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Work performed for
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Prepared for
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LIGHTNING ACCOMMODATION SYSTEMS FOR WIND TURBINE GENERATOR SAFETY

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Wind turbine generators are being evaluated as alternative producers of electric energy. The Department of Energy (DOE) and NASA are currently engaged in the development of large wind turbines ranging in rated power output from 100 kW to multimegawatts. Safety in the design and operation of large wind turbines has been a primary consideration throughout the development efforts. The approach to implementing the system safety aspects has been adequately described by D. W. Reilly (ref. 1). As a result of this approach the wind turbine safety program identifies the naturally occurring lightning phenomenon as a hazard with the potential to cause loss of program objectives, to injure personnel, and to damage system instrumentation, structure, and support equipment and facilities. Since the naturally occurring phenomenon cannot be eliminated or effectively controlled, the hazard impact and probability must be assessed.

All structures are endangered only by cloud-to-ground lightning strokes, although ground-to-cloud strokes can be initiated by structures of sufficient height. Thus a major factor to consider in determining the probability of lightning hitting a structure is the frequency of occurrence of lightning strokes to ground in a given area for a given time. Precise quantitative data for the specific areas of interest do not exist and thus a secondary measure, the frequency of thunderstorms, must be used. U.S. Weather Bureau stations over a number of years have recorded thunderstorm days (the number of days per year on which thunder is heard). This index is called the isokeraunic level. Even though the index does not distinguish between cloud-to-cloud and cloud-to-ground discharges or account for the duration of the storm, the index does serve as a secondary measure of a potentially dangerous situation. Superimposing presently active and candidate wind turbine sites on an isokeraunic level map of the United States (fig. 1) clearly illustrates that the areas of favorable location for the wind turbines (high wind density) coincide with the area of high incidence of the thunderstorm activity. These locations, coupled with the 30-m (or larger) diameter rotor blades, make the wind turbines probable terminations for lightning strokes.

Available methodology to predict lightning stroke probability and especially its frequency and magnitude is based largely on theories evolved from observational experience. Descriptions and discussions of these theories and experiences are readily available in literature written by a number of very learned investigators, such as M. A. Uman, R. H. Golde, J. D. Robb, F. A. Fisher, and J. A. Plumer. On the basis of the data available from numerous publications and especially as discussed in reference 2, the following parameters provide a sufficient description of the naturally occurring lightning environment to which a lightning accommodation system must be designed and the characteristics to be achieved in simulated lightning tests.

(1) Peak current (kA) describes the current amplitude in lightning strokes, which can range from 3 to 400 kA, with most strokes exhibiting peak currents between 5 to 50 kA. Current amplitudes exceeding 80 kA can be regarded as rare. This is one of the most important parameters with respect to the damage that may be caused by a lightning stroke. The peak current is related to the explosive effect of lightning, the maximum voltage that can develop across ground resistance, the risk of side flashes, the possibility of sparking interfaces, and so on. The first return stroke is generally of the highest amplitude.

(2) Rate of rise (kA/μs) describes the rate of rise of lightning current, which can range from 5.5 to 100 kA/μs, with the most probable range being 5.5 to 30 kA/μs. This parameter is important in determining the amount of voltage that can be induced into electrical equipment. It is also used to determine the number of lightning conductors needed and their placement.

(3) The action integral $\int I^2dt$; (A^2sec) expresses the proportional temperature rise in a metallic conductor when unidirectional current of constant amplitude flows through the conductor for a time.

(4) The charge (C) is most probably in the range 3 to 20 C.
The values of these parameters can vary over wide limits because lightning flashes are quite variable. Therefore correlation between these and any other parameters can be achieved only in general terms.

The wind turbine system, which may be subjected to the energy levels discussed above, basically consists of a mechanical system and a control system. Integral components of the mechanical system shown schematically in figure 2 are the turbine rotor, the nacelle, the tower, the hoists, and any accompanying control buildings. The control system for a down-wind machine in its simplified form is schematically represented in figure 3. The components in these two systems that are most vulnerable to direct effects of a lightning stroke are the rotor blades, the bearings, and the microprocessor with its integral sensors and command instrumentation. The microprocessor is also highly susceptible to damage by the indirect effects of a lightning strike, such as induced voltages, voltage surges, and electromagnetic interference. The indirect effects may be the result of a primary strike on the structure itself, a strike to a nearby structure or utility line, or even improper grounding techniques.

