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FIBERGLASS COMPOSITE BLADES FOR THE 2 MW MOD-1 WIND TURBINE GENERATOR

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ABSTRACT

In mid-1979, NASA contracted with Kaman Aerospace Corporation for the design, manufacture, and ground testing of two 100 foot composite rotor blades intended for operation on the Mod-1 wind turbine. NASA stipulated that the blades utilize, to the maximum extent practicable, the technology developed in a forerunner program in which Kaman produced a 150 foot test blade.

The Mod-1 blades have been completed and are currently stored at the Kaman facility.

This paper describes the design, tooling, fabrication, and testing phases which have been carried out to date, as well as testing still planned. Discussed are differences from the 150 foot blade which were introduced for cost and manufacturing improvement purposes. Also included is a description of the lightning protection system installed in the blades, and its development program.

Actual costs and manhours expended for Blade No. 2 are provided as a base, along with a projection of costs for the blade in production. Finally, cost drivers are identified relative to future designs.

INTRODUCTION

Thus far, large U. S. wind turbine generators have utilized rotor blades made from metal or wood, since the technology involved in these materials is well understood. However, the use of composite construction has long been considered to also have excellent potential for large blades. The advantages of glass fiber reinforced composite structure include:

- Nearly unlimited design flexibility in adopting optimum planform tapers, wall thickness taper, twist, and natural frequency control
- High resistance to corrosion and other environmental effects
- Low notch sensitivity with slow failure propagation rate
- Low TV interference
- Low cost potential due to adaptability to highly automated production methods.

Composite construction has been in successful use for some years in helicopter rotor blades. To assess the state of composite technology for wind turbine blades, especially in the very large sizes, NASA contracted with Kaman Aerospace Corporation in 1977 to design, build and ground-test a 150 foot all-composite blade. This program (see Reference) was accomplished successfully; i.e., design and manufacturing methods were developed, the blade constructed, and measurements and structural testing confirmed that the design analysis methods had satisfactorily predicted the strength and dynamic characteristics of the final article. The 150 foot blade is the largest composite rotor blade ever constructed.

Based on the encouraging results with the 150 foot blade, NASA decided to extend the investigation of composite blades into an operational test phase. Accordingly, NASA contracted with Kaman, in mid-1979, to design and build two 100 foot blades to be installed and evaluated on the Mod-1 wind turbine in Boone, N. C. NASA stipulated that these blades were to directly utilize the technology developed in the 150 foot blade program; i.e., they were to be designed and manufactured using the same methods and basic structural configuration. In this program, NASA assumed responsibility for assuring compatibility of the blades with the Mod-1 system; to this end, NASA provided all design load cases and interface parameters. Kaman's task was to carry out the structural design and analysis, manufacture the tooling and the blades, and conduct limited ground testing prior to delivery.

SUMMARY

At this writing, the design and construction phases of the Mod-1 composite blade have been successfully accomplished. The two blades are completed, as shown in Figure 1, and are stored at the Kaman facility pending availability of funds for completion of the ground-test phase of the contract, followed by shipment and installation on Mod-1. The 150 foot blade, which preceded the Mod-1 blades, is shown in Figure 2.

Two primary constraints were influential in the design; first, the blades were to directly utilize the 150 foot blade technology, and second, the composite blades were required to match the static and dynamic characteristics of the steel blades they are to replace. The latter requirement proved to be particularly challenging since the modulus of elasticity of the composite is approximately one-sixth that of steel. Considerable care was thus required in selecting cross sections and wall thicknesses of the spar, which is the blade's main structural element. Achieving appropriate stiffness and dynamic properties was greatly facilitated by the nature of composite construction which readily permitted dimensional variation to be built into the spar as required.

The Mod-1 blades utilize wound fiberglass Transverse Filament Tape (TFT) for the spar, a material used in the commercial pipe industry and further developed for the 150 foot blade. The afterbody portion of the airfoil is comprised of upper and lower panels of fiberglass and paper honeycomb sandwich construction. Means of attachment to the wind turbine hub is provided by a steel adapter fitting, permanently mounted in the blade spar at the inboard end. Use of an aft spar member at the trailing edge, such as that employed in the 150 foot blade, is eliminated in the Mod-1 design for simplification and cost saving. A lightning protection system is incorporated in the Mod-1 blades. The system was developed under the contract, using the services of a lightning test laboratory for developmental testing and substantiation of the design. This was a new development, not having been provided in the 150 foot blade. The resulting protective system has been shown capable of sustaining the 200,000 ampere stroke level specified by NASA.

The blades were weighed and CGs measured. Final blade weight is 26,846 lbs which represents an increase over the steel blade weight; however, since the spanwise CG location is farther inboard than that of the steel blade, the growth in mass moment is minimal and satisfactory for Mod-1 use.

Certain planned testing of the finished blades, and installation of the required instrumentation, is being held in abeyance pending DOE funding for continuation of the Mod-1 wind turbine program.

Cost of manufacturing the Mod-1 blades was carefully tracked. Blade No. 2, which is considered the more representative base case, cost $307,000. This projects to approximately $5.70/lb for the 100th blade with appropriate tooling and the application of a learning curve. The requirements to utilize the 150 foot technology and to match the steel blade's properties, represent some compromise to production design and, hence, to cost. Elimination of this effect could reduce the above cost per pound figures by 25 to 30%.

DESIGN

Design Concept

NASA retained responsibility for the interface of the blade to the wind turbine. To assure compatibility, NASA provided all design parameters, as well as the static and fatigue load cases required by Kaman to carry out the structural design.

Also stipulated was the basic configuration of the blade, which was required to utilize the design features of the 150 foot blade to the maximum extent. However, as the design process evolved, Kaman recommended certain changes to the configuration to introduce more recent thinking in blade construction and to effect a reduction of complexity and cost. One such change, concurred in by NASA, was elimination of the trailing edge as a primary structural member reacting edgewise bending. This allowed deletion of a trailing edge spline, as well as the inboard truss structure necessary to accommodate spline loads in the 150 foot blade. In the Mod-1 blade, the forward spar was increased in its chordwise dimension to serve as the main structural member, carrying the primary loads. Afterbody panels react only local airloads.

The requirement that the Mod-1 blades duplicate stiffness and natural frequency characteristics of the Mod-1 steel blades, resulted in growth of the blade inboard beam thickness to effect the necessary sizeable increase in section moment of inertia. Chord length was required to grow in proportion; thus, the blade's planform and root thickness represent the most evident difference from the Mod-1 steel blade. This entailed some compromise in performance, weight, and cost from an optimized blade design.

Configuration

The Mod-1 blade is shown in Figures 3 and 4 which depict the planform and cross section.

Critical Structural Areas

Spar Buckling

Discussed earlier was the required stiffness match of the composite blade and steel blade. Since stiffness is a function of the product EI, and the E value for the glass fiber/epoxy composite is approximately one-sixth that of steel (5×10^6 psi vs 29×10^6 psi), it was necessary to provide a compensating increase in I by means of larger cross sections. However, with blade weight also a prime consideration, the wall thickness of the larger size shell had to be held to a minimum; thus the critical design consideration became buckling or wall crippling in a thin-wall shell. Fortunately, Kaman's analytical programs for design of TFT composite shells had been substantiated by empirical results of the full-scale buckling test in the 150 foot program. In addition, a trial Mod-1 spar was manufactured and subjected to further buckling tests to provide direct correlation of analysis and actual results. Thus, the final spar is considered well designed and substantiated for strength under the critical buckling load cases; these proved to be the emergency rotor overspeed and the hurricane wind condition.

In addition to providing adequate buckling capacity, the spar also was designed to meet the bending moment distribution called for in NASA's design specification.

T-Clip

The afterbody panels attach to the spar by means of a lap joint and a T-clip for the outer and inner panel skins, respectively; this is shown in Figure 4. The cavity between these attachments is filled with syntactic foam to act as a shear connection, reacting the shear loads resulting from applied airloads over the panel area.

