N83 19244 D13

DESIGN AND EVALUATION OF LOW COST BLADES FOR LARGE WIND DRIVEN GENERATING SYSTEMS

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NASA-Lewis Contract DEN 3-129

ABSTRACT

The program task was to develop a low cost blade concept, based on the NASA-Lewis specifications, and to evaluate its principle characteristics, its low cost features, advantages and disadvantages. A blade structure was designed and construction methods and materials were selected. Complete blade tooling concepts, various technical and economic analysis, and evaluations of the blade design were performed. A comprehensive fatigue test program was conducted to provide data and to verify the design. A test specimen of the spar assembly, including the root end attachment, has been fabricated. This is a full-scale specimen of the root end configuration, 20 ft long, and will be fatigue tested by NASA. A blade design for the Mod. "0" system has been completed.

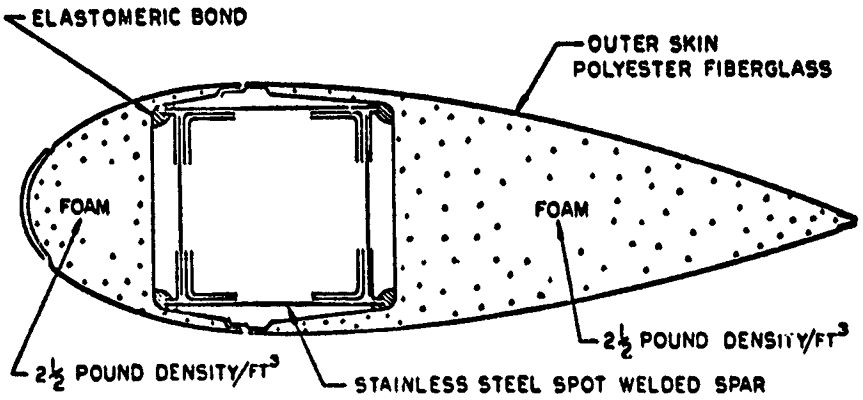
OVERVIEW OF CONTRACT OBJECTIVES

The design of large wind turbine blades have conflicting requirements and criteria. Cost is the most sensitive requirement and structural reliability is the foremost criterion. The basic design is predicated on the premise that large blades should be an industrial product of predictable performance and uncomplicated structure. In order to be successful, rotors must be capable of being produced in volume at reasonable cost. The Budd Company draws upon its background and knowledge in fabrication of long-life carbon steel and stainless steel structures and mass fabrication of glass-reinforced structural parts. Fabricating techniques combined with a long history of successful product designs assures that the program objectives can be met.

BUDD DESIGN CONCEPT

In conventional design, the leading edge section, or the D spar area of the blade, is used to carry the operating loads, and the trailing edge is essentially non-structural, carrying air loads for the trailing edge only. The Budd design does not have a conventional forward D spar. The design uses a central spine spar that is essentially non-dimensional relative to the aerodynamic surface; that is, it is a simple, rectangular spar located within the envelope of the aerodynamic contours. This spar carries all the basic edgewise loading and all the basic flatwise loading and provides primarily all the torsional stiffness for the blade system.

The leading edge and trailing edge fiberglass components are designed to distribute the air loads to spar and are segmented spanwise to prevent them from having to carry high loads in the spanwise direction due to spar bending deflections. These sections are bonded to the spar using an elastomeric adhesive. The illustration is an idealized section cut at station 187 of the blade. There is a center spar composed of spot welded stainless steel. This structure is composed of top and bottom cap strips, two shear webs, one on the front and one on the aft side of the spar. This spar is built with a 10° twist from the root end to the outer end. The leading edge and the trailing edge of the assemblies are fabricated of fiberglass reinforced plastic composed of multiple pieces that are then filled with urethane foam. These fiberglass subassemblies are bonded to the spar at the four flange corners of the spar. The leading and trailing edge assemblies are also bonded and mechanically fastened at the high camber point of the blade. The leading edge of the blade is protected by an elastomeric sheet to provide energy absorption due to impact of hail and other abrasive elements. The leading and trailing elements are designed so as not to contribute significantly to the structural stiffness of the blade.



TYPICAL SECTION
WIND TURBINE BLADE

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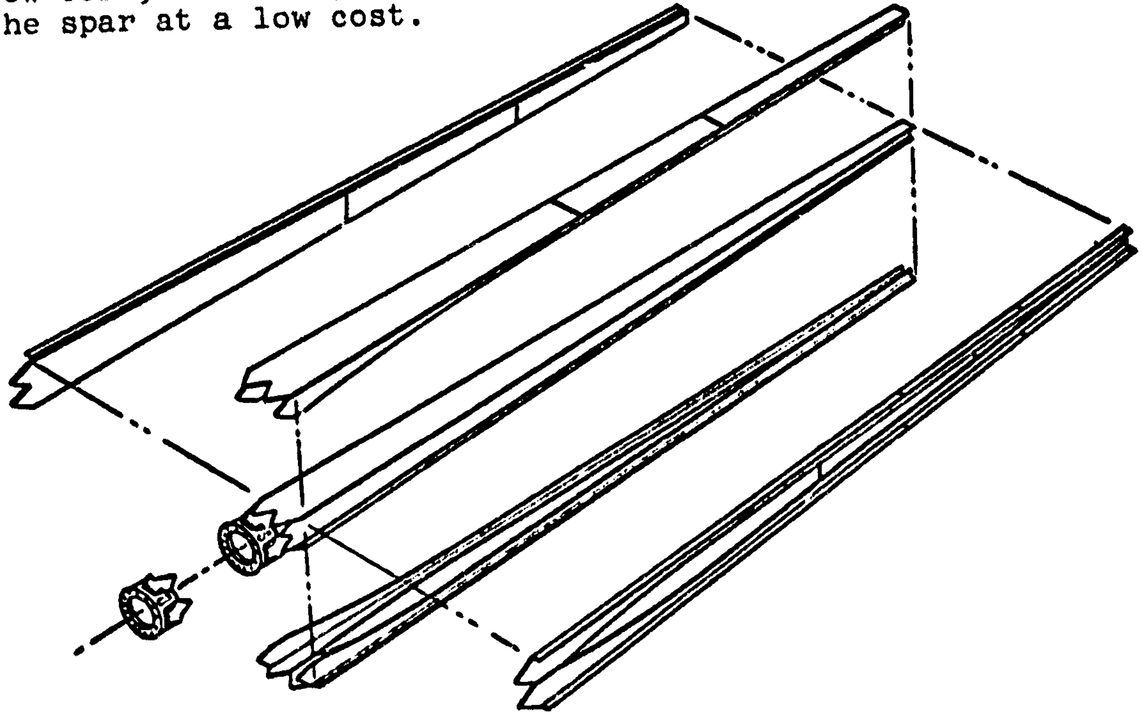
Shown is an exploded view of the spar assembly. The spar is composed of four sub-assemblies, an upper and lower cap strip plate assembly and a front and rear spar web assembly. The selection of stainless steel and the spot weld process provides a unique method by which the spar stiffness can be effectively tapered to provide a near uniform stress from the root end to the tip of the spar. This tapering is accomplished by the use of tapered angles that are spot welded together and are joined to the upper and lower cap strip plate. The thickness of the top plates are tapered in three steps using a butt arc weld to join each thickness. This is a specialized process that was developed during the Budd 301 testing program. This provides a weld of high reliability in fatigue strength. By controlling this taper, we are able to provide uniform tapering of the basic properties of the spar section. The angles are first tapered in the blank and, as a result, there is essentially no material lost. The angles are then formed and then spot welded to the spar cap assembly. This is all done in the flat and then they are elastically twisted to match the 10° twist of the spar. The spar webs are composed of two angles and spar web. The two angles and web are spot welded in place to form the web for the spar. There are two of these. These are also built flat and elastically twisted to form the 10° twist to the spar. The four assemblies are then assembled into an assembly fixture with the 10° twist provided and are spot welded together. This provides a very efficient tapering of the spar without machining and at a very low cost, using rolled sheet material. The use of stainless steel also provides excellent corrosion protection for long life of the spar. Spot welding provides a low cost, reliable, efficient assembly process to assemble the spar at a low cost.



