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PRELIMINARY DESIGN AND FABRICATION ASSESSMENT FOR TWO SOLAR SAIL CANDIDATES

Prepared Under Contract No. 954720

for

Jet Propulsion Laboratory

California Institute of Technology

4800 Oak Grove Drive/Pasadena, California 91103

by

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Frederica, Delaware 19946

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1.0 FORWARD

This report presents the results of a Preliminary Design and Fabrication Assessment for each of two competing Solar Sail Candidates performed by ILC Dover under Jet Propulsion Laboratory Contract No. 95A720.

Mr. Ralph W. Weis served as Project Engineer for this effort; other engineers who were principal contributors were Messrs. David H. Slack, Franklin L. Beck and John D. Scheible.

Numerous organizations provided technical support on various material, process, and equipment related topics. Design Technology Corporation, Burlington, Mass., was a contributor in the area of equipment design and development assessment.

2.0 INTRODUCTION

The concept of traveling throughout the Solar System with huge space "sailing vehicles" is one of the most exciting aerospace challenges ever proposed. The versatility of such proposed vehicles and their potential adaptability as reuseable space workhorses, transporting both orbiting and landing payloads to distant planets, would initiate an entirely new era in space exploration.

There are two different solar sailing vehicle concepts proposed for this type of space travel, each of which has its own unique critical design characteristics which impact both performance and manufacturing reliability. In-house work at the Jet Propulsion Laboratory and work by other contractors has been underway to evaluate the two proposed concepts from a performance standpoint. In order to assess the manufacturing ramifications of the two designs, the JPL issued a Request for Proposal and subsequently awarded one of two contracts to ILC Dover.

During the first part of this effort, the primary emphasis was on the preliminary design and fabrication assessment of the square solar sail concept. Later, performance analysis trade-offs at JPL resulted in a change in program emphasis to the spinning sail, and ILC was directed to shift its emphasis to the manufacturing assessment of this concept. The results of both efforts are reported herein.

The square sail activity is incomplete due to the technical redirection. The primary content of this report is directed toward the spinning sail design and fabrication assessment. Several methods of fabricating the spinning sail blades are presented and compared. Evaluations are made of each proposed design, as well as the baseline design presented by JPL. These efforts resulted in the recommendation of an apparent optimum design and fabrication plan with an assessment of the major advantages/disadvantages of each concept considered.

3.0 SAIL DESIGN CRITERION

3.1 Material

3.1.1 Requirements

The base material from which the spinning sail blades are fabricated is a DuPont polyimid manufactured under the trade name "Kapton". Kapton is a stable, relatively high modulus thermoset film which exhibits good elevated temperature stability. The general requirements of the film sheet in the solar sail blade design are as follows:

- Thickness--0.1 mil (0.0025 mm) $\pm$ 0.01 mil (0.00025 mm) chemically etched or electro-deposited on a substrate.
- Film weight = 3 grams per square meter of 0.1 mil thickness (1.42 g/cc).
- Coatings--full width and length of material.

  Sun side = 1000A° $\pm$ 100A° Specular (Light Reflecting) Aluminum.

  Shade side = 125A° $\pm$ 25A° Heat Emissive Chrome.
- Coated film is desirable in 1M wide rolls minimum.
- Film must be able to operate in space environment for approximately four years (0.25 A.U. - 1.84 A.U.).
- Film must be compatible with coatings and capable of achieving good coating adhesions.
- Film must be flexible and durable to withstand fabrication and packaging.

- Film must be manufactured in required quantity by specified date.

- Specular reflectivity $>.85$ for maximum photon impulse, minimum heat absorption, and radiation protection from UV and proton damage.

- Heat emissivity of chrome coating $>.40$.

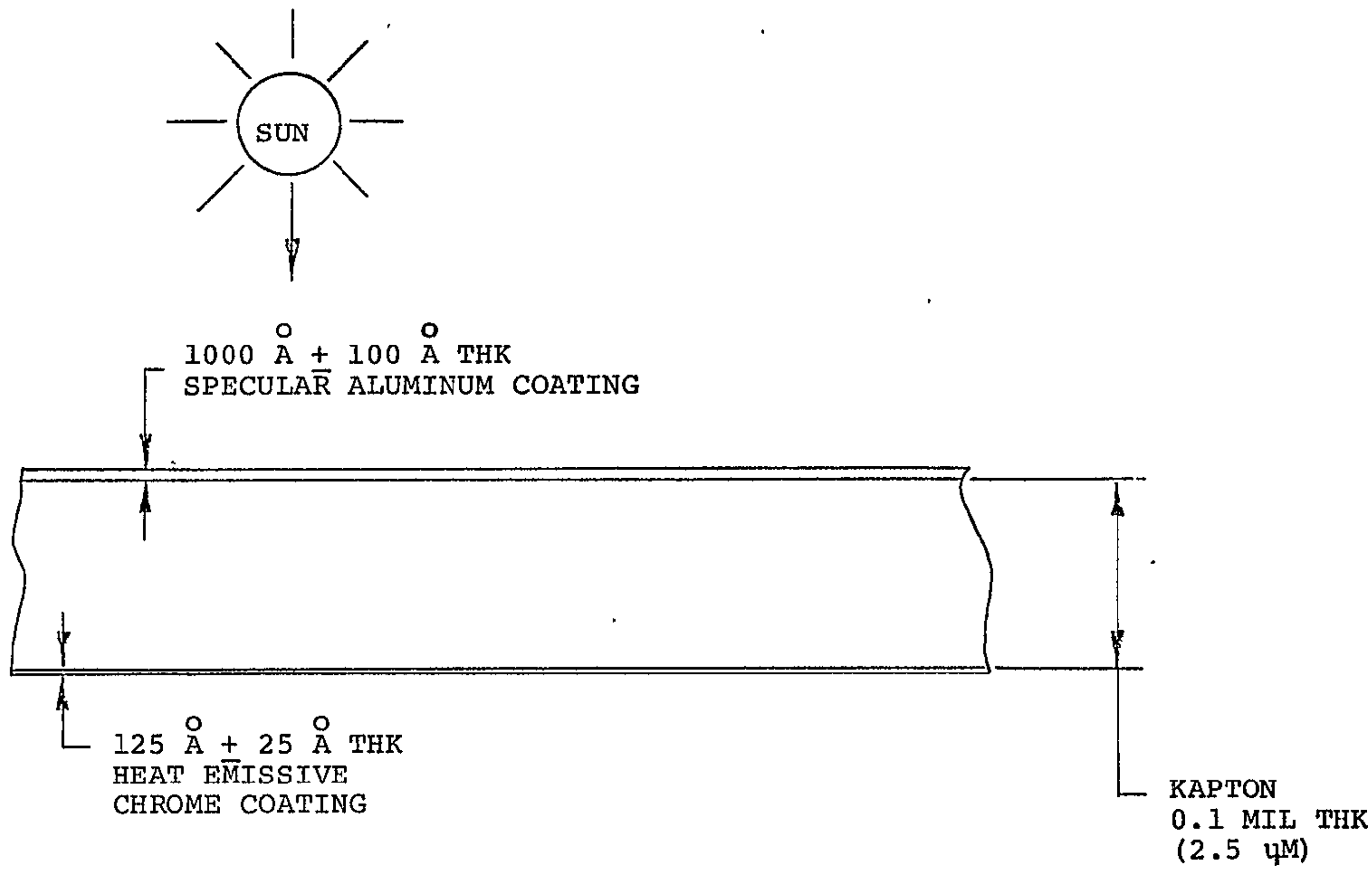


FIGURE 3-1 KAPTON FILM
Scale 10,000/1

3.1.2. Process Considerations

- Basic Film - Numerous manufacturing processes must be completed on the sail film material prior to its use for sail fabrication. Some of the required operations cannot be accomplished utilizing present marketplace facilities; for example, 0.1 mil Kapton film is not presently available, although the manufacturer, DuPont, is attempting to assess the feasibility of producing it on existing equipment. An alternative to manufacturing 0.1 mil Kapton is to procure 0.3 mil Kapton and chemically etch its surfaces to produce a film thickness of 0.1 mil. This method of obtaining Kapton of the required thickness has been used successfully in the laboratory at JPL, but is not used commercially at this time.

The chem etching method, since it is a controlled removal process, has inherently undesirable characteristics such as film thickness and tensile strength variations. Random film thickness variations present in the original Kapton film prior to chem etching (0.3 mil $\pm$ 0.06 mil) would yield a final film thickness of 0.1 mil $\pm$ 0.06 mil. This film thickness, particularly on the low side of the tolerance, would result in either the film being completely dissolved via the chemical etching process or areas where the material would be excessively thin and have critically low tensile strength.

Tensile characteristics for Kapton film in thickness less than 0.1 mil (<2.5 uM) should be consistent with that of thicker films. However, it is felt that film thickness variations and surface defects manifest themselves in extremely thin films by significant reductions in tensile strength. An illustration of this phenomenon is contained in DuPont Bulletin H-66-1C "General Purpose Specifications Kapton Polyimide Film Type H." In this document, minimum tensile values are not published for 0.1 mil (2.5 μM) film. However, the minimum tensile properties for 0.3 mil and 0.5 mil films are stated as 10,000 PSI and 14,000 PSI respectively, while the minimum tensile values noted for 1.0 mil through 5.0 mil films are 20,000 PSI.

- Metalization - Metalization of 0.1 mil Kapton film in 1 meter width must be evaluated in greater depth. Facilities are presently available to aluminize films in widths up to 84" and thicknesses down to 0.25 mil. However, facilities for chrome metal deposition on film 1 meter wide are not currently available due to the difficulty encountered in achieving coating uniformity over higher width materials. Presently, chrome metal deposition in limited to 12 inches in width.

- Adhesive Application - Adhesive application in the thickness of 0.15 mil to both ripstop and sealing tapes has been successfully accomplished in the laboratory at JPL. However, application of adhesives in the thickness range of 0.1 mil to 0.3 mil to film substrates of less than 0.5 mil is not accomplished commercially.

3.2 Joints, Seams

3.2.1 Requirements

Several types of seams will be utilized in spinning blade fabrication; some are used to join adjacent film panels, some to introduce 1% spanwise fullness, and still others contain high strength edge reinforcements.

The basic panel joining seams contain, by far, the most footage of any seam type. This seam must be extremely reliable and be capable of continuous fabrication. General performance requirements of the joining seam are as follows:

- Strength of seams should be greater than joined film material. (Shear Test)
- Extruded adhesive material should be removed from sun side of film to prevent high thermal absorption, and subsequent burn-through of film material.
- Exposed butt joint gaps on sun side should be less than 0.3 mil wide to prevent burn-through.
- Joints may be butt, lap, or other, but must meet strength, reliability, and temperature control requirements.
- Width of tape, if used, should be 1 cm maximum.
- Adhesive used must dry thoroughly to prevent unwanted bonding of film layers.

- Joint cure cycle must be compatible with overall manufacturing processes and schedules.

- If tape is used on sun side of material, adhesive extrusion must be minimized.

3.2.2 Design Candidates

3.2.2.1 Sewn Seam - The baseline design (Figure 3-2) is to sew the reinforced edges of the sail film to each other and to the prefabricated catenary edge member assemblies. The 1 meter wide rolls of Kapton, with its spectural and emissive coatings, will have 2.5 mm wide x 2.5 μM thick Kapton reinforcing tape, also coated, bonded to the edges of the film with NR150-B2G adhesive. Also, along the length of the roll every 7.4 meters, a 5.0 mm wide crosswise tape will be bonded. The 5.0 mm tape would then be cut in half, yielding a sail film panel 1 meter wide x 7.4 meters long, with 2.5 mm wide x 2.5 μM thick reinforced edges. These panels would then be inspected, weighed, and rolled into a cylinder to be stored for subsequent use. During final assembly, these panels would be sewn to each other and to catenary edge member units using a zig-zag stitch.

One major disadvantage of the above plan is the tremendous amount of cataloguing, recording, and retrieving of panels; there would be 89,910 panels and 2,136 catenary edge member assemblies to be sewn together.

The proposed thread would be approximately 6 mil dia., stranded, and of metallic material; threads of graphite, quartz or glass could also be considered. Temperature problems will exist at the thread-film interfaces since the thread laying on the sun-side of the film creates hot spots due to reflections of sunlight between thread and film. It has been

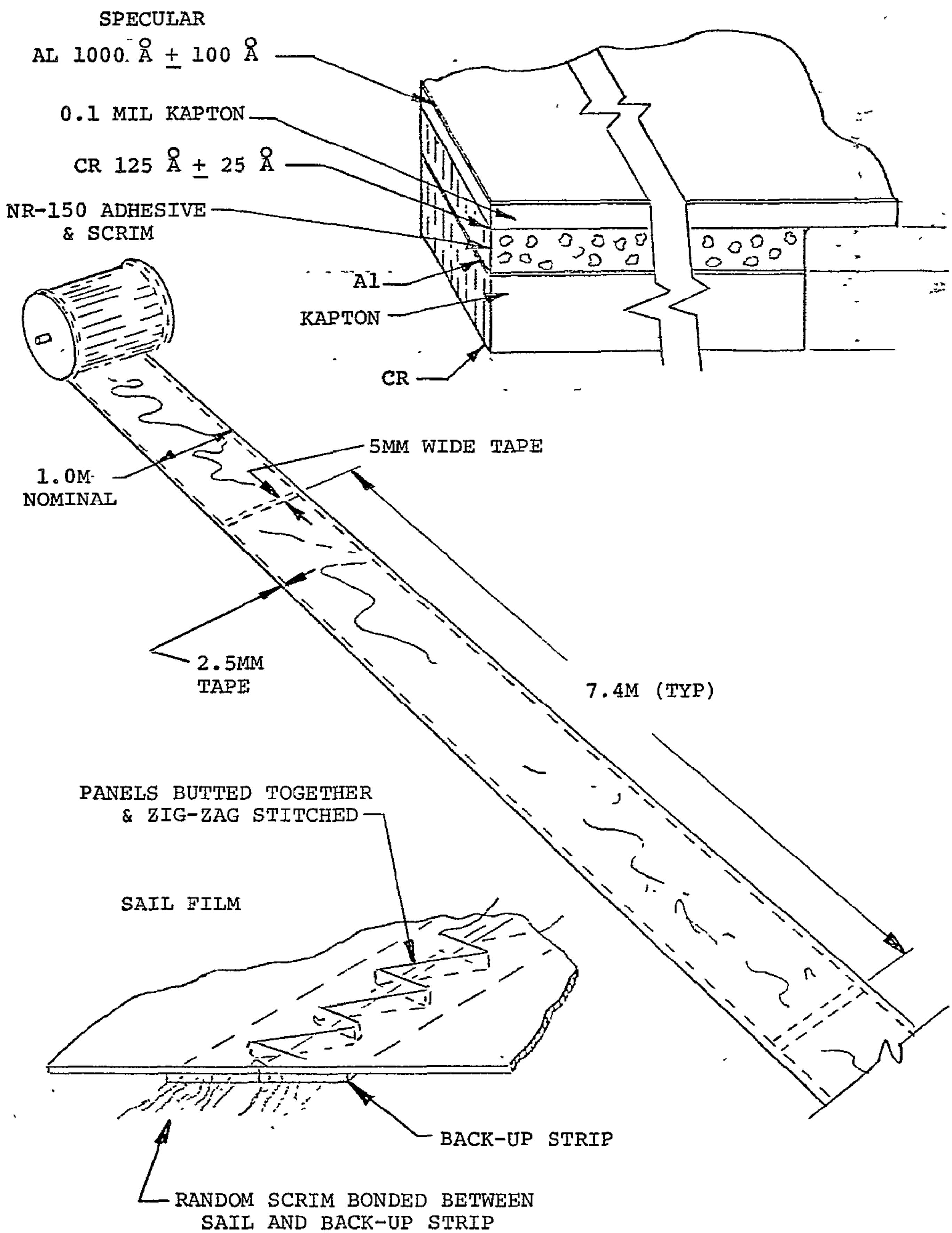


FIGURE 3-2 BASELINE SEAM CONSTRUCTION

calculated that the temperatures in these areas could reach 900°F, far too high for the substrate blade material.

3.2.2.2 Butt Seam with Overlap (Shade Side) - In this plan a 1 cm wide tape would be thermally sealed to join edges of Kapton film together. (Figure 3-3) It has been calculated that the gap on the sun side should not exceed 0.3 mil width because of temperature control requirements. It edge gaps exceed 0.3 mil, it is possible that the exposed NR150-B2G adhesive would be unable to conduct heat away from the gap and would create a localized "hot spot" resulting in burn-through. It is feared that such a localized failure could easily propagate along a seam. Because of this potential propagation effect, the possibility of a gap of $>$0.3 mil should be eliminated as a design requirement. The machine and manufacturing tolerances required to attain this gap eliminate this joining concept as a design candidate. This gap is considered a "tight" tolerance even when working with metal; with Kapton, the degree of difficulty is much greater as the slightest variance in film flatness, edge straightness, etc., could easily cause the gap to exceed 0.3 mil.

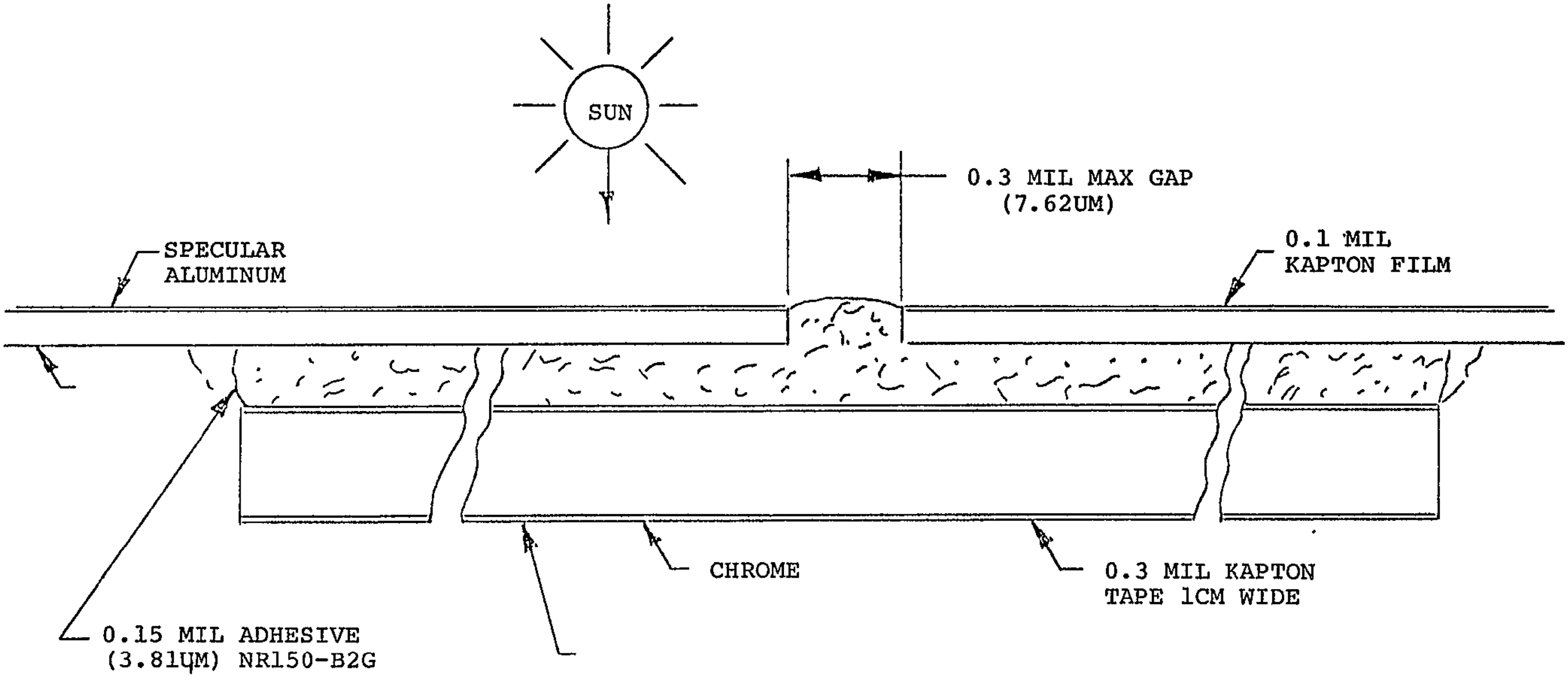


FIGURE 3-3 BUTT SEAM W/OVERTAPE
(SHADE SIDE)

3.2.2.3 Butt Seam with Overtape (Sun Side) - This joining concept (Figure 3-4) is similar to that of 3.2.2.2, except that the 1 cm wide tape is applied on the sun side of the film. This method eliminates the stringent gap tolerances required when the tape is on the shade side.