The T-clip reacts tension loads in the panel inner skin arising from the panel reacting airloads as one member of a truss in conjunction with the lower panel, and due to bending in the panel itself. The T-clip is a structural connection whose principal design challenge lies in developing an arrangement which can be manufactured with consistent bond quality in a relatively inaccessible area. The solution proved to be a good example of a cooperative effort among engineering personnel in the design, stress, materials, and manufacturing disciplines, acting together to develop a satisfactory design. The result is considered a significant improvement in strength and consistency over the T-clip of the 150 foot blade. Development of the manufacturing technique was carried out on a full-scale section of the outboard 30 feet of the blade.

Adapter/Spar Attachment

As in the 150 foot blade, a steel adapter fitting is located at the inboard end, attached to the composite spar by means of a double row of bolts (18 total) as shown in Figure 5. A large diameter bushing is employed at each bolt, seated by means of a heavy clamp load against a spotfaced surface of the adapter fitting. Thus, the bushing serves essentially as a rigid stud, integral with the adapter fitting. Deflection of the joint under the eccentric loading, inherent in the single-shear arrangement, is accommodated by means of a taper machined in the bushing wall. This taper serves to bring about, in the deflected joint, an even distribution of bearing stress between the bushing and the composite socket.

To provide adequate bearing strength for the bolt (bushing) loads, the composition of the laminate at the root-end was carefully chosen using a Kaman finite element code for analysis. The laminate in this area is changed from that of the outboard spar by introduction of additional spanwise unidirectional as well as circumferential and $\pm 45^\circ$ materials. The result is an essentially isotropic laminate with considerable thickness buildup, to approximately 5 in. (vs 1.5 in. of the nominal spar wall). Fatigue testing of four quarter-scale specimens of this joint, begun in the 150 foot program, was carried on to intentional failure under the Mod-1 contract. Results confirmed the adequacy of the joint for the 30 year design life imposed by the design specification.

Materials Selected

The primary structural material of the spar is Transverse Filament Tape (TFT), which was also employed in the 150 foot blade. As the name implies, TFT is a fiberglass tape in which all structural fibers are aligned across the tape width, that is, perpendicular to its length. It is commercially available and has been used for some years in the manufacture of less critical structures such as wound pipe, storage tanks, etc. When wound circumferentially with an overlap, followed by a minor amount of conventional 90° windings to provide compaction and hoop strength, extremely rapid laydown of predominantly spanwise fibers is accomplished.

The TFT material is E-glass, 17 in. wide tape of 36 oz/sq. yd density. The hoop band consists of 64 rovings of S2-glass at 750 yds/lb density; S2-glass is also used in the various reinforcing layers of material added at the root-end. Because of its excellent fatigue properties under adverse environmental conditions, an epoxy resin system is utilized for the spar and for all other bonds in the blade.

Afterbody panels are lightweight sandwich construction, made from 2.3 lb/cu. ft phenolic-impregnated kraft paper honeycomb core faced on both sides with E-glass cloth/epoxy laminates.

The adapter fitting, a weldment made up of forged and rolled sections, as shown in Figure 5, is HY-80 steel. This high yield strength alloy, which was recommended by NASA materials specialists, possesses exceptional toughness, strength and ductility in the as-welded condition without the requirement for stress relief. It is widely used for construction in large, thick section applications such as submarine hulls and missile test platforms.

Lightning Protection System

A lightning system was developed by Kaman for the Mod-1 blade. No lightning considerations were included in the 150 foot blade program, so this represented a new technology development. NASA's design specification required a capability of sustaining 200,000 ampere strokes, a very stringent level of infrequent occurrence in nature.

A straightforward and effective approach could have been taken by simply covering the blade with grounded metal screening or incorporating several conductive cables to ground. However, it was considered desirable, in this wind turbine blade, to seek a more optimized approach in order to minimize cost and also to preserve the inherently low electromagnetic interference of composite blades. The latter feature would have been severely compromised by incorporation of an excessively large, metallic conductive system.

Consequently, a development program was carried out in conjunction with a lightning test laboratory, Lightning and Transients Research Institute, St. Paul, Minnesota, in which a full scale portion of the blade was tested. This included long arc strokes on the unprotected specimen, applied and photographed to identify the discharge paths which lightning strokes would take during a natural occurrence. Stroke current was kept low enough to permit repeated tests without incurring damage. These tests demonstrated that lightning protection is needed for composite blades.

A protection system was devised and installed, in stages, during subsequent long arc tests to determine the minimum configuration that eliminates discharge paths inside either the spar or afterbody cavities, since this is the critical condition which must be avoided. The final protection system thus developed, shown in Figure 6, was successfully subjected to the high current, 200,000 ampere strokes without damage.

The protection system configuration consists of a metal tip cap incorporating a short flange, or skirt, on the outside of the blade. This is connected to a single conductor cable of flattened copper braid, which is mounted along the entire trailing edge and is connected to ground through the steel adapter fitting. The copper strap is imbedded in plastic to effect a resilient attachment to the blade so as to prevent load pick-up by the strap during blade bending. A shield is provided at the inboard end, consisting of a Thorstrand® covering on the outside surface of the blade root, extending just outboard of the extreme end of the adapter fitting inside the blade. Thorstrand® is a woven cloth of aluminized glass fibers. This shield, which was not included in the developmental test program, was added as a means of preventing a build-up of pre-stroke streamers emanating from the adapter fitting within the spar, which could provide an inside path to ground for a lightning stroke attaching at the blade tip. Kaman's experience with lightning tests of helicopter blades indicates that such a shield can be effective in this manner.

It should be noted that although the system is considered substantiated for a single, high amperage stroke, the repeatability of the system has not yet been substantiated. Kaman has proposed additional testing to determine the amperage level which can be repeatedly sustained; to date this portion of testing has not been contracted.

MANUFACTURE

Blade Elements

Figure 7 depicts the various elements which comprise the Mod-1 composite blade, consisting of: spar; afterbody panels; miscellaneous closures and wraps; inboard adapter fitting; lightning protection; and paint. Manufacturing of these areas is discussed in the following paragraphs.

Spar

Construction of the spar is carried out as a single stage winding operation, utilizing a large, lathe-like machine. This system and process are illustrated in Figure 8. The primary tooling member is the winding mandrel, Figure 9, mounted as a semi-cantilever beam. Designed by Kaman as a steel weldment, this mandrel represents a departure and considerable improvement over the winding system of the 150 foot blade. The latter used a steady-rest support at approximately mid-span; this, along with the method used for spar removal, necessitated winding the 150 foot spar in four separate stages, each requiring the complete sequence of winding and curing.

Manufacturing the Mod-1 spar involved thirteen winding passes, each laying down a TFT layer followed by the hoop roving band for compaction, Figure 10. Certain of these winding passes were varied in length to produce wall thickness taper, a simple matter with the TFT winding process as compared with conventional filament winding. Additional broadgoods and TFT layers were locally introduced at the inboard end by hand layup between spanwise runs. The spar was cured using portable oven sections, assembled over the total spar, and a hot-air heating system which produced the 180° - 250°F curing temperature. Each cured spar, weighing over 18,000 lbs, was released from the mandrel by a hydraulic jack system which exerted approximately 1.5 million pounds of force against the bucking ring to loosen the cured spar.

The entire winding process for the first spar required 5.5 days, shortened to 4.5 days for the second spar. Considerable further reduction in this process would result from elimination of the extensive hand layup through implementation of production methods. Also, the use of the 36 oz/sq. yd TFT necessitated resin preimpregnation, involving pressure/vacuum cycles in a special tank to ensure full wetting of the transverse roving bundles. Kaman has experience in utilizing a lighter weight TFT in its more recent 40 kW wind turbine blades, with considerable shortening of the winding process resulting from elimination of prewetting.

Afterbody

The six curved panels were fabricated by use of an adjustable bond fixture, shown in Figure 11. This tool consists essentially of a caul plate which can be reset for each panel assembly to provide proper curvature and twist. For each panel, the preimpregnated glass cloth outer skin was first layed up on the caul, followed by the lightweight honeycomb core material; the panels varied from 3 in. to 1 in. thickness for each spanwise set. The inner skin was then layed up, followed by curing of the panel assembly in an autoclave at 250°F.

