FABRICATION OF EXTRUDED VERTICAL AXIS TURBINE BLADES

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An important component of the modern Darrieus type vertical axis wind turbine is the extruded aluminum blade. This is made possible by the requirement that they be hollow, of constant airfoil shaped cross section, and be capable of being bent into a near-troposkein shape about the flatwise axis. They should be light weight, strong, and need a minimum of maintenance. These characteristics describe some important attributes of aluminum alloy extrusions.

Alcoa initiated its wind energy program in 1976 with the fabrication of extrusions for Kaman Aerospace, who furnished the original NACA 0012 53.3 cm (21 in.) chord blades for Sandia Laboratories' 17 m research VAWT.[1] A typical section of these blades (Fig.1) contains a D-shaped nose extrusion and vee-shaped trailing edge extrusion. Honeycomb provides the filler for the balance of the blade section, and the assembly is covered with glass fiber reinforced plastic.

Alcoa Laboratories also furnished formed hollow extruded 15.3 cm (6.03 in.) chord blades for the Sandia 5 m research machine shown in Fig. 2. The blades were extruded as 6061-T4, bent to the straight-curve-straight approximate troposkein contour, and age hardened to -T6 temper.[2] Several other sets of these blades have since been furnished for other experimental and commercial VAWT projects.[3]

A unique project involving a 10 kw Darrieus VAWT is now in operation at Clarkson College in Potsdam, New York. (Fig. 3) The Mechanical Engineering Department at Clarkson sponsored a program with contributions from Agway, Alcoa, Allen-Bradley Company, Chromalloy Farm Systems, Niagara Mohawk Power Company, Reliance Electric Company, Sign-X Laboratory, PCB Piezotronics Corporation, and Unarco-Rohn Tower Division, in which the VAWT is mounted on a typical silo. The silo provides a solid base and extra elevation to take advantage of the increased wind power at moderate elevations. The special cantilever mounting system places the rotor above the top of the silo, where there are few, if any obstructions to the wind, and no guy wires are used which would obstruct normal farming operations.

In late 1978, Alcoa Laboratories furnished a set of 61 cm (24 in.) NACA 0015 blades to Sandia for the 17 m research turbine. These blades were extruded in 24.5 m (80 ft.) lengths in alloy 6063-T6, and formed by Alcoa personnel at Sandia. The forming press was shipped on a low-boy trailer and set up in a vacant hangar where the forming was completed. An overall view of the forming setup is shown in Fig. 4. The 61 cm blade is nearly complete in this photograph.

Alcoa's Lafayette, Indiana extrusion facility is one of the largest in the world, containing a number of presses and associated equipment, including two extrusion presses of 14,000 ton capacity. Utilizing this large equipment, we have demonstrated the capability to produce 74 cm (29 in.) chord blades, large enough to equip a turbine with rated power over 500 kw. Fig. 5 shows the 74 cm blade beside the 15 cm blade for comparison.

An intermediate blade size with a 35.5 cm (14 in.) chord width is available for VAWTs in the 30 to 90 kw capacity range.

The design breakthrough came in 1976, when experimental data was made available that showed that mass balance at the quarter-chord point was not necessary for Darrieus vertical axis turbine blades. [(2) (4)] This discovery permitted design of cost-effective extrudable blade shapes. Some of the basic principles of the extrusion process may help explain how this is accomplished.

The extrusion process is basically hydraulic--causing hot plastic metal to flow through a die under pressure. Extruded shapes fall into three classes--solid, semi-hollow, and hollow. Solid shapes have no internal voids such as bars or angles; semi-hollows are solid shapes that have deep channels like window framing members; hollow shapes have totally enclosed voids, for example, tubes or our blade extrusions.

We have different size presses for a variety of reasons. Harder alloys require more pressure, larger sizes of shapes require large dies and presses to handle them, and some shapes are just harder to extrude than others and require more pressure.

In Fig. 6, the basic solid shape die set is shown, consisting of die, die holder, die block and tool carrier. All this fits into the press cylinder. The hot metal billet is pressed against the die and under sufficient pressure flows through the tee-shaped opening and exits down the runout table as a structural tee.

To make hollow shapes, the die is either a bridge or porthole die. (Fig. 7) The bridge or front die is used to support a mandrel at the center of the external opening, and the metal flows between the mandrel and the die to form the inside and outside contour of the hollow. Only certain alloys like 6061 or 6063 can be used in this process because the billet is actually split into segments in the front die and welded back together inside the die under the heat and pressure of extrusion. Other alloys do not attain sound welds under these conditions. The desired shape emerges as a one-piece hollow extrusion, ready for heat treatment and final straightening. Alloy 6063-T6 is a moderate strength, ductile material and can be fabricated in many ways. The VAWT blade extrusion is normally shipped in approximate 12 m (40 ft.) lengths, although longer lengths up to 26 m (85 ft.) are available on special inquiry. These are bent to the contour of the approximate troposkein using a large hydraulic three-point bender. After the desired contour is reached, they are cut to exact length and prepared for joining or terminating.