With the material edge gap and exposed adhesive line on the shade side of the blades, the performance function which will govern acceptable gap limitations, is the shear strength of NR150 adhesive in its cured state. Experiments at JPL have indicated that shear seams of 0.25 cm overlap would be sufficient to realize full material strength across a joint. This bond area tolerance could be used to advantage in the design of the fabrication equipment by reducing the degree of accuracy and control required on raw material roll alignment.

Further, standard material roll width tolerance (on 0.3 mil Kapton) is ± 1/16". The wider gap between edges permissible with the sealing tape on the sun side will permit utilization of the material as it is received from the vendor without provision for extremely accurate width trimming. With the utilization of a 1 cm tape, it is conceivable that a 0.5 cm gap could be tolerated from a structural standpoint; the impact of such tolerances on thermal balance must yet be determined analytically and verified experimentally.

Until this work is done and it can be demonstrated that there are other performance limitations on the joint, a shade side gap tolerance guideline of 0.125 inches maximum will be assured.

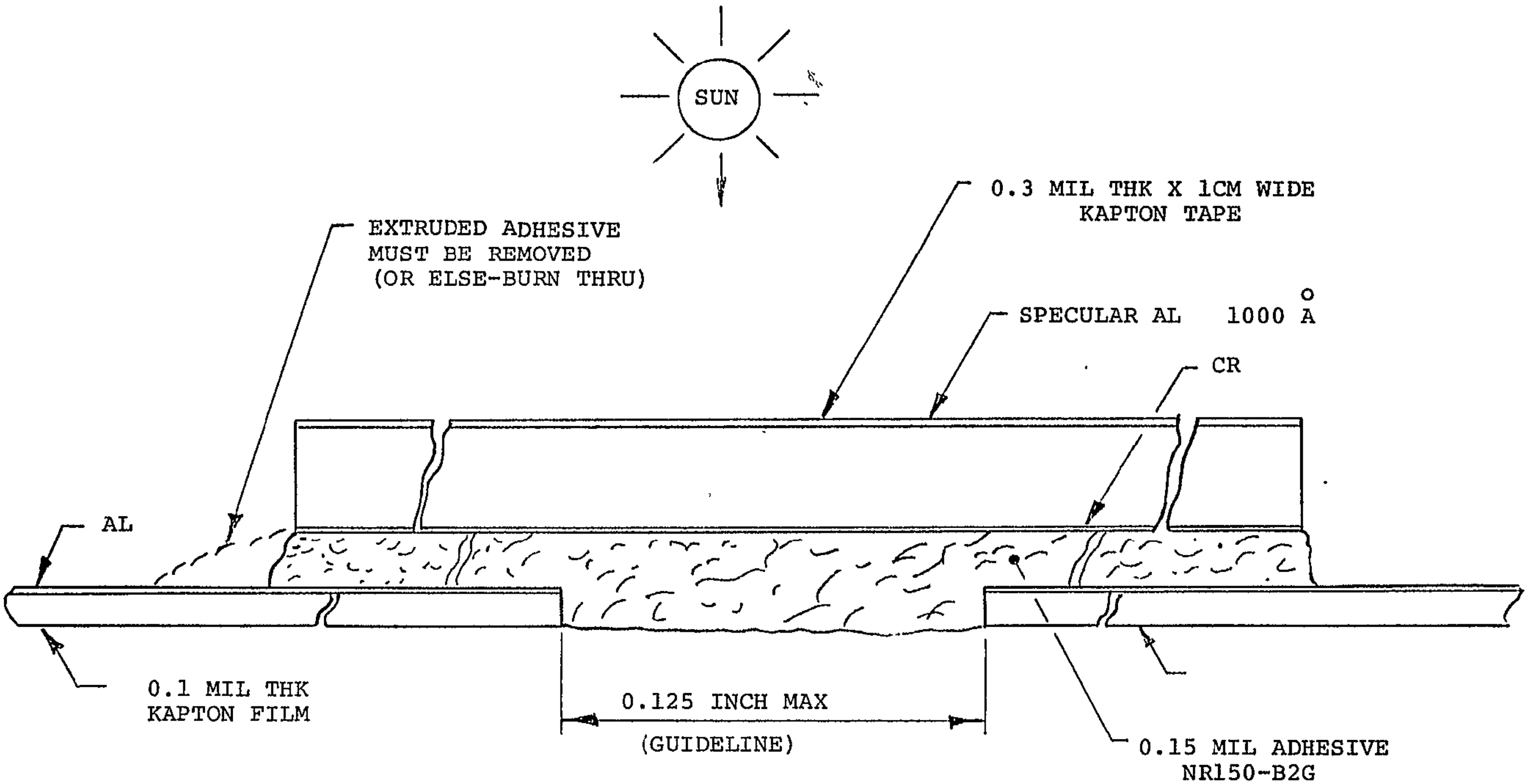


FIGURE 3-4 BUTT SEAM W/OVERTAPE (SUN SIDE)

3.2.2.4 Lap Seam - The lap joint initially appears simpler than any of the other proposed joints since no additional material; i.e., thread, tape, is required to joint the Kapton film edges. The problems anticipated with this joint are in the application of the NR150-B2G adhesive. If the adhesive is sprayed on just prior to bonding, there is a strong possibility of overspray which would create temperature control problems on the sun side. Also, the oven equipment to remove solvent and partially cure the freshly sprayed adhesive would greatly complicate the sealing equipment. If the continuous sealing operation has to be stopped for a tear, adding of a new Kapton roll, etc, it would be difficult to start and stop the spray without experiencing areas with excessive adhesive buildup or with an absence of adhesive.

The prospect of applying and curing the adhesive on the edges of the raw material would eliminate the machinery complexity; however, it would introduce an additional operation and all of the associated handling, inspection, and quality control functions to which the film stock must be subjected.

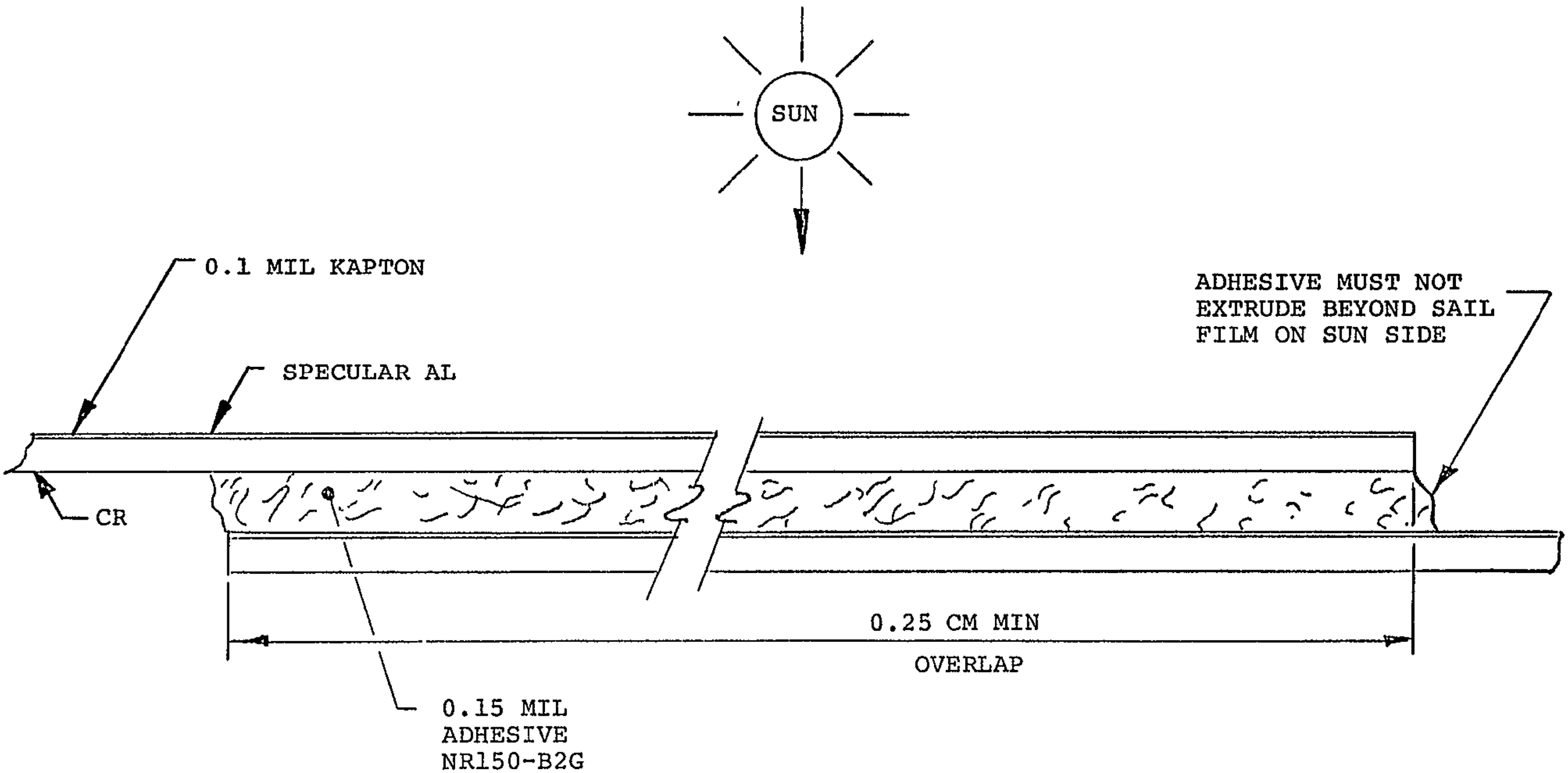


FIGURE 3-5 LAP SEAM

3.2.3 Recommended Design

The butt seam with the sealing tape on the sun side is recommended as the basic panel joining seam. The separate fabrication and curing of the sealing tapes, as well as the elimination of the impractical 0.3 mil gap tolerance, are primary advantages of this concept. The advantages of this seam over the baseline sewn seam include weight, thickness, and the reduction of tear potential.

One area that must be addressed and controlled in this seam is the adhesive flash or extrusion beyond the tape edge on the sun side. This excess adhesive could cause a thermal hot-spot and burn-through. One concept to prevent this from happening utilizes an absorptive Nomex tape which would be rolled over the hot sealed joints to absorb excess adhesive.

3.3 Ripstop Protection

3.3.1 Requirements

Kapton films exhibit extremely low resistance to tear propagation. Any film separation which is initiated in a panel will propagate randomly through the film until a high tear resistance is encountered. This resistance will take the form of ripstop devices, mechanisms or processes. The general ripstop performance requirement is that tears are precluded from propagating for more than eight meters.

3.3.2 Methods

There are two general tear resisting concepts which may have application to this program. Tears which are propagating in a homogeneous material are stopped or resisted when they intersect a step function high modulus change or when they propagate through edge of the substrate.

Ripstop tapes bonded to the basic film will serve as high modulus boundaries to stop tears. These tapes could be made of .3 mil Kapton film with the baseline NR-150-B2G adhesive applied to the aluminum side. Tapes would be applied to the shade (chrome) side of the film panels to minimize adverse thermal control problems caused by adhesive extrusion.

It is anticipated that the basic film material will be perforated to enhance surface to surface electrical shortcircuiting and also to facilitate the escape of entrapped air during and subsequent to fabrication. Tears which intersect any of these holes will also experience a high modulus change (in this case a material edge) and be stopped.

In order to evaluate the effectiveness of such holes as ripstop provisions, ILC had various thickness samples prepared and tested for tear resistance. A commercial film perforating house produced samples of 1 mil, 0.5 mil, 0.3 mil, and 0.1 mil films perforated with .050 inch holes on approximately three inch centers. The holes were mechanically punched using a male/female interference perforating drum. Samples were prepared as tongue tear specimen per FTMS 191 #5134 (modified). Tear propagation values through the basic film, as well as tear initiation after a hole intersection, was recorded and compared. The results of these tests follow:

Table 3-1 -- TEAR PROPAGATION--KAPTON FILM

GAUGE	BASIC MATERIAL	HOLE TEAR	TEAR	INCREASE FACTOR
1.0 MIL Kapton	6 gms	175 gms	169 gms	29
.5 MIL Kapton	5 gms	58 gms	53 gms	11
.25 MIL Kapton	2 gms	23 gms	21 gms	11
.1 MIL Kapton	.5 gms	6 gms	5.5 gms	12

3.3.3 Considerations

It is assumed for the purpose of this report that ripstop resistance greater than that afforded by tapes will be desired for the spinning sail blades.

- If the construction of the sail blade is crosswise, no ripstop tapes will be required since the sealing tape between panels will perform that function, and maximum length of panels is 8 meters.

- If the sail construction is lengthwise, ripstop tapes will have to be applied every 8 meters.

3.4 Edge Reinforcement

3.4.1 Requirements

The general performance requirements of the catenary edge reinforcement are as follows:

- Edge reinforcement structure is required to take all centrifugal force of sail and never be unloaded by sail film.
- Sail film is to be suspended crossways between catenaries or scallop shapes which are uniformly cut to a throat depth of .24 M. Chordwise stiffening members, battens, are spaced at locations along the blade such that the catenaries exert an equal chordwise tension on the sail film.
- The edge reinforcement structure must be designed with a high degree of reliability from meteoroid degradation.
- The edge reinforcement structure must be attached to the sail blade in such a manner that 1% spanwise fullness is introduced along the scallop shape.
- The edge reinforcement tape thickness should be minimized to enhance blade storage on the flight reels.

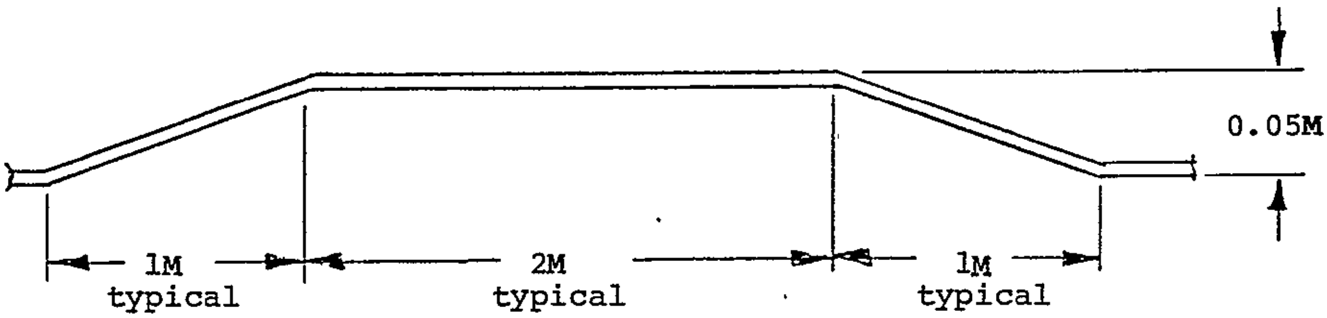
3.4.2 Design Candidates

3.4.2.1 Baseline Trifilar Tape - The baseline edge reinforcement concept is a structural tape which consists of three graphite polyimide composite ribbons. See Figure 3-6. This configuration utilizes an alternating zig-zag scheme to structurally integrate the three individual ribbons. This distribution has been proposed to be accomplished by sequentially off-setting all three ribbons or by using two straight edge ribbons with one ribbon alternating between the two edge members.

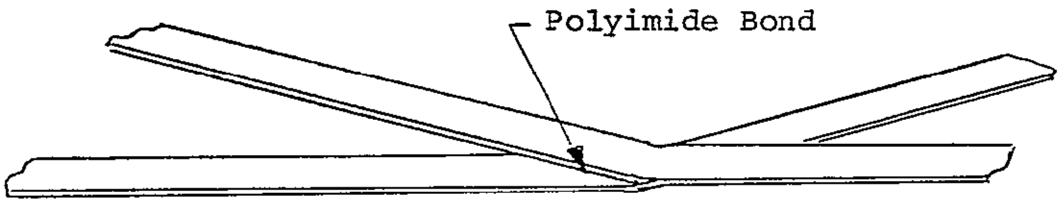
Both of these concepts present several potential functional and fabrication difficulties which need resolution in order for it to be a viable component in the final proposed design configuration.

Sail reliability is directly dependent on the bond between the catenary edge reinforcement and the Kapton film. Any bonded joint should be continuous and free of voids to prevent areas of discrete thermal imbalance which could result in film burn through. The three ribbon trifilar zig-zag concept will be difficult to bond or otherwise adhere to the Kapton substrate because the type of continuous bond sealer envisioned for this operation could have difficulty providing secure uniform bonds through the rough and irregular trifilar tape cross-section. Air pocket voids or excessive adhesive fillets around the ribbon are potential problem areas.

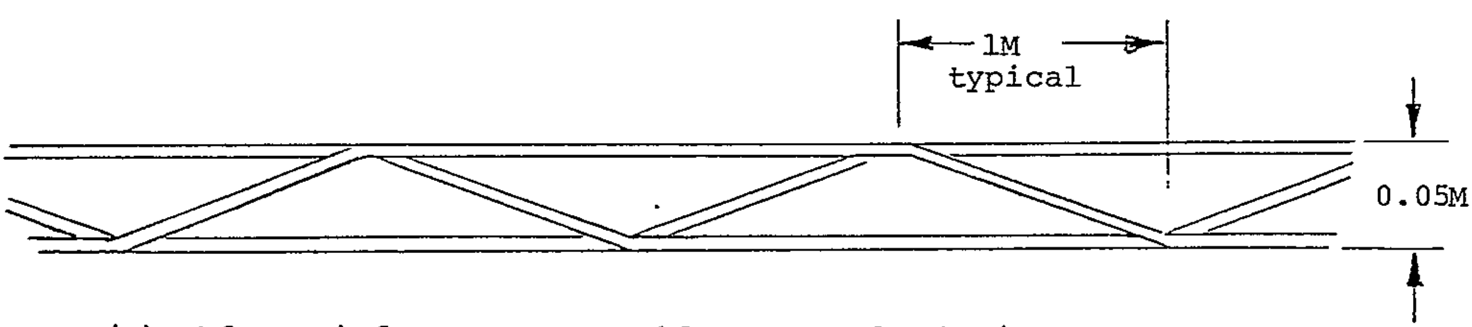
The proposed joining of the internal zig-zaging ribbon (or ribbons) to other ribbons during the tape manufacture will result in a potentially highly loaded adhesive joint. If this



(a) Basic preformed element. 2.1 x 0.18 mm graphite-polyimide unidirectional tape.



(b) Joint detail. Bond mass 0.004 g



(c) Edge reinforcement assembly. Mass 1.77 g/M

FIGURE 3-6 BASELINE EDGE REINFORCEMENT
(Scale distorted for clarity)

attachment is to be an in-plane joint, the contact area will be limited to some small straight segment of ribbon. In a situation where this joint had to carry a high load because of failure of one of the two edge ribbons, the force per unit shear loading will be quite high. It will be necessary to verify that the polyimide system can sustain such loading.