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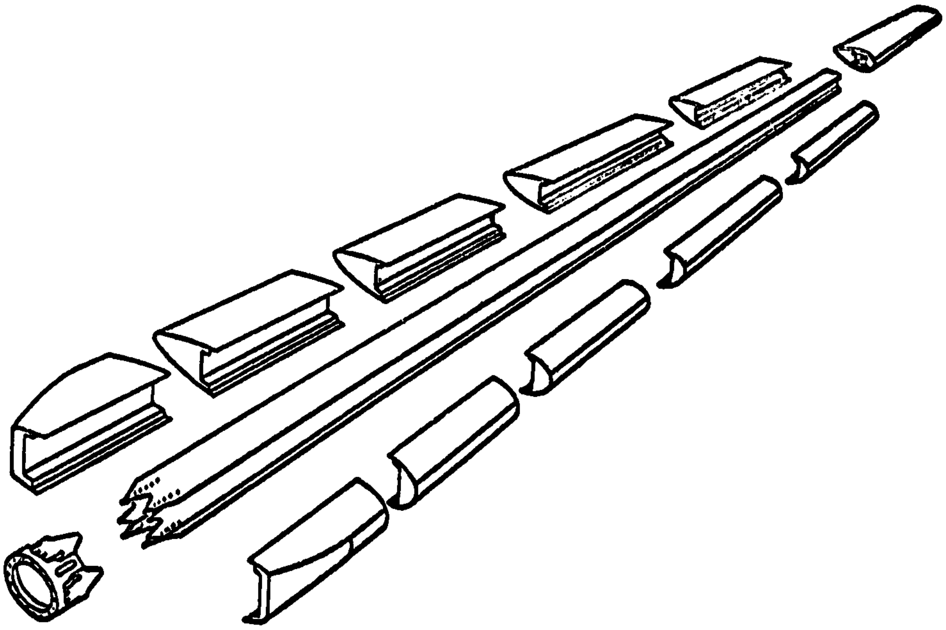
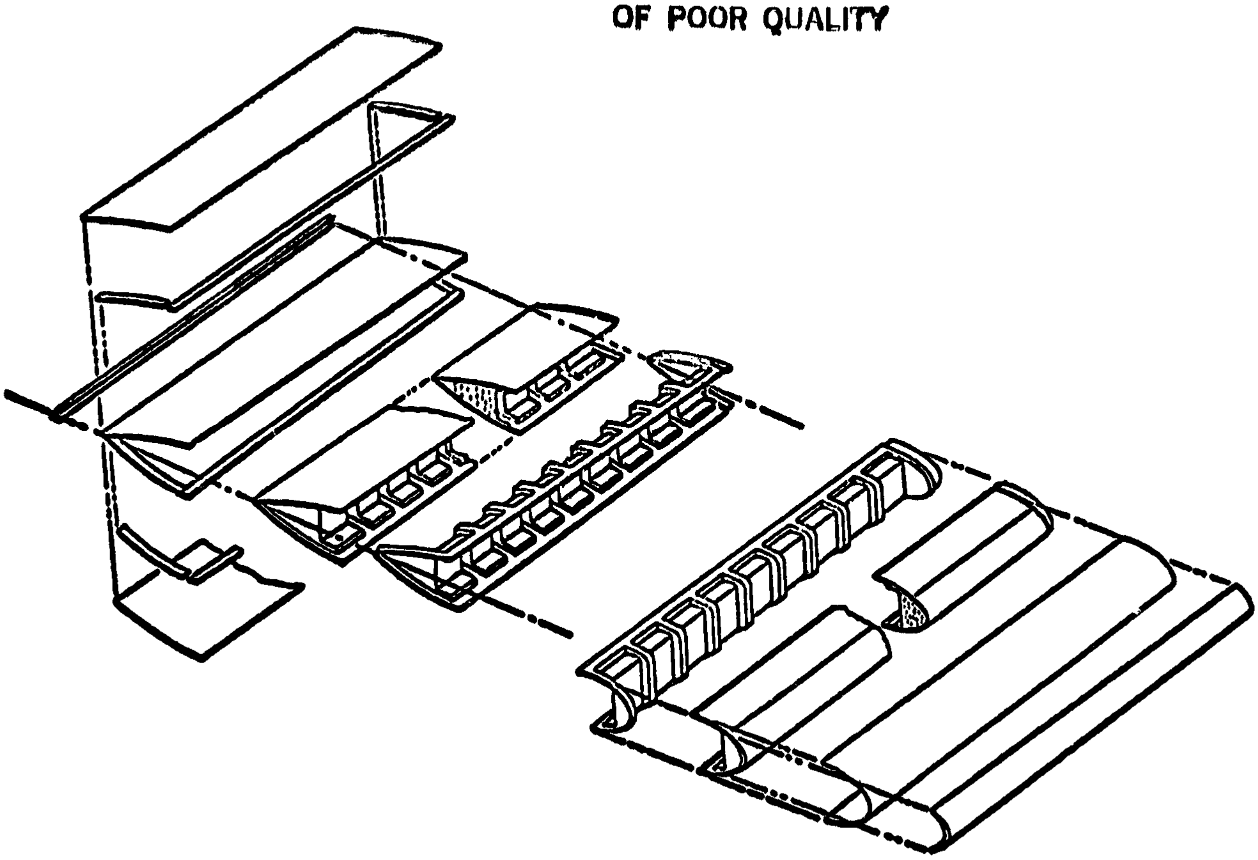
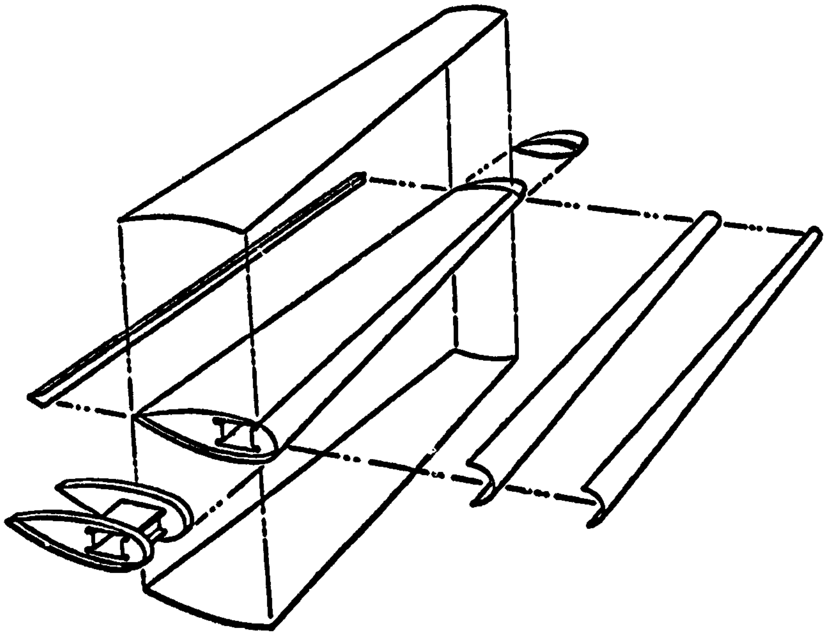
The illustration shows a breakout of all the major subassemblies of the blade.