Resolution of the problem imposed by the naturally occurring lightning phenomenon is complicated not only by the inability to accurately predict the probability of lightning strike and restrike, the energy level to be dissipated, and the extent of damage that could be sustained, but also by the limitations of the test methodology required to verify adequacy of the energy accommodation systems and the trend to use composite materials as structural members. Epoxy-glass and epoxy-wood material combinations are already being used as rotor blade structural materials. The possibility of using these highly dielectric materials as other structural members of the wind turbine system structure enhances the need of proper lightning protection.

One additional factor emerged recently that imposes limitations on lightning accommodation system design concepts - television interference. Locating wind turbine systems equipped with metallic blade rotors close to residential areas has degraded the quality of local television reception, understandably irking residents of the affected area. Use of the composite material blade structure should alleviate most of the problem. However, installing metallic components on composite blades could compromise the potential improvement.

An acceptable lightning hazard accommodation system must be

(1) Capable of dissipating the energy imparted by lightning without deleterious effects to personnel, structure, or instrumentation
(2) Low installation and maintenance costs
(3) Compatible with wind turbine rotor blade manufacturing processes
(4) Capable of withstanding repeated lightning strikes
(5) Easily field repaired
(6) Noninterfering with television reception

In meeting all these requirements the system shall not compromise the design weight or arm moment of the rotor blade.

One other limiting condition to be kept in mind is that there is no record of horizontal-axis wind turbine structures actually being hit by lightning. Thus the energy levels imparted to the structure and associated instrumentation are not known, further complicating the system design task.

Experiences with helicopter blades and discussions with experts in the field of lightning studies especially related to aircraft safety clearly suggest that one of the most important objectives for the lightning accommodation systems in conjunction with composite rotor blades is to keep the charge on the outer blade surface and effectively eliminate internal "streamering." This is illustrated schematically and photographically in figure 4.

At present, lightning accommodation systems for composite blades are being individually developed by each blade manufacturer. Therefore the highly individual blade manufacturing processes are not compromised or forced to become unnecessarily complex. The concepts are then analyzed and tested by submitting subscale samples to simulated lightning tests by the Lightning and Transients Research Institute in Miami Beach, Florida, and St. Paul, Minnesota, and by Lightning Technologies, Inc., at the General Electric High Voltage Laboratory in Pittsfield, Massachusetts.

The test procedures generally conform to the procedures described in reference 3. Not all the requirements and tests outlined in this reference are applicable to wind turbines. Selective test waveforms and procedures described in reference 4 have been adopted to wind turbine needs.

With respect to simulated lightning tests, several points should be carefully evaluated and certain limitations should be clearly understood. The most important point is that there is no facility that can begin to simulate the actual natural lightning energy. However, the procedures used to date do approximate the situation and with expert analysis develop reasonably accurate conclusions.

Two systems are presently under consideration. One of the two systems is still in the preparation stage because of blade manufacturing schedules; the second is already in use.

Mod-Zero A wood blades manufactured by Gougeon Bros. of Bay City, Michigan, are an epoxy-wood laminate construction with plywood-glass-covered tail panels (fig. 5). The manufacturing of this blade consists of laying up the blade structural components into female molds starting with glass cloth skin and ending with internal laminates. In this case the lightning accommodation system consists of simply covering the blade from tip to root with aluminum window screen. At the tip the two halves of the screen either overlap or are in close proximity and at the root the screen is mechanically bonded with 1/16-in.-thick aluminum angle and electrically bonded to the metal spool piece by flat, braided grounding straps.

This scheme was tested by Lightning Technologies, Inc., at Pittsfield, Massachusetts. Detailed test procedures and results are described in reference 4. Two sets of tests were conducted. The first set of tests consisted of a series of 16 high-voltage strike attachment tests using waveform A (fig. 6, ref. 3). Since the available sample was not provided with any lightning accommodation system, the testing sequence was arranged to test the sample with aluminum screen tacked over both surfaces of the sample, leaving the leading edge uncovered. Steep front-voltage waves (fig. 7) were directed at the uncovered leading edge to determine if attachment and puncture would occur at the edge. Both positive and negative polarity waves were used. In 11 attempts none of the high-voltage strikes did penetrate the gap between aluminum screens along the leading edge. Since the gap is considerably wider than in the fabricated blades, this series of tests indicate that no punctures should occur if operational blades are hit by lightning.

To further verify the effectiveness of the aluminum screen lightning accommodation system concept, a 61-cm by 61-cm square plywood Nomex sandwich panel (fig. 8) with aluminum screen bonded under a 0.13-mm-thick layer of fiberglass was subjected to high-current damage evaluation tests. The sample panel was installed in the high-current generator with about a 3-cm electrode gap. A 210-kA pulse with action integral of $3.5x10A^2s$ was applied to the sample. The results, as shown in figure 9, consist of evaporated or blown-off aluminum screen and fiberglass coating in a 76-mm-radius circle under the entry point, some additional peeling of the fiberglass, and delamination from the Nomex honeycomb below. The delamination does not exceed the 76-mm circle boundary, and no further major structural damage was evident. The damaged area can be easily repaired in the field.

