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# Reliability and Quality Assurance on the Mod 2 Wind System

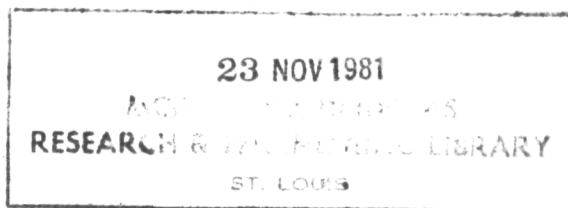
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Work performed for  
**U.S. DEPARTMENT OF ENERGY**  
**Conservation and Renewable Energy**  
**Division of Wind Energy Systems**



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Fifth Biennial Wind Energy Conference and Workshop  
sponsored by the Solar Energy Research Institute  
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## RELIABILITY AND QUALITY ASSURANCE ON THE MOD 2 WIND SYSTEM

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### ABSTRACT

This paper describes the Safety, Reliability, and Quality Assurance (R&QA) approach developed for the largest wind turbine generator built to date, the Mod 2. The R&QA approach used had to assure that the machine would not be hazardous to the public or to the operating personnel, would operate unattended on a utility grid, would demonstrate reliable operation, and would help establish the quality assurance and maintainability requirements for future wind turbine projects. Since the objective of the wind energy program is to provide wind power at a cost competitive with other energy sources, the R&QA activities were to be accomplished at a minimum of cost and manpower. The significant guideline consisted of a Failure Modes and Effects Analysis (FMEA) during the design phase, hardware inspections during parts fabrication, and three simple documents to control activities during machine construction and operation. This low-cost approach has worked well enough that it should be considered by others for similar projects.

### INTRODUCTION

Recent shortages in the supply of clean energy coupled with the cost of fuel have precipitated a national wind energy program under the direction of the U.S. Department of Energy (DOE). The program is designed to determine the practicality of using the wind turbine to produce electricity. NASA Lewis Research Center was assigned the phase of the program to develop the technology for design fabrication and operation of large (100 to 3000 kW) horizontal-axis wind turbine systems such as the Mod 1 (fig. 1) which was operated at Boone, North Carolina.

Wind energy systems have been used for centuries. The applications have ranged from the Dutch version for pumping water and grinding grain to the Danish models used in the early 1900's for generating electricity. Until the "New Deal" of 1930, wind machines played a significant role in rural America by providing cheap electricity for the farmers. These early machines were relatively small and did not produce much power.

In this century several attempts have been made to tap this widespread source of energy with relatively large machines. One of the first was built in 1931 by the Russians. Its rotor was 31 meters (100 ft) in diameter and it was placed on a 31-meter- (100-ft-) high tower; the maximum rated power was 100 kilowatts at wind speeds in excess of 56 meters per second (25 mph). In the 1950's and 1960's a number of



wind turbine systems were built principally by the Germans, French, Danish, English, and Americans. Most of these machines produced useful power but eventually were dismantled because the cost per kilowatt-hour was too high. The present world fuel dilemma has caused a reexamination of wind energy as a possible future source of power. This paper describes the latest design, to date, to be tested and operated, and it introduces the R&QA concepts that were used to support this program.

## MOD 2 DESCRIPTION

The world's first multimegawatt ( $\sim 7.5$  MW) wind farm (fig. 2) consists of three wind generators that were designed, manufactured, and erected by the Boeing Engineering and Construction Company. The farm is located in the Goodnoe Hills, Washington, on the Columbia River near the town of Goldendale. These wind generators will supply electricity for the Bonneville Power Administration, which provided the site and designed and constructed the substation and transmission facilities. Bonneville will integrate this energy into the Northwest electrical grid.