A typical blade design is that evolved from the low-cost 17 meter VAWT we are doing for DOE.[5] The turbine operating and loading requirements resulted in the design of the 61 cm chord blade. (Fig. 8) It is a 6063-T6 hollow extrusion with a weight of approximately 27 kg/m (18 lbs/ft). Economic considerations of size, truck trailer length, handling and fabricating suggested limiting the piece length to about 12 m (40 ft.).

Blade end-to-end splices (Fig. 9) will be required when the total length between points of attachment is longer than the shipping length of 12 m (40 ft.). Stress analysis of the blade at maximum crisis load (75 rpm, 35 m/s) and buckling under maximum survival wind gust load (67 m/s) showed that the joints can often be safely located in a minimum stress zone. The lengths of the blade sections will be finally adjusted to obtain this position for the joints. These stresses are approximately 22 Mpa (3200 psi) in tension due to centrifugal forces, combined with $\pm$ 12.4 Mpa (1800 psi) in bending due to aerodynamic loads. The bending loads are cyclic, depending upon whether the blade is at a position of maximum or minimum lift. Insert sections are sized and proportioned to satisfy fatigue strength criteria and a flatwise bending stiffness across the joint. The extruded inserts of 6061-T6 alloy have been designed to fit closely into each of the hollows in the blade. Counter sunk head blind rivets will be used to attach the inserts to the blade, and a layer of epoxy will be applied before riveting in place to prevent movement which can lead to fretting fatigue failures. When finished, the joint will present an airplane wing appearance, have minimum aerodynamic resistance, and fulfill structural design criteria of restoring full tensile strength across the joint.

The solid blade-to-torque tube connection (Fig. 10) is the result of several design iterations prior to selection of the final concept. These have included socketed type connections which employed metal castings that were welded and/or bonded to the ends of the extrusion, flexible connectors which allowed the blade to float, epoxy bonded systems which were safety clamped,and mechanical clamping techniques that enabled the blade to be rigidly attached to the central torque tube mounted to the central tower.

Analyzing the forces, it became apparent that the loads were not difficult to resist. However, it was estimated that the connection may undergo one billion stress cycles during the 30-year life of the turbine. For this type of life cycle criteria, it was necessary to reduce component fatigue stresses to an absolute minimum.

This fitting was required to be rigidly connected to hardware which attached to the torque tube. Concepts employing cast or welded members for this connection became very large and expensive and were ultimately abandoned. As the concept evolved, the use of a simple end fitting on the rotating torque tube, together with a trusslike stiffener, allowed the connector parts to be simple to fabricate, easy to procure from common stock, and relatively light in weight. Additionally, the aerodynamic drag of this rotating mass was reduced by opening this attachment area to allow air to pass through. This stiffener can then be welded to one of the torque tube flanges in the factory or sandwiched between the mating flange surfaces and secured to the flange using the flange through bolts in the field.

The blade assembly is bolted to the bracket and the stiffener. Safety devices on the fasteners are used to prevent them from loosening during service.

The most unique element of this blade connector is an extruded aluminum blade attachment fitting comprised of two extrusions, approximately 2 m (6 ft.) long, which are welded to the ends of the straight blade sections. The welded attachment was first conceived to grip the blade at the extreme leading and trailing edges and transfer the loads to the end fitting. Upon closer study, concern developed that the extreme fiber tensile stress in the trailing edge would not be capable of withstanding the estimated billion-cycle fatigue criteria. Moving the attachment point inward linearly reduced the weld joint fatigue stress, thereby improving reliability for 30 year life without blade replacement. Care should be taken to assure that this blade assembly weld is surface ground and peened to reduce any stress risers. This surface was tapered to ensure a gradual stress transition. This design is considered to be a cost-efficient, sound approach to a complex problem, and will be used for the four demonstration machines expected to be constructed on this contract.

Marketing studies [6] have already given us information about future generations of large wind energy conversion systems, and the emphasis of this workshop is on these large machines. It is of interest, therefore, to consider what role extruded blades can play in the future for large vertical axis machines. (Fig. 11)

The first composite blades by Kaman Aerospace showed the feasibility of using extrusions with other high strength structural materials. It is reasonable to expect that airfoils of about 1.5 m chord could be fabricated with one or more extrusions and honeycomb intermediate structures.

We are also looking at extrusion designs to be used together and with heavy sheet or plate components (Fig. 12) Assembly tolerances and joining practices will require significant investigation, because typical assembly dimensions would be in the range of 23 cm across the blade, and standard extrusion tolerances would be $\pm$ 0.16 cm. Further, twist and bow tolerances need to be considered. These shapes are long and flexible, so standard twist tolerances of 3 to 5 degrees should be satisfactory. Bow is the longitudinal deviation from a straight line and is more critical for long assemblies. The industry standard bow tolerance in a 12 m length is 1.0 cm, so jigs and fixtures need to be designed to pull in at least this much.