The afterbody panels were assembled to the spar using the same bonding fixture developed for the 150 foot blade. This consists of a series of formed wooden cradle headers, modified for the Mod-1 contour, and a movable upper steel frame which reacts forces exerted by pneumatic hoses in bonding the lap joint of the outer panel skin to spar. The inner skin was bonded to T-clips which were preassembled to the aft wall of the spar; the T-clips themselves were layed up as two individual angle legs. Bond pressure for the clip-to-panel joint was applied by use of temporary backing plates drawn tightly into place by mechanical fasteners.

The remaining step in the panel installation consisted of injecting the syntactic foam material through temporary holes in the outer skins.

Closures and Wraps

The trailing edge closure consists of a three-ply cloth layup over the full length, cured under vacuum pressure.

Panel-to-panel joints take the form of large ten-ply overwraps which comprise full circumferential bands around the spar and afterbody. Five such bands were required by NASA as a secondary means of retaining the afterbody in the event of any loss of integrity in the panel/spar joint.

The inboard closure member is a flat panel, built as a skin-honeycomb-skin sandwich in the same manner as the afterbody panels. Edge closure of the triangular panel utilizes seven layers of cloth doubler material; this build-up serves to carry afterbody secondary loads forward into the spar.

Adapter Fitting

As shown in Figure 5, the steel fitting is constructed as a weldment in three sections, a forged ring and two rolled rings, the latter being 1.25 in. and 1.5 in. thick. Welding was multiple-pass shielded arc.

The end bolt circle, being critical for field attachment to the Mod-1 rotor hub, was drilled using a drill template. An identical template was provided, and checked by NASA against the actual hub in Boone, North Carolina, as an additional dimensional confirmation of this essential joint.

The adapter fitting was installed into the spar end using optical tooling for alignment of the fitting axis with respect to the spar quarter-chord axis, and for pitch orientation. Used as a reference in this process was a template placed inside the spar at the three-quarter blade span station. By means of this system, the two blades were matched to within $0°1.6'$ angularly, and $0°3.6'$ in pitch.

Epoxy adhesive was injected into the voids around the fitting, once it was aligned, to act as a liquid shim to ensure an intimate fit of the adapter in the as-wound spar socket. Temporary bolts were then used to hold the fitting in place while the main bolt/bushing holes were drilled. This consisted of locating and boring each hole to final size and perpendicularity with respect to the adapter fitting. A Bridgeport boring head was mounted on the adapter fitting for this process. The bolts were torqued by means of a hydraulic torque wrench, using measured bolt stretch as the criterion for achieving proper tension.

Lightning Protection System

Each tip cap was built as a sheet metal, welded assembly fitted to the blade end. The trailing edge ground strap was constructed of a flattened braided copper tube, around which was molded a thermoplastic coating using a platen press. The plastic-encased strap was then bonded to the underside of the blade, at the trailing edge, and overwrapped with a two-ply cloth layup. The Thorstrand® layer at the inboard end of the spar was wound in-place during the spar fabrication process.

Paint System

All portions of the blade are protected with an epoxy primer and polyurethane top coat. This paint system has been found effective in helicopter blade use to protect against environmental attack, including the ultraviolet sunlight influence on resin.

The outboard one-third of the leading edge has a built-up heavier layer of the polyurethane outer coat, to a thickness of 8 - 10 mils. Again based on helicopter technology, this material and thickness have been found to provide effective protection against erosion due to sand and rain impingement.

TESTING

Developmental testing carried out to date under the Mod-1 program consisted of:

Full-scale spar buckling

Quarter-scale fatigue, adapter-to-spar joint

TFT laminate material characterization, static coupon

Weight and balance, finished blades.

The weight and balance measurement, noted above, established the total weight and spanwise CG only, chordwise CG having been determined analytically. Results of the measurements were:

Blade No. 1	25,698 lbs at sta. 354.9
Blade No. 2	26,846 lbs at sta. 360.2

The weight difference of 1,148 lbs is larger than had been anticipated analytically from variations to be expected in the weight of components. The growth is considered primarily due to increased resin content observed in the second spar. A different technique for resin application and squeeze-out had been employed during a portion of the second spar's winding process. The result shows that spar weight is much more significantly influenced by the resin application technique than had been anticipated. For production spar winding, this point should be carefully addressed, and manufacturing means and procedures developed to insure consistent resin application.

Mass balancing to bring the CG difference within specification limits has not been carried out for the blades at this writing. It is anticipated that this will take the form of composite material added internally at the tip end of the spar of Blade No. 1; mass balance will be determined in conjunction with the natural frequency testing to be conducted at a future date. The added mass must be of a non-conductive material due to the lightning consideration.

Tests Planned

Certain further testing and pre-deployment tasks were included under the contract but are currently being held in abeyance by NASA due to funding uncertainty. These include:

- Static bending of finished blades: proof testing to critical limit loads in flatwise and edgewise modes
- Installation of permanent instrumentation: bending strain gage bridges inside of spar
- Calibration of instrumentation
- Natural frequency determination: flatwise and edgewise.

BLADE COSTS

In assessing the significance of the recurring costs expended for the Mod-1 blades, certain special considerations should be noted.

First, the two blades were built on soft tooling and used shop methods suitable to the manufacture of two articles only. Thus, much hand labor was employed in lieu of automated methods; an example is the hand lay-up of approximately 140 layers of broadgoods for local reinforcement at the spar root-end. For the afterbody panel installation, the critical location and orientation of the T-clips was accomplished without locating or holding fixtures. Hole preparation of the adapter-to-spar hardware was done entirely without drilling fixtures or gauges, necessitating dial indication for perpendicularity and individual diameter measurements for each of the 36 holes. Many other hand operations were employed throughout the blades.

In addition, a considerable amount of manufacturing development and tool tryout was required in building of the first blade. The second blade benefitted from this non-recurring effort and represented a more straightforward fabrication job with a minimum of further development needed. For this reason the second blade is considered the more representative baseline for the cost of the Mod-1 blade.

Records were kept of labor and materials, showing that Blade No. 2 required 5,109 manhours of shop and inspection labor and $161,000 material cost (1981 dollars). With Kaman's labor rates and overhead burdens applied, the cost was $307,000, or $11.40/lb. For comparison purposes, the 150 foot composite blade, described earlier, cost $14.50/lb (in same year dollars).

A projection of the Mod-1 cost-per-pound was made for a manufacturing run of 100 blades of the present design. This included the effect of learning curve slopes derived for each element of the blade, based on Kaman's helicopter rotor blade experience. Also introduced were the effects of modest production tooling and handling equipment. The result is a $5.70/lb cost for the 100th blade. This projection is conservative and considered readily achievable for this blade design.

It is recognized, however, that certain features of the design represent cost drivers; these resulted from NASA's requirement to retain the design approach used in the 150 ft blade, and from the special need for equivalence with the steel Mod-1 blades. The former includes such design areas as the bolted adapter fitting and the built-up afterbody assembly. More production-oriented methods have been demonstrated to improve these areas, with attendant cost reduction. For example, Kaman utilized a molded-in-place foam afterbody for the blades now operating on the Company's 40 - 65 kW wind turbine. Production methods of fabricating this type of afterbody, including the introduction of fiberglass skins over the foam, can be accomplished in a one-shot manufacturing procedure. Regarding the inboard attachment fitting, its configuration totally depends on the initial design of the blade-to-hub joint; much can be done to simplify such a connection, resulting in possible elimination of the need for a fitting altogether, or at least the discarding of a multi-bolt connection to the spar tube.

It is believed that this type of redesign will effect a reduction on the order of 25 - 35%, in the production cost of a 100 ft blade while still retaining all the benefits of composites described earlier.

CONCLUSIONS

- As the result of this program, two composite blades have been successfully produced, meeting the Mod-1 interface requirements, which will permit operational evaluation of the benefits of composites for large wind turbine blades.

- The anticipated potential of composites for reducing manufacturing and life-cycle costs in WECS blades continues to be borne out as the result of the work of this program.

- Analytical methods developed for the 150 foot blade, and refined for the Mod-1 blades, are adequate for design of operational blades.