The DOE/NASA requirements were for a multimegawatt machine that was capable of a 30-year service life and of producing electricity for 2 to 4 cents per kilowatt-hour referenced to the 1977 dollar value if mass produced. On the basis of the Mod 0, Mod 0A, and Mod 1 experience, the Mod 2 (fig. 3) design resulted in the following innovations: the load on the blades being controlled by feathering only the blade tips; the use of the "soft" steel shell tower; the use of a compact, lightweight gearbox; and the reduction of loads on the turbine by teetering the rotor at the hub. Thus, the successful Mod 2 design consists of a 65.77-meter- (193-ft-) high steel tower, a 12.61-meter- (37-ft-) long nacelle containing gearbox, generator, and other equipment, and a 91.4-meter- (300-ft-) diameter rotor. The entire machine is 106.68 meters (350 ft) tall with the blade at its highest point and it weighs 285,083 kilograms (628,500 lb).

Some of the unique characteristics of the Mod 2 machine and its components provide an insight into the role and approaches of R&QA methodology encountered during the design, fabrication, and construction phase. The 91.4-meter (300-ft-) rotor consisting of hollow steel shell on a steel spar framework (fig. 4) was built as a single, continuous structure rather than as two separate blades. Each rotor was assembled at the site by bolting together five welded sections consisting of two tips, two midsections, and a hub. This approach in rotor construction resulted in greatly increasing the rotor's strength and resistance to fatigue. The rotor is oriented upwind by rotating the entire nacelle on its tower. Such an orientation of the rotor reduces blade fatigue and wear on other mechanical parts and increases power output by not being subjected to the "tower shadow", which is a pulse induced by the sudden, sharp reduction in wind speed as a downwind blade passes behind the tower as experienced by the Mod 0A and Mod 1 machines. To further reduce the physical stress or loads on the

rotor and other components caused by variable windspeeds at different heights above the ground and erratic wind gusts, the Mod 2 rotor is designed to teeter up to  $6.5^{\circ}$  off the vertical on its hub.

To extract the maximum amount of energy from the available wind, the outer 13.72-meter (45-ft) segments of each rotor (tips) are continually adjusted by hydraulically changing the pitch of the tip up to  $90^{\circ}$ . This capability also permits control of the machine's response to the wind. Machine shutdown is accomplished by fully feathering the tips. These aforementioned rotor characteristics resulted in lighter, less expensive rotors and support structures.

The Mod 2 nacelle (fig. 5), is connected to the tower by a full  $360^{\circ}$  rotating yaw system, which houses the drive train and the generator. The torque of the wind-driven rotor is transferred by teeter bearings in the hub to the low-speed shaft. The latter takes the energy into the nacelle. The low-speed shaft assembly contains a quill shaft, which is a flexible steel tube that absorbs oscillations and vibrations from the rotor's rotation and thus reduces stress on the gearbox. The gearbox increases the shaft rotation speed from 17.5 to 1800 rpm driving the generator through a high-speed shaft. The gearbox is a three-stage compact planetary gear. It is smaller, lighter, less expensive, and more efficient than a similarly rated parallel shaft gearbox. The mechanical torque from the gearbox is transformed to electrical power at 4.2 kilovolts in the generator. The generator is an alternating current model rated at 2.5 megawatts. It is of synchronous design and works at constant rpm. The electrical energy is transmitted to the substations and subsequently to the Northwest electrical grid.

## BACKGROUND

Components for the Mod 2 were built by Boeing and subcontractors in 17 states and in Sweden (fig. 6). The subassemblies were shipped to a Bucyrus-Erie plant in Pocatello, Idaho, where the nacelle was built (fig. 7). These subassemblies (i.e. generator, gearbox, etc.) (fig. 5) were fitted in the nacelle, and integration tests were conducted. The nacelles were then shipped to Goodnoe Hills, Washington. The rotors were built by Pittsburgh - Des Moines Steel Company at three locations: the center section (hub) at Provo, Utah; the mid-section and tips at Des Moines, Iowa; and the machined ribs and heat treating of the tips at Pittsburgh, Pennsylvania. Each section was completed at its respective plant and then shipped to the site where the five sections were bolted together to make each rotor. The tower was welded in sections at Chicago Bridge and Iron Plant in Salt Lake City, Utah, and it was assembled (fig. 8) and field welded at the site.