3.4.2.2 Unidirectional Graphite Filament Prepreg Tape - An alternate catenary edge reinforcement concept which would provide a much thinner and more uniform cross section is a prefabricated unidirection prepreg graphite filament tape. In this configuration, 1000 filament yarns would be calendered and spread or encapsulated with a polyimide system. Some work has been done along these lines with the DuPont NR-150 system; however, our information indicates that minimum thicknesses achieved so far have been about 3.0 mils with 3000 filament yarns. A candidate prepreg would use graphite filaments which have an ultimate tensile of 350K PSI and a modulus of 30×10^6 PSI. Typical fiber volume loading density for a prepreg unidirectional tape of this type is 60-65%. In order to achieve a weight similar to that of the proposed baseline while maintaining a two inch width (for comparable meteorite protection) such a tape would have to be about 1.0 to 1.5 mils thick. The graphite yarns used in unidirectional tape fabrication are available in 1000 filament tows. It should be possible to achieve a thinner calendered tape with this substrate yarn. A major area of concern in trying to make such thin prepregs is uniformity of filament lay and elimination of voids in the cross section.

It should be noted that ultimate elongation of these graphite filaments is on the order of 1.00 - 1.16%. Realizing this, it is apparent that one should carefully scrutinize any fabrication process which involves highly stretching the graphite polyimide edge reinforcements. A method of shrinking or uniformly wrinkling the Kapton to attain 1% spanwise fullness may be a more desirable approach. Perhaps a combination of some stretch (to ensure uniformity) and some programmed wrinkling or feeding would be a good approach.

The primary reasons for considering the high count, uniform cross section tape are:

- To provide a smooth, flat, uniform surface for the binding or attachment equipment.
- To minimize the possibility of unsealed contact areas.
- To minimize excessive adhesive fillets along the individual large yarns
- To provide a more manageable tape for automated equipment.

3.4.2.3 Alternate Unidirectional Tape - A primary disadvantage of basic graphite prepreg tape is the 60 - 65% fiber density. Excessive resin simply adds weight with virtually no increase in strength capability. A possible scheme for increasing fiber density of a unidirectional tape is being considered. The basic concept involves laying graphite filaments onto a pressure sensitive tape to the desired width and thickness. Then a diluted solution of polyimide adhesive resin is sprayed on the graphite yarns and partially cured. In this manner, a spray coat with bleed-through and good fiber wetting would be achieved. It is expected that the amount of resin build-up with this technique would be less than that of an impregnated calendered system.

In this concept, the heat for tape application could be applied through the pressure sensitive tape. Also, it might be possible to utilize a special tape for this purpose which would absorb excessive polyimide adhesive extruded by the joining equipment.

3.4.2.4 Cured Graphite Prepreg Tape - The graphite prepreg tape needed for the spinning sail blades is not currently available in the high fiber density and thin cross section required. Normal manufacturing processes involving lamination of prepregs are designed to compress the tape plies and bleed excess resin during the cure cycle. It is anticipated that the amount of resin bleeding required or the heat and pressure cycles required may be inconsistent with the overall manufacturing flow plan of the sail blades.

If this cure cycle poses any serious problem, a potential solution is to have the tape manufactured and supplied in the cured state. This would permit tighter control of tape thickness and weight, since cure pressure, temperature, and resin could be controlled to optimize the tape structure without special consideration of the seaming processes.

Subsequent attachment of the tape to the film would then be accomplished by means of a normal heat curing polyimide adhesive system. The adhesive could be pre-applied to the polyimide/graphite tape, prior to attachment to the blades.

3.5 Battens

3.5.1 Requirements

Leading and trailing edge separation is maintained by light-weight compression beams called battens. These battens are to be attached to the carenary edge reinforcement tapes at prescribed locations along the blades. General performance requirements of the battens are as follows:

- Battens are chordwise stiffening members; 89 per blade, total for 12 blades = 1068 including a tip batten; attached to the catenary members only at calculated lengths to cause the catenaries, when centrifugally loaded, to exert a uniform chordwise tension on the sail film.
- Battens must be collapsible so they can be rolled up on the same reel with sail blade.
- Maximum compressive batten load is 6.1 N on the innermost batten. (Design load 12.2 N.)
- Batten construction is to be of minimum weight and must meet strength, reliability, and collapsibility requirements.

3.5.2 Design Candidate

The baseline design is shown by Astro Research Corporation Drawing SK-1813 dated May 23, 1977. The attachment of the batten to the catenary edge reinforcement is a very critical interface with regard to blade integrity. The proposed attachment method involves the use of titanium plates, riveted and cemented in place.

The hinge design which permits the folded flat batten to be rolled up with the blade and subsequently deployed to a rounded shape has disadvantages due to the large quantity (220 per batten), and the associated potential malfunctions when deployed in space. If a hinge jams, batten will not "pop-out" to full diameter and batten stability will be destroyed.

The batten structure is composed of 6 longerons 0.48 mm square x 8 m long, approximately (.020" square x 26 feet long). The helix spiral members are also 0.48 mm square. The spirals must be bonded to the longerons at their intersections.

The greatest factor of concern with this proposed design is its potential degradation of the sail film with which it comes into contact. The "hard" batten structure, the sharpness of the graphite/polyimide composite, and the numerous hinges represent potential sheet punctures.

The baseline batten attachment method, which involves the use of titanium reinforcement plates and rivets, could present serious limitation on the durability and reliability of the spinning sail blades. An alternate attachment method using a larger bonding process would be preferred in the proposed design.

The overall batten concept and particularly its interface with the catenary edge tapes, is an area recommended for design improvement; however, its analysis and re-design are not within the fields of expertise of ILC.

3.6 Mesh

3.6.1 Requirements

The inboard section of each spinning blade is to be free of reflective sail material to prevent excessive heat build-up in the spacecraft. The blade's structural integrity in this region is maintained by a leading and trailing edge reinforcement, and a diagonal intersecting mesh. The general performance requirements of the mesh are as follows:

- Mesh structure extends from upper and lower flap hinge posts to innermost batten #88, a distance of about 163M.
- Mesh structure is bonded to catenary edge reinforcement tapes.
- Function of mesh is to provide shear stiffness for edge members and to substitute for film in the inboard blade section.
- There must be no longitudinal load on mesh; edge members take all longitudinal (centrifugal) loads.

3.6.2 Design Candidate

The baseline mesh design (Figure 3-7 & 3-8) consists of a square network of structural tension filaments oriented on a 45° bias to the blade's length direction. The filament material is presently undefined; however, quartz, graphite, and metallic substrates are potential candidates.

The baseline configuration specifies 200 mm spacings between the filaments. Specific data regarding the shear stiffness is unavailable at this time; however, it is recommended that mesh spacing be expanded as far as possible.

It is anticipated that the mesh edge members could be similar in design to the catenary edge reinforcement tapes; however, metallization in some form of thermal balance control will be necessary to protect the polyimide resin in the composite structure.

Inboard and outboard mesh terminations should be self sufficient and should not require attachment to other hardware or to blade film. If blade film is attached to the outboard mesh termination it should be only a non-structural joint for the purpose of fixing the free end of the blade sheet.

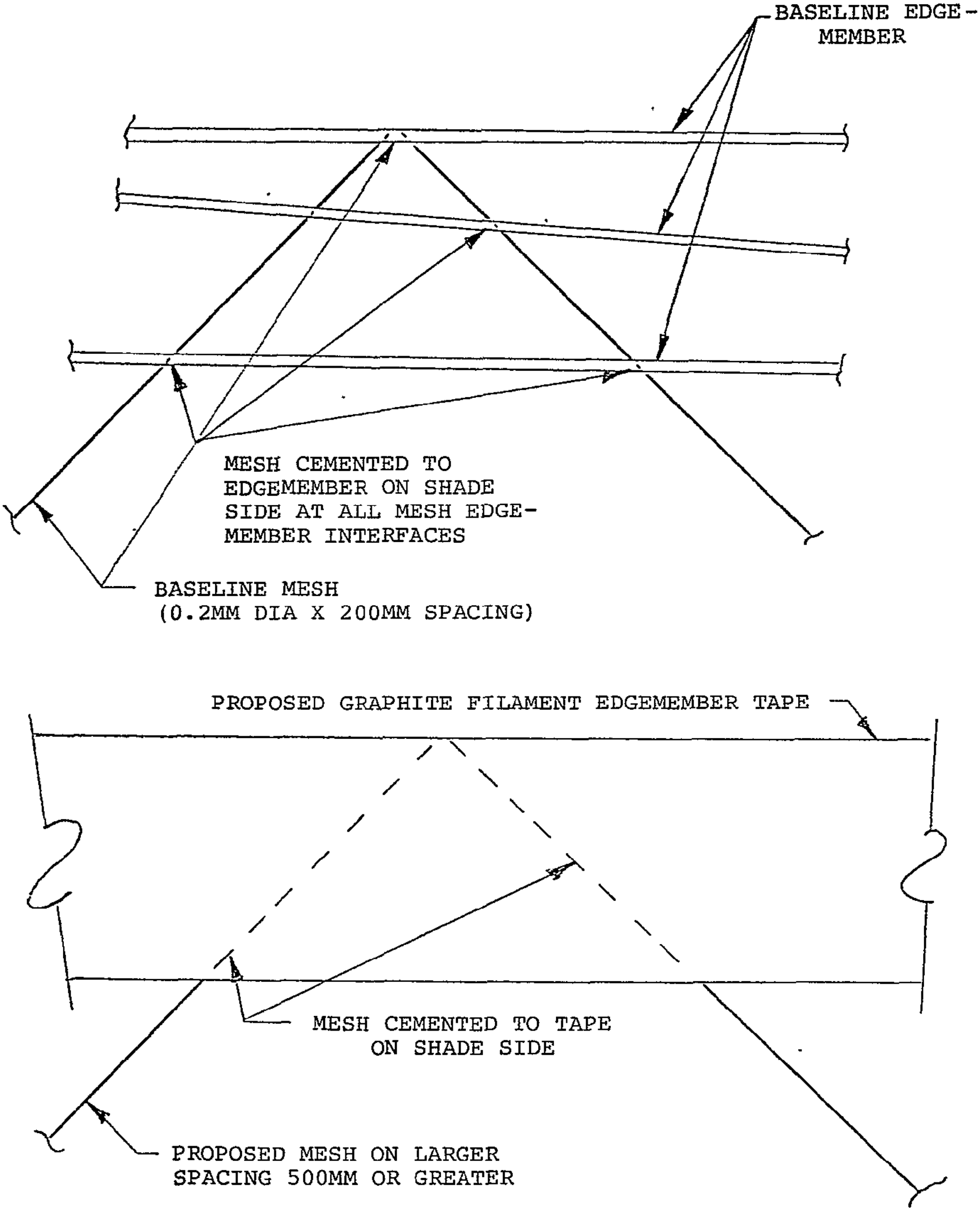


FIGURE 3-7 MESH/EDGEMEMBER INTERFACE

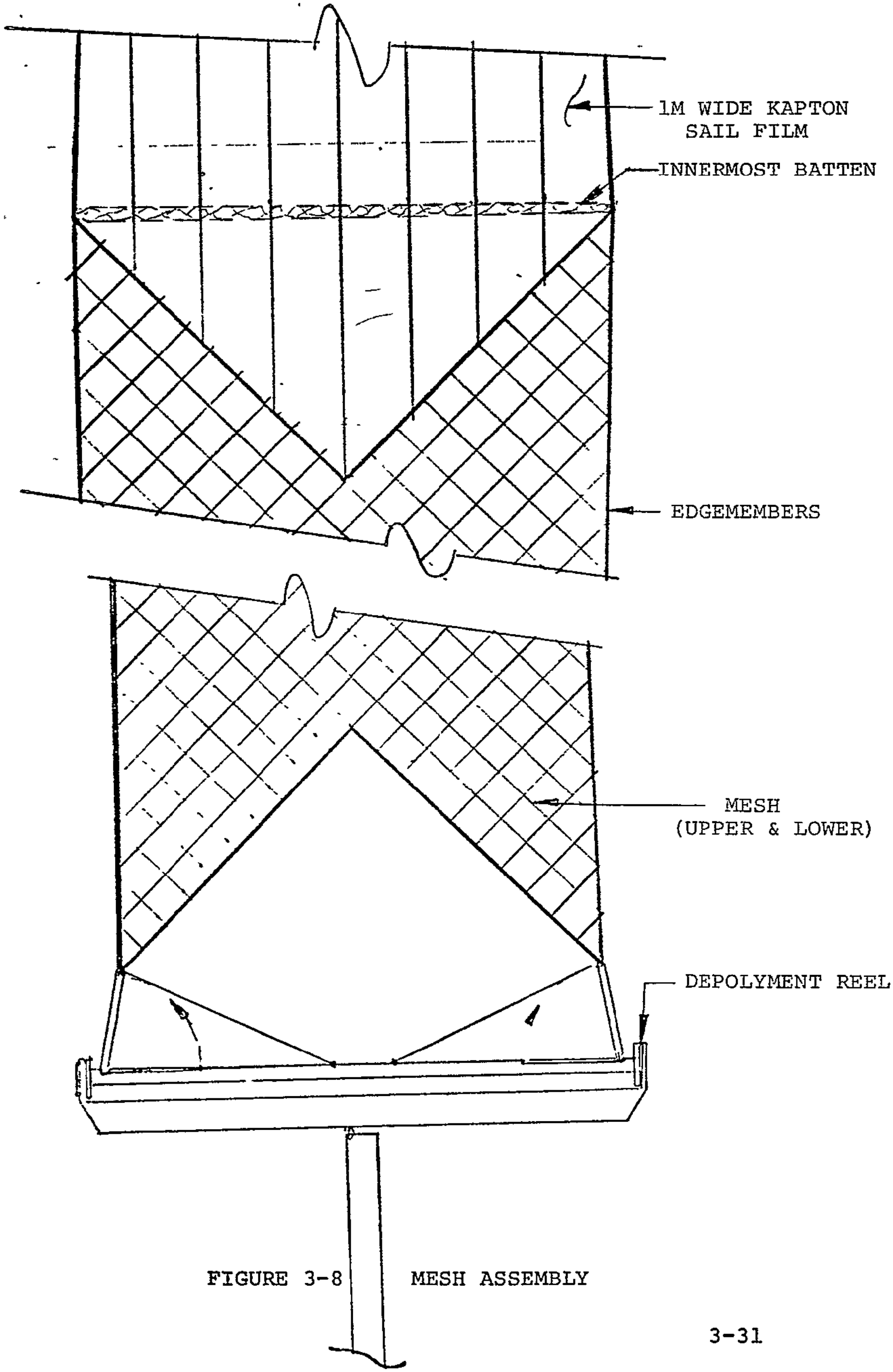


FIGURE 3-8 MESH ASSEMBLY

3.7 Weight Schedule

A weight estimate of the soft goods elements of the spinning sail blades has been compiled. The primary interest in generating such a listing is to compare relative unit weights and total weights of the alternate concepts proposed to those of the baseline design.

For the purpose of these calculations, the film portion of the blade was taken as 7327 meters. The length of the catenary run was taken as 7327 meters also since the length difference between catenary and tip to tip chord length was found to be only .06M for the most severe scallop. The relative lengths of seams is shown for the proposed lengthwise fabrication plan and also the Astro Research baseline.

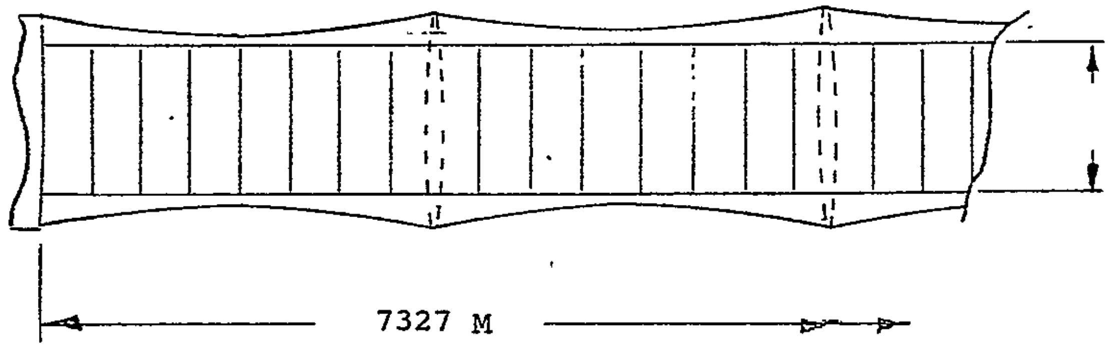
The specific seam lengths of the two basic fabrication plans (crosswise seaming and lengthwise seaming) are shown on the following page.

Film weights in either fabrication plan would be similar. For the purpose of calculations, the following weights assumptions were made for the type of seams proposed by ILC.

Film Weight	.1 mil Kapton	3.607 gm/M^2
	Coatings	.36 gm/M^2
		3.967 gm/M^2
Proposed sealing tape Wt.	.3 mil Kapton	10.829 gm/M^2
	Coatings	.36 gm/M^2
	Adhesive (.15 Mil)	5.41 gm/M^2
		16.599

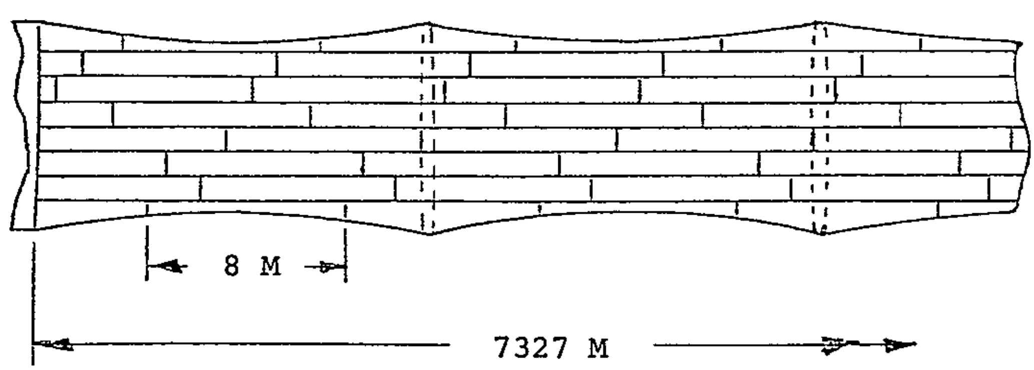
.166 gm/m @ 1 cm wide

SEAM LENGTH - BASELINE DESIGN



Seam Lengths:	7327 (7.4 M) + 7327 M (2) 54,220 M + 14,654 M 68,874 M per blade 826, 488 M Total
Edge Tendon Lengths:	7327 M (2) = 14,654 M per blade 14654 M (12) = 175,848 M Total

SEAM LENGTH - LENGTHWISE DESIGN



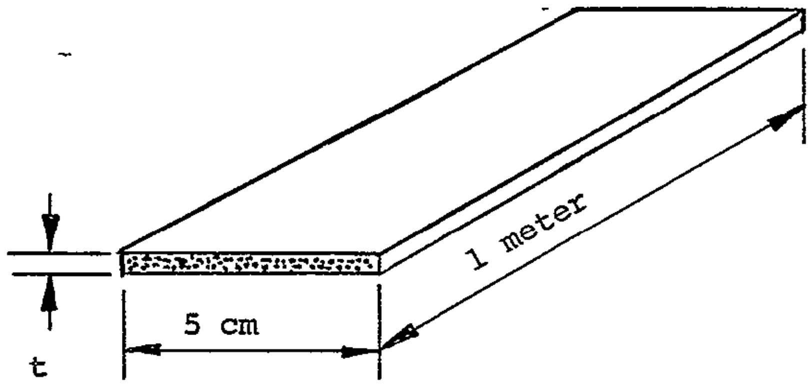
Lengthwise Joining Seams:	7327 M (7) = 51289 M per blade 51,289 M (12) = 615, 468 M Total
Ripstops:	$\frac{7327}{8}$ (8 M) = 7327 M per blade 7327 M (12) = 87,924 M total
Edge Tendons:	7328 M (2) = 14,654 M per blade 14,654 M (12) = 175,848 M Total

Ripstop Tapes	.3 mil Kapton	10.829 gm/M^2
	Coatings	.36 gm/M^2
	Adhesive (.15 mil)	5.41 gm/M^2
		16.599 gm/M^2
	.083 gm/m @ .5 cm wide	
Catenary Edge Shrinkage Tape	.1 mil Kapton	3.607 gm/M^2
	Coatings	.36 gm/M^2
	Adhesive (.15 mil)	5.41 gm/M^2
		9.377
	.469 gm/m @ .5 cm wide	
Catenary reinforcement:	load capability 77ln x 3 safety factor	
	65% fiber volume density	
	2.44 gm/M (5 cm wide) (as calculated on the following page)	

Using these weights and the baseline weights provided in the baseline design reports, a comparison weight tabulation has been generated and is shown in Table 3-1.

