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MODIFIED AEROSPACE RELIABILITY AND QUALITY ASSURANCE METHOD FOR WIND TURBINES

William E. Klein
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

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Modified Aerospace R&QA Method for Wind Turbines

William E. Klein, P.E.; NASA Lewis Research Center; Cleveland

Key Words: System Safety, FMEA, Safety, Low Cost, Hazard Analysis, Methodology, Quality Assurance, Reliability

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Abstract

This paper describes the Safety, Reliability and Quality Assurance (SR&QA) approach developed for the first large wind turbine generator project, MOD-0A. The SR&QA approach to be used had to assure that the machine would not be hazardous to the public or 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 ultimate objective of the wind energy program is to provide wind power at a cost competitive with other energy sources, the final SR&QA activities were to be accomplished at a minimum of cost and manpower. The final approach consisted of a modified Failure Modes and Effects Analysis (FMEA) during the design phase, minimal 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

The NASA Lewis Research Center is conducting research and development of large horizontal axis Wind Turbine Generators for the Department of Energy as one phase of the overall Federal Wind Energy Program. Wind turbines ranging in size from 100 kilowatts (kW) to 3000 kW are being designed and built as part of this program. The object of the program is to develop wind turbines which will generate electricity at a cost which is competitive with alternatives, particularly oil. This paper describes the SR&QA approach developed for the first large wind turbine project, MOD-0A, a 200 kW, 125-foot diameter machine. This project is a combination of in-house and contracted effort and is a unique joining of aerospace technology and standard utility practices. This project forms the base for future development of large wind turbines.

Machine Description

A photograph of one MOD-0A machine, located on Culebra Island, Puerto Rico, is shown as Figure 1. Identical machines are located in Clayton, New Mexico, and on Block Island, Rhode Island. A fourth machine will be installed on Oahu, Hawaii in the spring of 1980 and should be in operation about mid-year. The two blades measure 125 feet, tip-to-tip. The hub centerline is 100 feet above ground level. The blades rotate at 40 rpm. The blades are mounted on the rotor hub, as shown in the cutaway drawing included as Figure 2. The pitch actuator pitches the blades through a set of bevel gears located inside the hub. The hub is attached to a low speed shaft which drives a speed increaser gearbox. A fluid coupling, attached to the 1800 rpm output shaft of the gearbox, helps dampen out power oscillations. A high speed shaft then transmits power to V-belts which drive a synchronous alternator. The machine is housed in an 8-foot diameter nacelle and is mounted on a turntable bearing located on top of a truss tower. A dual yaw drive system keeps the machine aligned with the wind.

The wind turbine is controlled by a microprocessor, two closed loop servo systems, and a safety system. The microprocessor is the heart of the control system. It continually monitors machine status and wind conditions. When the wind speed reaches 12 mph, the microprocessor signals the pitch controller to start pitching the blades, gradually increasing blade rotation. When the alternator reaches synchronous speed, the alternator is synchronized with the utility grid. After synchronization, the blades remain in the full power position, generating increasing power as the winds increase, until the full output of 200 kW is reached at a wind speed of 24 mph. As winds increase further, the blades gradually feather, spilling some of the wind, to maintain the 200-kW output.

If the wind speed drops below 10 mph, the machine is shut down. If the wind speed increases above 40 mph, the machine is shut down to avoid high blade loads. When the wind speed drops back to 35 mph, the machine is restarted. The microprocessor also monitors several noncritical variables to shut the machine down if necessary.

The first closed loop servo system regulates the pitch of the blades. Blade pitch regulates machine speed from initial blade rotation until synchronization with the utility grid and regulates the power generated after synchronization. The second closed loop servo measures the difference between the actual wind direction and the nacelle direction to keep the machine aligned with the wind. The machine operates with the blades downwind and is kept aligned within 25^{o} of the wind direction.

The safety system, as the name implies, measures several operating variables, shutting the machine down if any of these variables go out of limits. These variables include overspeed, overcurrent, pneumatic and hydraulic pressures, several overtemperatures, and high vibration, plus several others. In most cases, the Safety System shutdown signal goes into the microprocessor, but there are several signals which directly shut the machine down, regardless of what the microprocessor or servo controllers are doing.