This Mod 2 program was a challenge for R&QA from design to acceptance but the state-of-the-art complexity and the size of the hardware was only part of the story. The geographic locations of the suppliers were also a complicating factor. Boeing's R&QA plan was dictated by the variety of tolerances, size of hardware, sophisticated fabrication,

and inspection processes. For example, the nondestructive testing of one rotor required the review and analysis of over 3000 radiographs. This plan covered design and fabrication ranging from the precision built planetary gearbox (fig. 9) to field welding the tower (fig. 8). The program required organization, scheduling, and exacting surveillance. Also, an important driver in establishing the level and scope of R&QA activities was the extreme public visibility and success orientation of the program.

## APPROACH

The Reliability and Quality Assurance Office (fig. 10) had the responsibility of determining the safety and R&QA requirements for the Mod 2 wind turbine program. This is a supporting function to the Wind Energy Project Office (WEPO) at the NASA Lewis Research Center. The R&QA Office had a member on the Source Evaluation Board (SEB) and had input to the Statement of Work (SOW) document when the request for proposal for this program was initiated. R&QA's input included requiring a Product Assurance Plan, drawing change control, nonconforming article control, failure reporting, etc. After the contract was awarded, the contractor's (Boeing) R&QA plan was reviewed and approved by the Lewis R&QA Office. The Lewis WEPO established a Mod 2 project support team with a representative of the R&QA Office as a member. This team participated in all design reviews with Boeing. The magnitude and geographic conditions of this program, with need for attention to detail, made it necessary for the government's R&QA people to work as a team with the contractor.

The failure mode and effects analysis (FMEA) was performed during preliminary design in order to identify all Mod 2 single-point failure modes. The FMEA was completed by the cognizant designers and reviewed by system engineers and a reliability specialist. In general, fail-safe design was employed wherever cost effective and a safe life design was employed. The failure severity code used in the analysis was to give a hazard category for the hardware. The hazard categories were (1) Minimal (repair as convenient), (2) Marginal (repair time limited), (3) Critical (shutdown), (4) Catastrophic (major damage). These hazard categories were used by Boeing to establish the quality level of the component or system, and this use dictated the inspection and acceptance procedure.

Completion of the FMEA by the designers as a part of the design process resulted in numerous design changes to either prevent serious failure modes or to reduce their impact. Whenever applicable, failure frequency data were included in the analyses. These data were used to quantify the probability of failure occurrences and hence to determine the impact of these occurrences on the cost of electricity and on the possible tradeoffs. Over 750 failure modes were analyzed, and numerous corrective actions were implemented to preclude costly failures. Special attention was directed at all potentially catastrophic failure modes.

Wherever practical, redundancy was used to preclude catastrophic failures. Safe life design was employed for items whose failure could cause serious damage but could not be made redundant (e.g., blade fatigue cracks). The ability to control each rotor pitch control surface independent of the other precludes several potentially serious failure modes such as control linkage binding or bearing failures (the Mod 2 design provides for an orderly shutdown with just one control tip operative). The most probable, potentially catastrophic failure mode is the rapid progression of a fatigue crack in the blade. As part of the safety system, Boeing included in the design a crack detection system that would result in an orderly shutdown of the wind turbine system before there is significant rotor damage (fig. 11). This detection system is a pressure-controlled positive flow system.

A special Quality Assurance Manual was developed by Boeing for the Wind Energy System which addressed nineteen quality assurance disciplines. These disciplines were employed during each phase of program development, manufacturing, and testing as shown on figure 12. The manual reflects total Boeing management approval and acceptance by NASA. Drawings, specifications, test procedures etc., were given critical reviews, and the Planning and Acceptance Reports (PAR) highlighted the requirements and guided the quality control program. Quality assurance preaward surveys were conducted on more than 25 suppliers. Source inspections were done at over 30 supplier's plants, and over 50,000 parts went through receiving inspection. Integration tests were conducted at assembly. The drive train was connected to large electric motor to rotate the drive train at 1800 rpm from the high speed end of the gearbox, and the operation modes were simulated and the systems and components exercised.

An important part of product assurance activities is the non-conformance/failure reporting system. This documentation system insures that proper action is taken to resolve any nonconformities that are found. The nonconformance report has four parts: description, analysis, review/disposition, and corrective action. The intent of the nonconformance/failure reporting system is to resolve problems in the best and most cost-effective manner. However, it also will provide a data base from which program problems can be detected. Starting with integration testing and on into operations the failure reports are entered into the NASA Lewis data system for configuration control and to calculate mean time between failures (MTBF).