Three tabulations are presented: 1) The Astro Research Baseline seam constructions and associated seaming configuration, 2) The ILC proposed seam construction with the same crosswise seaming configuration, and 3) The ILC proposed seam construction with the proposed lengthwise seaming configuration.

Two of the baseline weights assumed appear to be quite low based on the information which is known about this composition. These weights and a proposed more realistic value which has been calculated for these seams is discussed in the notes under Table 3-1.



Assume 65% fiber density by cross section area

$A_T = 5 \text{ cm } (t \text{ cm}) = 5t \text{ cm}^2$

$A_G = 5 \text{ cm } (t \text{ cm}) (.65) = 3.25t \text{ cm}^2$

$A_R = 5 \text{ cm } (t \text{ cm}) (.35) = 1.75t \text{ cm}^2$

$P = 77 \text{ln} \left(\frac{1 \text{lb}}{4.448 \text{n}}\right) \text{ X } 3 \text{ (Safety Factor)} = 520\#$

$\sigma_T = 350{,}000$ psi ultimate tensile strength

Assume Graphite takes all load

$A_G \sigma_T = P$

$A_G = \frac{P}{\sigma_T} = \frac{520 \text{ lb}}{350{,}000 \text{ psi}} = 1.486 \text{ X } 10^{-3} \text{ in}^2$

$A_G = 1.486 \text{ X } 10^{-3} \text{ in}^2 \left(\frac{2.54 \text{ cm}}{1 \text{ in}}\right)^2 = .00959 \text{ cm}^2$

$.00954 \text{ cm}^2 = 3.25t \qquad t = 2.95 \text{ X } 10^{-3} \text{ cm}$

$\text{Weight/meter} = W_g\text{/meter} + W_r\text{/meter}$

$= 3.25 (2.95 \text{ X } 10^{-3}) \, 100 \, (1.74 \text{ gm/cc} +$

$1.75 (2.95 \text{ X } 10^{-3} \text{ cm}) \, 100 \, (1.30 \text{ gm/cc})$

$= 1.67 \text{ gm/meter} + .67 \text{ gm/meter}$

$= 2.34 \text{ gm/meter}$

TABLE 3-2

COMPARISON WEIGHTS

	BASELINE (ASTRO SEAMS, TAPES, ETC.)			CROSSWISE (ILC PROPOSED SEAMS, TAPES, ETC.)			LENGTHWISE (ILC PROPOSED SEAMS, TAPES, ETC)		
	Quantity	Unit Weight	Total Weight	Quantity	Unit Weight	Total Weight	Quantity	Unit Weight	Total Weight
FILM	703,392 M^2	3.967 gm/M^2	2790 Kg.	703,392 M^2	3.967 gm/M^2	2790 Kg.	703,392 M^2	3.967 gm/M^2	2790 Kg.
JOINING SEAMS	826,488 M	.204 gm/M** (.296)	169 Kg. (245)	826,488 M	.166 gm/M	137 Kg.	615,468 M	.166 gm/M	102 Kg.
RIPSTOPS							87,924 M	.083 gm/M	7 Kg.
SHRINKAGE TAPES				175,848 M	.469 gm/M	82 Kg.	175,848 M	.469 gm/M	82 Kg.
EDGE TENDONS	175,848 M	1.77 gm/M* (2.40)	311 Kg. (422)	175,848 M	2.34 gm/M	411 Kg.	175,848 M	2.34 gm/M	411 Kg.
TOTAL			3270 Kg. *** (3457)			3420 Kg.			3392 Kg.

* This weight estimate appears to be low when related to the same graphite physical properties as those used to calculate the estimated weight of the proposed flat unidirectional tape. Using $Y = 35 \times 10^6$ psi $\varepsilon = .3\%$, P = 771 n, ribbon cross section = 2.1 x 0.18 mm, the following calculation was made.

(SEE NEXT PAGE)

** This weight estimate may be low when all film, adhesive, and thread components are tabulated. A 0.1 mil thick x 0.25 cm wide reinforcement tape bonded to each edge with 0.5 mils NR 150 adhesive is assumed. The 6 mil diameter seam sewing thread is assumed to be titanium with a structural fiber density of 80%. A 45° stitch angle with 8 stitches per inch was assumed also. Using these assumptions the following seam weight calculations were made.

(SEE NEXT PAGE)

*** This total weight estimate reflects the two revised unit weights calculated above.

*From Table 3-2

$P = 77ln = 173$ lbs.

$\sigma = \varepsilon Y = .003\ (35 \times 10^6 \text{ psi})$

$= 105{,}000$ psi.

$\sigma = \frac{P}{A} = 105{,}000 \text{ psi} = \frac{173 \text{ lbs}}{A}$

$A = .00165 \text{ in}^2 = .01063 \text{ cm}^2$

Graphite density = 1.74 gm/cc

In one meter there is .01063 cm^2 (100 cm) = 1.063 cc of graphite, or: 1.063 cc (1.74 gm/cc) = 1.85 gm per meter

This calculation indicates that the baseline edge reinforcement would weigh 1.85 gm/M in graphite alone. This assumes no weight for the resin which forms the laminate. (Resin density would probably be on the order of 30 - 35% by volume at a density of 1.30 gm/cc.)

If a 30% weight increase is assumed to cover this resin, the unit weight for the baseline edge reinforcement would be on the order of 1.85 gm/M (1.3) = 2.40 gm/M nearly identical to that of the proposed alternate (to achieve the same safe factor, and operational elongation from similar material properties the weights would, in fact, be similar)

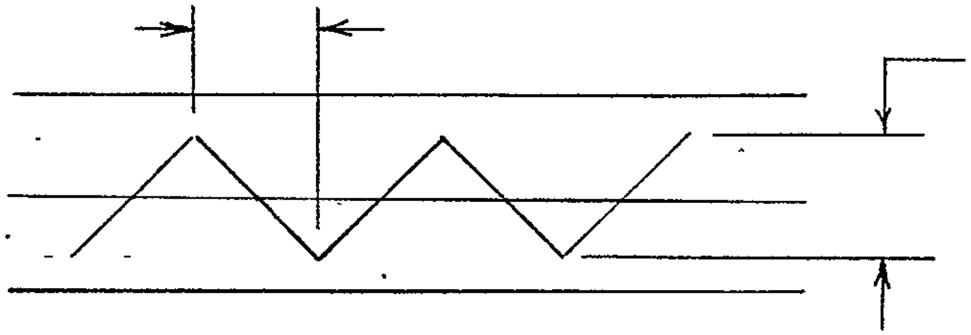
This would indicate a similar weight for the edge reinforcement in either design, which would reduce the comparative weight of the proposed design to within 22 Kg. of the baseline.

**From Table 3-2

Tape weight:	0.1 mil Kapton	3.607 gm/M^2
	Coatings	.36 gm/M^2
	Adhesive (.5 mil)	18.035 gm/M^2
		22.002 gm/M^2

.11 gm/meter @ .5 cm wide

Thread Length:



Thread length = 8 (1.414) .125" = 1.414" per side

= 2.828 inches of thread per inch of seam

or 282.8 cm thread/meter seam

Thread Weight: Titanium density = 4.512 gm/cc

Cross sectional area = $\pi\left(.003 \text{ in } \frac{2.54 \text{ cm}}{\text{in}}\right)^2$

$= 1.82 \times 10^{-4} \text{cm}^2$

Unit Weight = 4.512 gm/cc $(1.82 \times 10^{-4} \text{cm}^2)$ (282.8) cm thread/meter seam

= .232 gm/meter

@ 80% density = .186 gm/meter

Total Sewn Seam Weight: (Tape and thread)

Tape	.110 gm/M
Thread	.186 gm/M
Total	.296 gm/M

4.0 HANDLING AND FABRICATION PLAN (SPINNING SAIL)

The most basic characteristic of the spinning blade fabrication plan is the direction in which film panel seams are oriented. Two general methods of joining film panels have been considered in this effort; chordwise seaming and lengthwise seaming. Each concept, if adopted, would establish specific manufacturing characteristics which would be reflected in the overall fabrication plan and equipment design.

4.1 Seam Direction

4.1.1 Chordwise Seams, Single Blade

Utilization of a chordwise seaming scheme would permit elimination of the production process of applying ripstop tapes to the spinning sail blades. Maximum individual piece panels would be limited to 1 x 8 meters.

Crosswise seaming would involve short (8 meter) seams which would be quite an advantage in possible repair of damages incurred during manufacturing. Randomization of material physical properties throughout the sail is also easily implemented with this scheme. Quality control data obtained during film manufacture and/or inspection could be assigned to any size panel grouping for the purpose of performance balancing. Changing groups or rolls of material would be very simple with this crosswise seaming method.

Figure 4-1 shows a rough schematic of a crosswise seaming arrangement. One meter wide rolls of material are fed from the side and sealed to the free edge of the accumulating blade.

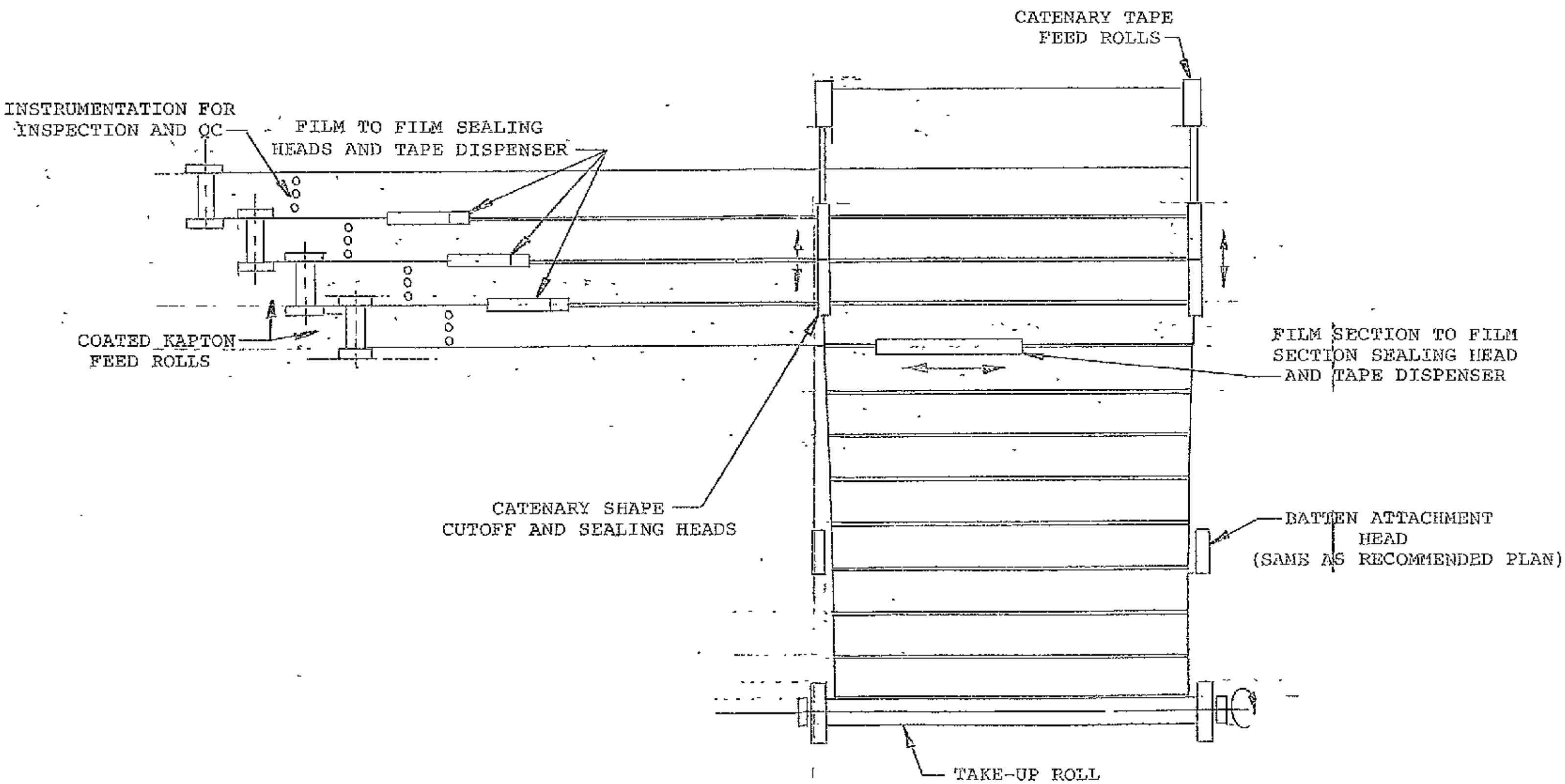


FIGURE 4-1 INTERMITTENT FEED AND CROSS-WISE SEALING

It is envisioned that several rolls could be fed prejoined as shown in the sketch. Scallop edge reinforcement tapes could be applied to the accumulating blade on a continuous basis per one of the methods discussed in Section 4-3.

It should be noted that if seam tape and catenary edge reinforcements are attached to opposite surfaces of the blade film, it would be necessary to feed one from the top and one from the bottom in any of the sealing concepts discussed.

4.1.2 Chordwise Seams, Multiple Blades

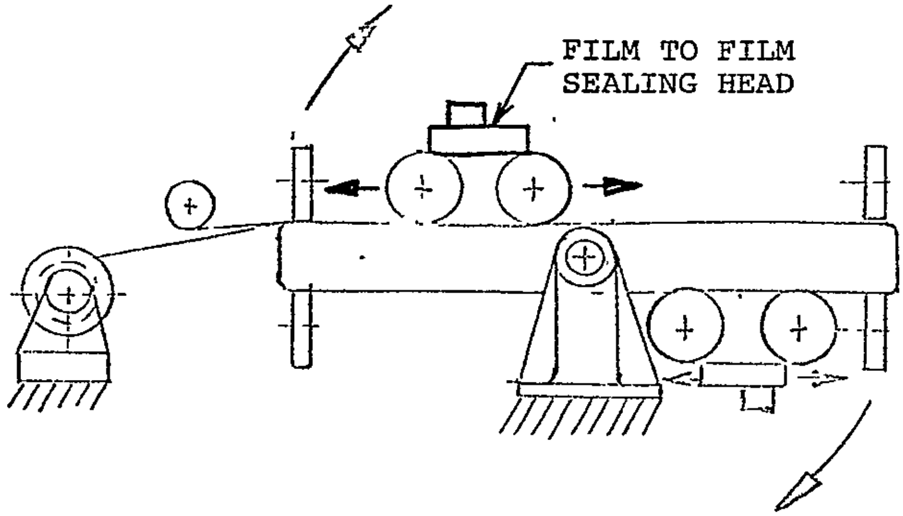
Several concepts have been formalized which utilize a rotating framework to fabricate multiple blades simultaneously. In these methods film and sealing tape are fed from stationary rolls and sealed by heads as the entire sealing heads and frame assembly rotate. The graphite/polyimide catenary edge members are fed from rolls inside the rotating table just after the pinch wheels. See Figure 4-2.

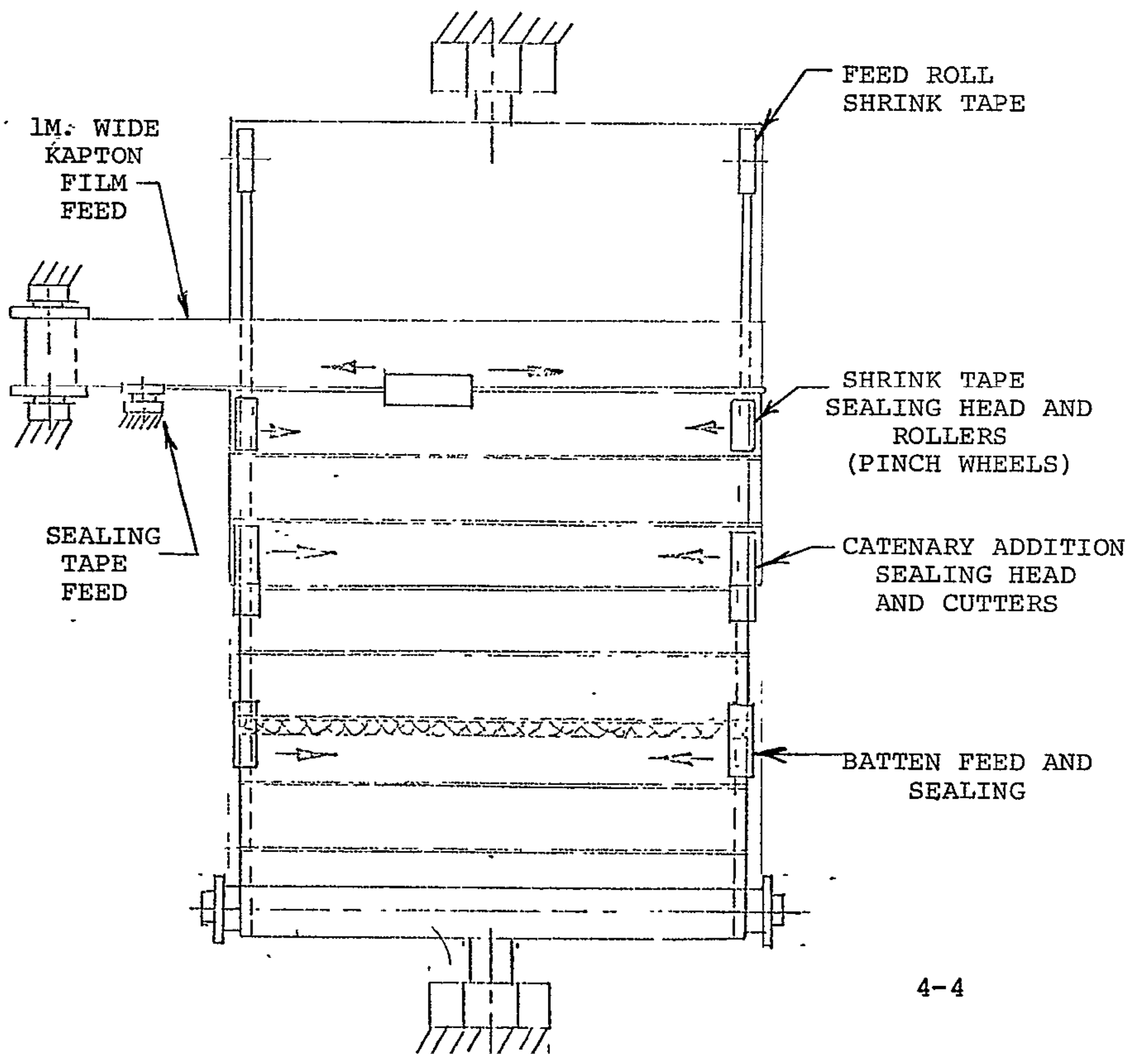
The 5 cm. shrinking tape is fed from rolls at one end of the table and is stretched when sealed to the film to induce the 1% lengthwise fullness in the film after relaxation. After the catenaries are sealed the battens are fed from inside the table to be sealed to the catenaries.

The stations along the length of this concept are similar to those on the lengthwise fabrication method (Section 4.1.3) with the following advantages:

- Two blades are fabricated simultaneously which reduces sail fabrication time.

FIGURE 4-2 DUAL BLADE ROTATING FRAMEWORK





- Seams are crosswise thereby meeting the ripstop requirements with attendant weight savings.

- Fabrication is easily halted for inspection, addition of new tape rolls, etc.