Consideration of blade-to-blade joints and blade-to-tube terminations will be needed. A concept that has been proposed but not completely designed would look like a bolted pipe flange, except, of course, airfoil shaped, which would be welded to the blade ends and mated in the field in a straightforward manner. The largest area of question in this design is the design of the welded joint at the leading and trailing edge where blade stresses have been calculated to reach 55 Mpa (8000 psi) to 62 Mpa (9000 psi). Blade-to-torque tube assemblies using the reinforced stiffener should be relatively easy to make, based upon our current experience.

These ideas are still being improved upon and by no means are the only ones to be considered. We have attempted in every case to consider field application problems and avoid the very sophisticated where factory-controlled environment is needed. Consultation with erection engineers and other building construction disciplines has been helpful in pointing out pitfalls before they become designed in, and costly to accomplish.

Alcoa supports development of our wind energy resource in the the most practical way possible, and hopes that these blade design efforts will help provide a cost-effective component in its development.

References

(1) Borzda, J. J., "Blade Design and Fabrication of 17-m VAWT" Vertical-Axis Wind Turbine Technology Workshop, Pgs. II - 205-221, May, 1976.

(2) Ai, D.K., "A Low Cost Blade Design for a Darrieus Type Vertical-Axis Turbine", Wind Technology Journal, Vol. 2, Spring-Summer, 1978.

(3) Rollins, J.P., Kear, E.B.,Jr., "Progress Report on Silo-Supported Darrieus Wind Turbine" presented at Annual Meeting American Wind Energy Association, Hyannis, Massachusetts, September, 1978 (To Be Published).

(4) Ham, N.D., "Aeroelastic Analysis of the Troposkein-Type Wind Turbine" Vertical Axis Wind Turbine Workshop, Pgs. II - 185-204, May, 1976.

(5) Ai, D.K., et al, "Design and Fabrication of a Low Cost Darrieus Vertical-Axis Wind Turbine System, Phase One-Technical Report", U.S. Department of Energy Cont. EM-78-C-04-4272, 1979 (To Be Released).

(6) Garate, J. A., "Wind Energy Mission Analysis" Proceedings, Third Wind Energy Workshop, Vol. 1, p. 209-218, J.B.F. Scientific Corp., 1977.

Discussion

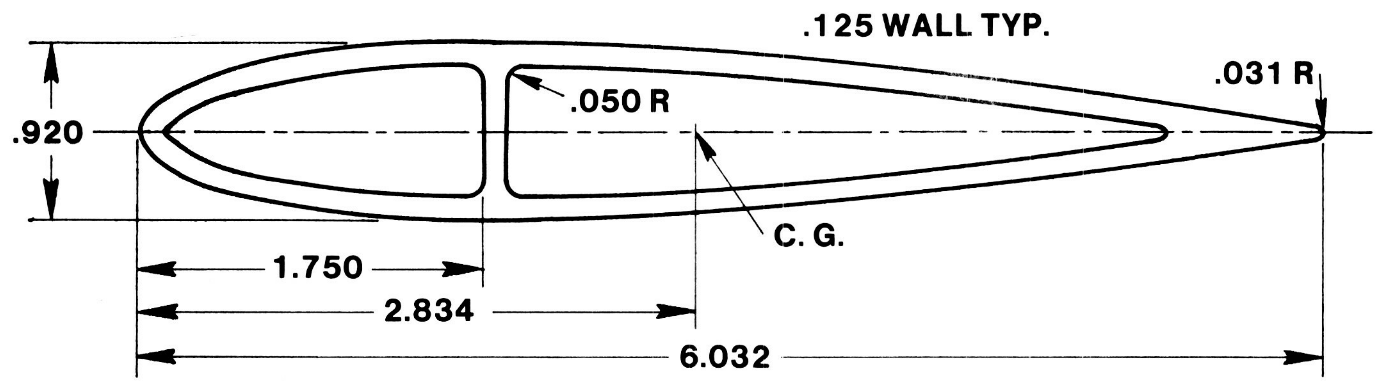
Q. Has the effect of residual stresses from bending on the overall strength of the blade been investigated?

A. This problem has been recognized and evaluated in a qualitative sense. The bending operation is confined to the outer periphery which is a relatively low stress area where the combined stresses would not be expected to approach the endurance limit. During bending, we use shaped dies to avoid developing kinks or sharp corners which would create stress concentrations.

Q. The reason for the previous question concerns the effect of surface defects in the extrusion causing increased stresses. What is the type of surface finish in the as-extruded condition?

A. Quality control procedures during ingot production, die construction, extrusion and final inspection are constantly on the alert to avoid surface defects such as die lines or inclusions. These are nearly always detected and corrected or replaced at the plant. Surface finish standards call for 100-150 RMS finish on the as-extruded exterior surface, with no individual defect exceeding .002".