Finally, a "Readiness Review" was performed on each machine before it is operated. The review was conducted by a team of Boeing and NASA personnel. They checked fabrication, assembly, and testing records to verify such things as bolting torques, greases and oils, burn-ins, etc. This review insured that all tests were completed and that failure documents were closed out. Lastly, this team insures that the operators' training has been completed.

## CONCLUSIONS

The modern wind turbine programs as monitored by NASA are a unique evolution of the procedures, experience, and technology developed by the construction, utility, and aerospace industries. The R&QA approach given here had as a baseline the research and development used in the first-generation projects (Mod 0A). This knowledge was revised and expanded as the second-generation machines (Mod 2) were constructed. We are prepared to apply the lessons learned and to revise our approach for future wind turbine projects (fig. 13).

The close working relationship between the government and the contractor is believed to have benefited this program and to have contributed to its cost effectiveness. The use of the FMEA to set up quality levels required fewer people and aided the design to insure reliability and safety. The planning and implementation of the product assurance program contributed substantially to effective program scheduling and hardware quality. The Readiness Review insured that all requirements were addressed, complete data recorded, and all systems were understood by the operating personnel before machine operation.

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Figure 1. - DOE-NASA 2000-kilowatt wind turbine at Boone, North Carolina.



Figure 2. - World's first multi-megawatt electrical power farm near Goldendale, Washington.

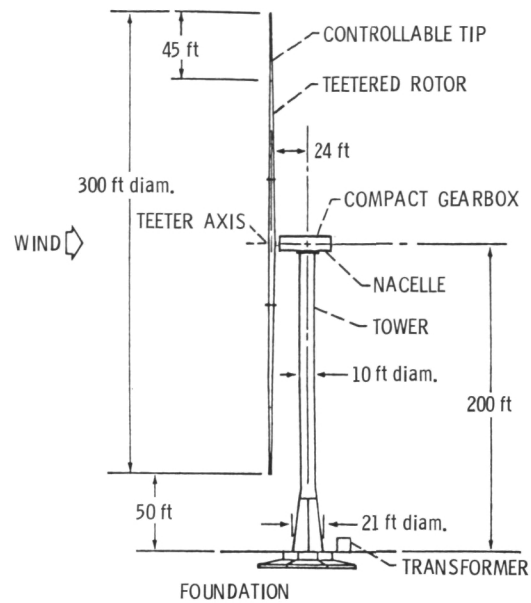


Figure 3. - MOD-2 wind turbine configuration.