Background

The Reliability and Quality Assurance (R&QA) Office was given the responsibility to determine the safety, reliability, and quality assurance requirements that were to be incorporated for these machines. In the past, the R&QA Office had been mainly concerned with launch vehicles, spacecraft, and aircraft engines. A wide variety of SR&QA techniques have been used on these programs. The list of these techniques is long and need not be discussed here. Looking at this type of background, the Wind Energy Project Office, which manages the wind turbine projects at NASA Lewis Research Center, was very concerned that we would initiate "expensive, time consuming, aerospace R&QA techniques" on their low cost program. We assured the project office that a very conscious effort would be used to keep the requirements at an absolute minimum.

This problem was further complicated by a unique combination of in-house and contract effort. The machine was designed in-house. Originally, this was a three machine program and the schedule was very tight. Therefore, Lewis Research Center ordered a few long-lead items for all three machines, several additional items for two machines, and all hardware for the first machine. The first machine was assembled in-house. The contractor was responsible for erection of the first machine, assembly and erection of the second machine (including the purchase of the remaining parts), and essentially all phases of the third machine. When the fourth machine was added, the contractor was given total responsibility for that machine. This meant that the SR&QA program had to operate under several combinations of in-house and contractor effort. The operation of the machine by the utility also had to be considered.

Safety and Reliability Approach

It was felt that one person could handle the R&QA efforts for the MOD-0A project. Therefore, the writer was assigned as the Product Assurance Manager (PAM), with responsibility for choosing the SR&QA requirements to be initiated for the program. The working relationship between the PAM and the Wind Power Office is shown in Figure 3. The PAM works in parallel with the Project Engineer, coordinating all activities through him. Although the working relationship between the PAM and the Project Engineer has been excellent for this project, the PAM has the option of going directly to higher levels of supervision, including the Center Director if necessary, in case of a dispute between the PAM and the Project Office.

As implied by the concerns of the Project Office, our normal aerospace R&QA procedures and paperwork did not seem to apply directly to a project of this type. However, we found that with some minor modifications, some standard procedures and paperwork could be modified for use on the wind turbine project.

The FMEA, the Preliminary Hazards Analysis, and the Operations Hazards Analysis can be listed on very similar forms and many of the entries are the same. In some previous projects, we were successful in having one person or team simultaneously review the project from a safety standpoint and from a reliability (or failure modes) standpoint. The results of this combined analysis can be listed on a relatively standard FMEA form. This could really be considered a System Safety review, since each possible failure is reviewed for its effects on the machine (reliability) as well as on personnel (safety). This combined FMEA technique works quite well and results in significant manpower savings. However, there is one drawback to this technique. Although it is easy to list failures that are not safety problems, it is just as easy to overlook safety problems which are not caused by equipment failures. Examples of this might be personnel getting caught in rotating machinery, shock hazards due to exposed terminals, or operator errors. These safety related items can also be handled using the combined FMEA if the reviewer makes a conscious effort to consider each of the hazards as a failure (failure of design - resulting in lack of proper guards; failure of operator - to follow procedures; lack of good human engineering - resulting in operator error).

After considering numerous R&QA and safety techniques, the PAM chose the modified FMEA to be the main tool for listing and analyzing the various possible failures, and the results or effects of those failures. Most of the FMEA was performed by the PAM and the Deputy Director of R&QA, with some additional help on one section by another member of the R&QA group. For the purposes of this project, the FMEA was performed for each functional mode of a system, subsystem, or component. The electrical portion of the FMEA was performed only to the black box level, showing only constant high level output or zero output. Wire harnesses, cables, and electrical connectors were considered to be part of the hardware. The level of detail in the mechanical portion of the FMEA varied. For catalog, off-the-shelf components, only common types of failures were considered. A remote operated valve was considered to be in the failed open or failed closed position only. The only consideration required for a pressure containment and distribution system was that the system pressure has dropped below the minimum safe operating level. Handvalves were considered part of the containment system and were assumed to be in the proper operating position unless the improper position was hazardous and could go undetected. It was not considered important to determine how or why a device failed, only that the failure could occur. The analysis was qualitative in nature and the actual probability of occurrence of a failure was not considered. However, the more probable failures, particularly those having severe consequences, were considered for possible redesign or addition of redundant systems. The basic ground rule used throughout the analysis was that no single point failure would be catastrophic even if a previous undetected failure had already occurred. For single point failure items such as the blades, tower, machine bedplate, etc., it was verified that the item had been designed to a safe operating life with a significant factor of safety.