The data from this sequence of tests clearly indicate that the aluminum screen concept used by Gougeon Bros. should be an effective lightning accommodation system. The extent of the system's interference with television reception in the operational site areas has not been assessed, and at this time it is not known whether the self-imposed design guideline has been successfully met. Two sets of blades are presently being used on Kahuku, Hawaii, and Block Island, Rhode Island, wind turbine machines.

The lightning accommodation system presently in the preparation stage is intended for use on the rotor blades designed and manufactured by the Kaman Aerospace Corp. for the Mod-1 series wind turbine machine. Each blade is 100 feet long and consists of glass-filament-wound D-spar to which honeycomb-glass-skin tail panels are attached, as shown in figure 10. The lightning accommodation system intended for these types of blades consists of an aluminum metal tip cap electrically bonded to a plastic covered (encapsulated) 1.25-in.-wide and 0.25-in.-thick flat braided conductor cable located on the trailing edge of the rotor blade and electrically bonded to the metal root spool piece interfacing the machine. The area at the root end is completely covered with Thorstrand (Hexcel Corp.'s trade name for aluminum deposit-covered glass cloth). The extent of coverage exceeds the length of the metal adapter enclosed inside the blade (fig. 10). This is done to preclude any possibility of internal streamering between the root piece and the tip cap or the possible attachment of a lightning stroke at the root of the blade. The concept was tested by Lightning and Transients Research Institute at their Miami Beach, Florida, facility under the direction of J. D. Robb and J. Herring. The series of tests using an 18-foot sample (fig. 11) consisted of the procedures similar to those described in reference 4. The data indicate that regardless of the high-voltage stroke attachment location on the sample, the charge stayed on the surface without stitching (penetrating the structure) until it reached the aluminum down conductor, tip plate, or root and fitting.

The data obtained during the high-current damage evaluation tests indicate severe pinching of the flat braided down conductor cable at 150 kA and destructive pinching at 210 to 230 kA (fig. 12). Pinching is the result of a magnetic field developed by the high peak current phase of the lightning flash flowing through sharp bends or corners of the test sample. The magnetic forces are proportional to the square of the magnetic field intensity and thus to the square of the lightning current. The resulting damage depends on the magnetic force generated and the response time of the system. Taking all the above into consideration, it is obvious that the interfaces between the tip cap and down conductor and the Thorstrand cover and the down conductor, as well as that between the Thorstrand cover and the metal spool piece, must be gradual-radius turns without sharp edges or abrupt changes of direction.

In general the test data indicate that the scheme should be adequate, although whether it would take less time to penetrate the highly dielectric composite material and streamer inside to the root metal piece or to transfer the charge on the surface to the down conductor has not been fully answered. The scheme is inexpensive, is highly compatible with Kaman's manufacturing process, can withstand repeated strokes at 100 to 150 kA and at least one stroke at 200 kA. After the latter, repairs to the lightning accommodation system would most likely be mandatory. However, the extent of the repairs could not be adequately assessed from these data. Considering that the probability of sustaining a direct hit of such a magnitude is 0.8 percent over a 30-year period, the scheme can be considered as adequate. On the basis of the data developed by T. B. A. Senior and J. E. Ferris of the University of Michigan at Ann Arbor (ref. 5), the lightning accommodation system described above would not be much more reflective than a composite blade without any lightning accommodation provisions. The scattering efficiencies, as determined in reference 5, are 0.587 for metal rotor blades, 0.244 for bare composite rotor blades, and 0.252 for lightning accommodation system using aluminum tape around the leading edge, the tip, and the root end.

A lightning accommodation system based on the Kaman Corp. and the Gougen Bros. simulated lightning test data and the information provided by Hamilton Standard funded efforts (ref. 6) was installed on the transverse-filament-tape composite rotor blade built by Structural Composite Industries, Inc. This system consists of an aluminum tip cap electrically bonded to 153-mm by 0.20-mm aluminum self-adhesive tape placed on the trailing edge as a down conductor with current diverters every 6 m chordwise electrically bonded to the trailing-edge down conductor. The aluminum tape was painted to protect against the environment. The current diverters were left unpainted.