- Similarly, the manufacturing techniques developed in both blade programs, particularly the TFT approach for applying composite materials, have been successfully utilized to produce operational blades. The method of resin application in the spar winding process will require further development in production to ensure consistent spar weight control.

- It has been determined that lightning protection is necessary for an all-composite blade. An effective protection system has been developed which meets NASA's 200,000 ampere stroke requirement.

- Cost of the Mod-1 Blade No. 2 was $11.40/lb in 1981 dollars, using soft tooling and many hand operations. Production methods and quantities would potentially reduce the cost level to approximately $5.70/lb for the 100th blade.

- A number of cost drivers have been identified which are amenable to design improvement within the present state-of-the-art, and which could further reduce production costs by 25 to 35 percent.

REFERENCE

Gewehr, H. W., "Design, Fabrication, Test, and Evaluation of a Prototype 150-Foot Long Composite Wind Turbine Blade," DOE/NASA/0600-79/1, NASA CR-159775, September 1979.

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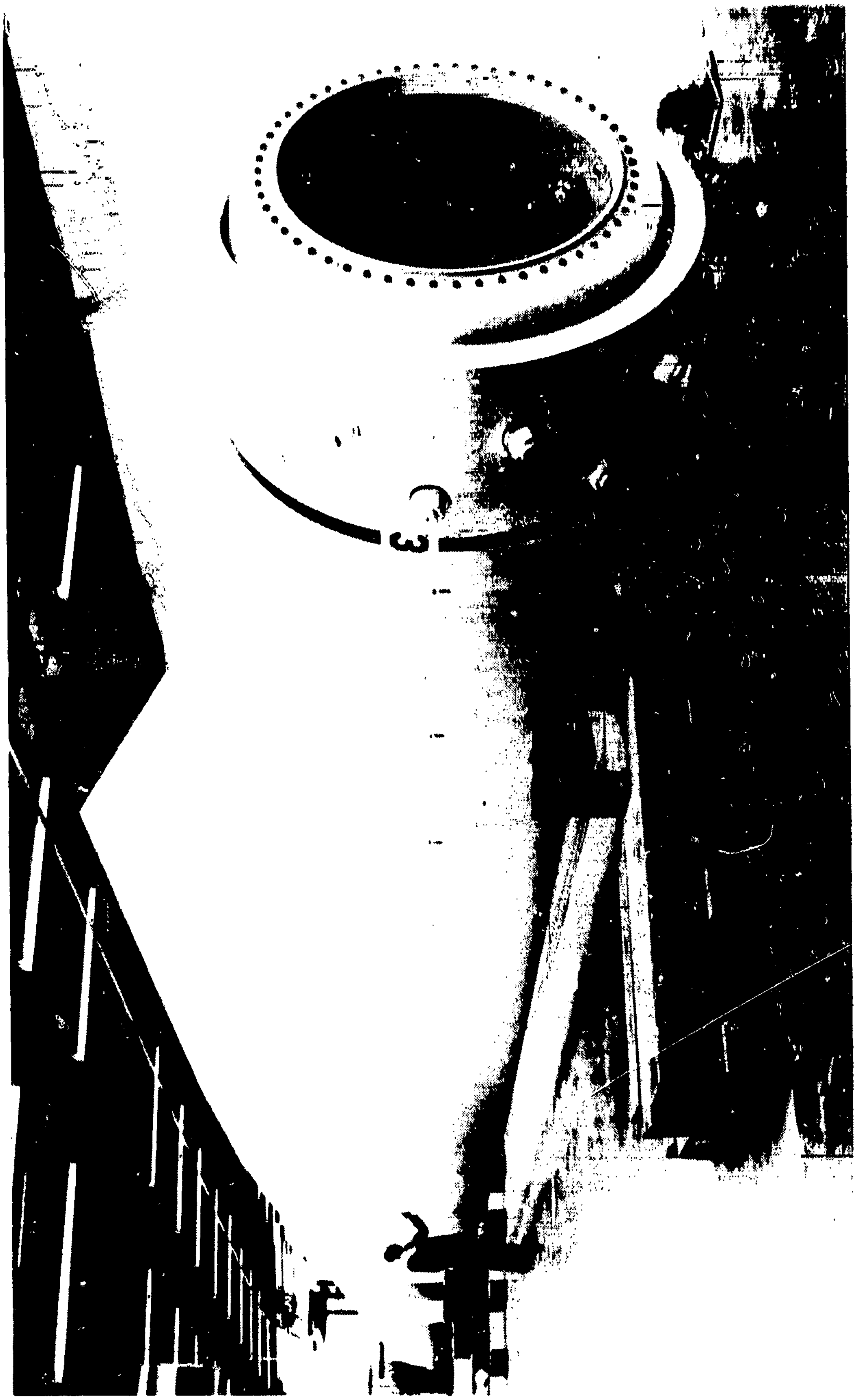

Figure 1. Mod-1 Composite Blade.

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Figure 2. 150 Foot Composite Blade.

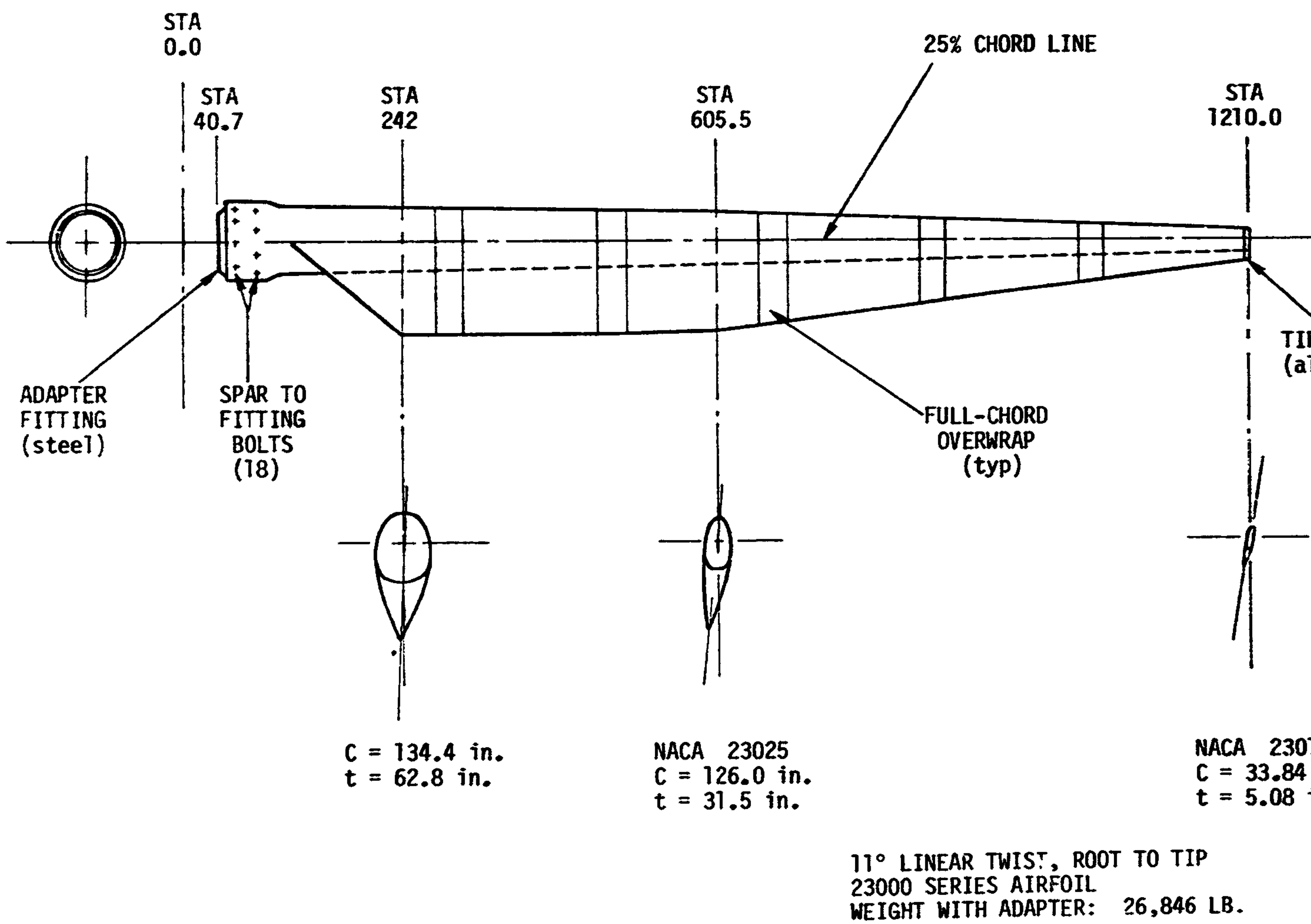

Figure 3. Planform, Mod-1 Blade.