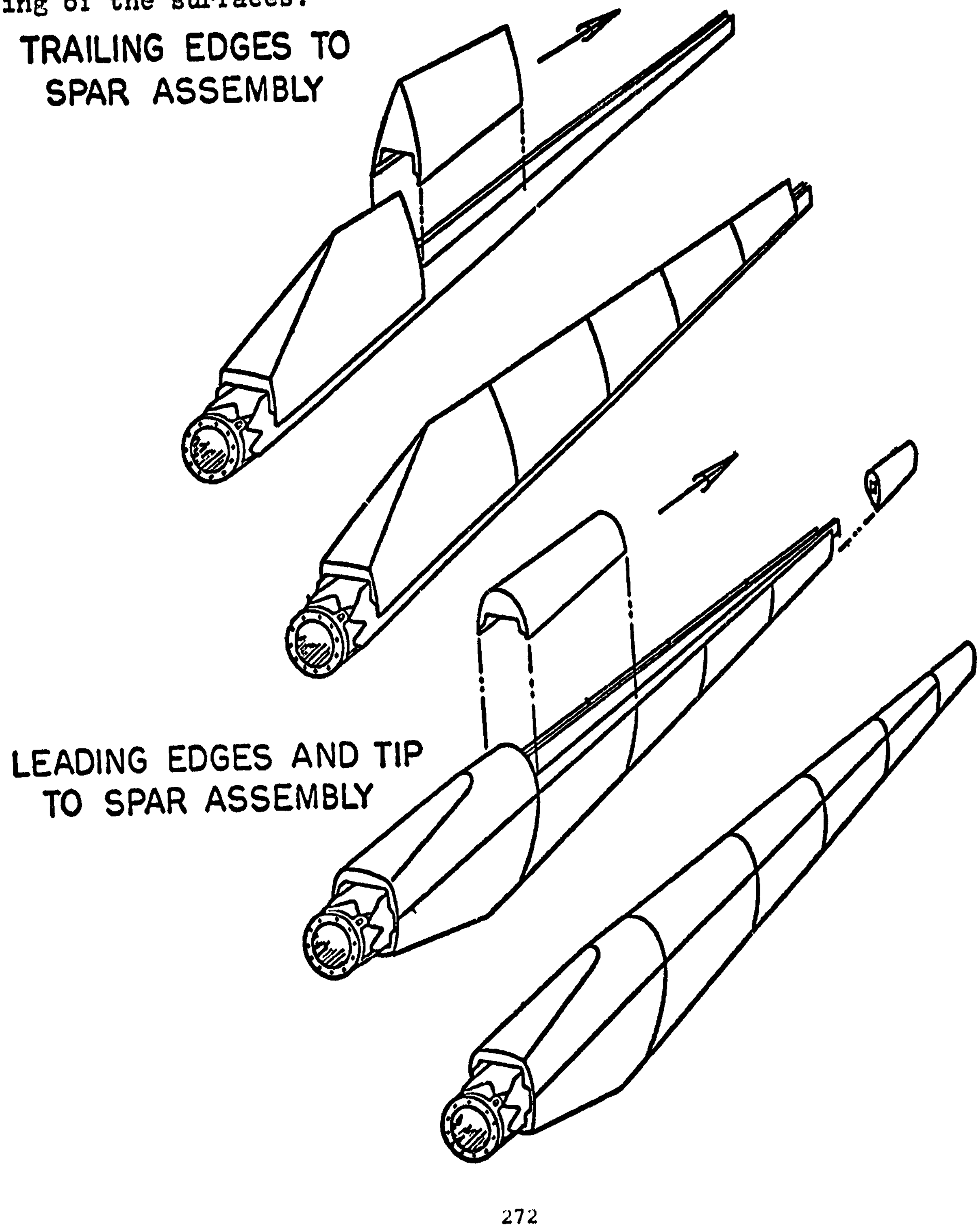
The illustration on the following page shows an exploded view of the leading edge and trailing edge assemblies. These assemblies are composed of low cost layup of fiberglass-reinforced polyester. A commercial grade of this material is used. Fiberglass elements are parasitic to the primary spar structure and are used only to distribute the air loads to the spar. Their design requirements are minimal. To stabilize these elements for fatigue, the fiberglass elements are filled with a semirigid, urethane foam of approximately 2 1/2 pounds per cubic foot density. This provides a light-weight, well-damped structure for the leading and trailing edge assemblies and prevents aerodynamic flutter of lightweight surfaces. This design permits accurate dimensional control of the aerodynamic surfaces at low relative cost.



To reduce weight and to improve mass distribution in the blade, the metal spar is cut short and a structural fiberglass tip extension is used. The illustration shows a breakout view of the tip parts.



The final assembly of the blade is accomplished in two major steps. The trailing edge assemblies are bonded to the spar. Working from the inboard end of the blade outboard, the leading edges are then assembled to the spar trailing edge major assembly by bonding and mechanical fastening, working from the inboard end outboard. The tip assembly is then bonded and mechanically joined to the blade assembly. The final step is the installation of elastomeric sealing strips between the edges of the fiberglass assemblies to provide aerodynamic sealing of the surfaces.



