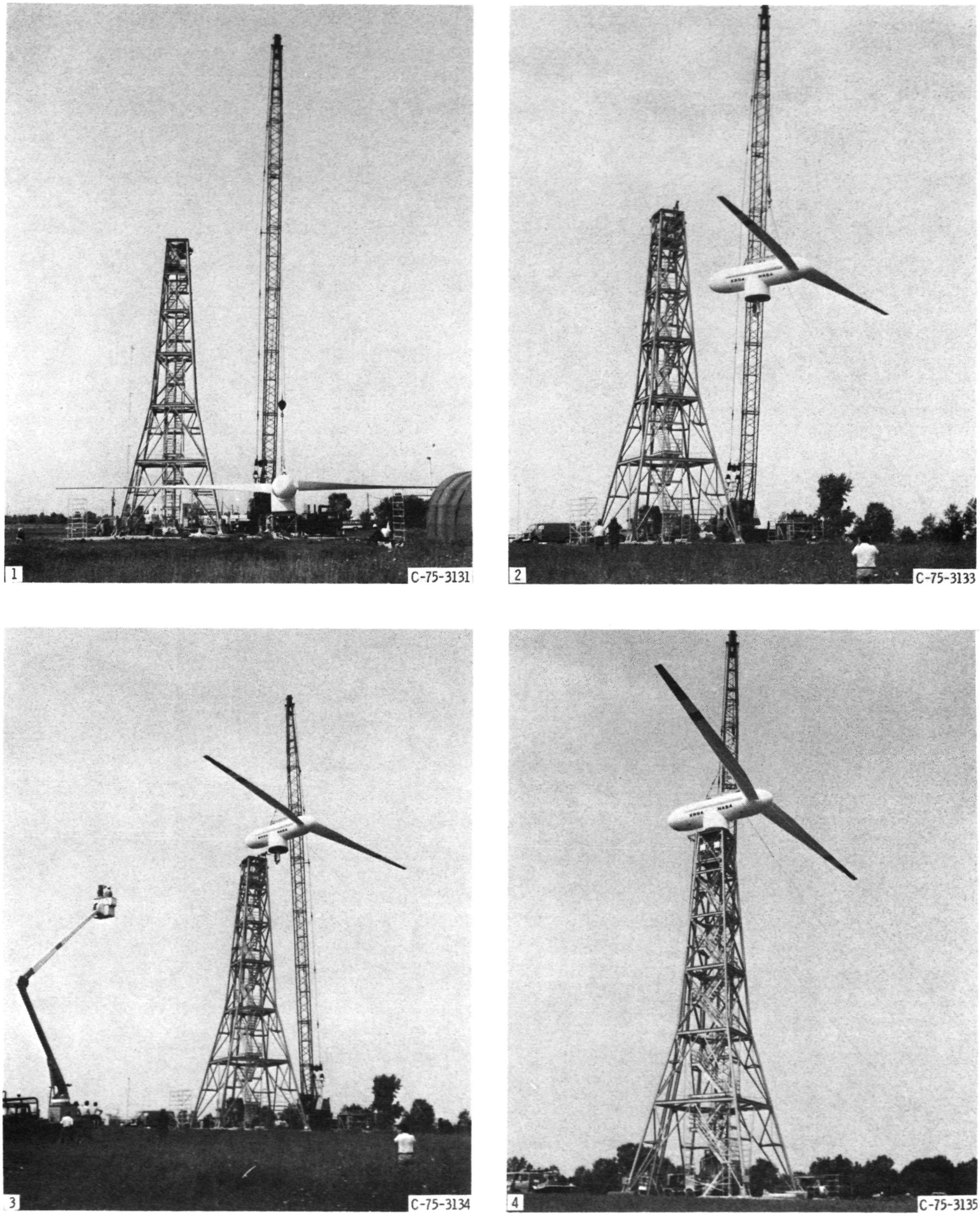


Figure 34. - Final assembly.

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—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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