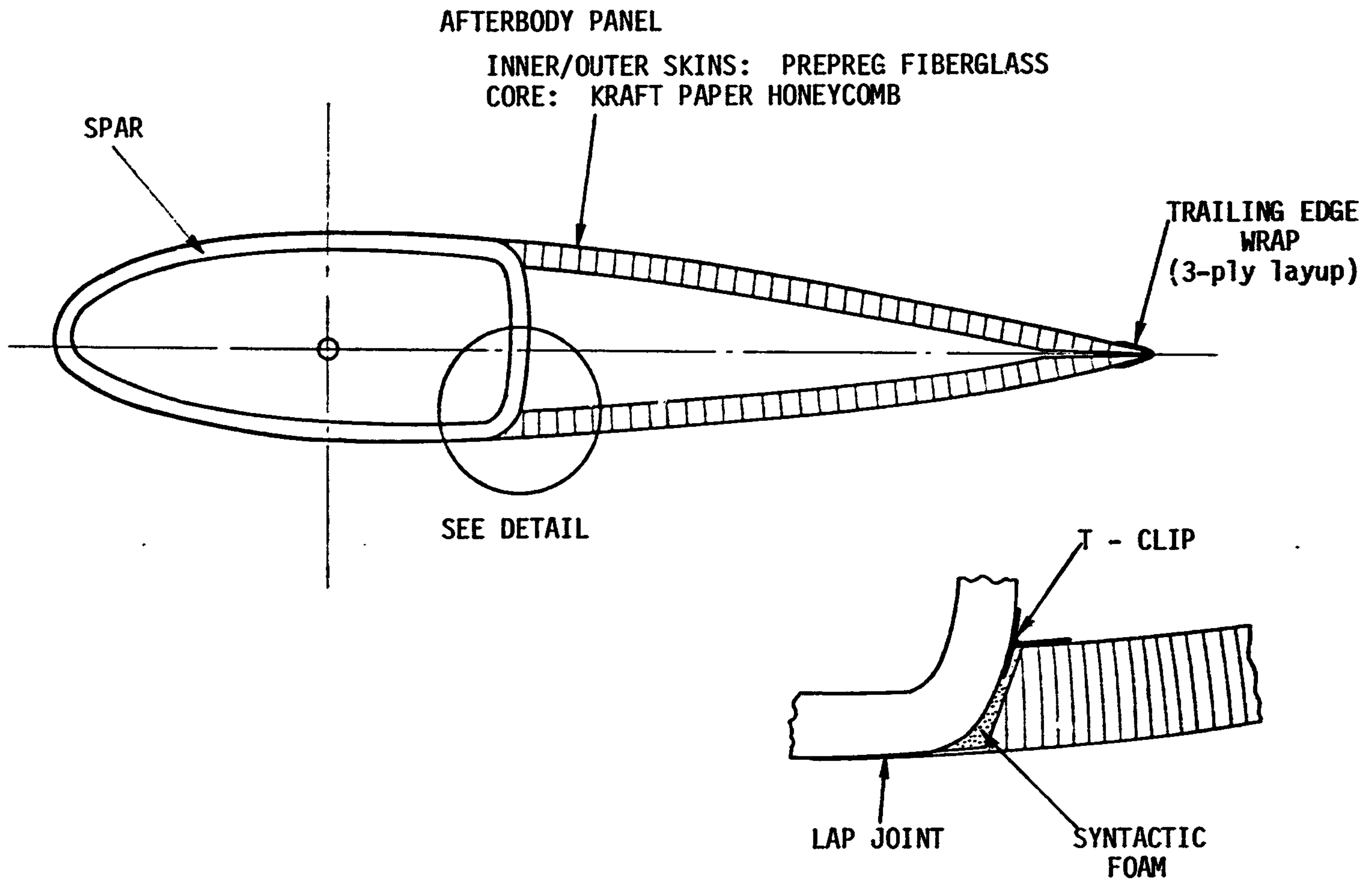

Figure 4. Cross Section, Mod-1 Blade.

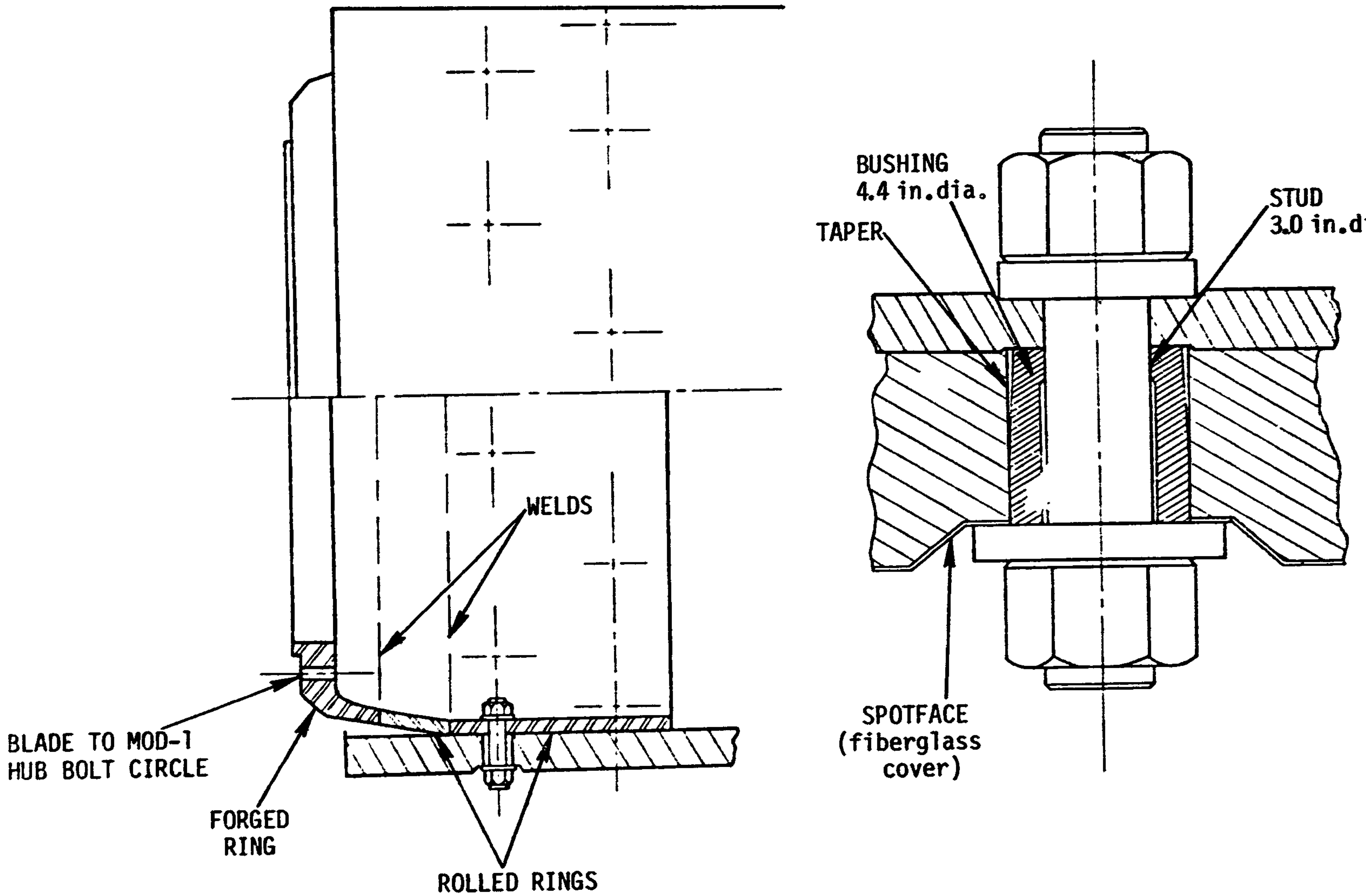

Figure 5. Inboard Adapter Fitting.