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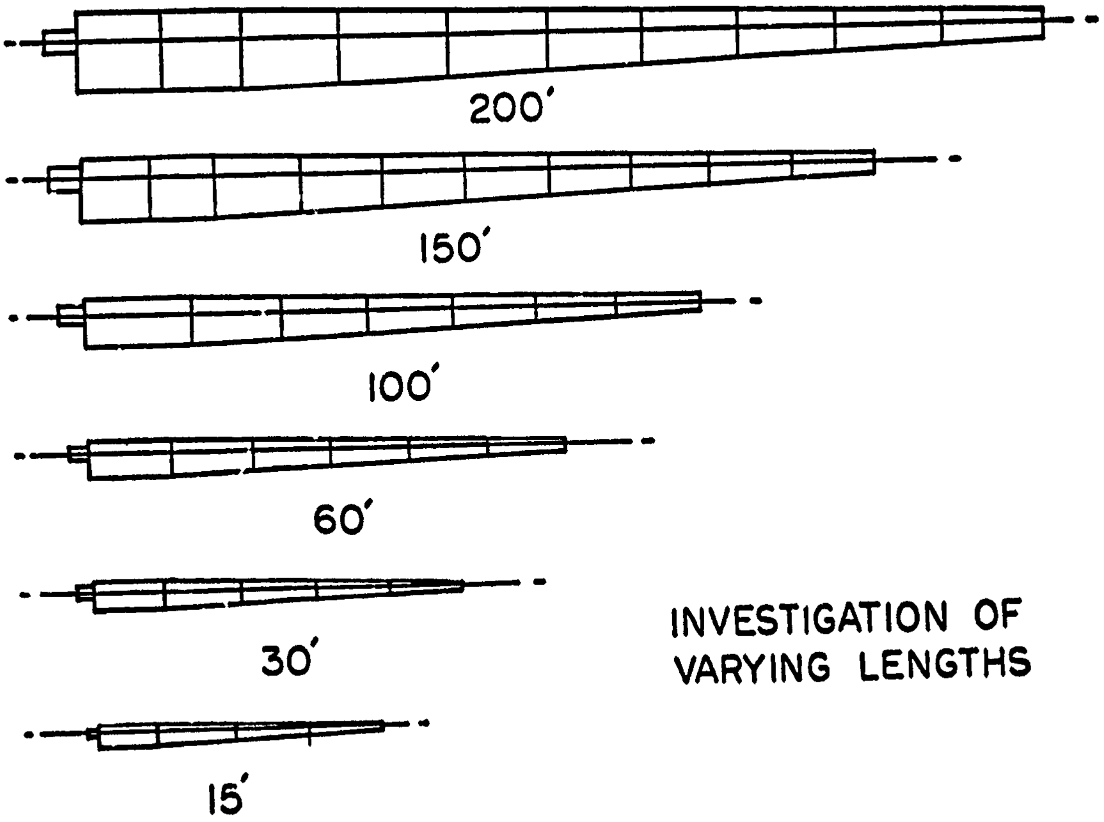
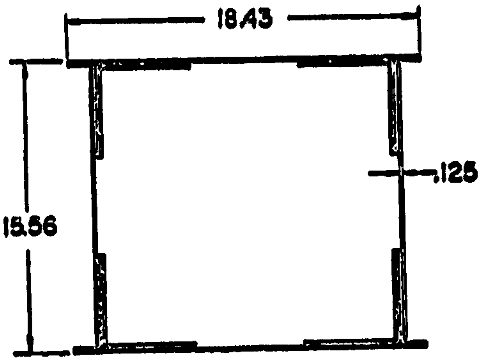
A study to determine whether the basic concept of the design could be utilized through the entire range of blade sizes was made. The basic concept of a rectangular spar inside the aerodynamic surface carrying the principal loads with parasitic aerodynamic elements directing the air loads into the spar can be applied to the entire range of blades. The illustration below shows the blades that were reviewed in this study. Using the present configuration, with a high aspect ratio blade, we would use a stainless steel spar from the 60-foot size blade down to the smaller sizes. The advantage of the stainless steel spar is the ability to taper and spot weld the assemblies together at low cost and with good corrosion resistance for the thinner gage materials needed on the smaller blades. From the 60-foot blade on up, we would use a high strength, low alloy carbon steel for the spar. The reason for this is that the gage of the materials will be out of the range of those producible in stainless steels. Thicker gage cryogenic stainless steel material might be used, but we do not think this would be economically feasible in the larger size.

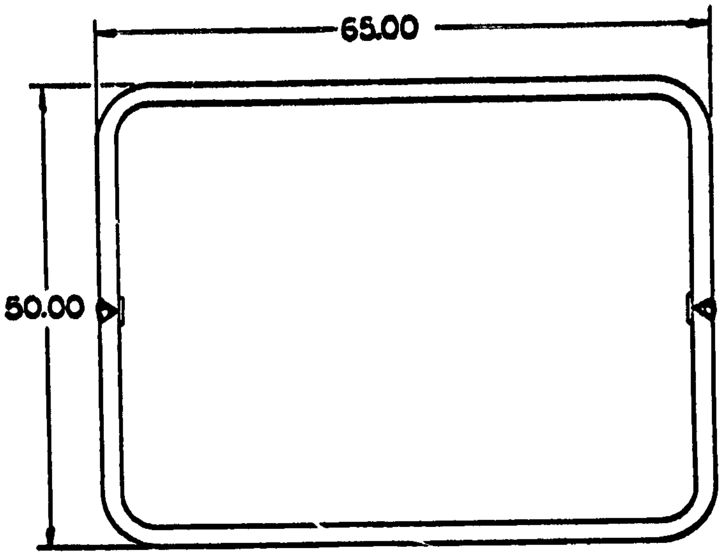


INVESTIGATION OF
VARYING LENGTHS

The illustration below shows the basic spar configuration for the 60-foot blade. This is constructed of 301 1/4 hard .125 thick stainless steel. Also shown is the general configuration of a spar of 200 ft length. It was basically the same design concept used for a 150-foot blade.



SPAR ROOT END OF 60' BLADE



SPAR ROOT END OF 200 FT. BLADE

Our first cursory judgements are that it may be more practical to produce, at a lower cost, a multiplicity of smaller blades rather than a low quantity of larger blades for the same power output. Since the blade is only a small percentage of the total system, this conclusion may not hold when the whole system is considered.

Larger blades enter into an area of manufacturing which is beyond the present state of the art in many areas. To provide a good, low cost design will require considerable investigation. In the area of transportation, a blade up to 85 feet in length can be shipped in one piece without major difficulty. Above that size, the blades would have to be shipped in multiple pieces. This, of course, increases the problems of design of the blade, inasmuch as this would require spar joints outboard in the blade that would have to have the same degree of reliability as the root fitting. This can add considerable weight and cost but can be done. We are doing further investigation into the effects of varying lengths on design and their relative cost and weight.

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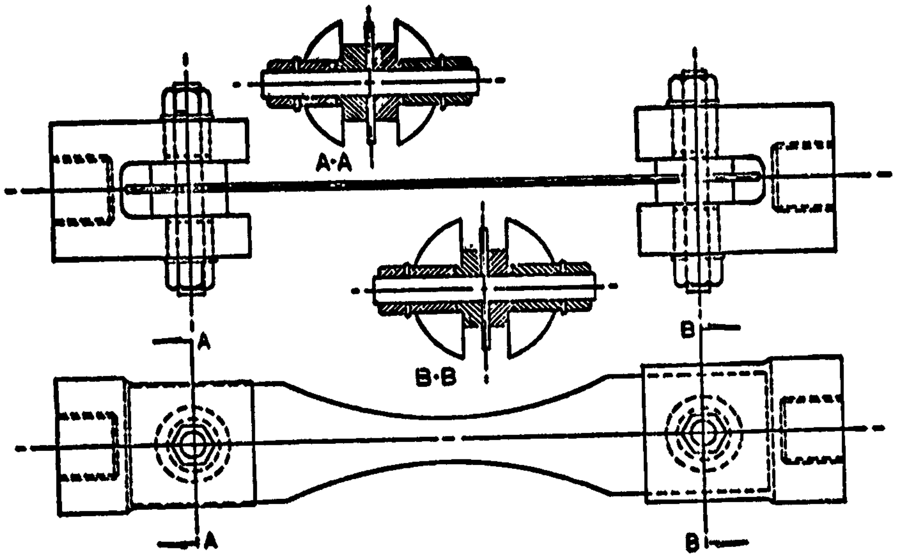
FATIGUE STRENGTH QUALIFICATION PROGRAM