Figure 1. Kaman blade cross-section.



COORDINATES

X	Y	X	Y
.000	.000	1.838	.460
.020	.076	2.450	.444
.077	.145	3.063	.405
.153	.200	3.675	.349
.306	.272	4.288	.281
.459	.322	4.900	.201
.613	.359	5.513	.111
.919	.409	5.819	.062
1.225	.439	6.005	.031
1.531	.455		

Figure 2. - Alcoa 6 inch (0.15 m) all aluminum blade (all dimensions in in.).

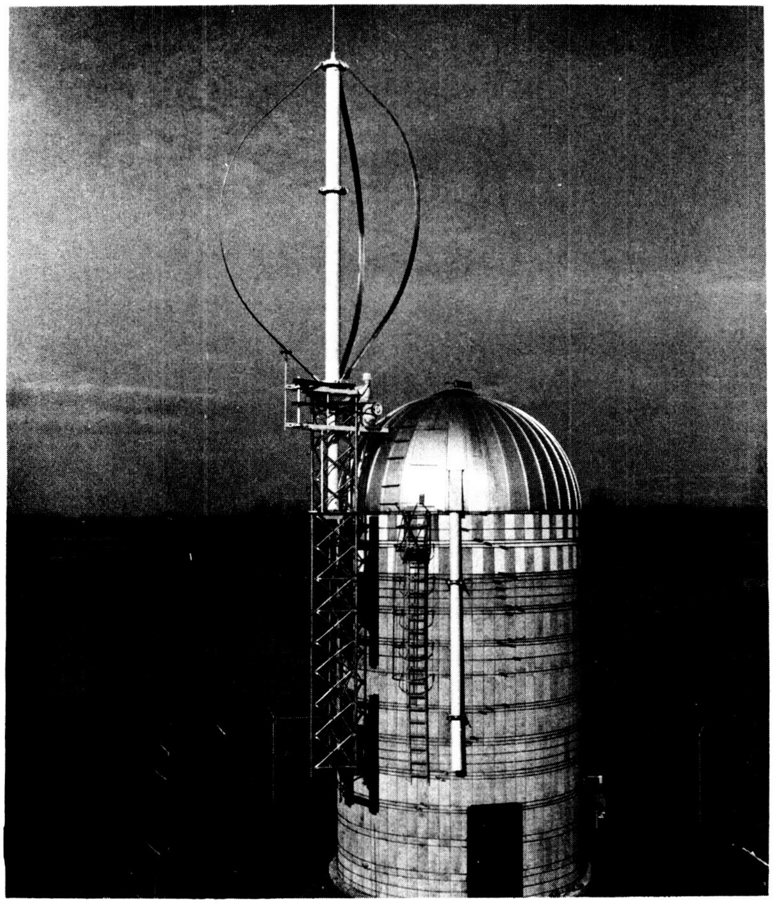


Figure 3. Clarkson College silo-mounted VAWT.

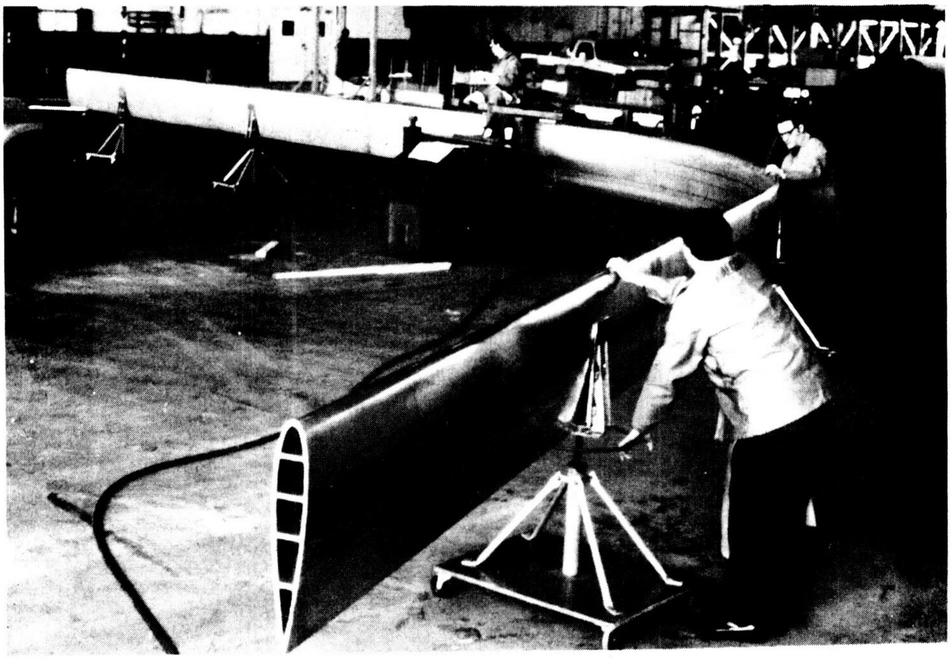


Figure 4. Alcoa 61 cm (24 in.) blades formed at Sandia Laboratories.