- The Kapton feed roll and sealing tape are always held by a set of catenaries thus eliminating the great disadvantage of having to reach 8 meters with a transfer mechanism and "grab" the edge of Kapton roll after it is cut to pull it across the machine as required in the single blade, crosswise seam concept.

The major disadvantages and complexities of the concept are:

- The rotating framework would be massive in size, approximately 9 meters (30 feet) wide, 3 meters (10 feet) thick, and 18 meters (60 feet) long.

- Since the sealing heads are rotating, a complicated slipring junction for controls would be required.

The necessary operations to fabricate the sail as presently conceived require extremely critical and precise control with present technology; to add an order of magnitude to the system by rotating the entire assembly makes the "rotating framework" concepts undesirable from a standpoint of machine complexity.

An alternative method of continuously fabricating blades with crosswise seams, and at the same time to reduce the complexity of the "rotating framework" concept to a more feasible plan, is to keep the framework" stationary and now rotate the Kapton feed roll with it's sealing tape around the table on an inside track (analogous to a planet on an internal gear) or on an off-set arm. See Figure 4-3.

In this alternate concept some of the disadvantages of the "rotating framework" could be eliminated. The complexity of structure and control still preclude this concept from being the primary recommended fabrication scheme at this time.

4.1.3 Lengthwise Seams, Recommended

Lengthwise seaming of the sail blades will offer a far more reliable and time effective process than any of the other candidates considered. Much consideration has been given to fabricating the central blade material and the catenary edge separately; the proposed fabrication plan is somewhat of a compromise between these two basic concepts. The manufacturing accuracy of the spinning sail blade is directly dependant upon the manner in which the two precisely matched catenary reinforcement tapes are applied. It is quite desirable that an intermediate step of joining tapes to Kapton edge scallop before joining the enti assembly to the sail be eliminated. This scheme would unncessarily introduced a second critical tolerance process.

Figure 4-4 shows a schematic of the proposed machinery which will perform all necessary production operations continuously and sequentially on a single run. The primary intent with the development of this concept is to provide for a slow but steady fabrication profile. The elimination of numerous starts and stops on the assembly line will greatly enhance

FIGURE 4-3 CONTINUOUS CROSSWISE FABRICATION PLAN
KAPTON FEED ON ROTATING ARM

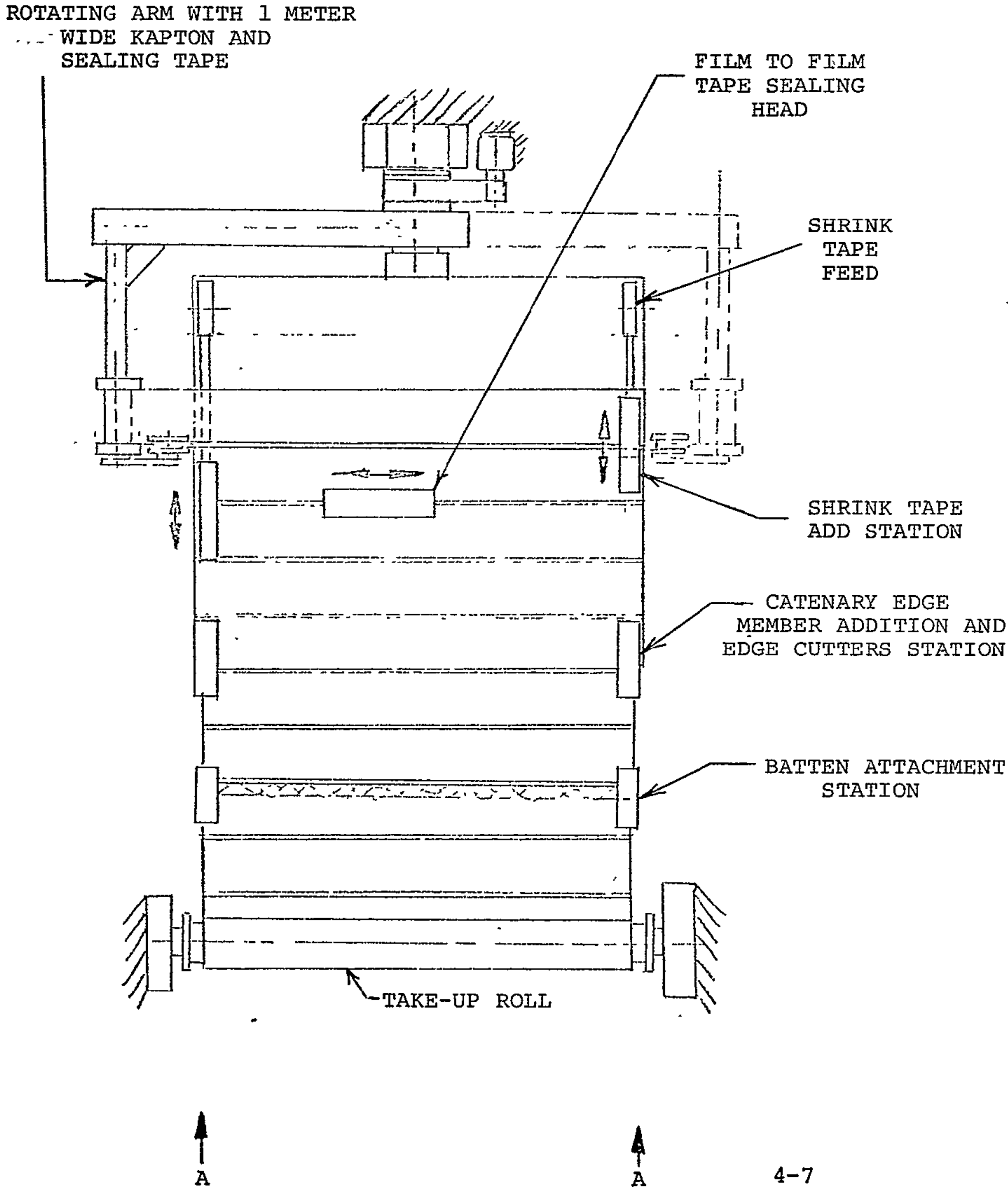
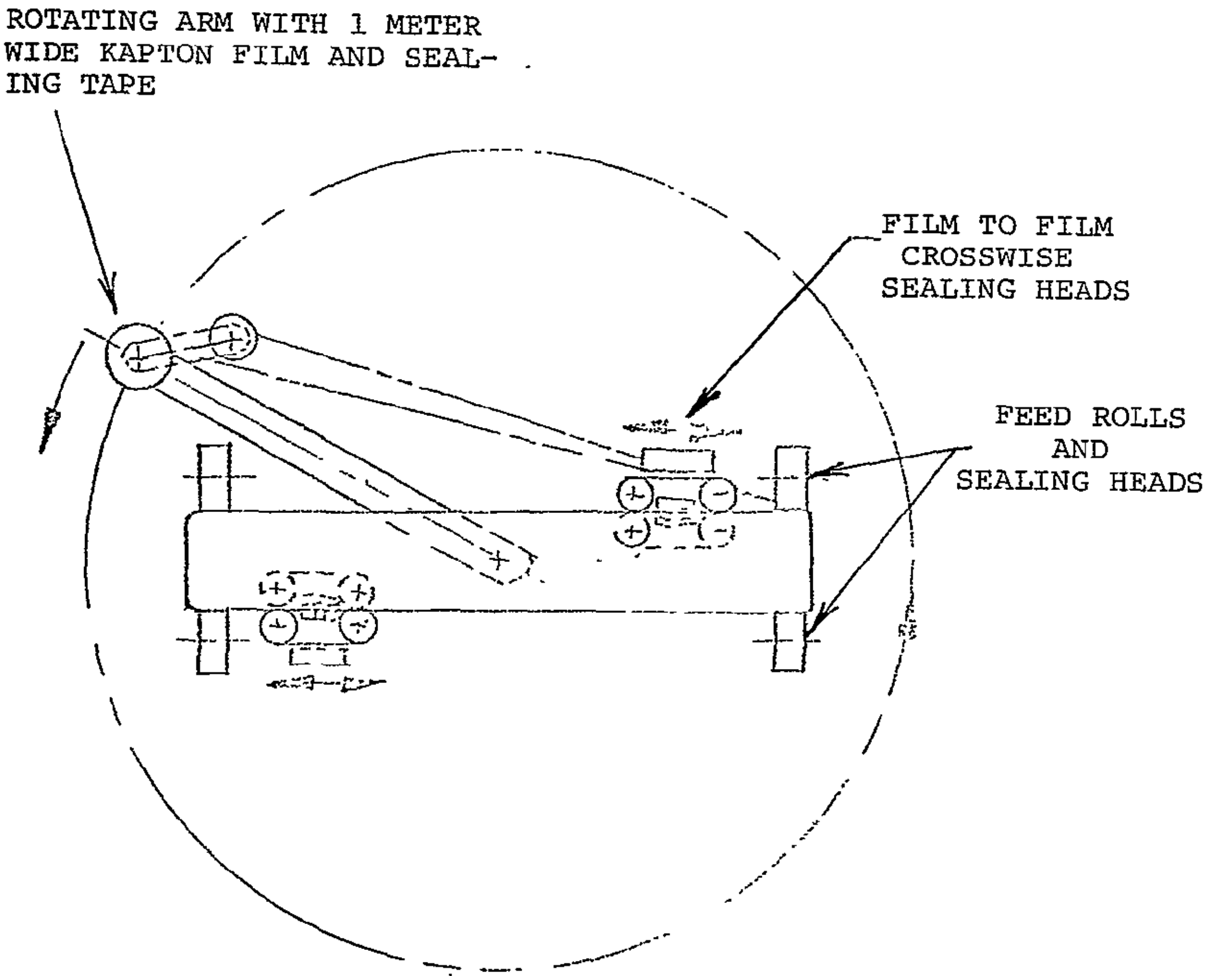


FIGURE 4-3 View A-A



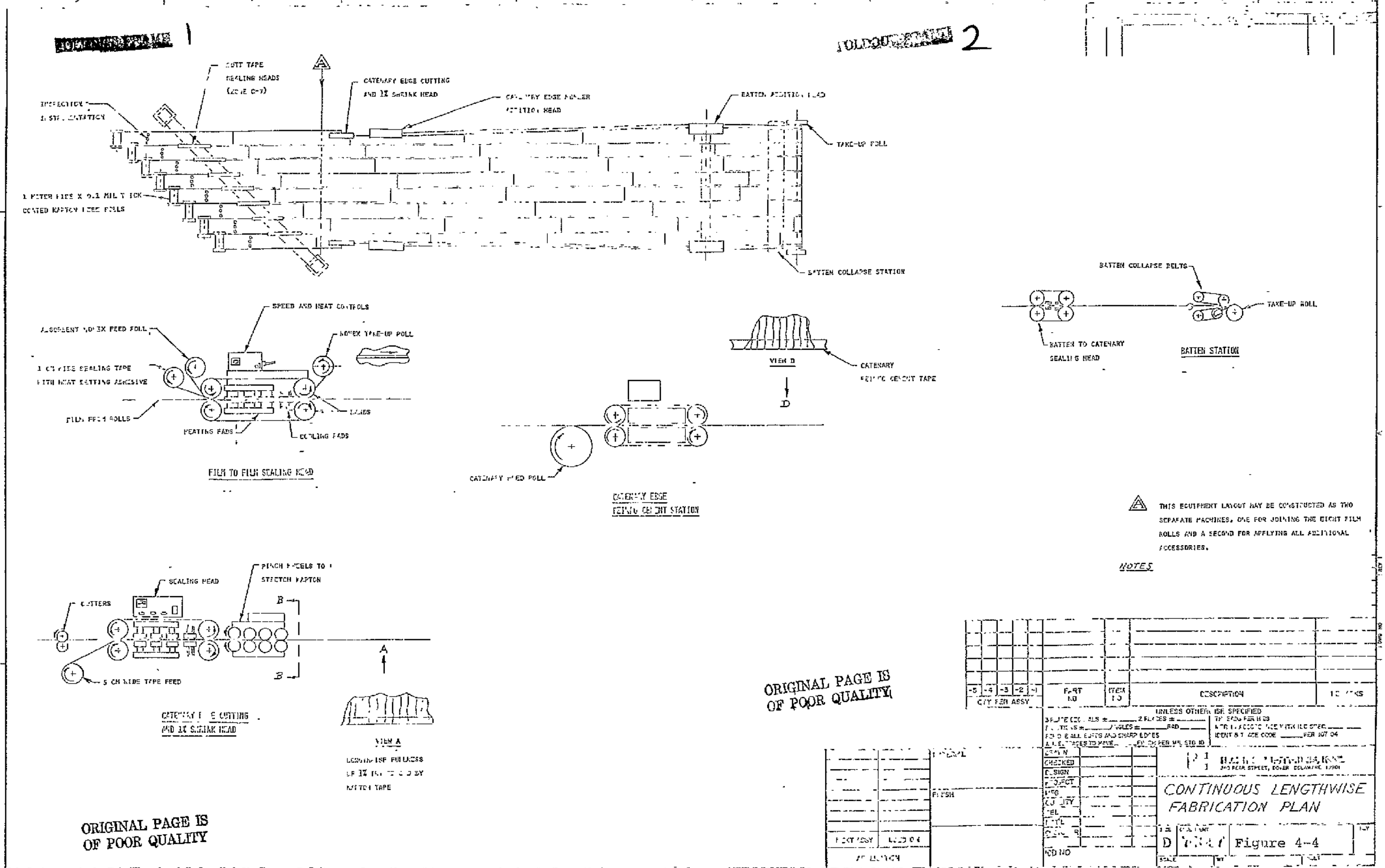
sealing head life.

In addition, this production scheme involves virtually no lost time for panel insertion from the side as required by the first crosswise seaming concept. No complicated transfer linkage is required to cycle, pick up and reposition a free end of film after each joining seam is made.

This continuous fabrication plan will permit extremely low linear travel rates. Such slow operating speeds will offer direct reliability advantages in material handling, seam control, lower temperature/longer time cure cycles, edge reinforcement application, and tolerance control.

Further, the linear sealing rate can be drastically reduced from that required by the sealing heads in the second crosswise concept, even though multiple blades would be fabricated at once.

The proposed fabrication plan would be as described in Figure 4-4 with the observation of Note A. By separating the fabrication plan into two sub levels, the critical control functions, i.e. 1% fullness provision, catenary reinforcement application, scallop cutting, etc., will not be burdened with potential down time of the basic panel joining sealing units. The reliability gained by removal of seven direct production operations and all their associated controls from the critical time/critical accuracy fabrication region is well worth the inconvenience of a second separate equipment module.



TAKE-UP ROLL
BATTEN COLLAPSE STATION
BATTEN COLLAPSE BELTS
TAKE-UP ROLL
BATTEN TO CATENARY
SEALING HEAD
BATTEN STATION
SPEED AND HEAT CONTROLS
NOMEX TAKE-UP ROLL
FILM FROM ROLLS
HEATING PADS
COOLING PADS
FILM TO FILM SEALING HEAD
VIEW D
CATENARY
CATENARY FEED ROLL
THIS EQUIPMENT LAYOUT MAY BE CONSTRUCTED AS TWO SEPARATE MACHINES, ONE FOR JOINING THE EIGHT FILM ROLLS AND A SECOND FOR APPLYING ALL ADDITIONAL ACCESSORIES.
NOTES
SCALING HEAD
CUTTERS
5 CM WIDE TAPE FEED
VIEW A
CONTINUOUS LENGTHWISE FABRICATION PLAN

Figure 4-4

4.2 Sealing Heads

The various seams of the spinning sail bladder are sealed with a thermo-setting adhesive NR150-B2G and various width and thickness sealing tapes. Laboratory tests of this adhesive at JPL have indicated two acceptable cure cycle conditions at 700°F for 10 seconds or 600°F for 2 minutes. The width of tape for film to film sealing is 1 cm (0.4 inch). The width of "shrink" tape that would be used at the catenaries is 5 cm (1.938 inches). The sealing heads would incorporate controlled and correctable drives, heating and cooling heads and feedback signals for synchronization with other elements in a continuous fabrication process.

An exhaustive survey of manufacturers was made to locate sources for continuous thermal sealing devices. The only manufacturer located who has made sealing heads which are nearly directly applicab to the sealing requirements of the spinning sail is Doboy Packaging Machinery, New Richmond, Wisconsin 54017. This company currently manufactures a continuous lap sealer, heating head (Figure 4-5) which will serve as a baseline for modification to meet the sail fabrication requirements. Areas which will require modification on the baseline sealing heads are as follows:

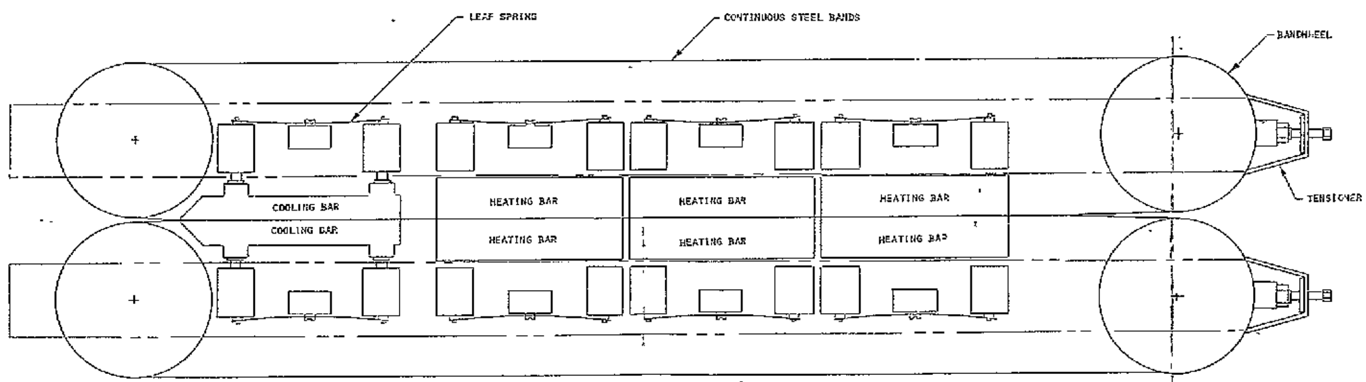
- Temperature: The currently envisioned modified head will have five sets of heating elements and one set of cooling elements. The power to attain the sealing temperatures is 1000 watts per element or 10KW per head. Cooling is by water via inlet and outlet ports for each cooling element; no problems are antici-

FOLDOUT FRAME 1

ORIGINAL PAGE IS OF POOR QUALITY

FOLDOUT FRAME 2

ORIGINAL PAGE IS OF POOR QUALITY



UNLESS OTHERWISE SPECIFIED

ILC INDUSTRIES, INC.

CONTINUOUS SEALING HEAD, SCHEMATIC

D 74897 Figure 4-5

pated in this function. Anticipated problems in the heating requirements are: large power requirements - 10 1KW elements per head and up to 13 heads (130KW); secondary heat dissipation for film room, etc.

- Band Width: Currently, the largest standard band width is 7/8", which is adequate for the 1 cm (0.4") film to film sealing tapes but short of the required 5 cm (1.938") width required for the "shrink tape" sealing to film. The development of wider band width sealer heads would be required to service the proposed blade fabrication plan. There is hope that a meteoroid impact reliability analysis of the proposed unidirectional reinforcement tapes will result in a reduction of required tape width.

- Motor Speed Controllers: Due to the advanced state of the art in solid state motor control and feedback devices, no problems are anticipated in synchronizing the seven sealing heads in the lengthwise fabrication plan. A central control unit with associated processes, memory banks, etc., will continuously monitor the temperature and linear output speed of the sealing heads and make any necessary corrections.

- Ganged Mounting: The Kapton film width on the feed rolls will be 1 meter wide. If the continuous lengthwise fabrication plan is used, eight film rolls will be fed simultaneously necessitating seven sealing heads operating at the same linear speed with continuous correction. A post and lintel structure is planned for support of both upper and lower heads, either on a diagonal or "V" plan to give access to the heads for repair, cleaning, etc.