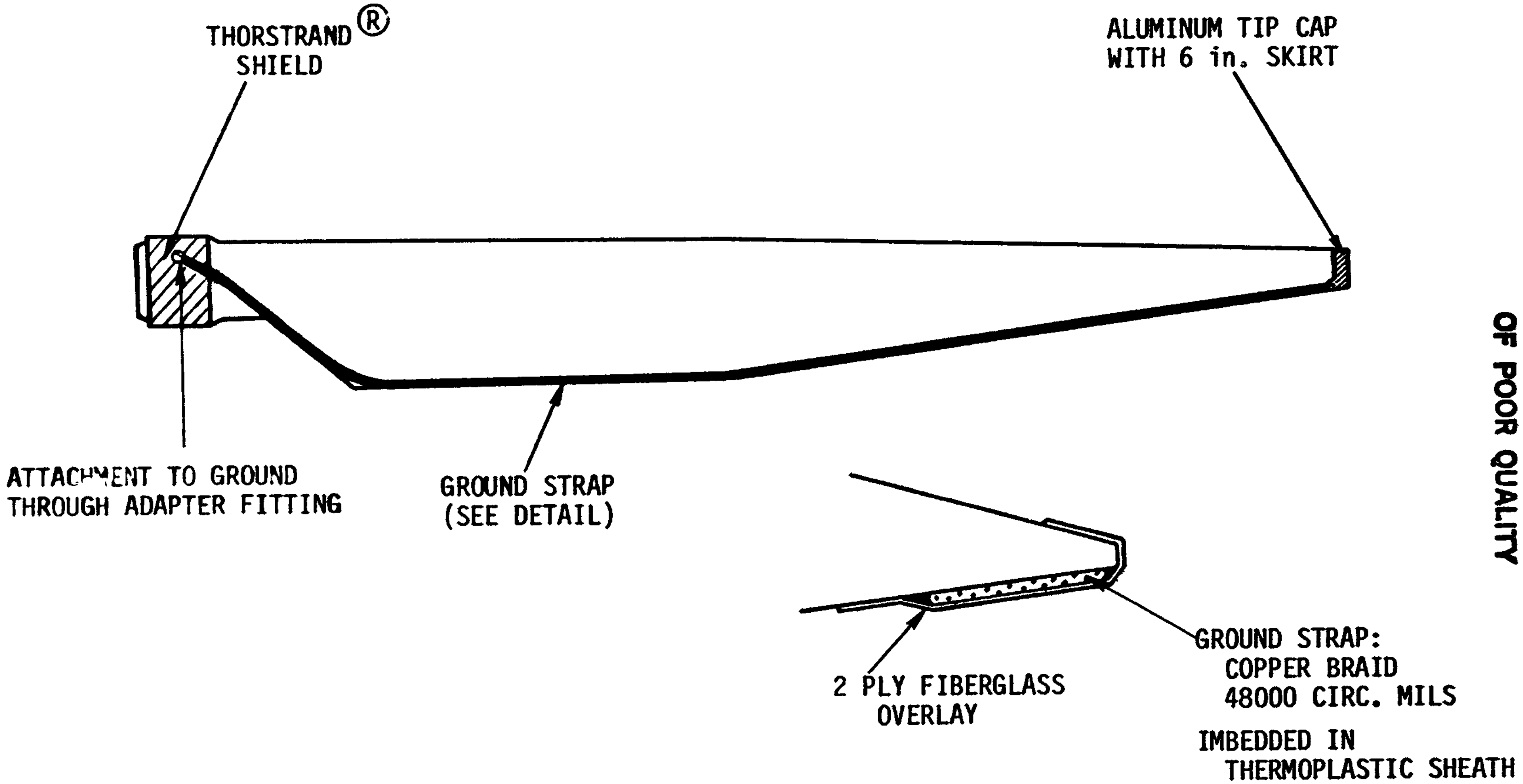

Figure 6. Lightning Protection System.

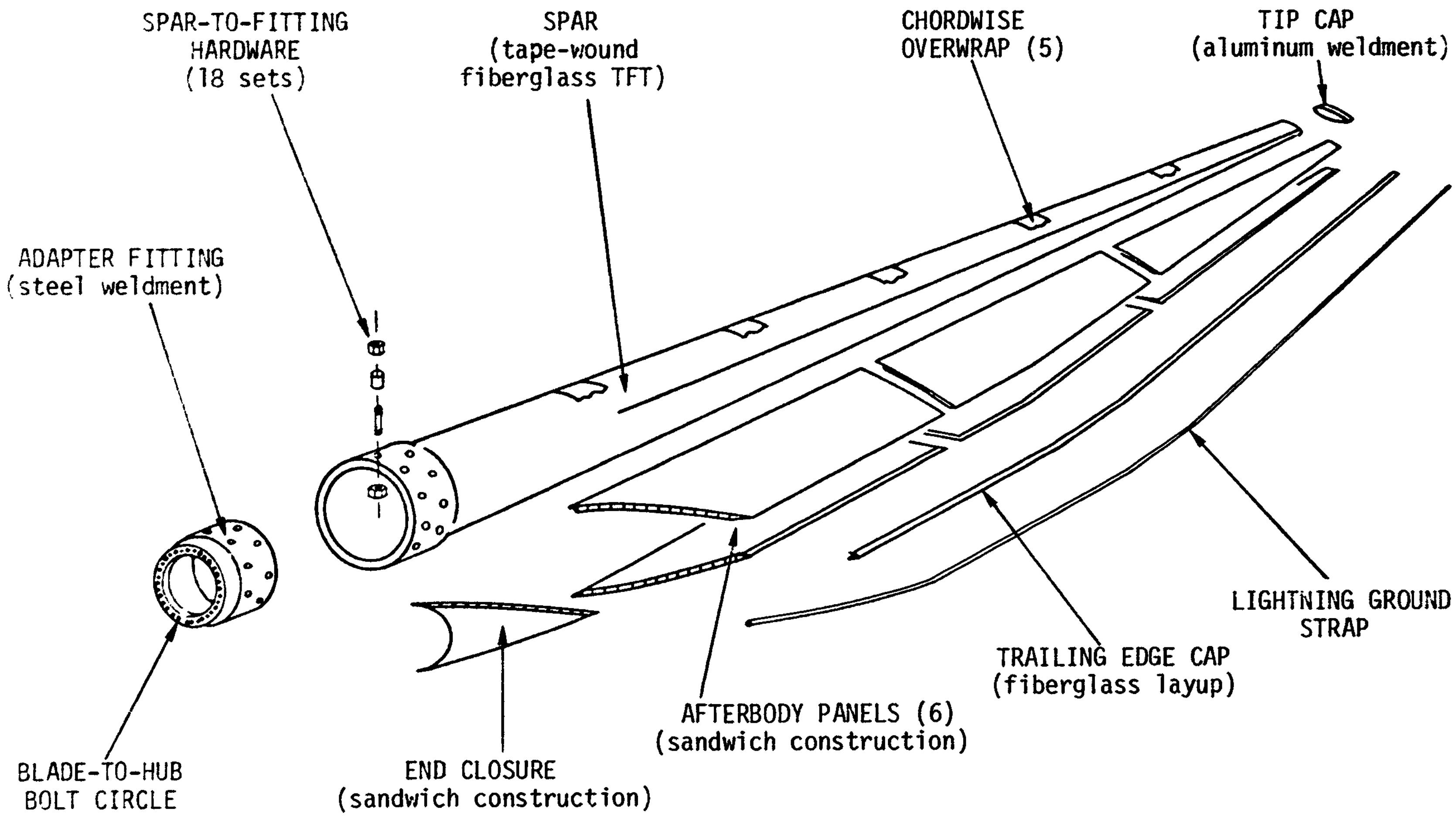

Figure 7. Exploded View, Mod-1 Blade.