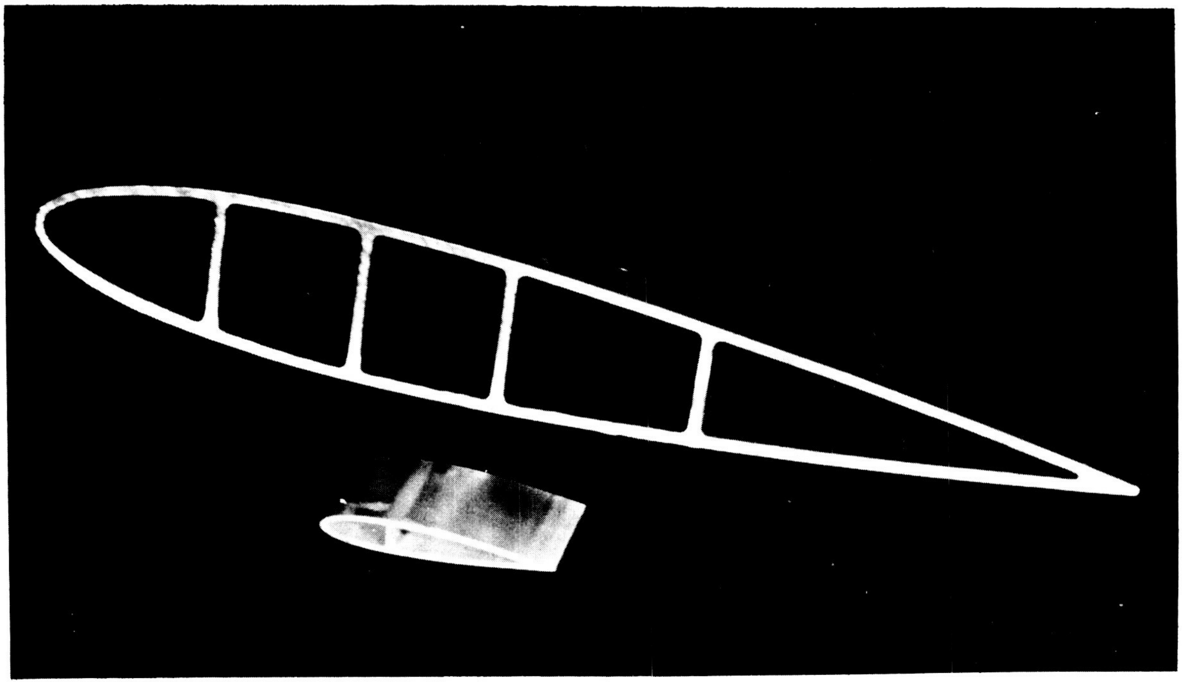


Figure 5. Alcoa 74 cm (29 in.) and 15 cm (6.03 in.) blades.

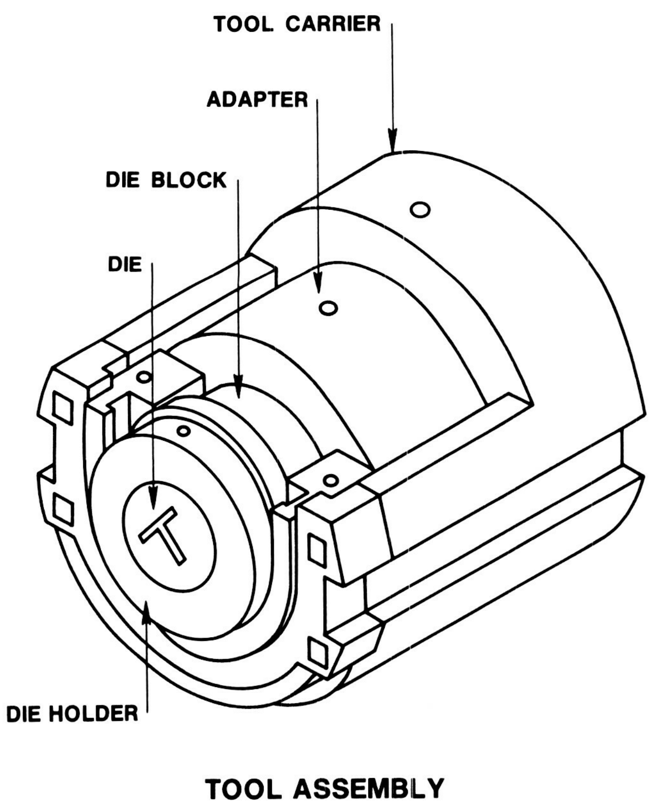


Figure 6. Typical solid die set.