The efforts discussed so far emphasize lightning accommodation systems for blades. However, the mechanical components, tower structure, generating equipment, instrumentation, and electronic components must be included in the total system design. Building structures and generator equipment without specific and proper provisions to accommodate currents imparted by a lightning stroke may have most undesirable consequences. The bearings may be rendered irreparable or their lifetimes may be considerably reduced. Development of induced voltages in instrumentation lines located in the tower structure or interfacing with utility power lines can cause extensive damage to instruments, sensors, microprocessors, computers, and control circuits. The consequences of these damages can range from a totally uncontrollable machine or unpredictable response to commands to total destruction of the operating system. An additional hazard is presented by field repairs or field installation of ice detectors, tip weights, and additional instrumentation. The real danger is that such actions may compromise a properly designed lightning accommodation system and render it ineffective.

To resolve the aforementioned concerns the NASA Lewis Research Center has begun to gather data of lightning strikes on active wind turbines and has entered a cooperative agreement with Southern Illinois University to develop a handbook of recommended procedures for lightning strike accommodation systems on operational wind turbines.

The lightning-strike-data-gathering activity consists of using passive lightning current detectors (ref 7) and acquainting site personnel with the need to record occurrences, damages, observations, effects, and delayed effects and to transmit the information to Southern Illinois University and/or the NASA Lewis Research Center. Southern Illinois University collates and analyzes the data, investigates damaged facilities, and documents the findings. These findings together with appropriate recommendations in conjunction with existing practices and methodology are being combined into a handbook of acceptable practices for wind turbine structures.

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7. Livermore, Stephen, "Development of Lightning Current Detector," NASA TMX-74154, 1976.

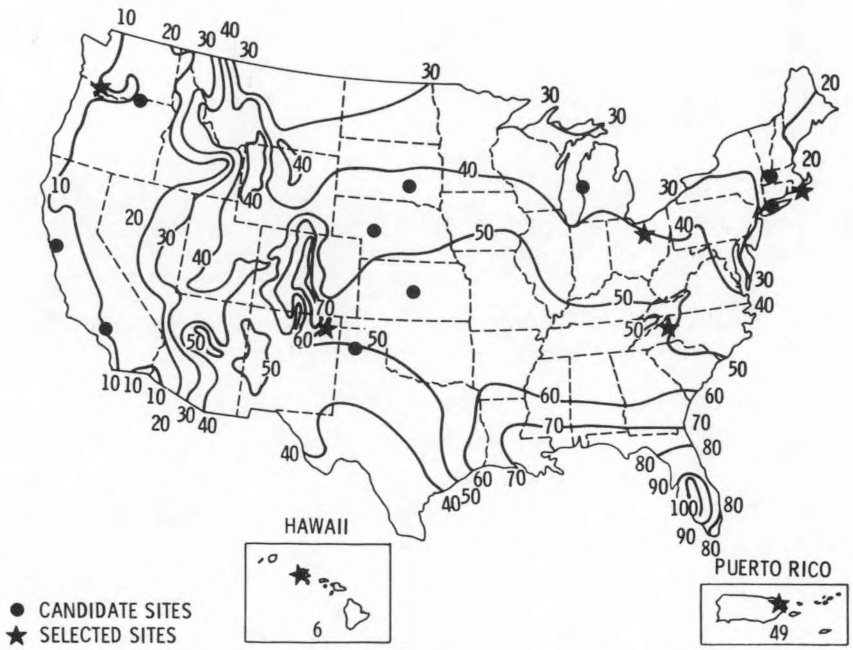


Figure 1. - Isokeraunic map of United States, showing mean annual number of thunderstorm days.