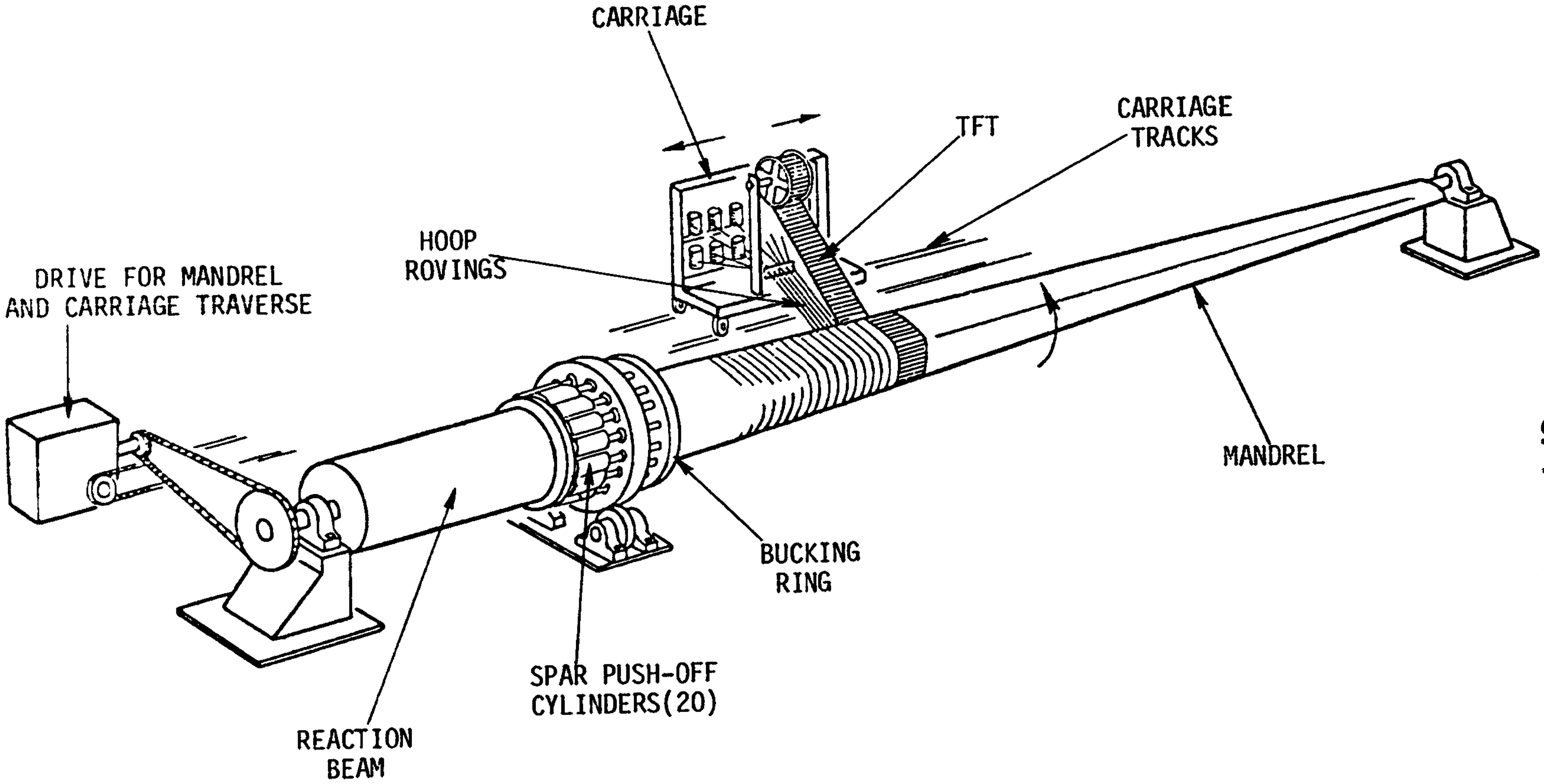

Figure 8. Spar Winding System.

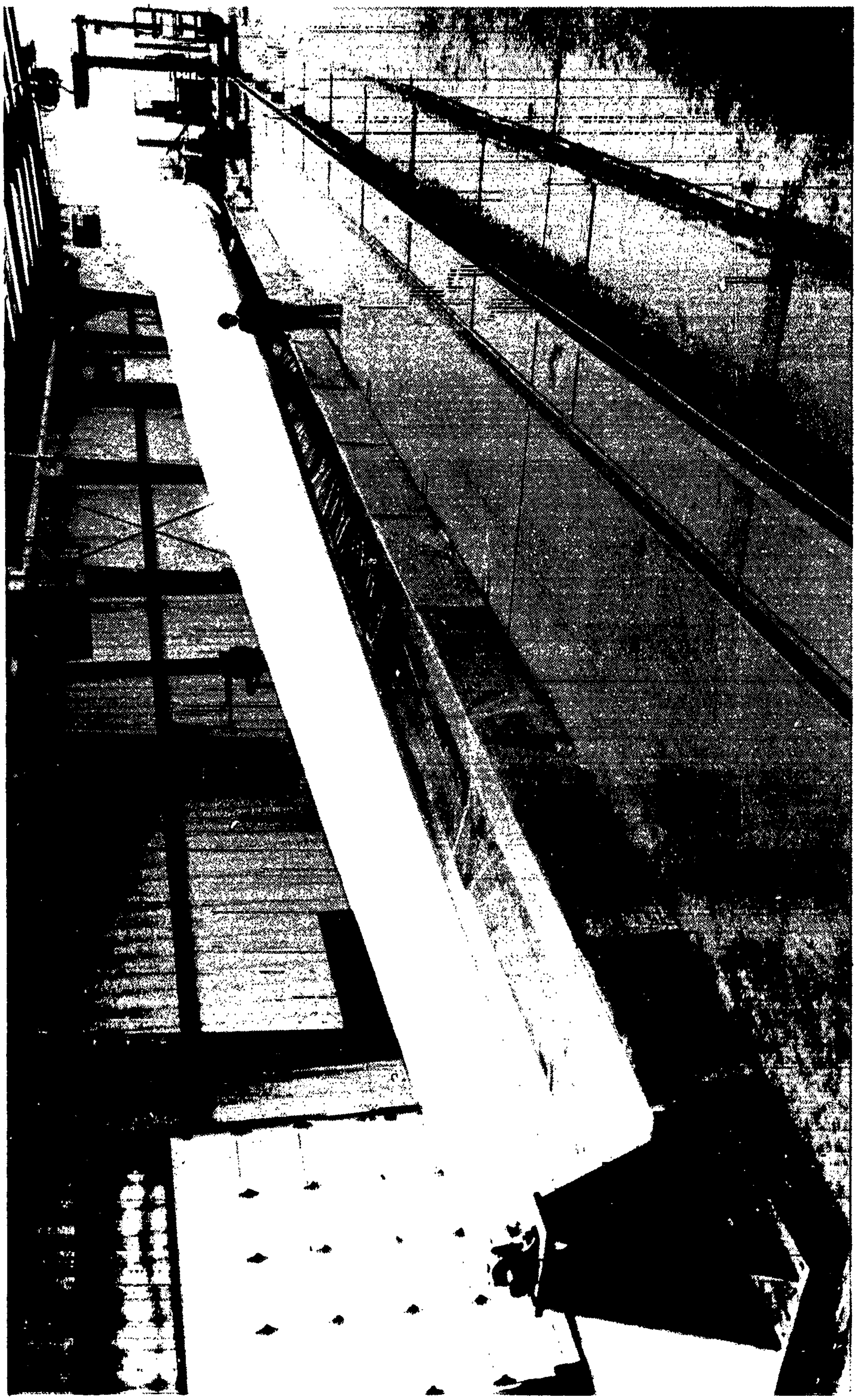

Figure 9. Spar Winding Mandrel.