The catenary and shrink heads will be on a lateral traversing mechanism to follow the edge shape. The maximum amount of travel is 0.240 meters (9.45 inches). The sealing heads that must traverse laterally are:

- One pair for "shrink" tape attachment.
- One pair for catenary edge member attachment.

Due to the fact that battens are few and far between as compared to the blade length, i.e., 89 battens with spacing up to 120 meters, it may be possible to accomplish the batten sealing with portable clamp type sealers.

All heads will be mounted on a release mechanism so that, if fabrication is stopped, all heads can be lifted away from the material being sealed to prevent over temperatures. Also, heads will be installed in modular assemblies so that a malfunctioning head, if it cannot be easily and quickly fixed in place, can be completely replaced in approximately one-half hour.

4.3 Edge Reinforcement Application, 1% Fullness

4.3.1 Baseline, Full Length Stretching

The most critical aspect of the spinning sail blade fabrication is the extremely high degree of length similarity required between the two edge reinforcements on each blade. The preliminary error budget indicates a total manufacturing error tolerance of 11 mm in 100 meters distributed between length measurement, indexing, load measurement, and jig or fixture accuracy. The baseline design and fabrication plan is basically a step process involving several discrete processes, each of which has an error potential.

Several manufacturing schemes were considered for blade fabrication. Early efforts were aimed at evaluating the practicality of the baseline concept. Toward this end, methods of attaching a graphite edge reinforcement along a prescribed curve while under 1% elongation were considered. A nominal 120 meter work table would be required in this scheme. (Figure 4-6)

In order to maintain the desired scallop in the edge reinforcement during the stretching and sealing operations, table grooves and pin guides were proposed. The tape would first be stretched 1% and then .1 mil Kapton film unrolled over the tapes. A heated band sealing head could then be programmed to travel the length of the tape while applying heat and pressure to effect a band.

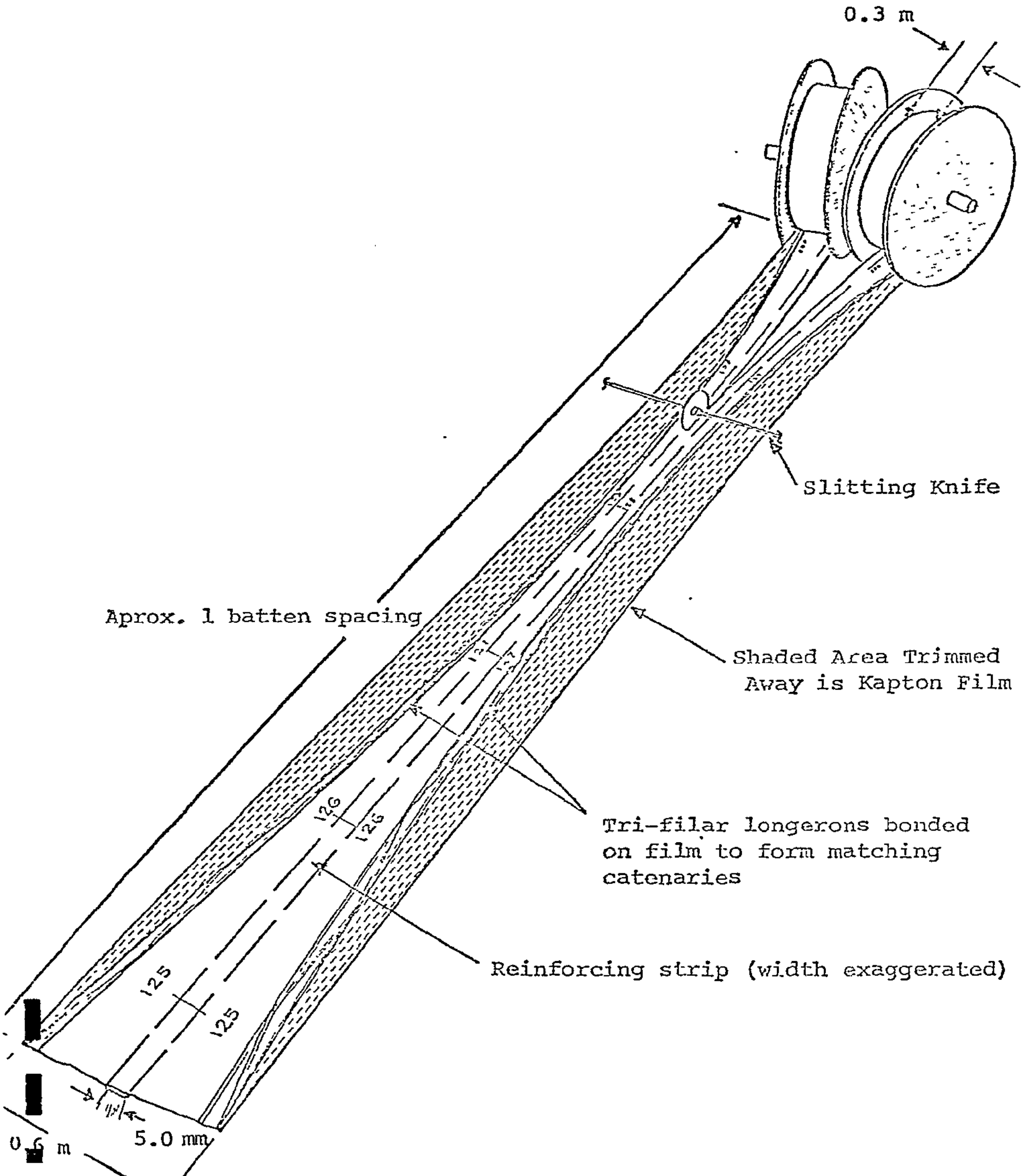


Figure 4-6 Baseline Edge Member Assembly

Deeper investigation of this idea indicated several potential problems with tensioning the graphite/polyimide in this scheme. Firstly, high tensile graphite filaments have an ultimate elongation of about 1.0 to 1.16%.

Loading the graphite edge reinforcement members to an elongation so near the ultimate elongation is an extremely undesirable characteristic of this scheme. A 1.0% "stretch" would place the graphite/polyimide members nearly at their failure point during blade fabrication. Secondly, the accuracy and controllability of the edge scallop shape when tensioned would constitute a severe shape reliability concern.

4.3.2 Continuous Stretching

Other manufacturing schemes were considered in which the edge reinforcements were stretched between pairs of opposing friction wheels while being sealed to the 0.1 mil Kapton film on a continuous basis. A continuous tape controlled fabrication concept has several advantages over the long lay seaming table concept discussed earlier. First, the task of holding the tape to the scallop shape reduces from a full length problem to one of a short segment of the scallop just in the immediate area of the sealing head. This reduction in the critical shape region of the fabrication facility manifests itself primarily in a smaller space needed and the absence of a multiplicity of shape guides, grooves or pins needed for the eighty nine different shapes.

In addition, a continuous sealing concept more closely approaches a roll to roll material transfer which induces far less handling abuse to the material than a long lay table operation where material must be rolled and unrolled repeatedly.

4.3.3 Continuous Overfeed

The low ultimate elongation of graphite and the high load needed to "stretch" the edge reinforcement made it apparent that alternate methods of providing 1% film excess should be developed.

The simplest approach to this scheme is to synchronize a 1% faster film feed to the graphite/polyimide tape supply. This feed, envisioned to be pair of opposing wheels, could be positioned on either side of the continuous band realing head. The entire sealing station would be controlled to follow the scallop contour.

The major concern with this concept is the severity of wrinkles at the edge of the reinforcement tape. Temperature analyses have indicated that full pleats and even concave wrinkles with small half angles may create temperature hot spots due to multiple reflection.

It is conceivable that this feed differential could be introduced by feeding the 0.1 mil film with contoured wheels while feeding the graphite/polyimide tape with smooth wheels. With this method, the wrinkles will be randomly captured as concave or convex distortions. Thus, it is expected that either condition be exposed to the sun side of the blade.

4.3.4 Stretched Polyimide Tape, Recommended

The chronological development of concepts has resulted in successive designs which tend to offer solutions to the functional shortcomings of their predecessors. The major disadvantage of continuous overfeed is the irregularity of the wrinkle pattern; i.e., wrinkles can be presented to the sun either concave or convex. The possibility of full pleats in that concept is a disadvantage.

One concept which offers a predetermined, controlled fullness involves the use of a stretched Kapton tape. In this scheme, Kapton tape (same thickness as base material) is continuously applied to the film while stretched 2%. After application, the tape pre-stretch is relaxed, and the film experiences a take-up of 1%.

It is extremely noteworthy that, by using this technique and by putting the tape on the shade side of the blade, evenly controlled, convex bumps are developed on the sun side. In this manner, concave wrinkles with small half angles which would cause multiple reflections and their associated heat build-up are avoided.

Experiments with a standard Kapton tape with a pressure sensitive adhesive have demonstrated the above characteristics very well. It has been noted that small channels sometimes develop between the tape and the film after relaxation; however, it is anticipated that, with an adhesive cured under heat and pressure, these could be minimized.

The proposed "pre-stretched" Kapton tape would be fed through a guided tensioning head and would deposit the tape along the desired programmed edge scallop shape. The tape would be cured under heat and pressure during its application. Immediately after the tape application, the graphite/polyimide edge scallop reinforcement would be applied to the back of the relaxed tape. In order to aid in providing uniformity of edge member lengths, the graphite/polyimide tapes should be tensioned some nominal value during application. Again this could be accomplished by a pulled tension feed.

4.4 Batten Integration

The baseline batten attachment concept is shown in Figure 4-7. Two 8.0 mil thick titanium clamping plates are potted to the trifilar edge reinforcement using two eyelets. The attachment location, in this design, can be moderately moved, if required, to preclude interference with one of the edge reinforcement trifilar elements. The attachment of the battens with ends captured in the clamping plates has been proposed to utilize small eyelets or rivets for attachment to the sail blades.

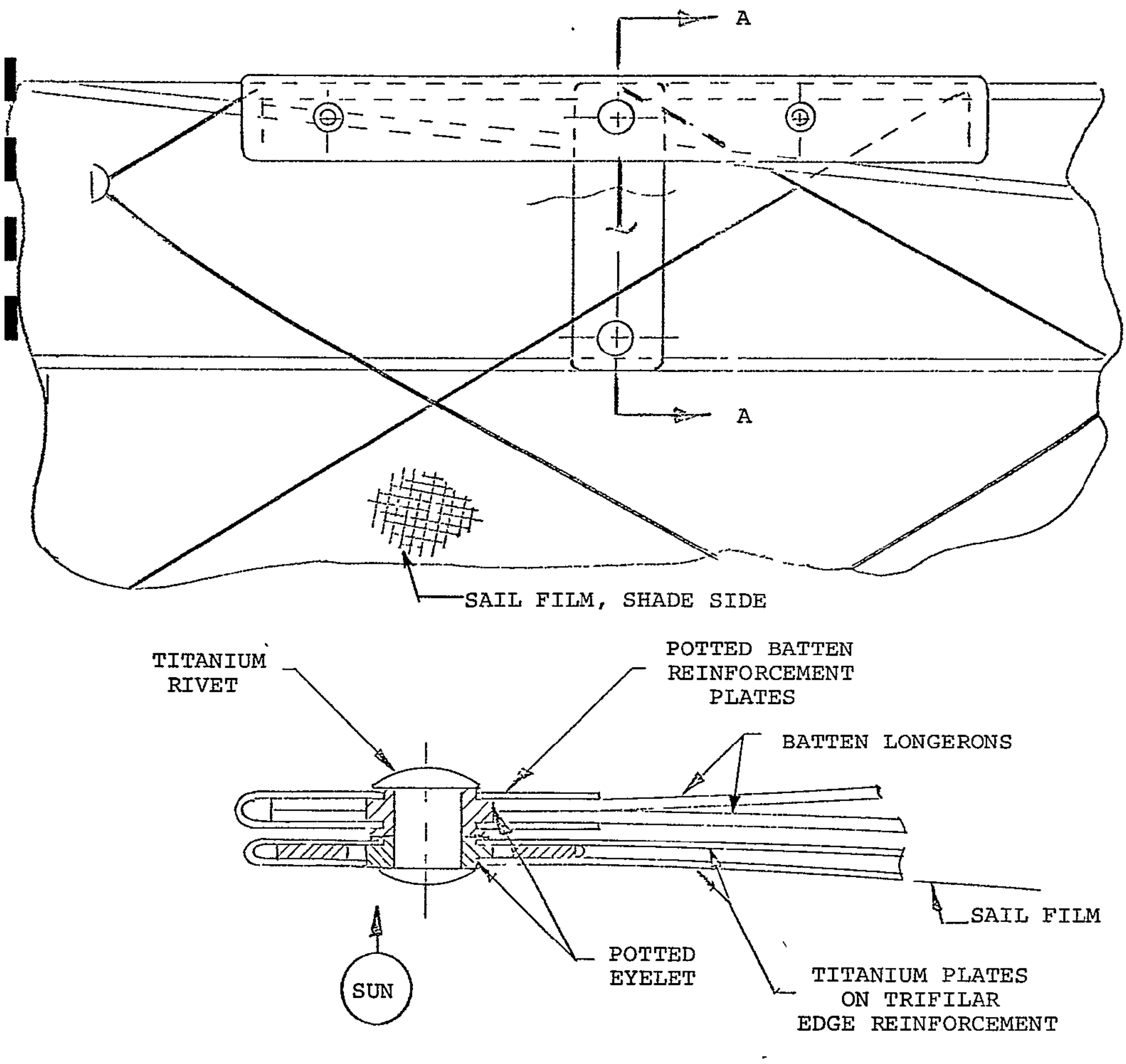
The proposed design and its attachments are shown in Figure 4-8. Here the batten and helix ends, both .020" square, are sealed to the recommended edge tape, 5 cm wide. Wherever the longerons and helixes meet at the ends, 3.1 cm wide x 5 cm long x 5.0 mil thick sealing and potting tape will seal the battens on the edge reinforcements. Due to (1) large spacing of the battens on the blade (up to 120 meters), (2) the small sealing area of batten/edge interface and (3) the slow moving rate of the sail, the batten integration sealing may be accomplished via clamp sealers that can be hand moved along with the sail.

After installation the battens are collapsed and rolled up on the flight hardware or other take-up reel roll. A device must be used which will keep the battens in a flattened position until wound on the reel and covered by a few turns of sail film which will keep the battens collapsed. One method would consist of a crosswise lockstitch thread woven across the batten to keep it flattened. After the batten is wound on the reel, this thread could be pulled out. Another method, feasible because of the slow moving speed of reel take-up and the relatively few battens, would be to station personnel along the take-up reel when the batten is about to be wound up, and have them hand hold the batten in the collapsed position for take-up.

Still another, method would be to have belt rollers and fingers to collapse and guide the batten during wind-up per Figure 4-4.

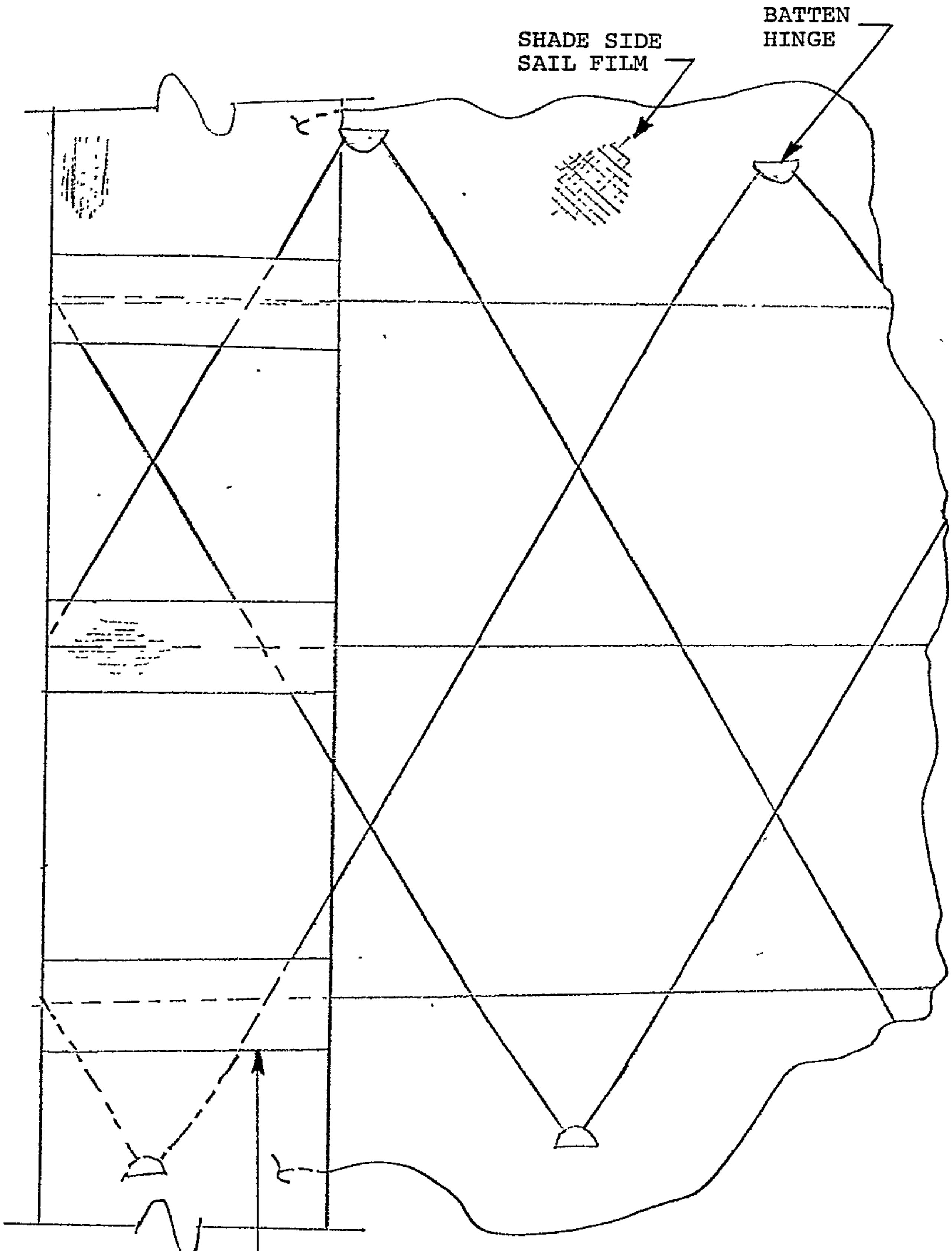
A great advantage of the proposed attachment method is that the proposed tape sealing method could be done without having to stop the continuous fabrication of the blade, where the riveted method would probably have to be done in a stationary position. Also, the titanium plate and eyelet installation entail several steps whereas taping and sealing the batten longeron and helix members is a one-step process compatible with the other sealing on the sail blade.

FIGURE 4-7 BASELINE; BATTEN TO TRIFILAR EDGE REINFORCEMENT ATTACHMENT



SECTION A-A (ROTATED 90°CCW) SCALE 4/1

FIGURE 4-8 PROPOSED BATTEN/EDGE REINFORCEMENT TAPE INTERFACE



EDGE REINFORCEMENT TAPE

4.5 Mesh Integration

The mesh is provided between the deployment reel and the innermost batten, approximately 164 meters from the reel. The function of the mesh is to provide shear stiffness in a region where film is omitted for other functional reasons, and to keep all centrifugal loads on the edge reinforcement tapes.

The mesh can be cemented to the 5cm wide edge tapes as illustrated in Figure 3-7. The baseline design is .020" square mesh on a 200 cm pattern. The recommended design is for mesh on a 500 cm pattern or larger. From a production standpoint, mesh on a 1 meter pattern would be much simpler and would decrease fabrication time. The mesh thickness may have to be increased to compensate for the fewer mesh strands in this concept.