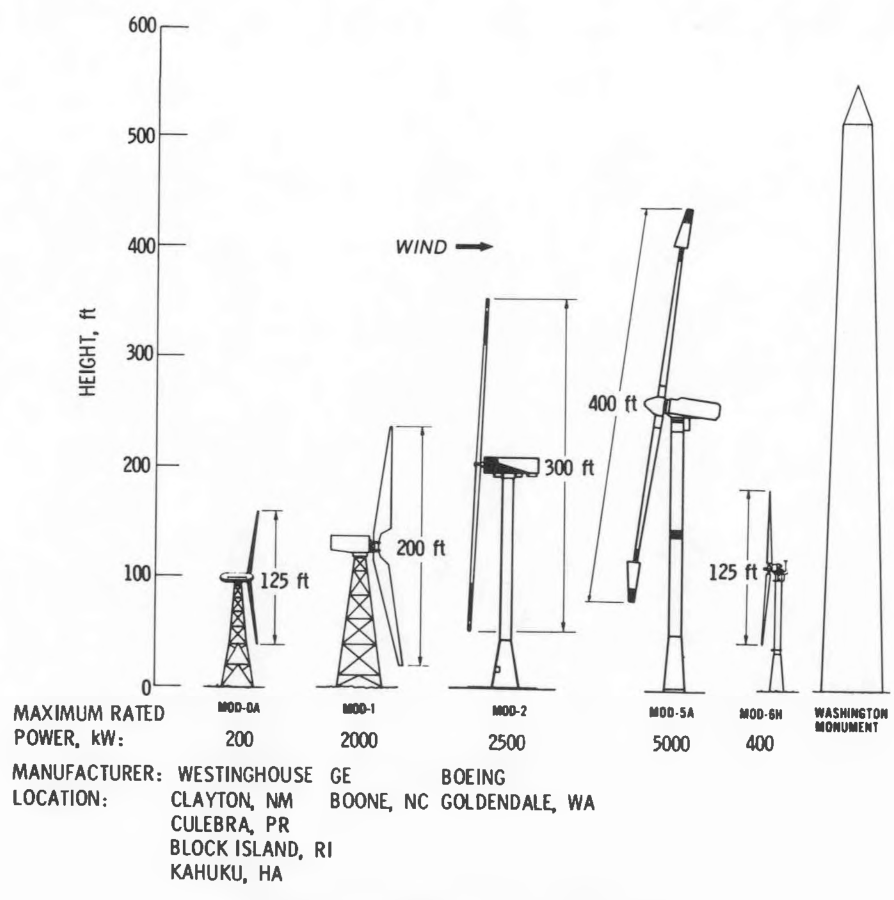


Figure 2. - Large horizontal-axis wind turbines.

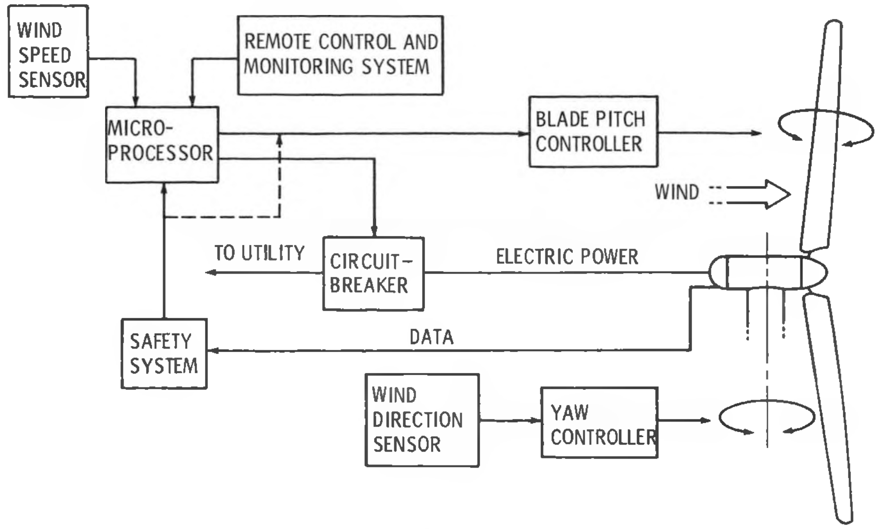
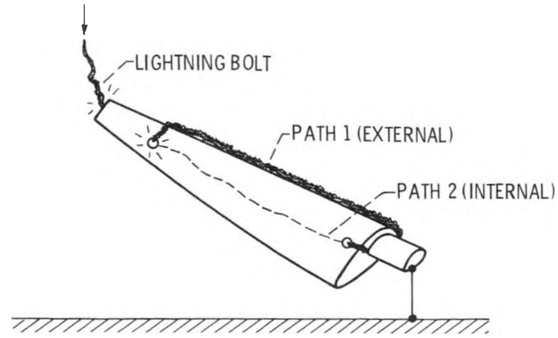
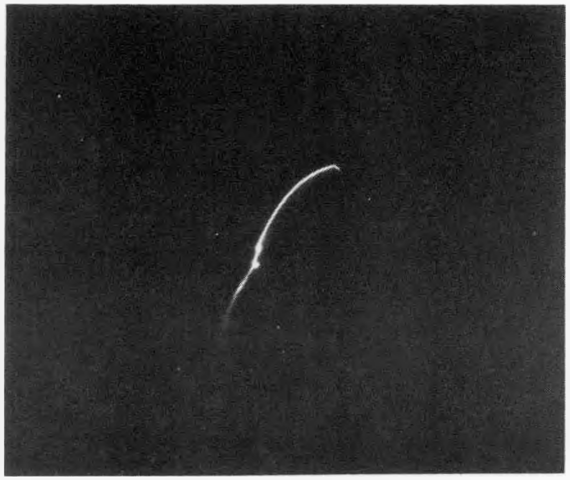


Figure 3. - Simplified wind turbine control schematic.