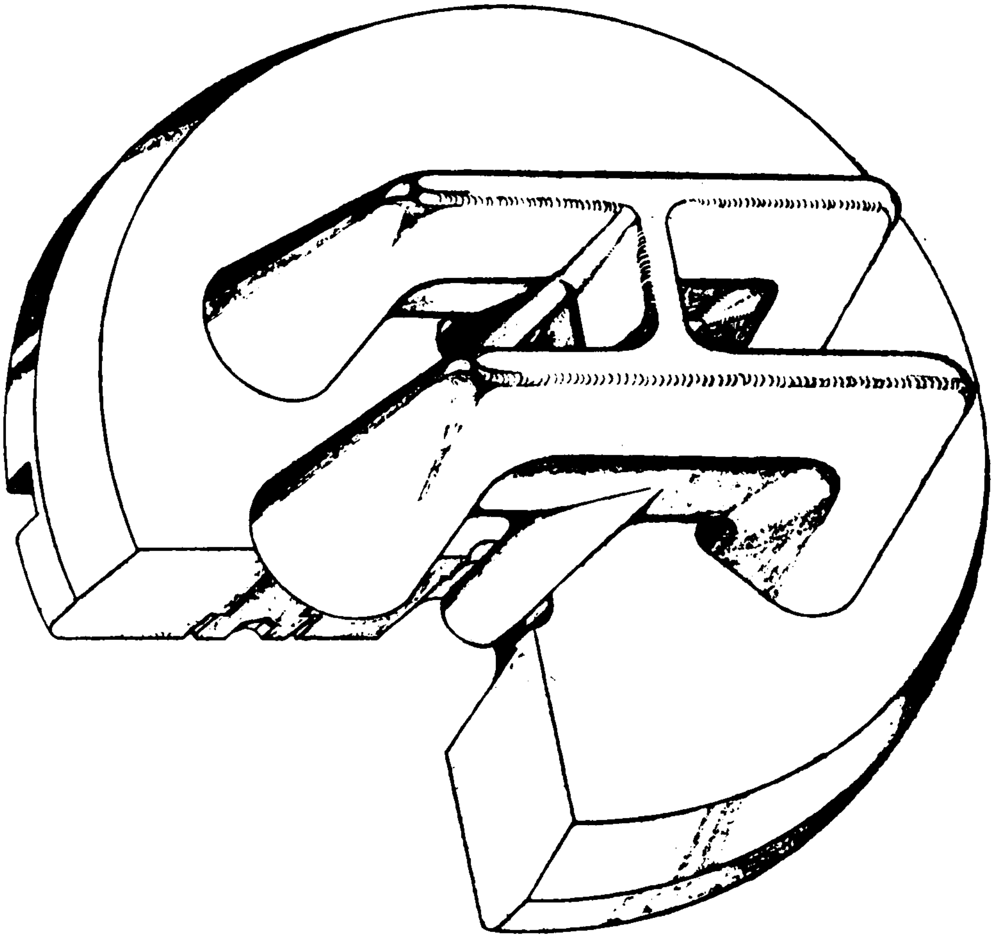
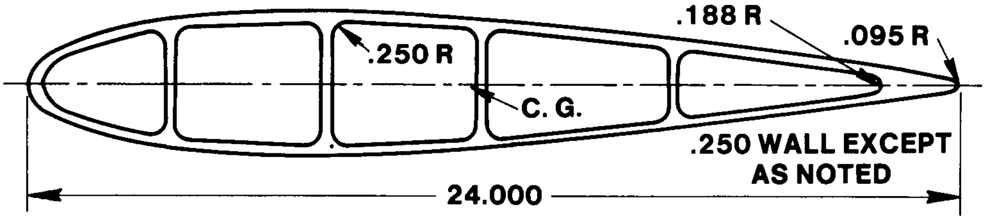
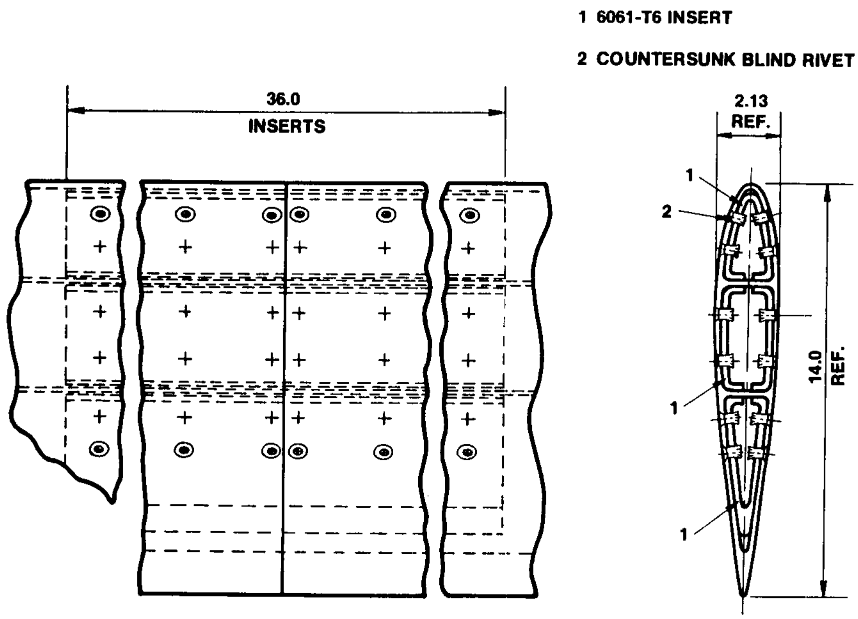


Figure 7. Typical bridge die assembly.