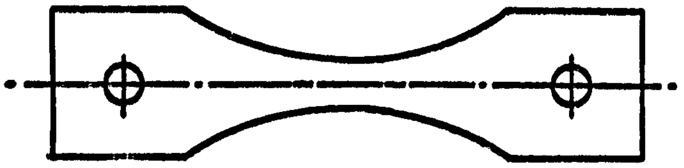
In this section, we present a summary of the fatigue test program and the structural analysis. It covers the testing and the development of the allowable stresses used in the design. Summarized are the structural properties of the blade design. Testing of the fiberglass structures are discussed. The fatigue test program conclusions and the final blade design configuration were presented to NASA-Lewis on October 20, 1980. The illustration shows the configuration developed for the fatigue testing program. Considerable development was required to be able to perform satisfactory fatigue tests on the large full scale test specimens.



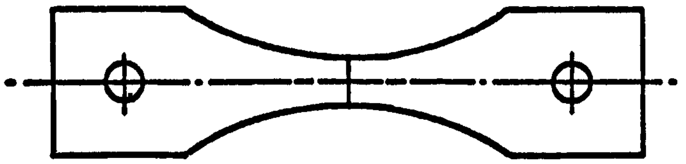
Parallel with the NASA full scale test element program, The Budd Company has conducted an in-house fatigue test program to obtain long term fatigue data on 301 stainless steel and the effects of joining techniques as related to long term fatigue. See the following series of illustrations and tables for the test results. We have used data from this program to supplement the full scale testing conducted under the NASA contract.

The 301 test series has been used to obtain base metal properties. All tests were run to 10 million cycles or more in tension -tension fatigue at +0.1 R value. Data presented are the minimum values without failures and have been adjusted to the blade design level of -0.5 R value using Goodman diagrams.

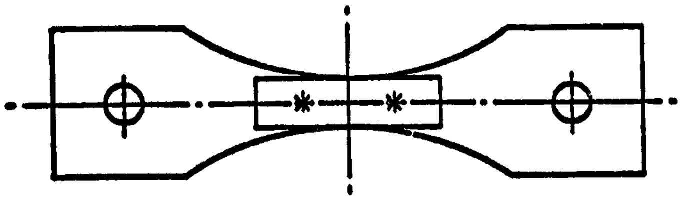
BASE LINE TEST RESULTS



DATA ± 49000 P.S.I. CYCLIC STRESS -.5 R VALUE



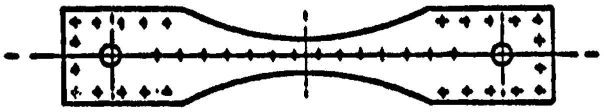
DATA ± 24000 P.S.I. CYCLIC STRESS -.5 R VALUE



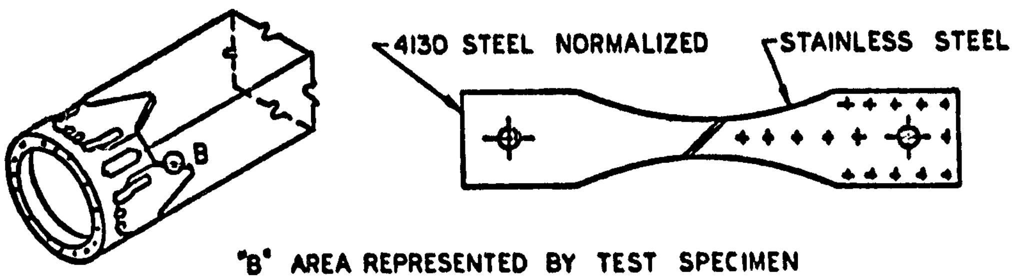
DATA ± 562.5 LBS CYCLIC LOAD PER
WELD. SINGLE SHEAR.

FULL SCALE CONFIGURATION TEST RESULTS

MULTIPLE LAYERS OF 301 STAINLESS STEEL
SPOT WELDED TOGETHER



DATA ±21000 P.S.I. CYCLIC STRESS -.5 R VALUE



"B" AREA REPRESENTED BY TEST SPECIMEN
DATA ±16000 P.S.I. CYCLIC STRESS -.5 R VALUE

TEST PROGRAM CONCLUSIONS
OF 301 1/4 HARD STAINLESS STEEL AND 4130 STEEL
SUMMARY OF TEST LEVELS AT 10 MILLION OR MORE LOAD CYCLES
ADJUSTED FOR "R" VALUE OF -.5

TEST	TEST VALUE	DESIGN ALLOWABLE (80% OF TEST VALUE)
	SHOWN IN CYCLIC STRESS	
BASE METAL (301 1/4 H STAINLESS STEEL)	± 49,000 PSI	± 39,200 PSI
BASE METAL (BUTT ARC WELDED & COLD WORKED)	± 24,000 PSI	± 19,200 PSI
BASE LINE SPARE - SPOT WELDED	± 21,000 PSI	± 16,800 PSI
MAX SHEAR LOADS IN SPOT WELDS (R = +.1)	± 562.5 (CYCLIC LOAD PER WELD)	± 450 (CYCLIC LOAD PER WELD)
ROOT END ATTACHMENT - ARC WELDED	± 16,000 PSI	± 12,800 PSI
4130 CHROME MOLY STEEL	± 38,000 PSI (CHART VALUE)	± 30,400 PSI

THESE ARE THE MAXIMUM ALLOWABLE STRESS LEVELS PERMITTED IN THE SPAR FOR FINAL DESIGN.

SUMMATION OF COMPUTED STRESSES IN THE SPAR

STA.	WEB	CAP	MEAN PSI	CYCLIC PSI	MAX. PSI	MIN. PSI	R = MIN/MAX	q (LBS/IN)
44.5	.125	.125	3340	11,000	14,340	-7660	-.53	103 ± 13
187.5	.125	.125	4814	15,914	20,728	-11,100	-.54	102 ± 18
300	.090	.125	5285	16,000	21,285	-10,715	-.50	104 ± 32
412.5	.090	.090	6753	14,300	21,053	-7547	-.36	85 ± 32
525	.060	.060	7790	12,383	20,173	-4593	-.23	73 ± 35
637.5	.060	.060	6278	6959	13,237	-681	-.05	74 ± 35