To provide good thermal control the mesh would have to be shielded on the sun side because the polyimide binder of the mesh graphite filaments would have temperature limitations similar to that of the basic Kapton film, $\approx 550^{\circ}$ - 600°F. Further study of these temperature effects should be made. The mesh strands may have to be coated on both sides similar to the sail film, the only difference being that thicker coatings (spectural aluminum on sun side and heat emissive chrome on shade side) may be required on the mesh.

At the deployment reel a structural "V" tape to anchor the mesh between the flap hinges will be required. This "V" of approximately 5.6 meters on a side could be made of the same tape used for the mesh edge tapes. A similar requirement exists at the innermost batten. It is envisioned that the mesh could be laid up on a production table separate from the continuous blade fabrication process. Accurate indexing of edge tapes will be a requirement here as it is on the basic blade edges.

The prefabricated mesh, both upper and lower will be wound on the flight deployment reel before blade fabrication is started and then the edge tape joints are made. This mesh edge tape to catenary tape interface must be a round structural bond capable of transmitting full centrifugal loads. The mesh edge tapes could be sealed to the sail film edge tape in a sandwich construction, i.e., upper mesh tape over the catenary edge tape, and lower mesh tape under the catenary edge tape. The first batten would be attached to the catenary edge reinforcement tape just outboard of this interface. When the upper and lower mesh have been sealed together and to the innermost batten with its catenary edge reinforcements, the continuous blade fabrication procedure can be initiated. At the completion of the sail blade fabrication, one complete blade, including mesh, would be rolled up on the flight deployment reel, not to be unrolled again until deployment in space.

4.6 Ripstop Provisions

The uniform distribution of film perforation will provide ripstop protection for the spinning sail blades. In addition it is proposed that ripstop tapes, nominally .5cm wide x .3 mil thick be bonded to the chrome side of the basic film at eight meter intervals. It is not necessary that their tapes be continuous across the chord of the blade; they may be randomly staggered on adjacent panels with no performance impact.

These cross panel ripstop tapes should be applied to the film substrate prior to the time the material goes into the blade fabrication equipment. It is anticipated that a reel to reel film transfer with 8 meter stop intervals to permit a tape application and cure cycle. By attaching these tapes at the sub-assembly level, potential ripstop equipment down time will not impact the blade assembly line.

4.7 Tolerance and Controls

One of the most significant requirements to be met by the fabrication of the sail blades is the high degree of accuracy required in the application of edge reinforcements. It is desired that the overall lengths of the leading and trailing edge reinforcement tapes agree to within 10 cm. This represents an overall accuracy requirement of 0.0013%. It is impossible to design this type of product involving several process tolerances to maintain such tight controls on a continuous basis. Specific individual processes cannot be held to such tolerances that full accumulation of the tolerances in one direction will still be within the desired specification.

Rather, it is proposed that cumulative lengths along the edge reinforcements be monitored throughout the blade's span. Potential problems exist, in that any attempt to measure cumulative lengths with a metering wheel would be quite difficult not only because of instrument accuracy, but also because of the possibility of wheel slippage, bumps, minor tape irregularities, etc.

A much more reliable method of length matching is proposed. The graphite/polyimide tapes should be made as a sheet or at least in widths wide enough for pairs of edge reinforcements. An indexing process will be used to identify desired batten locations as well as other match marks between the battens. The edge tapes will be match marked in pairs prior to slitting to their final width to ensure that the two tapes are as nearly symmetrical as possible. The match marks could be light sensitive marks, notches, small holes, etc., which would be optically monitored by a sensing device mounted at the sealing head of the edge reinforcement station.

The similarly indexed benchmarks should always appear simultaneously on each side of the machine. Since the tapes are put down under minimum tension (some nominal value to ensure straightness, no intended stretching) any deviation between benchmark pairs would be attributed to a non-similarity of the catenary curves being followed by the two sides of the machine. This information would then be used in a feedback control to adjust the longer side catenary and increase its programmed throat depth until the length mismatch is corrected. By utilizing closely spaced benchmarks (say 5 meters) any deviations will be detected and corrected before building to any magnitude which could cause blade performance degradation.

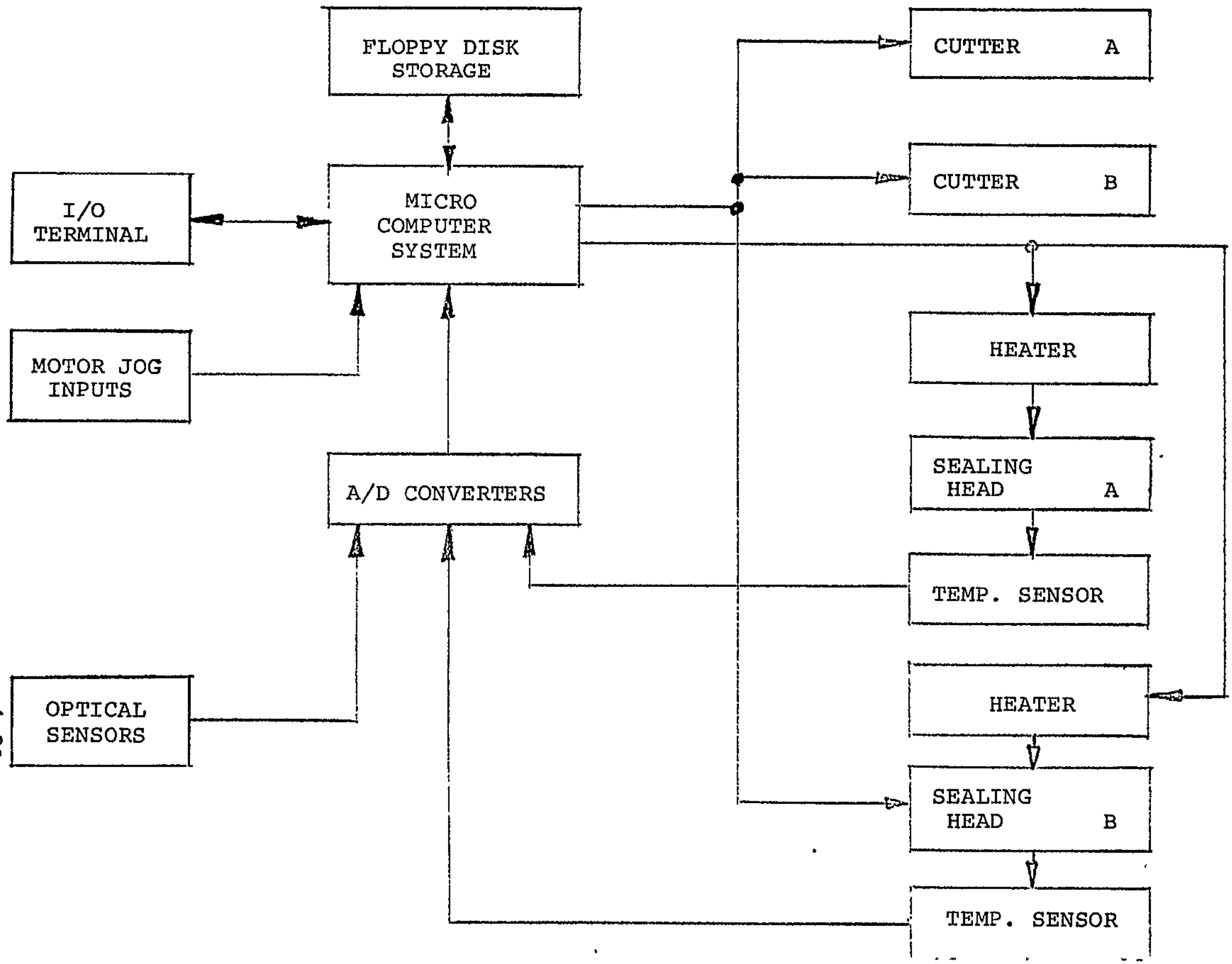
The spool load or back tension applied to the graphite tape is the other major variable to be "perfectly" matched between the two blade sides. It is expected that the magnitude of this force is not as critical as the requirement that they be similar on each edge. At the present time, it is anticipated that an electric clutch mechanism with dampers to prevent start and stop surges can be used for this application.

The entire blade fabrication machine would be computer controlled. Each catenary section would be programmed to identify its shape, and the location of benchmarks. In addition, correction subroutines which would allow independent control of the two edge reinforcement sealers would be provided to receive feedback signals from the optical benchmark monitors. The program would permit this error correction capability to override the basic production program until the deivation was corrected.

The control computer would also serve to receive, monitor, and record any quality control and inspection data being gathered on the production machine. In this manner data would be continuously recorded on the production tape for each balde. Monitoring of all equipment, i.e., pressures, temperature, speeds, tensions would also become a part of this record.

A simple computer control schematic for the proposed spinning sail blade fabrication equipment is shown in Figure 4-9.

FIGURE 4-9 MICROCOMPUTER CONTROL SYSTEM



5.0 SAIL DESIGN CRITERIA (SQUARE SAIL)

(TBD)

6.0 HANDLING AND FABRICATION PLAN (SQUARE SAIL)

(TBD)

7.0 QUALITY ASSURANCE PLAN

7.1 Materials

Evaluation of all solar sail design concepts has indicated that the completed sail must have the highest possible degree of reliability since it cannot be subjected to final acceptance testing due to its configuration and size. To accomplish this end, the reliability desired for the total system must be established and than apportioned to the subsystem and assembly level via a reliability logic diagram. This apportionment should be based upon criteria and factors developed from engineering experience and judgement, considering effects of failure upon the system, complexity of design and state of the art.

A numerical prediction of the sail reliability which provides a useful tool for recognition of areas where reliability improvement is most effective should be generated in conjunction with the reliability logic diagram and reliability apportionment. This mathematical model could be programmed into a computer to facilitate iteration for sensitivity analysis and rapid assessment of proposed design changes.

A more cost-effective alternative to this math model would be the generation of a Failure Mode Effects and Criticality Analysis (FMECA). This would have the added advantage of documenting the investigations of possible design improvements, redundancies, and other available corrective actions during the development phase.

Quality Assurance will establish inspection requirements considering the reliability apportionments to assure compliance with design requirements. A continuous monitoring/inspection program is envisioned to provide process and fabrication accept/reject data along with specific material physical characteristics such as reflectivity, emissivity etc. This data must be correlated and computerized in such a way that characteristics of any portion of any blade can be quickly retrieved and evaluated.

To accomplish the above, material specifications must be developed for each material. The critical areas to be monitored, characteristics to be inspected, specific processes to be utilized and acceptance criteria shall be noted within each material specification.

The coated film proposed for use on the solar sail will be exposed to numerous inprocess operations at different vendor facilities prior to becoming a finished material. Each of these operations require the use of special processes thus each operation has its own unique set of controls. Considering "worst case" conditions, where a separate supplier is involved for each specific operation, the following parameters should be considered as being mandatory relative to inspection, material control, and data documentation.

A. Raw film procurement (.3 mil or .1 mil)
   1. Physical properties
   2. Lot identification
   3. Thickness

4. Width

5. Handling (packaging and shipping)

B. Perforate

1. Perforation size and spacing
2. Weight
3. Cleanliness

C. Chemical etching of film to .1 mil thickness (if required).

1. Physical properties
2. Thickness
3. Width
4. Cleanliness
5. Handling

D. Chrome deposition

1. Coating thickness and uniformity
2. Coating "bleed" thru at perforations
3. Emissivity
4. Coating adhesion
5. Weight
6. Cleanliness
7. Handling

E. Aluminum deposition

1. Coating thickness and uniformity
2. Reflectivity
3. Coating adhesion

4. Physical properties
5. Coating "bleed thru" at perforations
6. Material length per roll
7. Material tension on roll
8. Cleanliness
9. Material weight per roll
10. Finished material width
11. Handling

F. Receipt of finished material

1. Review and verify acceptance of previously completed operations.

2. Assign unique identification to each roll of material.

3. Process accepted material to a clean controlled environment.

The above parameters are applicable to the sealing tapes which have the additional parameters of adhesive thickness, state of cure, and tape width imposed on them.

Vendor selection will be accomplished by evaluating prospective suppliers to assure that they are capable of meeting the standards/requirements of the contract. This evaluation as a minimum should include review of product and facility information, equipment listing, organizational policies and structure and suppliers quality and reliability procedures. Process procedures should be reviewed for adequacy of controls. These procedures should contain as a minimum the following information:

A. List and description of process equipment.

B. Material used in the process (chemicals, etc.)

C. Frequency of in-process checks and analysis and records maintained on solutions, ovens, etc.

D. Frequency of periodic temperature checks of ovens, etc.

E. Each process step and sequence thereof, including technical data, time, temperature, voltage, current density, bath control limits, precautions, etc.

F. In-process and end item inspection methods and procedures.

Source inspection should be utilized at each intermediate suppliers facility. The source inspector would be responsible for verifying successful completion of the various control parameters prior to material shipment.

7.2 Fabrication

Controls during fabrication of the spinning sail blades will vary slightly, dependent upon the fabrication technique/concept selected. However, for the purposes of this report the known critical parameters and the methods of verifying compliance with these parameters will be discussed. Critical parameters are noted below:

A. Blade Length

B. Blade Width

C. Batten Spacing

D. Reflectivity

E. Emissivity

F. Seam tolerances and adhesive extrusion (bond verification)

G. Material Accountability

H. Edgemember/batten Interface

I. Ripstop

J. Blade Material Fullness

K. Catenary Length

Overall blade length and catenary lengths must be controlled during fabrication and assembly. Control of the blade catenary lengths and their interface with the blade battens will determine overall blade length and leading/trailing edge symmetry. It is anticipated that catenarys will be assembled in pairs, each side being continuously tensioned to a predetermined nominal value during attachment to the blade film. The blade film must be trimmed on throat side of the catenary after reinforcement application. A film edge to catenary edge dimensional inspection requirement must be established.

Blade width will be controlled by batten length and batten/catenary interface. Batten lengths will be dimensionally controlled during the fabrication process, and will be verified during receiving inspection for each batten.

Reflectivity and emissivity will be monitored and recorded at each blade station, a station being defined as a discrete distance, sufficient to accumulate total and average blade data. Specific methods to be used to accomplish this monitoring are at this time undertermined, however, the use of optics and/or infrared are being considered.

Regardless of the method of seaming finally selected i.e. butt seam, lap seam, etc., seam tolerances will have to be established. These tolerances will be derived after minimum bond area, allowable seam separation, maximum unbonded edges, and maximum adhesive extrusion is established. The seams will be continuously monitored via non-destructive test techniques which must be developed.

The NDT equipment utilized to monitor reflectivity, emissivity, seaming, etc., must be capable of providing actual conditions either directly by readout or indirectly via a programmer thru a computer. The conditions reported must be correlated with blade stations and specific blades in order to obtain meaningful, usable data for subsequent spinning sail performance analysis.

Material accountability i.e., control based on reflectivity, emissivity, weight, etc., will be determined by computer after the specific blade fabrication configuration has been established. It is envisioned that in-process data will be utilized to determine optimum film location on any given blade by blade station. In this way material usage for each blade is determined prior to fabrication and as a consequence balanced blades having predicted characteristics will be fabricated.

8.0 PACKAGING

Finished blades will be rolled onto take-up reels which are, in actuality, the flight hardware deployment reels. Retainers will be installed on the rolls to prevent accidental film deployment during handling and shipping. The specific configuration of the retainers has not been established, however, it is felt that the retainers should apply tension around the blade film to minimize relative movement of the film and battens.

Upon completion of fabrication, each blade will be placed in a poly bag, slowly evacuated to remove entrapped air, flushed with nitrogen to provide an inert atmosphere, re-evacuated and sealed. This assembly will then be placed into a second poly bag which will be purged with nitrogen, evacuated and sealed to assure maintenance of an inert atmosphere. The completely packaged blade assembly will be processed and maintained in an environmentally controlled bonded storage area until shipment.

Shipment should be accomplished with the blades individually packaged in cushioned containers capable of minimizing vibration and shock transfer and maintaining an inert atmosphere. The recommended mode of shipment is via air transport or air ride electronics transport van carrier.

It is anticipated that final assembly of all components will be in a "clean area" environment at atmospheric pressure and room temperature. The sails, after removal from shipping and protective packaging will be assembled per a final assembly plan to be determined.

The rolled sail blade assembly must be protected from environmental shock and unacceptable pressure transients during launch. The necessary protection particular to the sail will be coordinated with those necessary for the remainder of the spacecraft. Of primary concern is a very slow bleed down of atmospheric pressure to near total space vacuum to prevent any blow outs of entrapped air pockets between layers of sail film. This "bleed down" from atmospheric pressure could be done in flight by means of controlled flow ports or before launch by means of vacuum pumps.

9.0 EXISTING EQUIPMENT AND FACILITIES

ILC Dover's present production facilities of 45,000 square feet in a permanent one-story structure and an additional 22,000 square provided by two (2) inflatable structures would be inadequate for fabrication of the spinning sail because of full open bay space limitations. However, there are facilities available with a five mile radius of ILC Industries which contain the physical space required, approximately 100' X 200' minimum.

ILC has complete machine shop/model shop capabilities housed in the present production facility which would be available for repair/modification/maintenance of the sail handling/ fabrication equipment. A partial listing of the machines contained in the machine shop/model shop follows:

1. 24" metal break
2. 24" metal roller
3. 30" metal shear
4. Rotary punch press
5. Jig welder
6. Arc welder
7. Silver solder equipment
8. Cincinnati toolmaster milling machine
9. Budgeport vertical milling machine
10. Do-All C-4 cutt-off saw
11. Do-All band saw
12. Clausing Lathe 15" x 48"
13. South Bend 16" lathe
14. South Bend 24" lathe

15. LeBlond 14" x 54" lathe

16. Heat treating oven 6" x 8" x 12"

17. Surface grinder, Brown and Sharpe

18. Tool and cutter grinder, Brown and Sharpe

19. Belt sander (2)

20. 2 ton hand press

21. 80 ton hydraulic press

22. Fosdich drill press

23. Dumore drill press

24. Spring winder bench type

ILC also maintains a complete physical testing laboratory within the present facilities. This test laboratory supports physical testing of incoming materials, production verification samples, and final testing of completed articles. New materials proposed for use on the various ILC products are also evaluated both physically and environmentally in the physical testing laboratory. These facilities would be available to support required physical testing on the spinning sail program.

A partial list of equipment housed within the physical testing laboratory is shown below.

Weight Determination:	Melter Balance w/Weighing Table
Tensile Testing:	Instron, Thwing-Albert
Environmental:	Missimer Chamber +600°F - 300°F Blue "M" - Air Circulating Ovens Blue "M" Humidity Chamber

Recording Device:	Foxboro - Multichannel Recorder 0-600°F Sanborn 350 8 Channel Recorder with Pre-Amplifier
Pressure/Leakage:	Fische Porter Test Stand 0-30 psig 8SCCM - 15SCFM
Calibration Equipment:	CEC 0-15 PSI Texas Instrument 0-500 PSI W&T Precision Manometer Meriam Inclinometer 0-10" H_2O
Physical Properties:	Taber Abrader Elmendrof Tear Mullens Burst

10.0 EQUIPMENT AND FACILITIES TO BE DEVELOPED

Plant facilities to fabricate the spinning sail would have to be obtained since those presently available at ILC lack the physical size required to house the proposed sail fabrication machinery. There are several options available to satisfy this need; lease an existing facility, purchase an existing facility, or build a new facility.

Leasing and/or purchase of an existing facility has the advantage of manufacturing floor space being immediately available. However, modification may have to be made to the facility interior to provide the necessary free span area (200 x 50 feet) to accommodate the sail fabricating machinery. There are two such facilities presently available to ILC on a lease basis.

Building a new facility for the purpose of housing the spinning sail fabrication equipment provides an opportunity to tailor the building design to its intended use. However, lead time required for design and construction could cause problems with the spinning sail schedule. An alternative to the design and construction of a conventional plant facility is the procurement of a prefabricated clear span structure shell. This structure could be finished with suitable insulation and utilities as required. The advantage of this approach is reduced lead time and a facility that is a permanent structure which can be disassembled and moved if necessary.