BLADE CROSS SECTION

Figure 8. Alcoa 61 cm (24 in.) blade section.



FLUSH BLADE-TO-BLADE CONNECTION

Figure 9. Typical end-to-end blade splice.

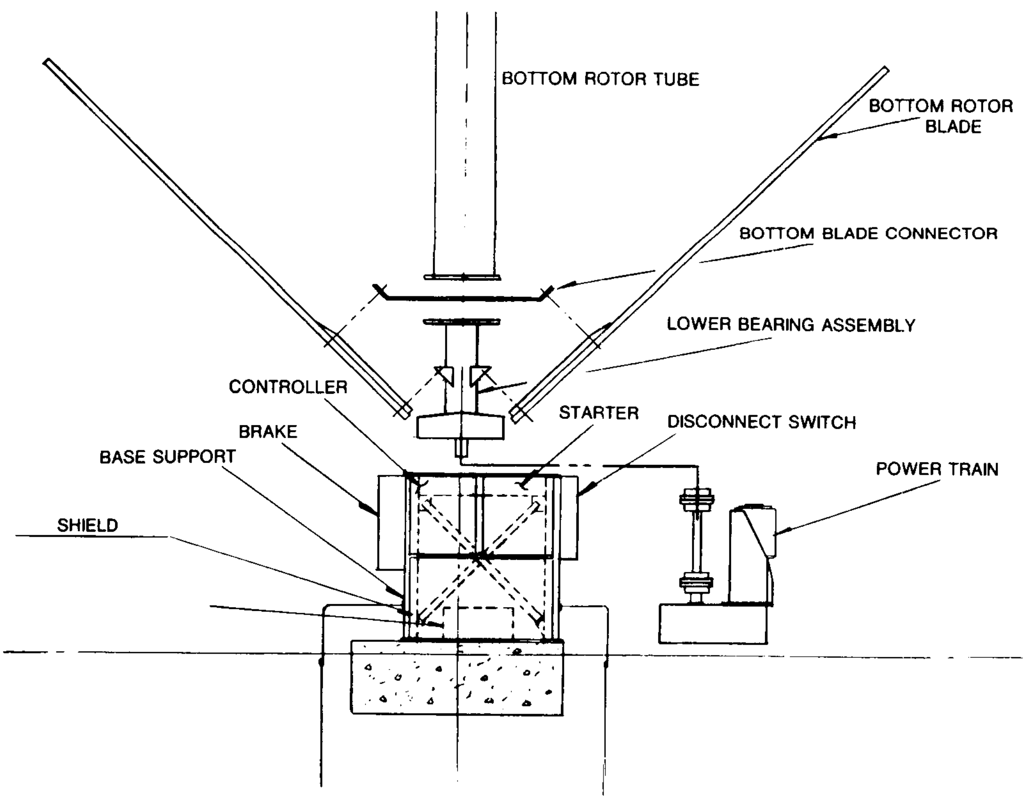


Figure 10. Reinforced blade/torque tube connection.