The FMEA was used extensively for design and operational safety reviews. It emphasized the criticality of some hardware such as the blades and hub. Based on the FMEA, several design changes were made and redundant systems added. For example, the FMEA showed that the worst possible failure was rotor overspeed. Two possible single point failures that could cause overspeed were jammed pitch change mechanism, with increasing wind, or a controller failure resulting in full power signal even at higher winds. As a result, a disc brake was added to the high speed shaft to stop the rotor, even with the blades in the full power position. Also, a redundant overspeed switch was added that would operate the brake directly, rather than acting through the safety system as most of the other sensors do. The FMEA gave project management a qualitative evaluation of the degree of risk the design imposed on both personnel and machine safety. Trade-offs of degree of risk versus the need for additional redundancy or periodic inspection or maintenance could then be assessed. The FMEA also proved very useful when new design changes were being considered.

To complete the reliability phase of the program, a simple Discrepance Report (DR) form was developed as the main failure reporting system. A sample DR is included as Figure 4. The DR form is also used to track failure analysis when required and to assure initiation of engineering changes and to help control configuration. The form is based on discrepancy and failure report forms used in earlier programs and works quite well. The DR is also used as the basis for a summary of failure information to be put into our wind turbine experience data bank.

A utility industry survey was initiated to determine what quality requirements were imposed by the utilities on their suppliers. Several electrical generating equipment manufacturers were also contacted to determine their in-house programs. This survey indicated that we need not concern ourselves with the vendors of purchased electrical equipment. We have also had good experience with several of the vendors that had previously supplied identical or similar hardware. As a result of this survey, good previous experience with the vendors, and the effort to keep costs down, there was very little government or required contractor inspection of purchased hardware early in the project. Only the most critical machined components were inspected upon receipt. Very little was done on fabricated items and even less on catalog items. This turned out to be a mistake. Both NASA and the contractor quickly found that virtually all machined components had to have a thorough inspection performed, including all critical dimensions. Critical components need to be inspected at the vendors plant during machining and assembly to save cost and schedule problems later. These requirements were added in later procurements. We also found that it was wise to perform some inspection and checkouts of the more important fabricated hardware, such as the switchgear. Where inspection at the vendors plant was not practical, receiving inspection activity was augmented. Highly stressed unique hardware such as the blades and hub were of particular concern. Further developments indicated the need to maintain dimensional records of critical components during assembly and maintenance operations to allow a continuing assessment of component performance in areas such as wear rates of sleeve bearings, deformation of structural elements, etc. The one area where it has not been necessary to upgrade the quality program is for established, off-the-shelf components. We have experienced very few difficulties in this area.

Two more activities round out the quality efforts on the project. An Engineering Work Order form is used to document changes made to the system. This form is virtually identical to the DR form in Figure 4, except for the Material Review Board items. This form documents the change to be made and is used for configuration control. The form also assures all personnel that the project manager has given his approval to make the change. Finally, a daily log is kept for each phase of the project to record all significant activities.

Most of the above discussion relating to Discrepancy Reports, Engineering Work Orders, inspection records (for recording dimensions, etc.) and the daily log was basically for our in-house efforts. However, we have been very successful in having each of our contractors and each utility use their own internal paperwork system to perform the intent of each of the above documents. For example, one of our contractors uses an Inspection Report form to document dimensions, etc. on incoming material as well as to report failures or discrepancies. They maintain a daily log to complete the R&QA requirements. Each utility maintains a daily log and reports all failures on their weekly summary reports. The Wind Power Office is responsible for filling out a Discrepancy Report for each failure in the utility and for writing all necessary Engineering Work Orders.