(a) EXTERNAL CHARGE TRANSFER AND INTERNAL STREAMERING.

Figure 4.



TEST 15.

TEST 16.

(b) D-spar tests.

Figure 4. - Concluded.

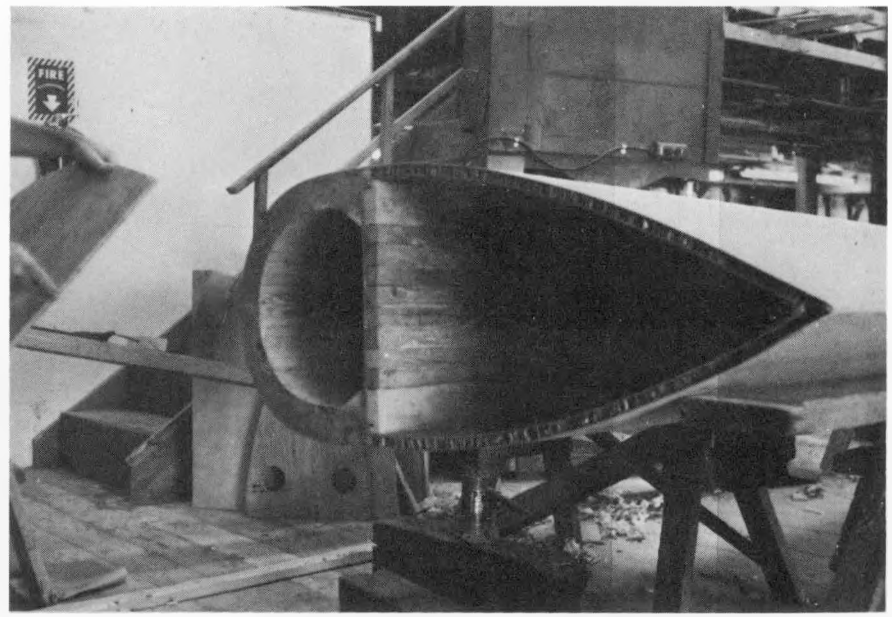


Figure 5. - Cross section of Gougeon Bros. blade.

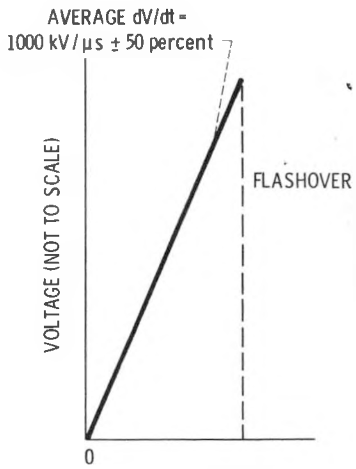


Figure 6. - Waveform A.
(From ref. 3.)

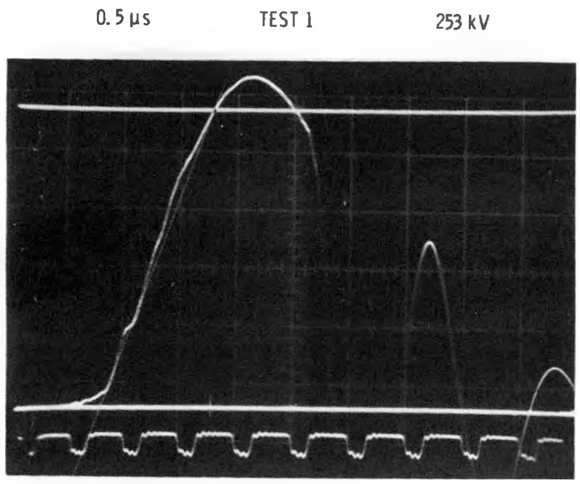


Figure 7. - Steep front-voltage wave test. (From ref. 4.)