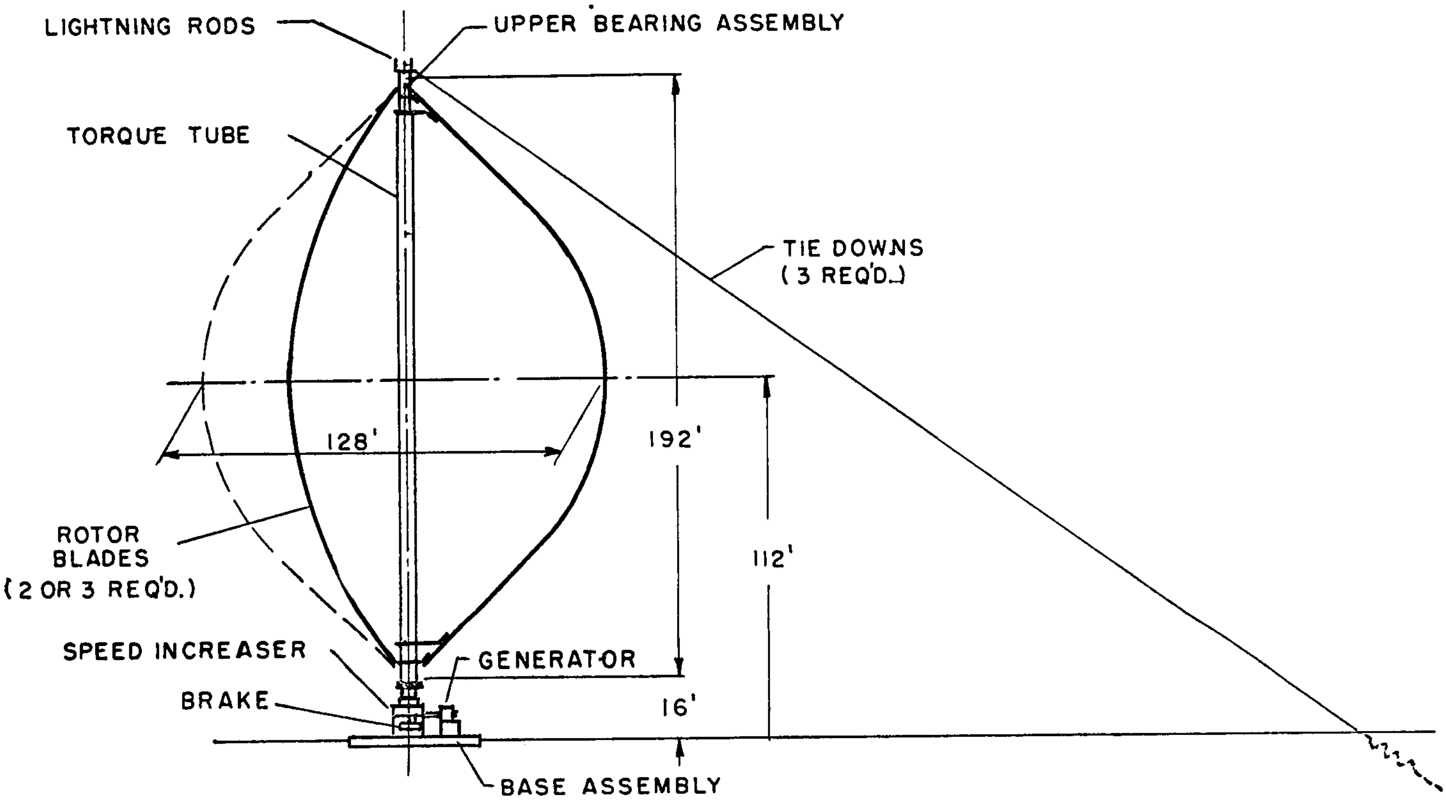


Figure 11. - Nominal 1 MW ALVAWT. Alcoa vertical axis wind turbine.

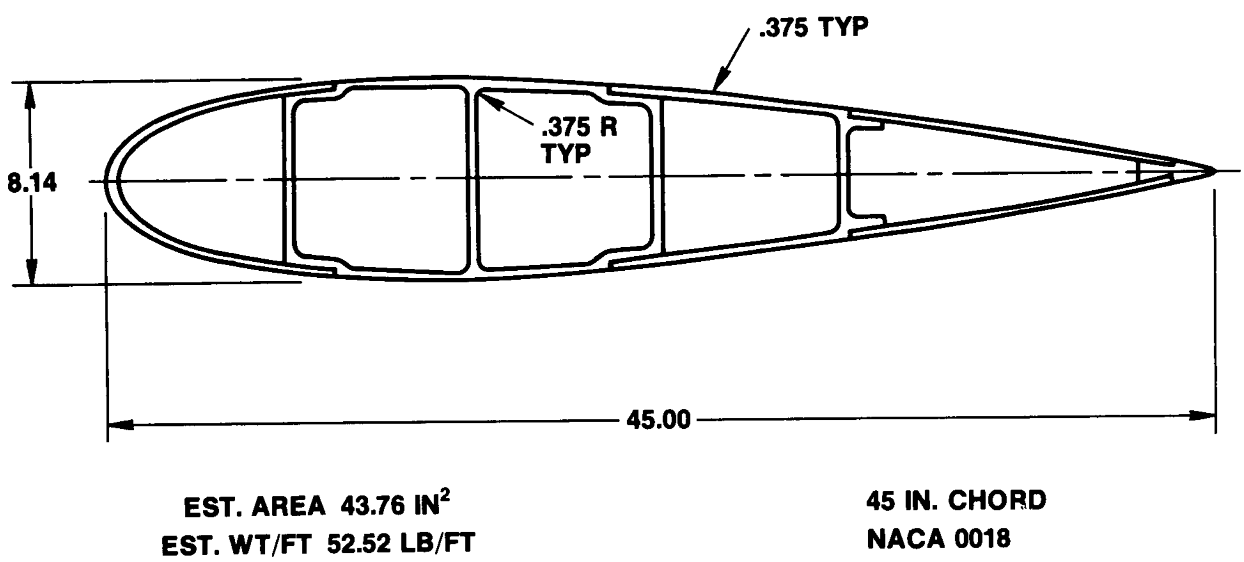


Figure 12. Alcoa 115 cm (45 in.) chord blade.