A Readiness Review is performed for each machine as the machine is being turned over to the utility for operation. This review is performed by two or three people who are knowledgeable about the machine, but are as independent of the Wind Power Office as possible. The assembly log books are reviewed to verify proper bolt torques, greases and oils have been added, subsystem checkouts were successful, etc. A checklist was assembled for this phase. The remainder of the activities are rather informal. The machine is inspected at the site to verify that there is no shipping damage and that the machine appears to have been assembled properly. The team verifies that operating procedures were written and reviewed by knowledgeable people and that all system checkouts were performed and were successful. Operator training is reviewed to be sure that the operators understand the machine and know what they should and should not do.

Conclusion

The SR&QA approach described above was initiated on what was basically a research and development project and then revised and expanded as the demonstration aspects of the project evolved. Part of the safety and reliability requirements are met by performing a modified FMEA during the design phase. A Discrepancy Report is used to record all failures and discrepancies. Finally, a Readiness Review is performed before the machine is turned over to the utility. Part of the quality requirements are met by performing some vendor inspections and inspecting all machined items and most of the fabricated items upon delivery. An inspection report is kept, recording all important dimensions. An Engineering Work Order form is used for configuration control. A daily log rounds out the quality control activities.

This SR&QA approach has been successful in assuring safe operation of the units and in demonstrating those aspects of standard safety, reliability and quality practices which are most applicable and cost effective to this type hardware. We are in the process of getting good dimensional data on critical hardware and we have a good record of the configuration of each machine. The first MOD-0A has accumulated 5000 hours of synchronized time and has reached an overall Mean Time Between Failures (MTBF) of 250 hours, with a MTBF of 310 hours average over the last 6 months. Although this sounds low, several utilities have told us they feel this is excellent for this stage of a development program for a new power source. The approach we developed for the MOD-0A program has been sufficiently successful that similar approaches are being instituted on the newer, more advanced machines leading to low cost commercialization of wind turbines.

The SR&QA approach described in this paper has worked well enough that we are recommending that such an approach be considered for projects of similar complexity. The prime considerations are that the approach needs to be reasonable and flexible.

Biography

William E. Klein, P.E.
NASA Lewis Research Center
21000 Brookpark Road
Cleveland, Ohio 44135

Mr. Klein is the Product Assurance Manager for the 200 kW Wind Turbine Project, which is being managed by the Lewis Research Center for the Department of Energy. Since 1977, he has been responsible for all reliability and quality assurance activities for this program. He is also Product Assurance Manager for two low cost wind turbine projects and for the 100 kW wind turbine being used for supporting research and technology at Lewis Research Center's Plum Brook Station. In 1976 and 1977, he was Product Assurance Manager for the Centaur Launch Vehicle inertial guidance system. From 1974 through 1976, he was Flight Systems Safety Engineer for the Canadian Communications Technology Satellite and contract auditor for launch vehicle contracts. From 1970 through 1974 he was the Project Engineer and from 1964 through 1970 he was a Systems Engineer (Mechanical and Electrical) at two large test stands at the Plum Brook Station. Mr. Klein received his Bachelor of Mechanical Engineering from General Motors Institute in Flint, Michigan and his Master of Science in Mechanical Engineering from Case Institute of Technology, Cleveland, Ohio.

Figure 1. - MOD OA Wind Turbine at Culebra Island, Puerto Rico.