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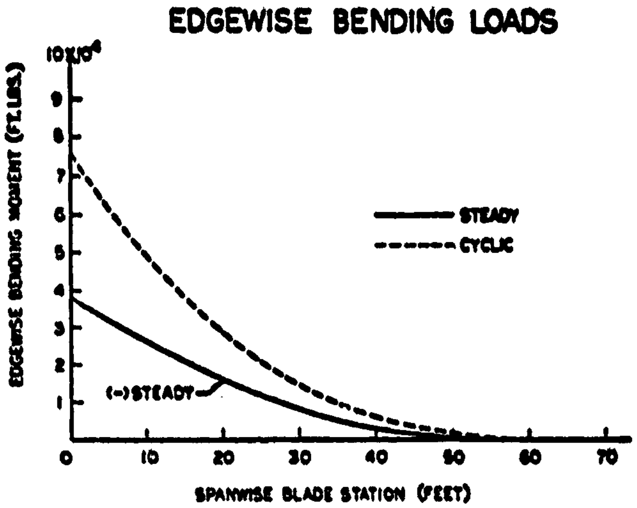
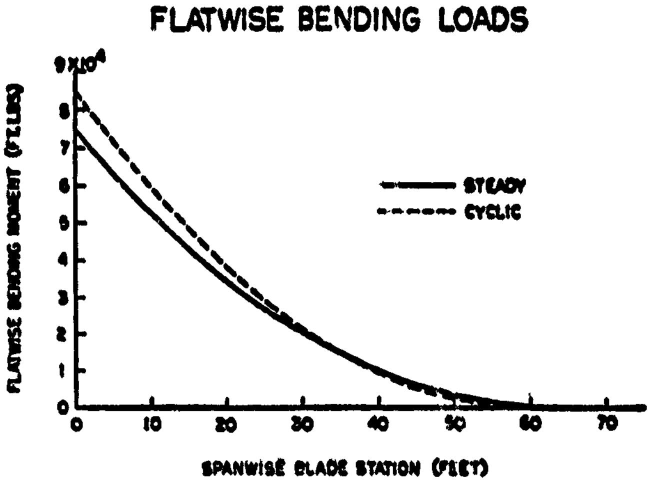
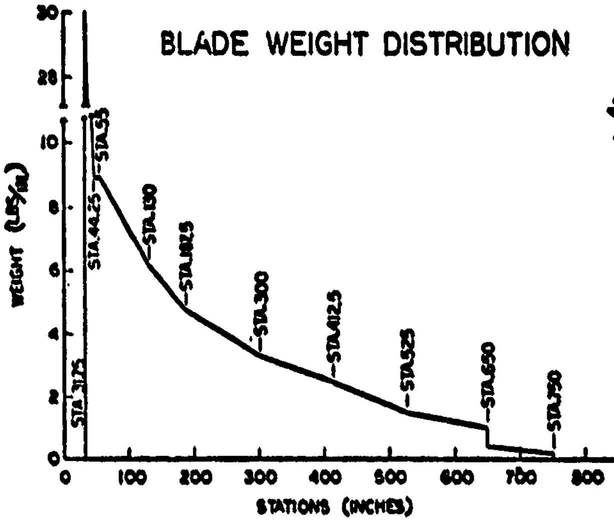
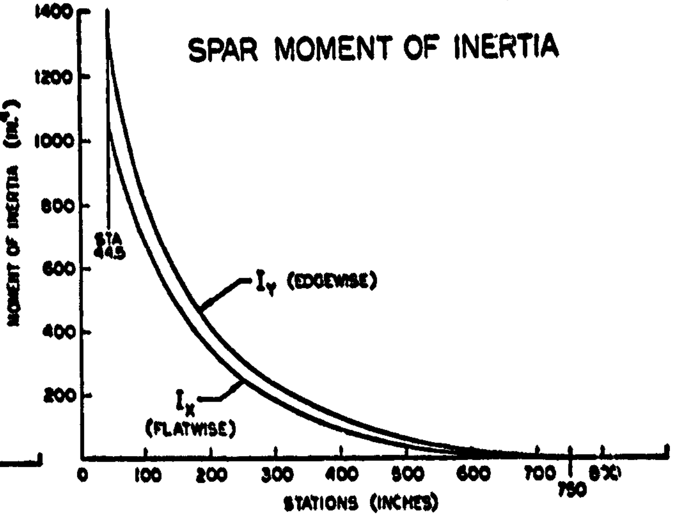
The following series of charts describe the basic loads used for the design and the structural properties of the spar.


EDGEWISE BENDING LOADS


FLATWISE BENDING LOADS


BLADE WEIGHT DISTRIBUTION


SPAR MOMENT OF INERTIA

Computed blade assembly natural frequencies are 1.86 Hz in the flatwise direction and 2.15 Hz in the edgewise direction.

A test specimen was designed and manufactured to be used to determine manufacturing feasibility for the aerodynamic surfaces and to provide the fatigue test data for the system.

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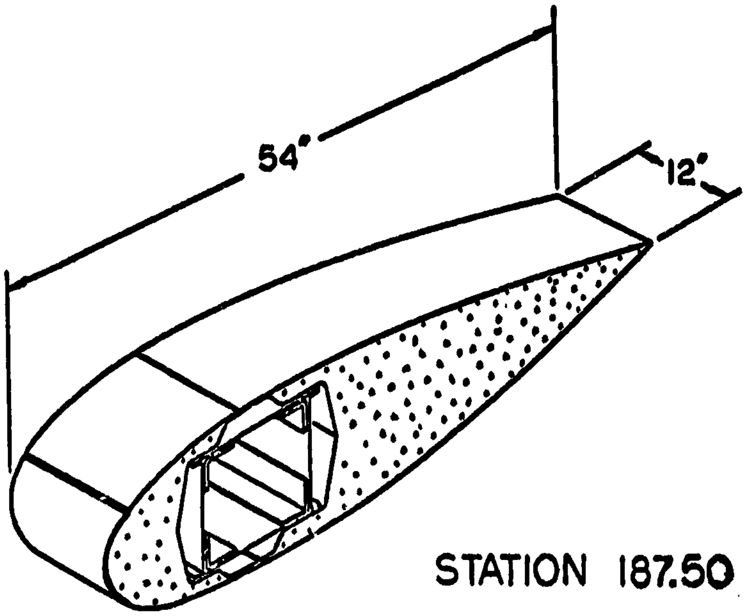
The illustration lists the basic materials used for the aerodynamic surfaces and shows the test specimen used to evaluate the fatigue strength of the system. Weights were bonded over the aerodynamic surfaces equivalent to 1/2 the maximum aerodynamic load distribution. The specimen was then cycled ± 1 G to produce a 0 to 1 G load factor for the aerodynamic load and, as a function of the mass of the test specimen, a cyclic load of ± 1 G for the mass of the section. Additional tests were run as shown in the summary data on the next page. The results of the tests are excellent and indicate the design is conservative.