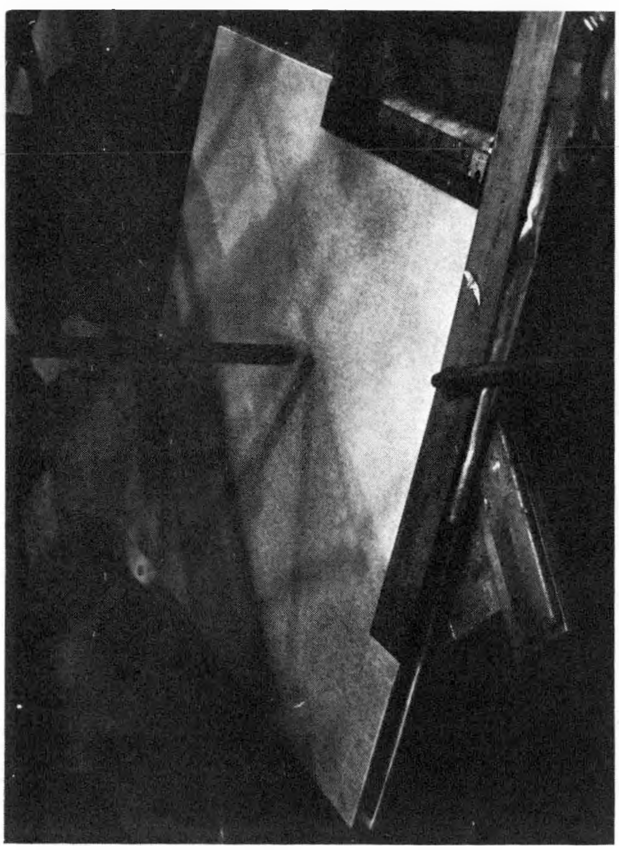


Figure 8. - Panel before high-current damage evaluation test.
(From ref. 4.)

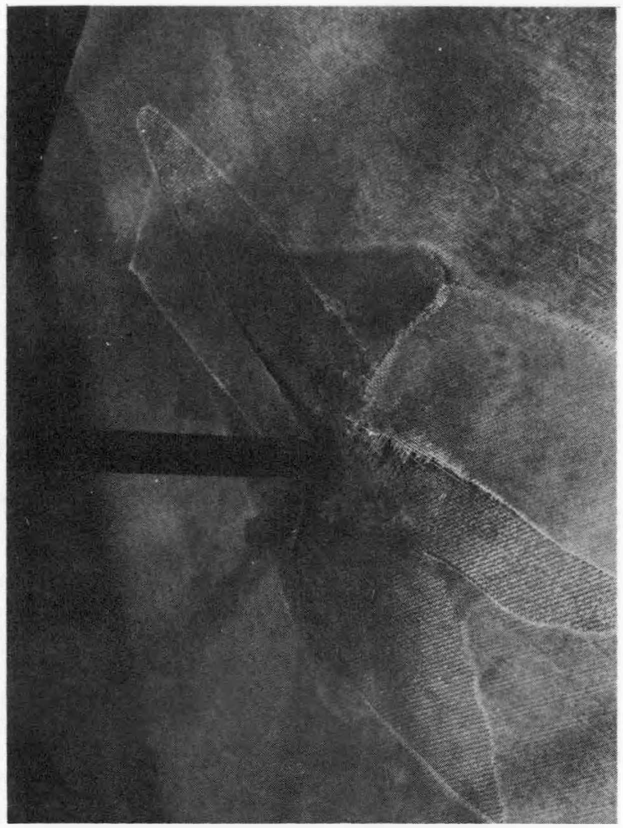


Figure 9. - Panel after high-current damage evaluation test. (From ref. 4.)