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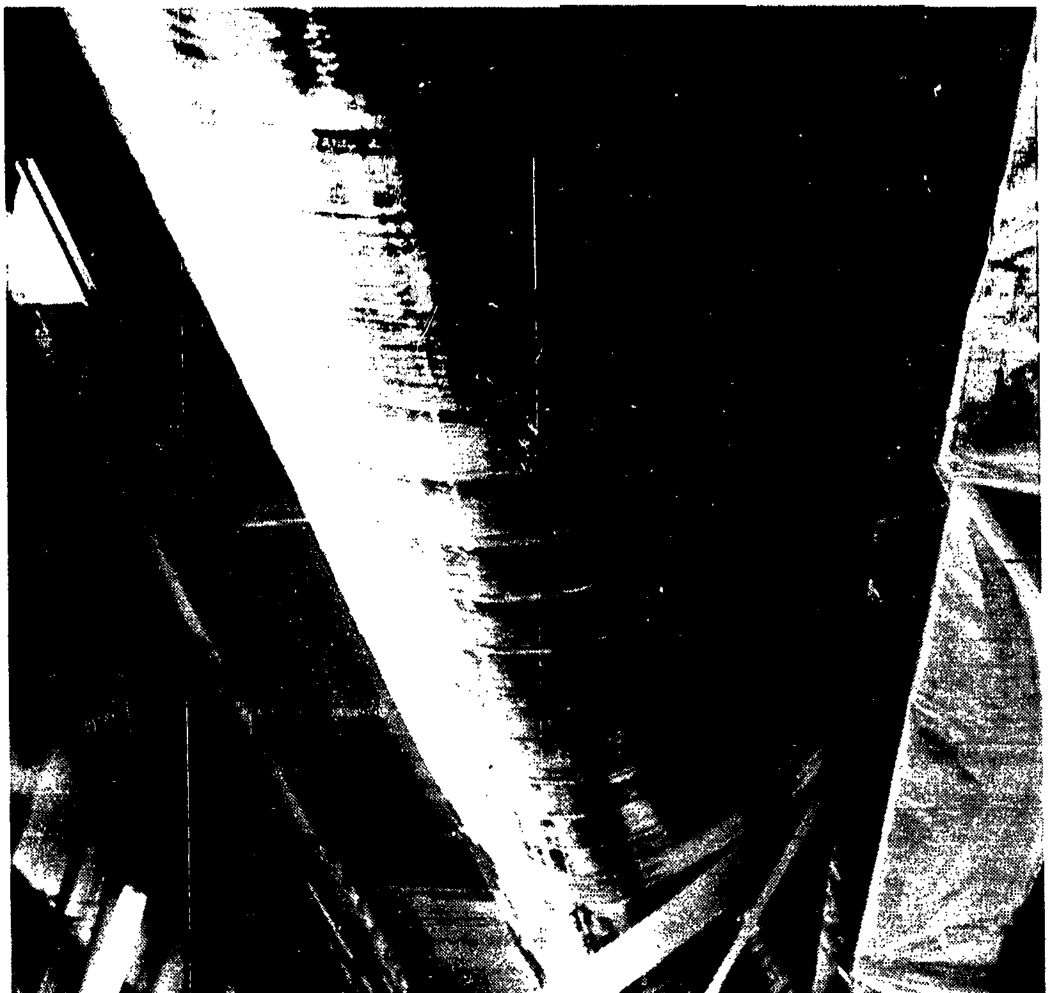

Figure 10. Spar Winding in Progress.

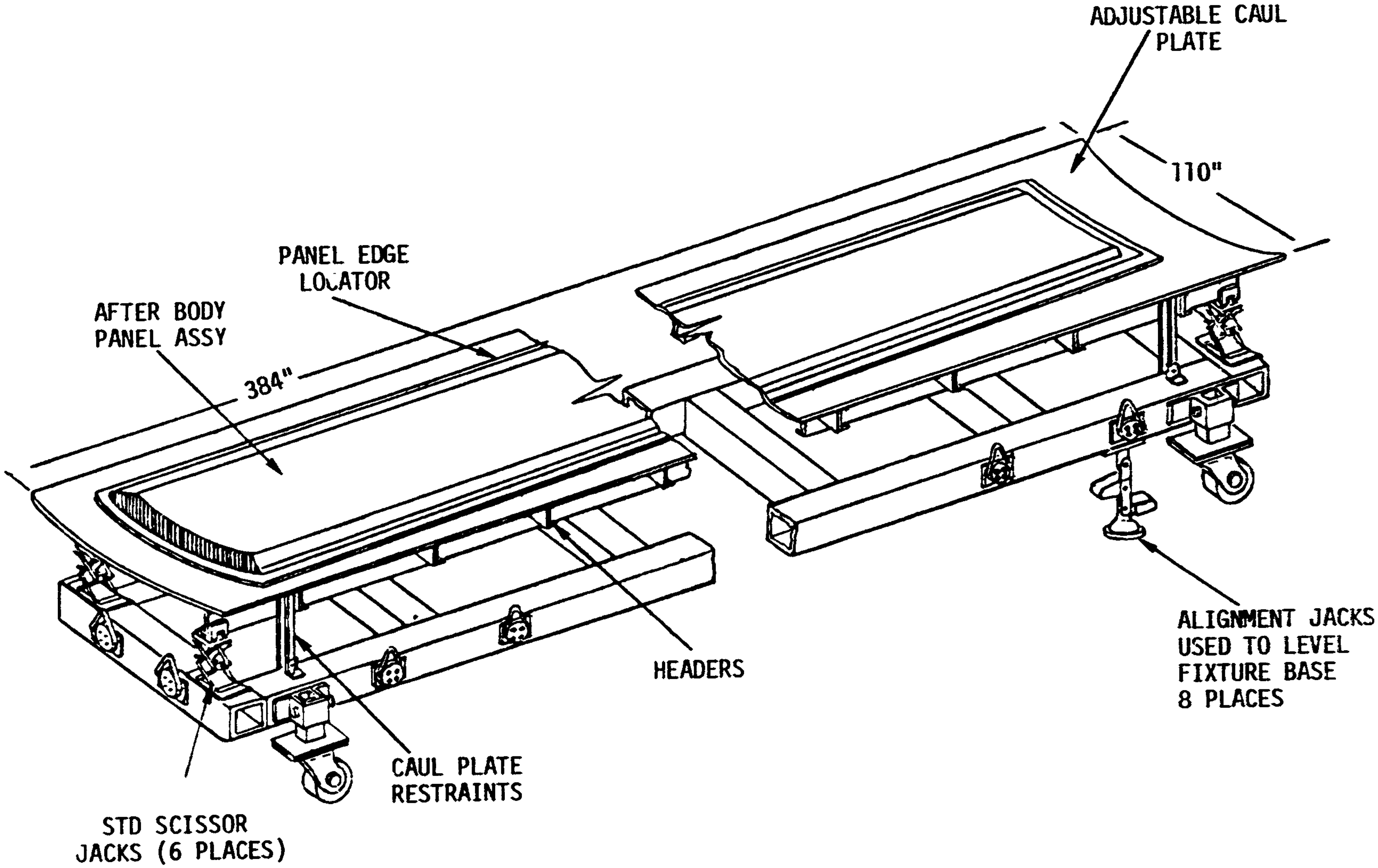

Figure 11. Afterbody Panel Bond Fixture.

QUESTIONS AND ANSWERS

W. R. Batesole

From: P. A. Bergman

Q: In winding the blade span as shown, what type of dimensional tolerances were attainable?

A: *Manufacturing procedures differed somewhat between the two blades in such areas as winding technique and resin application. Therefore, a quantitative level of tolerance control for repetitive manufacture has not yet really been investigated. The built-in twist was compared for the two spars and found to match very closely, although a quantitative value is not available.*

From: F. P. Molly

Q: Is it really necessary to protect a GRFP rotor blade against lightning? GRFP is an electrically nonconducting material. Are there any experiences from WECs?

A: *The full-scale tests showed that lightning discharges were attracted to the steel hub adapter inside the spar, entering at the tip. Similarly, other discharges occurred through the afterbody panels, "stitching" in and out through the panels from tip to root. High current strokes passing through the inside of a confined cavity in this manner will cause catastrophic damage to the blade.*