ONE FOOT WIDE BLADE SECTION
USED FOR FATIGUE STRENGTH EVALUATION

MATERIALS OF AERODYNAMIC SURFACES

BASIC MATERIAL	GLASS REINFORCED POLYESTER WITH 17% MIN. GLASS CONTENT
TRAILING EDGE SKINS	.030 COMMERCIAL SHEET (AS ABOVE)
LEADING EDGE SKINS AND INNER CHANNELS . .	COMMERCIAL LAY-UP (.060 TO .125)
FOAM (2-1/2 LB. DENSITY	RIGID URETHANE FOAM (MOBAY CHEMICAL CO. MB-23793BA)
ADHESIVE	3-M TWO COMPONENT ADHESIVE (EC-3549 B/A)

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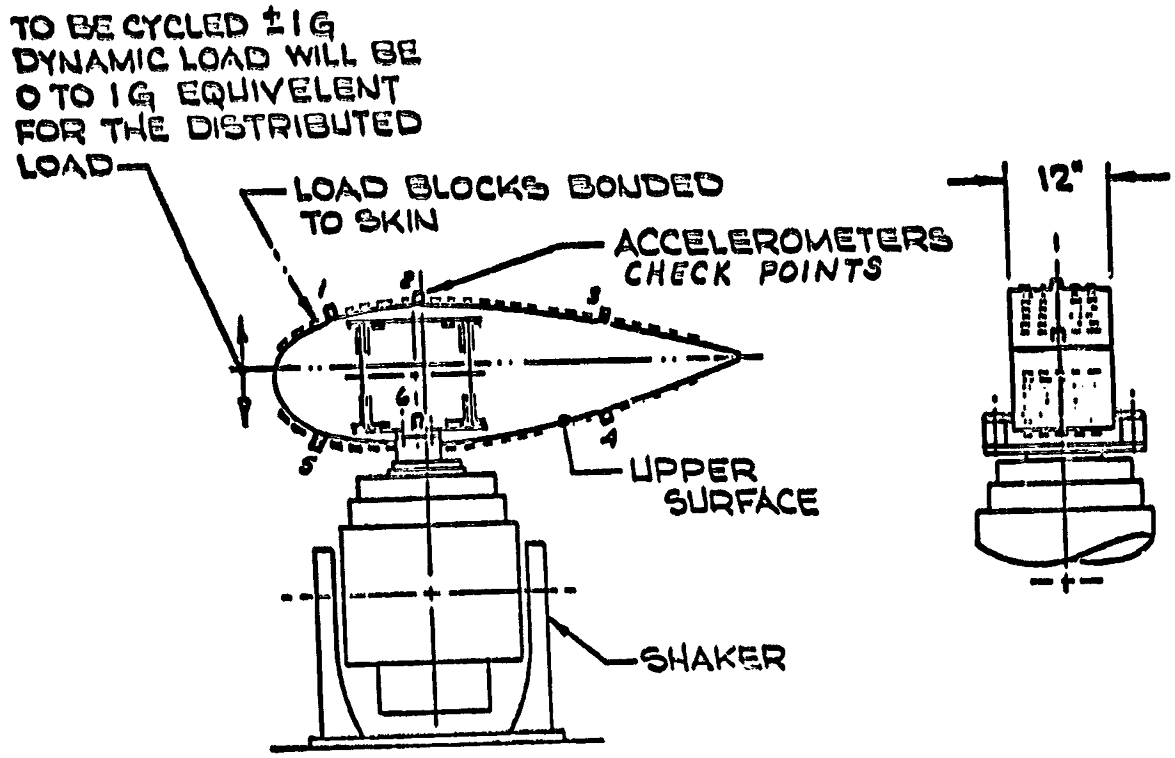
SET UP FOR STA. 187.5 FATIGUE TEST



SUMMARY DATA

TESTING OF FIBER GLASS AERODYNAMIC SURFACES

DESIGN LOAD 50 LBS. PER SQ FT. PROOF LOAD

FATIGUE TEST

TEST #1

AERODYNAMIC LOAD EQUIVELANT FROM 0 TO DESIGN MAX.
MASS LOAD EQUIVELANT FROM 0 TO 2 G
TESTED AT RESONANCE (APPROX. 18 CYCLES PER SECOND)
11,000,000 CYCLES (NO FAILURE)

TEST #2

AERODYNAMIC LOAD INCREASED TO -1 TO +2 DESIGN MAX.
MASS LOAD INCREASED TO -2 TO +4 G 1,100,000 CYCLES
(INDUCED MINOR FAILURE IN URETHANE BOND TO SPAR)

STATIC TEST

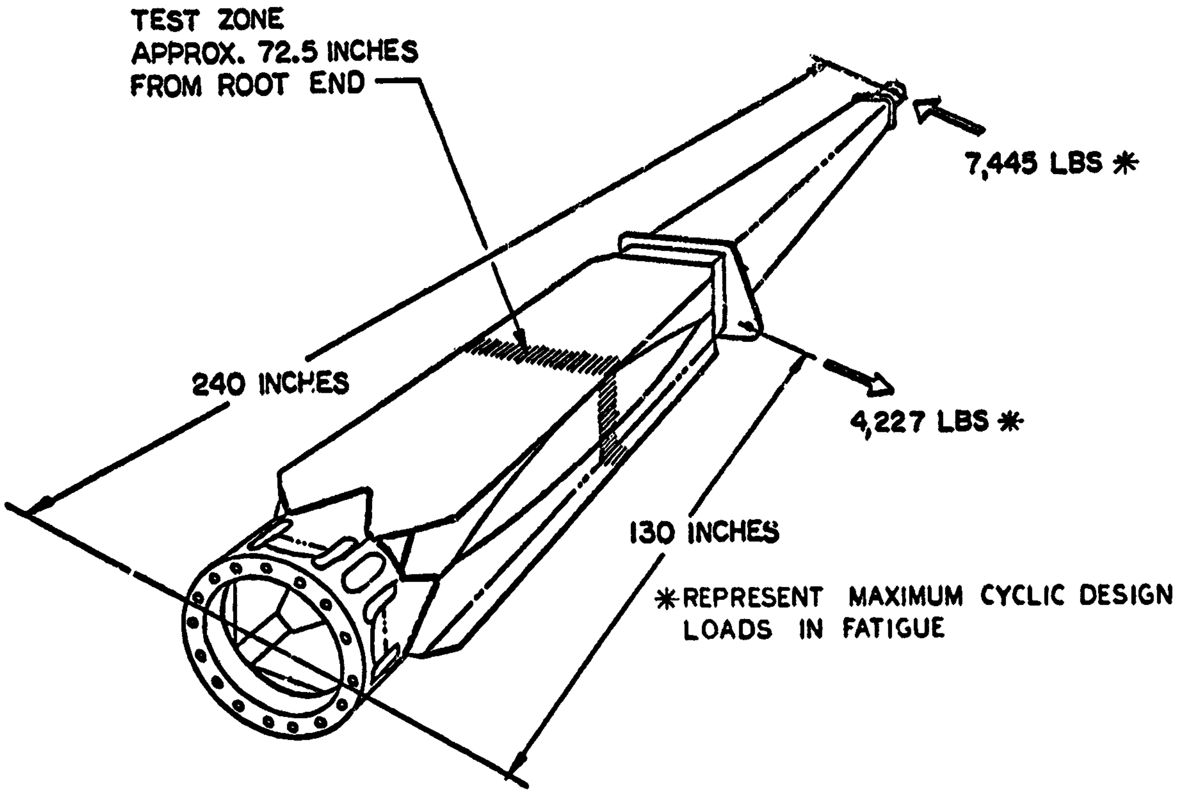
TEST 1 - LOADED TO 175 LBS. PER SQ. FT. (NO FAILURE)
(CONTINUED
NO REPAIR)
TEST 1 - 24 HR. CREEP TEST AT 175 LBS. SQ. FT. (NO CREEP)
(CONTINUED)

ROOT END TEST BEAM

To provide confirmation of the spar design, a full scale root end test section has been manufactured. This specimen was designed to apply the design load to the root end attachment fitting and at a zone approximately 6 ft from the root end to provide the maximum bending stresses in the spar determined by the analysis.