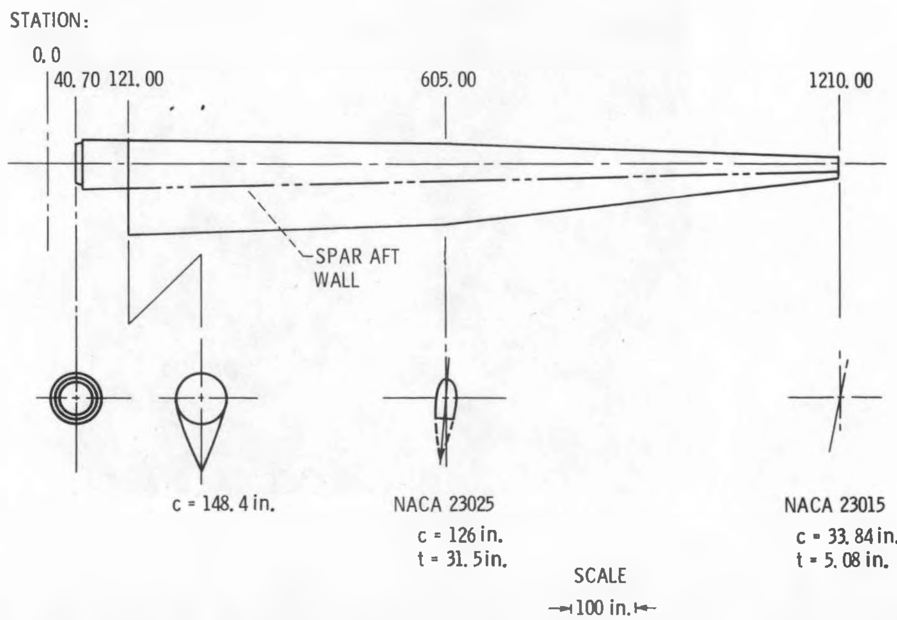
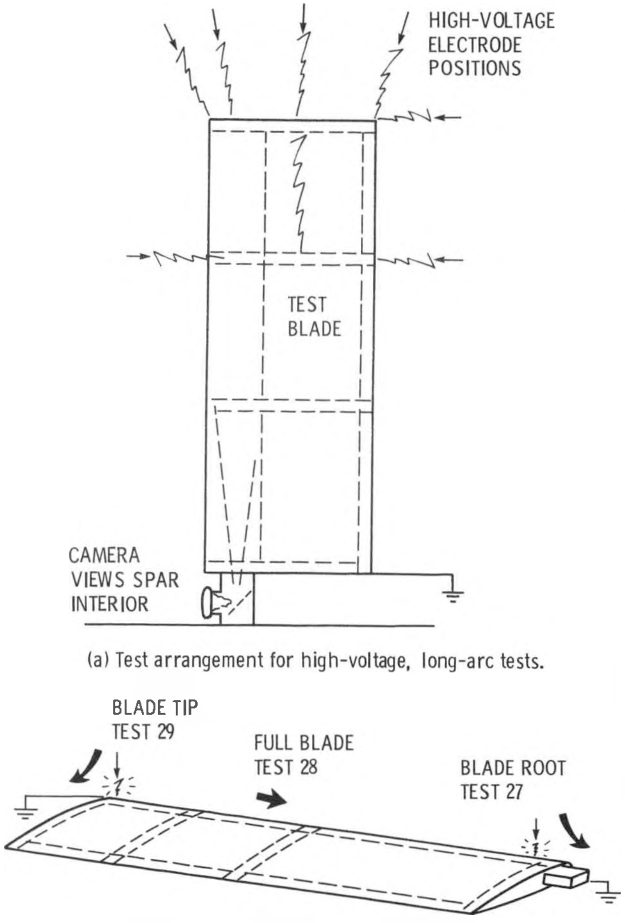


Figure 10. - Kaman blade structure. Linear twist, root to tip, 11°.



(a) Test arrangement for high-voltage, long-arc tests.

(b) Test arrangement for high-current tests of blade.

Figure 11. - Test sample and setup at Lightning and Transients Research Institute.

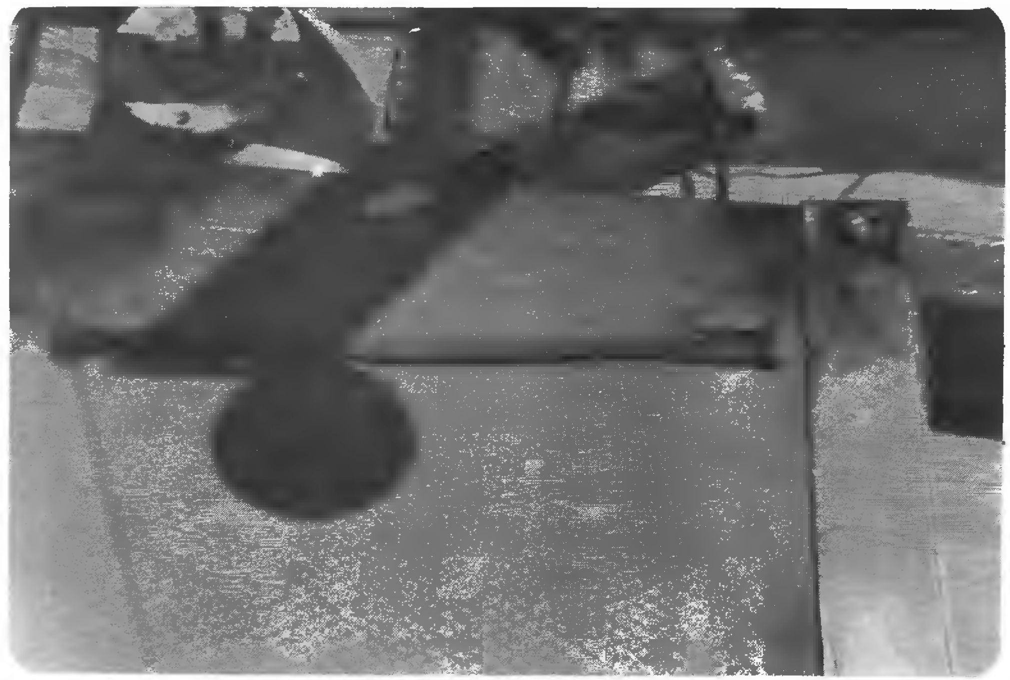


Figure 12. - Mechanical pinching effect on flat braided cable.