Cleanliness is an essential parameter in the fabrication of the spinning sail. Particle contamination of the sail materials must be controlled since an accumulation of dust contamination on sail film surfaces will increase the weight of each blade. Particulate contamination during fabrication can be controlled by housing the entire fabrication process in a clean controlled area or a clean room. The clean environmentally controlled area is favored primarily because electrostatic devices will be utilized to remove particulate from the sail material during assembly and as it is being accumulated on the flight reel. The accumulated finished sail will also be protected in the same manner.

Economics is a significant factor in favoring an environmentally controlled clean area over a clean room. A class 100,000 clean room of the size required for sail fabrication will cost between $50.00 and $60.00 per square foot of floor area. This figure does not include the sail fabrication and storage equipment. In addition, a facility is required to house the clean room and a 7 month lead time is required; an environmentally controlled clean area utilizes the existing facility. The establishment of a controlled clean area would require installation of limited access, positive pressure and environmental control provisions (air conditioning, heating, etc.). In addition, low particle shedding materials would be used for the ceiling, floor, and walls. Estimated cost for an environmentally controlled clean area are $30.00 to $40.00 per square foot.

Refrigeration/freezer equipment will be required to prolong the useful life of the sealing tapes and catenary edge tapes. These items are to be supplied with the adhesive/resin in a semi-cured state which is age sensitive. Dependent upon the lot delivery schedule anticipated, a single walk-in cooler or several commercially available refrigerators would be specified.

The sail fabrication machine with computer control and feedback loops must be designed. The bulk of the machine components are currently available in industry. However, many of these components will require modification for adaption to the sail fabrication machine. See Section 4.0 for machine description. Estimated cost is $1.0M and time required to design, assemble, test and install is 26 months.

11.0 SCHEDULE

The Solar Sail Program will require an extensive amount of engineering development in many fields. Not only is this program faced with a requirement for new production equipment, but most of the raw materials envisioned for use in the program will involve a large degree of process refinement. Nearly every proposed material consists of a basic substrate which has real time, production, and performance history. However, in this application, specifications for material thickness, coating uniformity, adhesive thicknesses, etc. are far more critical than they have ever been in the past. The ability to extrapolate known manufacturing processes to the limits necessary to produce raw materials with the necessary degree of accuracy and control is the most serious program uncertainty.

The proposed materials when "built" on paper to the desired thicknesses, weights, and tolerances, etc. may indicate excellent spinning solar sail performance characteristics. The actual production of such materials may, however, be more difficult.

If materials, tapes, coatings, adhesives, prepregs, battens, etc. can be produced as specified, the actual fabrication of the spinning sail blades can be accomplished in the manner proposed and according to the schedule shown in Figure 11-1.

MANUFACTURING EQUIPMENT DEVELOPMENT

The program for development of equipment for fabricating and packaging 7500 M x 8 M spinning solar sail blades from 0.1 mil metalized Kapton would be broken down into phases as follows:

Phase I - Development of Feasibility Models

All design modification, which have been recommended during the preliminary design and fabrication assessment to facilitate reliabile blade production, will be evaluated for conformity to all sail performance requirements. The overall fabrication plan will be critiqued and finalized.

Specific fabrication problems will be identified and modeling will be undertaken to prove out the feasibility of adopting the specific approaches. The outcome of this evaluation will be a final concept selection, supported by enough process testing results to establish a high degree of confidence that the equipment will perform the intended functions.

As an example, final selection of the sail design and fabrication plan presently proposed, the following areas would require preliminary evaluation including feasibility modeling.

(1) Sealing two panels together, including removing excess adhesive with expendable Nomex tapes or some other means.

(2) Seam strength-testing module.

(3) 1% fullness tape sealing.

(4) Edge sealing of reinforcement tapes form scallops.

(5) Batten attachment, flattening and windup.

(6) Process failure mode analysis, and the development of tools and techniques for dealing with the anticipated process failures.

Items 1, 3, and 4 above can be evaluated, in sequence or concurrently, by buying one or more commercial heat sealing machines and adding the required special attachments.

Item 6 would be done in conjunction with competent computer process control specialists.

The scope of Phase I activity is very difficult to define, because it is difficult to determine how many sail design concepts may be evaluated before a selection is made.

Phase II

Once the feasibility models have been refined and are yielding acceptable results, a detailed design of all the stations making up the sail assembly machine will be undertaken.

Phase III

In this phase manufacturing drawings are made and checked and sources of all required purchasable items will be found. Bid packages will be sent out.

Phase IV

Quotations will be evaluated and purchase orders let, starting with the long lead items. Expediting will be carried out to make sure subassemblies can be put together on schedule. Parts will be received and inspected. Assembly work will proceed without delay in order to uncover discrepancies as early as possible. Assembly and individual check out of each station will be accomplished at the equipment manufacturer's facility. Final assembly of all stations into the facility will take place at the final manufacturing facility.

Phase V

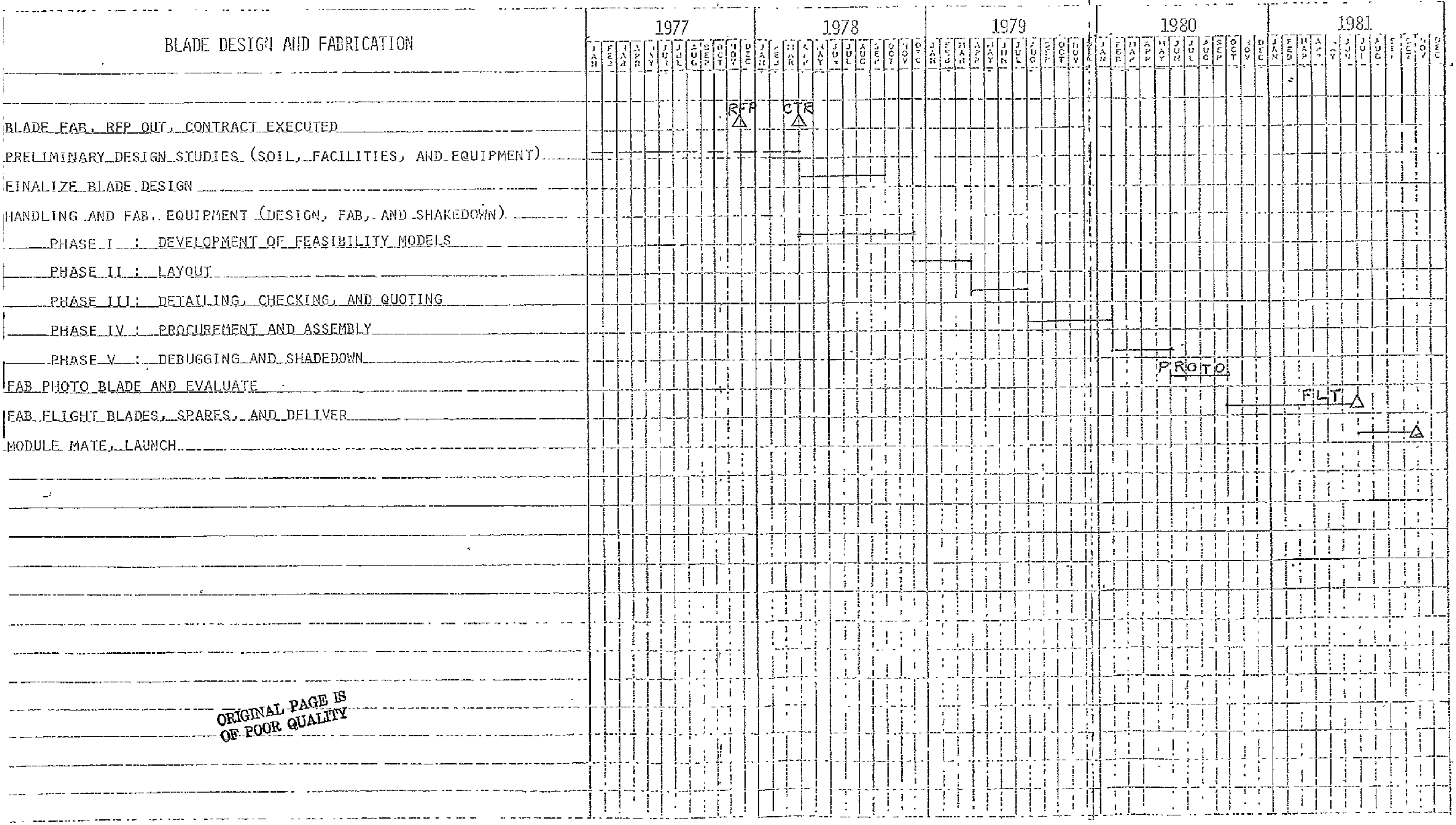
Debugging to isolate and solve operational problems of the individual stations will be done at the equipment factory where possible. Debugging of the total facility will be undertaken at the manufacturing site.

MACHINE DEVELOPMENT COSTS

The cost of developing blade manufacturing equipment of the type proposed herein has been estimated. It is envisioned that the proposed phased development effort would cost in the order of $1.0 M, distributed as follows:

- Phase I : Development of Feasibility Models - $150 K
- Phase II : Layout - 80 K
- Phase III: Detailing, Checking, and Quoting - 65 K
- Phase IV : Procurement and Assembly - 625 K
- Phase V : Debugging and Shakedown - 80 K

FIGURE 11-1 SCHEDULE



12.0 RECOMMENDED AREAS FOR ADDITIONAL EFFORT

The intent of this preliminary design and manufacturing assessment has been to address the overall scope of solar sail production with respect to the capabilities and limitations of today's technology. It has been a very unique task because of the lack of similar products, materials or processes being used anywhere today. Much of the technological needs identified with the proposed solar sail design and production are currently in practice; however, in no case have they been refined and perfected to the extent required by this program. In several instances, analogous processes are used, but either on thicker substrates, on narrower materials, at lower temperature, or to wider tolerances.

An overall manufacturing plan has been presented herein. Some changes have been made to the baseline design to facilitate blade production. For example, alternate basic seams and alternate catenary reinforcement materials have been recommended. The effect of proposed design changes should be evaluated with respect to mission performance requirements.

With the assurance that the basic fabrication plan will produce a satisfactory solar sail, subsequent tasks should be undertaken to evaluate each of the specific material and process concepts proposed. It is recommended that the following specific concepts or processes be evaluated to ensure and verify that all needed technologies can be extended and applied as proposed to this program.

- Material Development - This has not been a topic within the scope of ILC's efforts; however, our investigations have led to an understanding that current technologies must be expanded to produce Kapton to the desired thickness specification. Preliminary experiments by DuPont indicate that a production capability for 0.1 mil Kapton film is possible with some additional development efforts. Chrome deposition in widths over twelve inches will require extensive machinery and process development. The question of perforating the Kapton film and the effects on metalization has not yet been resolved. These specific base material related processes need to be investigated further due to the long lead time in some machinery and process developments. It would be wise to intiate these efforts as soon as possible.

- Band Sealer Design - The basic sealing band concept is a proven design and has been used on other materials at lower temperatures for many years. The higher temperatures, more precise controls and potentially wider band widths are areas which will need development. (See Section 4-2)

- Seam Tape Fabrication - The tape processing industry has had little experience with very thin tape production. The thinnest tape produced commercially consists of 0.5 mils of adhesive on a 0.5 mil substrate. It is expected that a layer of 0.15 mil thick adhesive could be applied to a 0.3 mil substrate under controlled conditions in relatively narrow widths (perhaps 4-12 inches). The 3M Company would be an excellent candidate for such an activity. It is anticipated that the development of equipment to run first quality samples of this type in a small laboratory set-up could be done for about $15K. Once developed, this equipment could be used to produce actual flight tapes. It is recommended that this activity be initiated as soon as good film materials are available.

- Edge Shrinkage Tape - The production of this tape is expected to require development of finer base film handling techniques. It is expected that after the development of the basic seam tape, the equipment could be modified, if necessary, to handle the thinner (0.1 mil) shrinkage tapes.

- Graphite/Polyimide Edge Reinforcement - To date this type of prepreg tapes have not been made in the thin cross section desired. A plan has been proposed whereby 1000 filament tows (rather than the standard 3000 filament) would be used to make a sample prepreg about 1.5 mils thick. This activity could be accomplished for about $10K on a laboratory basis. Narmco Materials Division of Whitaker Corporation and Fiberite Corporation are two candidates who are qualified to do this work. Such an activity should include yardage sufficient to evaluate uniformity of section stiffness since this characteristic will be extremely important when requiring pairs of edge tapes to exhibit equal strain when loaded by centrifugal force.

- Batten Design and Prototype Production - Efforts should be made to develop a batten design which will provide a soft interface with the sail sheet. Conformity of batten attachment process with the overall manufacturing plan should be verified.

- Mesh - Mesh material selection and processes must be considered in subsequent efforts. The thermal capabilities of candidate materials and the benefits of potential shielding concepts are unknown at this time.

- Overall Machine Design - An overall machine development program has been described and outlined in Section 11.0. It would be a five phase effort involving sequential design and development tasks leading to completed, on-line spinning sail production equipment.

  The first phase of such a program would involve a more detailed identification of the specific manufacturing processess and equipment required for a blade production facility. Concepts will be verified through feasibility modeling and process testing to establish a high degree of confidence that the proposed equipment will perform its intended functions.

  This effort would require representative samples of various materials, tapes, battens, etc., to be most effective; however, because of the extremely tight schedule limitation it would be beneficial to initiate this effort as soon as possible and utilize existing commercially available materials wherever possible to evaluate first order equipment characteristics such as handling, transfer, control, etc. It is envisioned that this effort would require six to eight months and would cost on the order of $100K.

APPENDIX A

ALTERNATE DESIGN CONCEPT

ALTERNATE DESIGN CONCEPT

Previous spinning sail design concepts have dealt with continuous uninterrupted film lengths and their attendant problems resulting from the material fullness requirement-heat buildup from wrinkles created by the 1% fullness at the edge reinforcement interface. The design concept presented herein reduces, and/or eliminates some problems associated with the other fabrication schemes.

Briefly, this design utilizes the same battens and edge reinforcements as proposed in previous concepts. The central film web however is not a continuous length; it is, instead, applied to the catenary edge reinforcement in discrete lengths with some specific spacing between these lengths which precludes the overlapping of film during or after deployment. See Figure A-1. No film will be applied over any batten, thus the film/batten contact problem is eliminated.

Spacing between sections of film will preclude the need for the 1% film fullness imposed on the continuous film length concept. The individual film lengths would be applied to the catenary edge reinforcements in a flat, smooth configuration. This uniformity will minimize random temperature variations of the blade in flight thus providing for potentially better blade temperature stability. It also eliminates the potential catenary edge member/film interface heat buildup created by the half angles of wrinkles induced by adding the 1% film fullness.

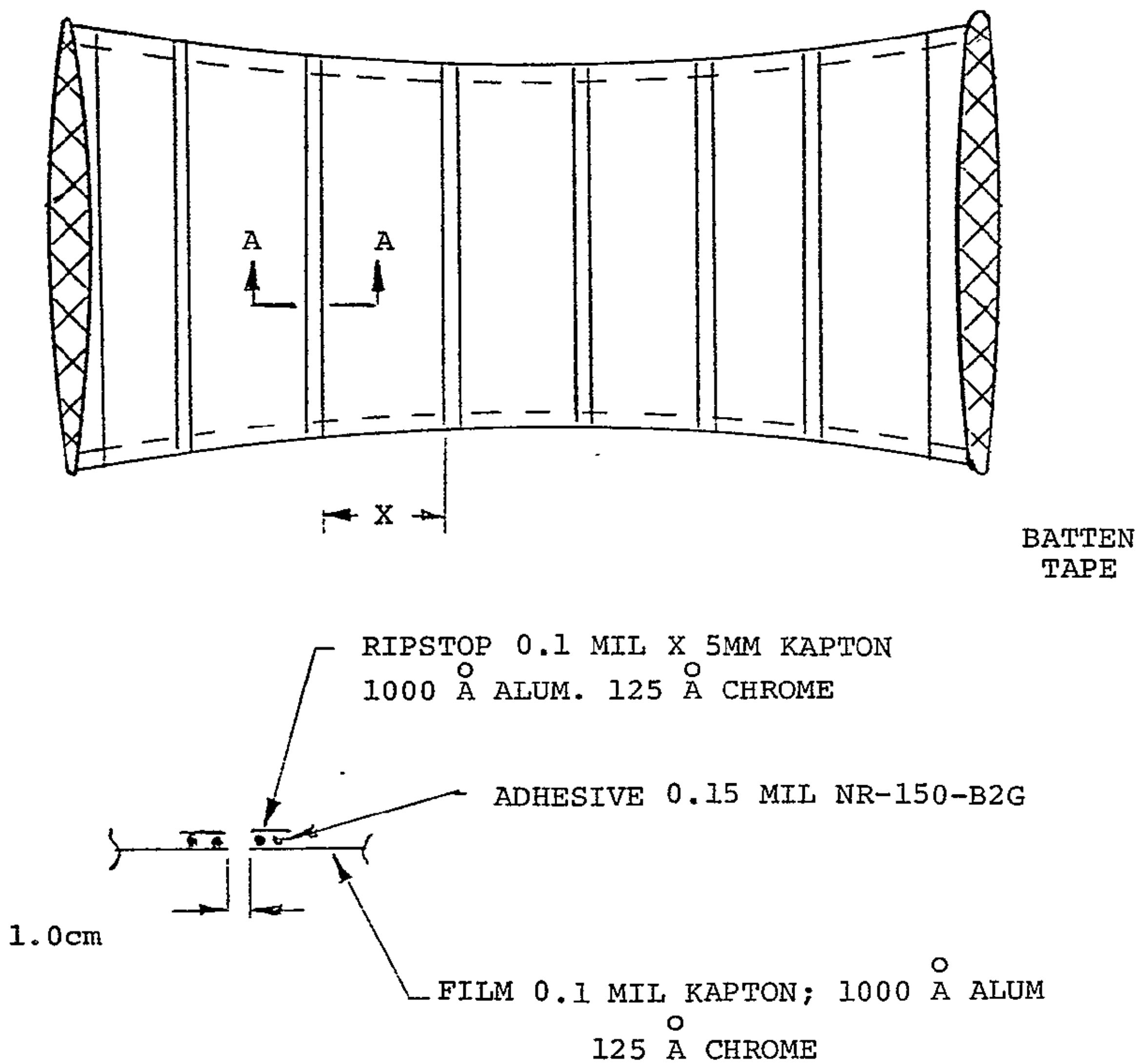
Assuming panel sizes of 1M X 8M maximum with a 1cm ± 5mm spacing between panels, and a 12cm spacing at each batten, the total film area of each blade would be reduced by approximately 750 square meters or 1.3%. The effect of this reduction of film area on the spinning sail performance must be evaluated with the consideration of this fabrication approach.

This concept also has the advantage of allowing the most efficient distribution of materials with regard to physical property mixing. Once the specific film lengths are determined the basic material characteristics of each lot or roll can be entered into a computer with its length. The computer can be programmed to "build" each blade on paper utilizing the measured material characteristics. In this manner, the entire blades physical properties can be iteratively tuned by the computer and specific roll use locations assigned.

The major disadvantages to this fabrication approach are that all battens and some portions of the catenary edge reinforcement will be exposed to direct sunlight. Also to be considered is the exposure of film panel edges to the sun's rays and the potential heat effects. All areas exposed by this fabrication method i.e., battens and catenary edge reinforcement would be coated with specular aluminum to enhance heat reflectance characteristics.

Panel edges reinforced with ripstop reinforcement are not expected to be exposed to direct sun rays. However, this configuration must be evaluated from a thermal standpoint to ensure the absence of overheat areas along the film panel edges.

This design concept involves a drastic deviation from the baseline design in that it utilizes a non-continuous blade sheet. It is presented for consideration and recommended for evaluation of performance characteristics since several of the most critical manufacturing operations could be eliminated by this design, that is, the 1% film fullness and attendant operations would not be required.



FILM PANEL CHORD SEAM REINFORCEMENT A-A

X = Discrete Panel Length (TBD)

Figure A-1 Alternate Design Concept