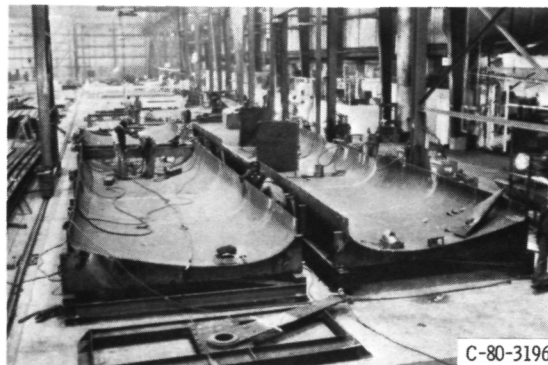


Figure 4. - 75-Foot two-piece midsection of the rotor before welding

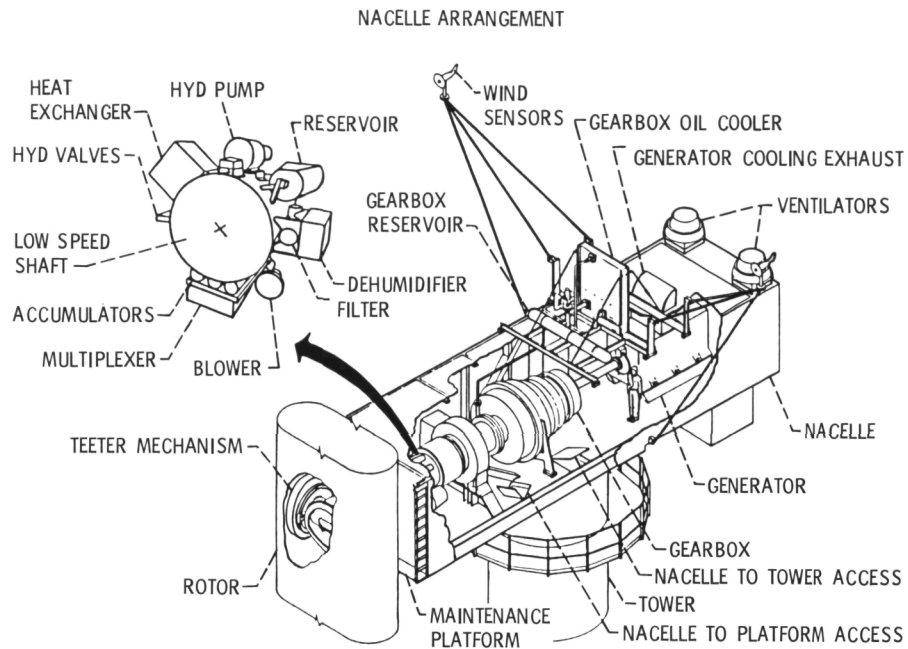
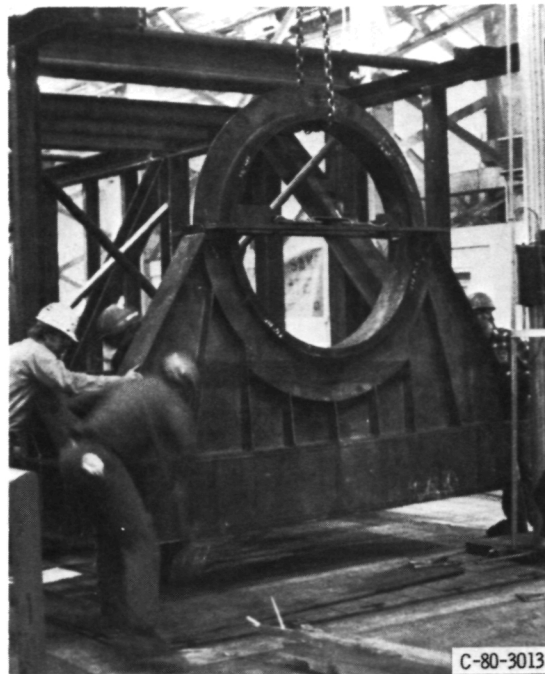


Figure 5. - 2500-kilowatt (MOD 2) wind turbine nacelle interior.



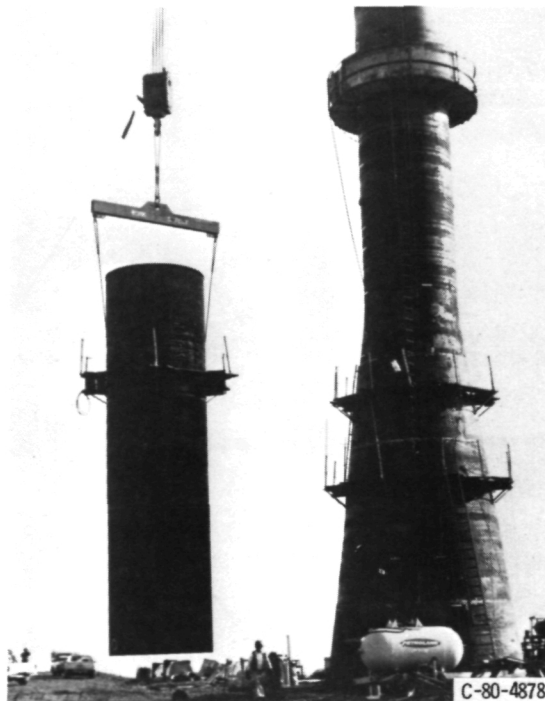
Figure 6. - Major supplier locations for MOD 2.