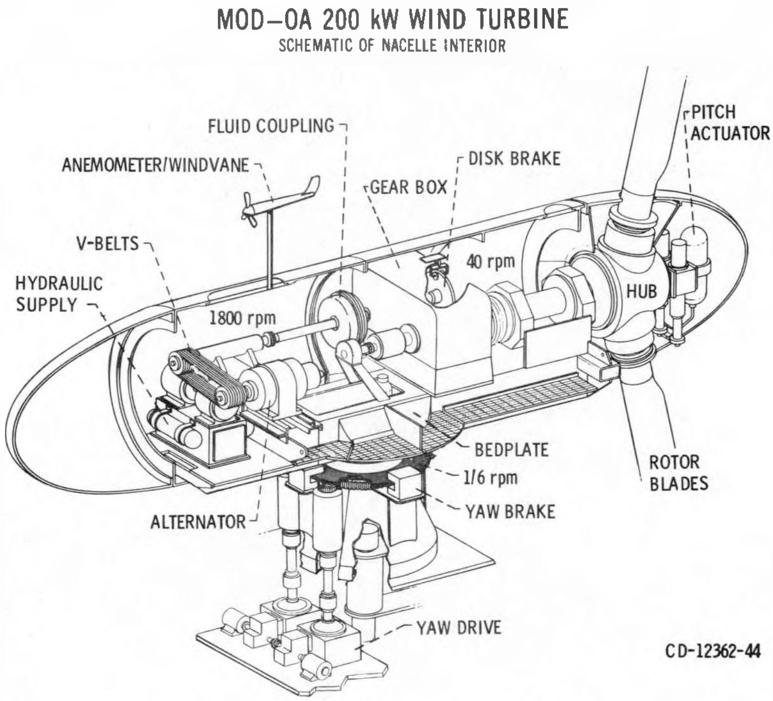

Figure 2. - Cutaway drawing of tower mounted equipment.

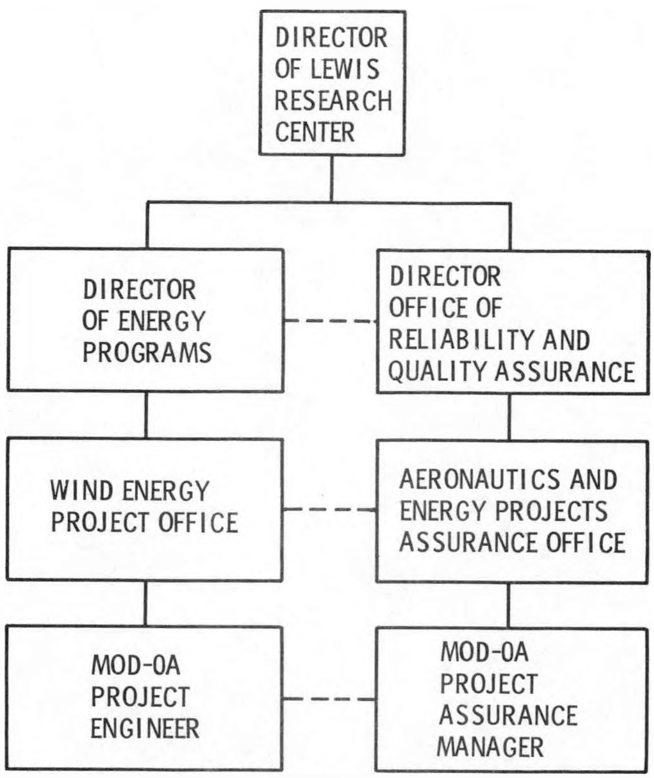

Figure 3. - Relationship of R&QA with Wind Power Office.

CONTRACT NO. FACILITY Clayton	**DISCREPANCY REPORT**	D. R. NO. 2066
PART NO. USED ON DWG. EQUIP. SYSTEM Pitch Hyd Sys	REPORTER R. Shaltens [X] PROJ ENG [ ] TECH SERVICES [ ] R&QA [ ] CONTRACTOR	PROJECT 200 KW WTG DA-1 DATE 11 SEP 78
AFFECTS FLIGHT HARDWARE [X] YES [ ] NO	REPORTER NOTIFIED PROJ ENG ______ R&QA ______	MR REQUIRED [ ] YES [ ] NO MRB REQUIRED [ ] YES [ ] NO

DISCREPANCY DESCRIPTION *(Refer to applicable drawing and procedure (Mfr. or test))*

H.P. DEUBLIN STARTED SPRAYING IN NACELLE

MR/MRB DISPOSITION

REPLACE H.P. DEUBLIN SEE EWO # 2133

MR/MRB

[ ] PROJ ENG ______ [ ] R&QA ______ [ ] TECH SERVICES ______ [ ] CONTRACTOR ______

SHOP/PLANNER	CORRECTIVE ACTION	TECH SERVICES BUY-OFF	QUALITY CONTROL

FINAL BUY-OFF

[X] PROJ ENG [signature] 24 Sep 78 [ ] R&QA ______ [ ] CONTRACTOR ______

NASA-C-12 (Rev. 2-75)

Figure 4. - Typical discrepancy report.