Shown in the illustration is the design of the root end beam. Analysis has shown that one way to accomplish a representative test is to apply opposing loads. This permits us to obtain a balance of the maximum cyclic stress on the spar and the maximum shear load on the assembly (top and bottom assemblies to side assemblies) spot welds. At the same time, the maximum moment and stresses are produced at the root end attachment. The loads described induce the maximum stresses used in the analysis. These are not the actual test loads. Testing levels will be adjusted to match NASA operating experience.

ROOT END TEST BEAM



*REPRESENT MAXIMUM CYCLIC DESIGN LOADS IN FATIGUE

COST STUDY 125 FT ROTOR

A comprehensive cost and weight analysis of the blade design has been made. The design was processed in detail and we have costed the blade as a function of the individual processes for each part and assembly.

The table shows the cost and weights of the blade and major sub-systems based on 100 units per year. The final blade design weighs less than 2,500 lbs.

COST ANALYSIS

BASED ON 100 BLADES ANNUALLY

PART.NO.	DESCRIPTION	QTY	WEIGHT	MAT'L	LABOR	COST	TOOL COST
0518-100101	Spar Assembly	1	1635.7	2442	2904	5346	441,300
104	Trailing Edge Assy	1	86.4	222	176	398	54,500
105	" " "	1	66.6	173	172	345	50,800
106	" " "	1	55.1	135	150	285	45,500
107	" " "	1	45.3	114	141	255	40,300
108	" " "	1	33,4	84	128	212	36,000
121	Leading Edge Assy	1	73.6	287	86	373	41,000
122	" " "	1	52.7	253	86	339	40,000
123	" " "	1	40.9	170	75	245	34,6[illegible]
124	" " "	1	30.9	138	66	204	30,500
125	" " "	1	21.5	107	60	167	27,800
126	Fiberglass Tip Assy	1	43.8	110	146	256	45,400
145	Joint Seal	5	12	10	-	10	-
146	Holding Brkt Boot	2	2	4	-	4	1,000
147	Upper Root Fitting Cover	1	7	24	5	53	5,200
148	Lower Root Fitting Cover	1	7	24	5	53	5,200
150	Spar Root Fitting Assy	1	1015.7	15	275	290	36,000
200	Root Fitting	1	180	169	396	565	66,000
	Adhesive	A/R	72.1	66	-	66	-
100	Blade Assy	1	-	53	704	757	219,700
TOTAL			2466	4600	5570	10170	1,215,000

Based on the guideline chart from NASA, we meet the cost criteria of the program. The cost estimate indicates a probably cost of approximately $13,150 per blade which is considerably below the maximum allowable. See the chart and cost summary on the following page.

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The chart below was supplied by NASA to provide guidelines for the cost envelope versus weight for any blade design.

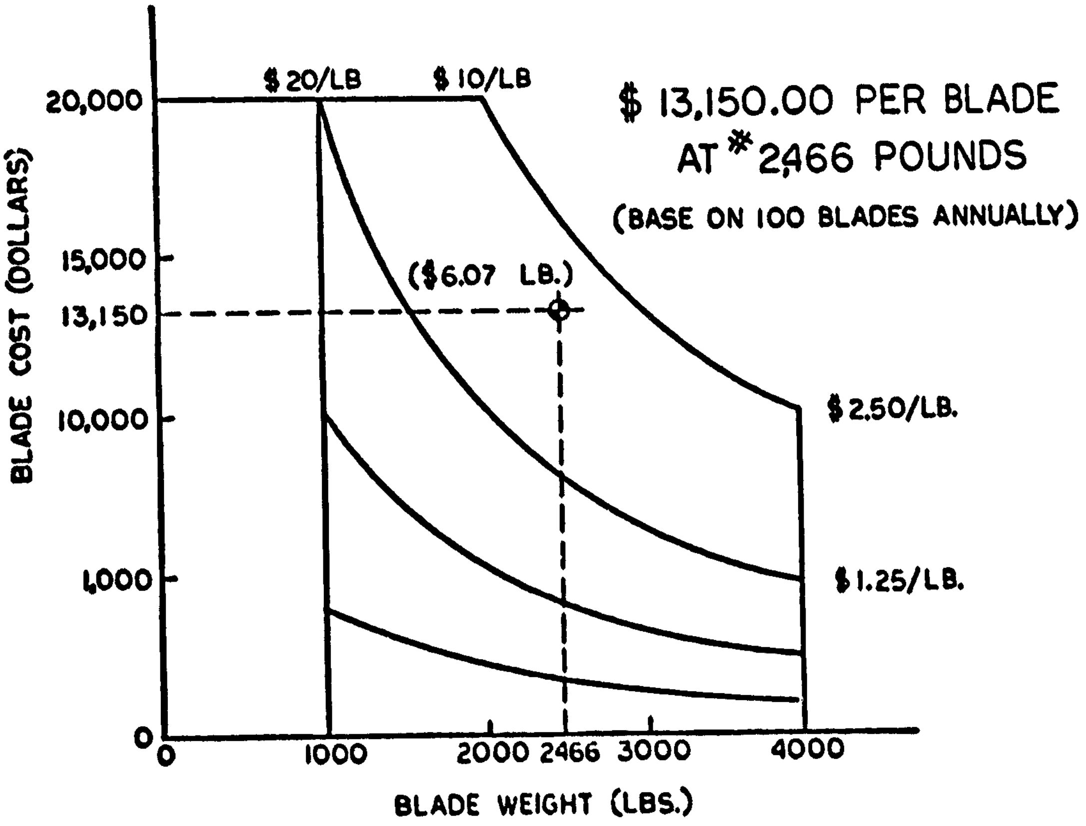
ESTIMATED COST SUMMARY
BASED ON 100 BLADES ANNUALLY

TOOL COST

Tools 1,215,000
Based on Production of 100
Blades Annually
Tool Cost 1,250 Per Blade
(Tools Prorated on
10 Years Production)

COST SUMMARY

Material	4,600
Labor	5,570
Tools	1,215
Total	11,385
5% G&A	570
Total Cost	11,955
10% Profit	1,195
Cost & Profit	13,150 Per Blade



COST VERSUS WEIGHT DIAGRAM
(COST CURVES FROM BASIC N A S A DATA)

CONCLUSION

The Budd Company completed Phase I of the contract. The Phase II program (Building of a Flight Set of Blades) is on hold pending future decisions on the need for blades for 125 ft diameter rotor systems and the funding for such systems. The trend of the wind energy program to build larger systems in the 300 ft rotor size requires further design study. We are very encouraged with the overall design concept and its many advantages when applied to larger systems. The concept permits the use of more complex airfoil systems with minimum effects on costs. It permits modular construction of all elements of the blade system which significantly improves producibility when applied to high volume production. The Budd Company is presently working on designs for application to large rotor systems and is available as a supplier to build such systems.