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Figure 7. - MOD-2 nacelle rib structure with the low-speed shaft bearing housing.



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Figure 8. - Lifting a tower section into place for welding the girth seam.

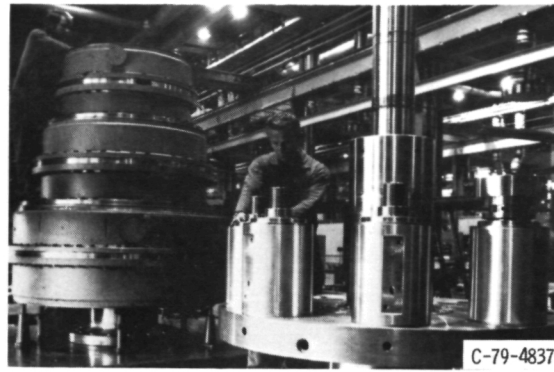


Figure 9. - MOD-2 planetary gearbox designed and built by Stal-Laval, Finspong, Sweden.

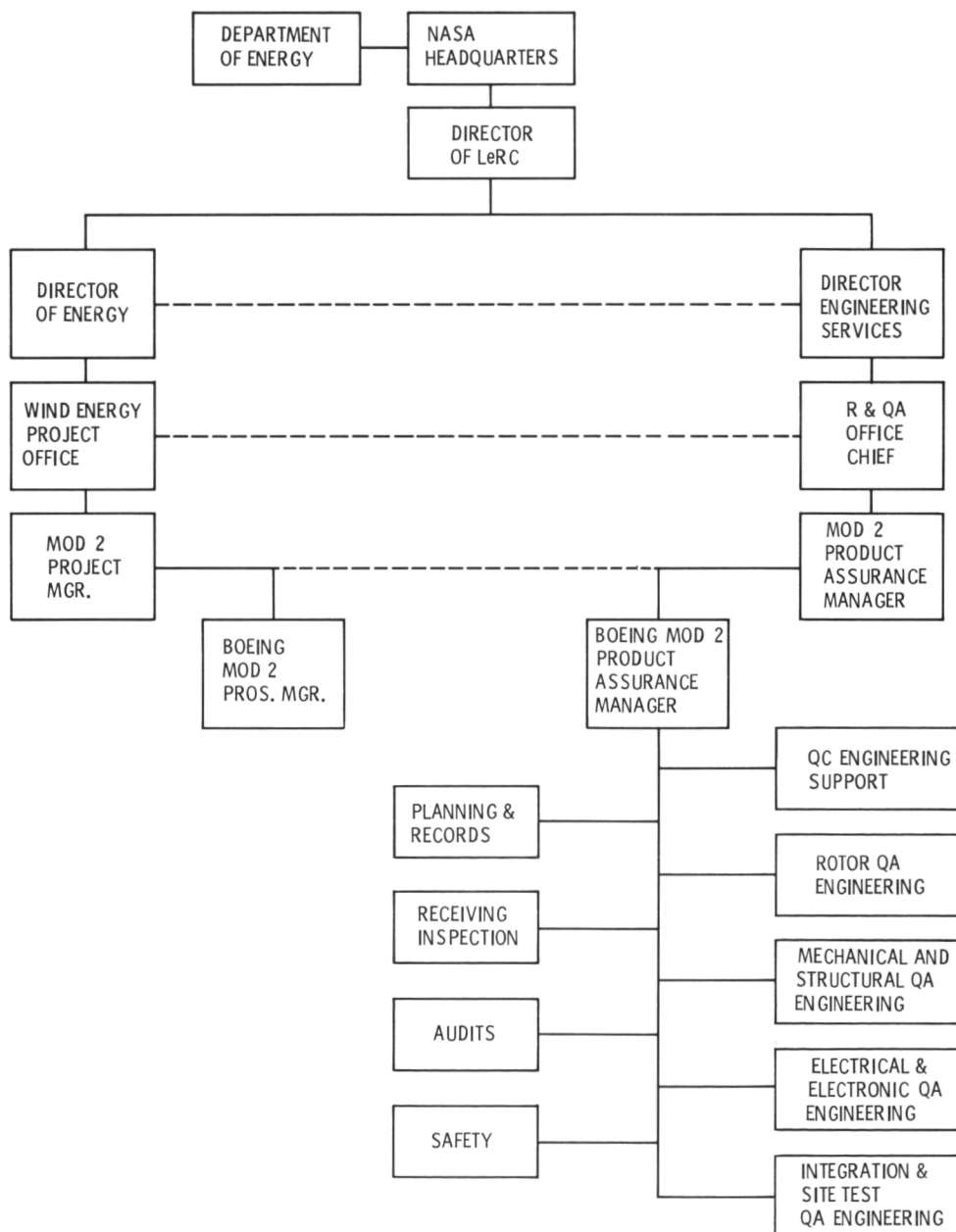


Figure 10. - DOE-NASA-BOEING relationship for MOD 2.

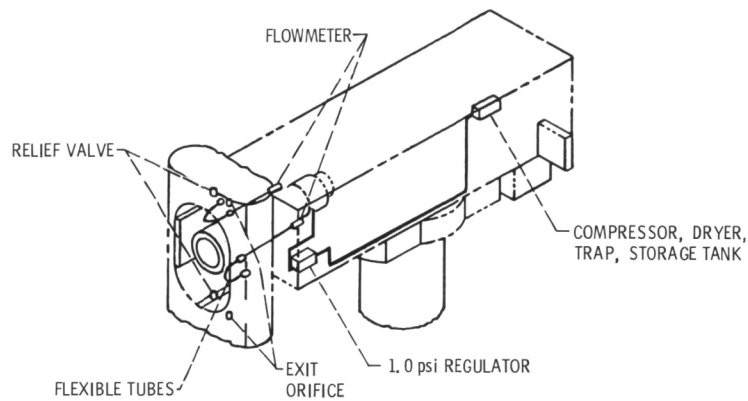
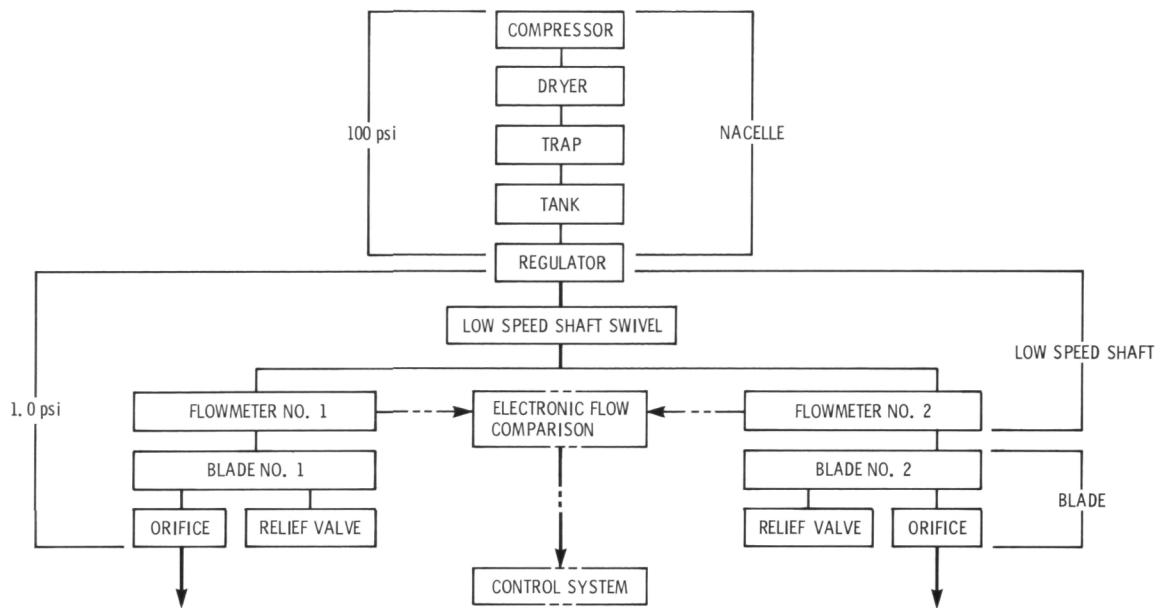
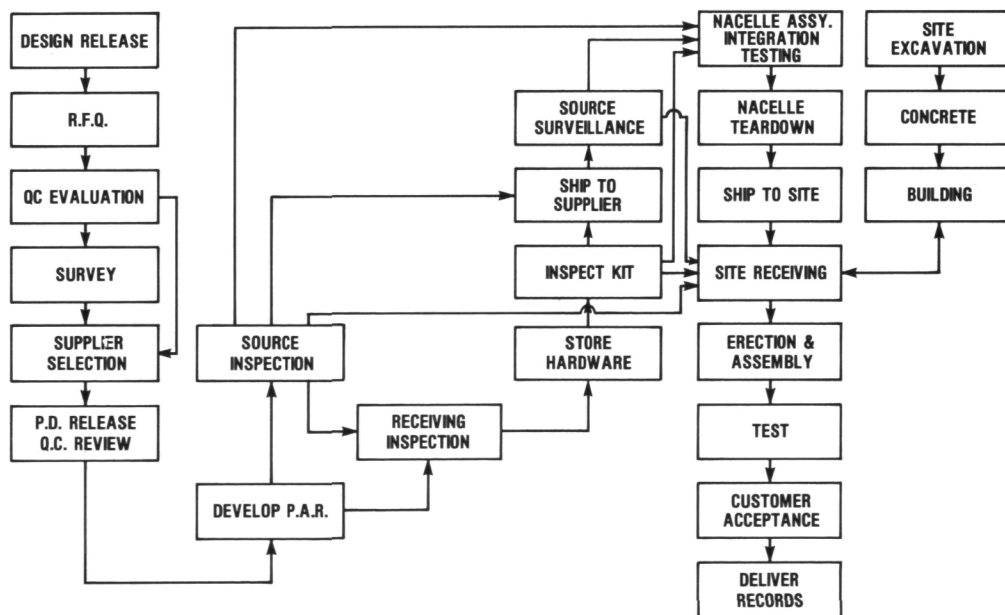


Figure 11. - Blade crack detection system.



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Figure 12. - MOD WTS product assurance flow chart.

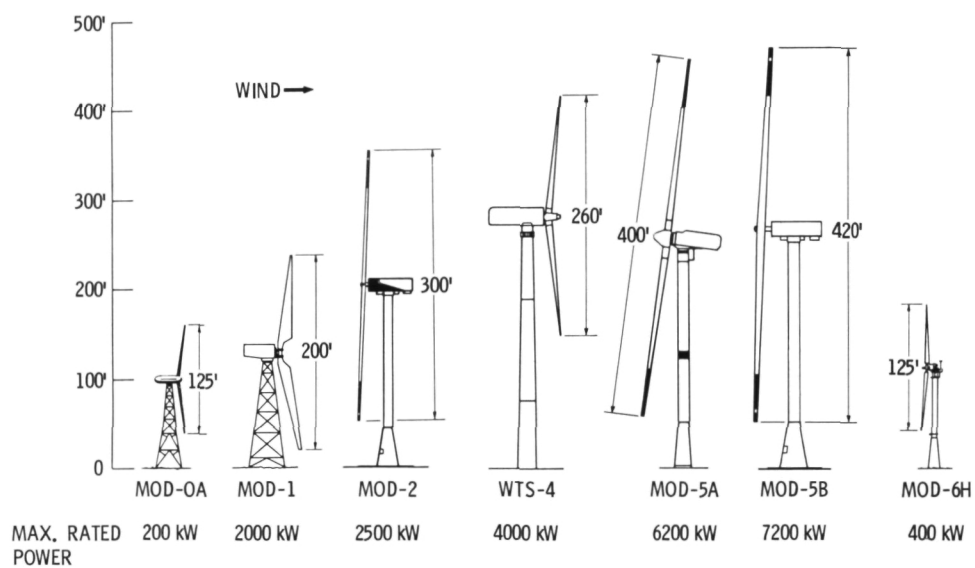


Figure 13. - Large horizontal axis wind turbines.

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