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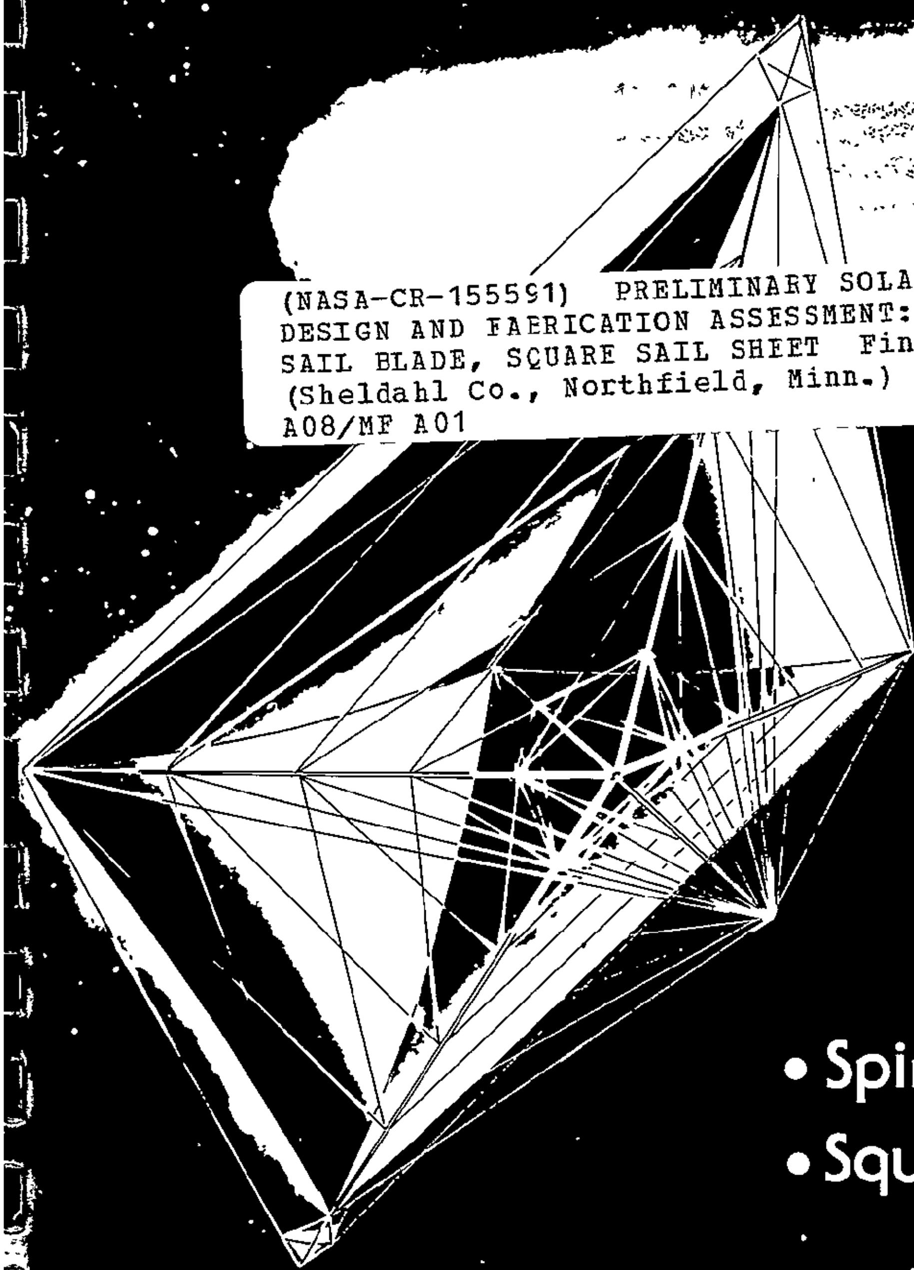
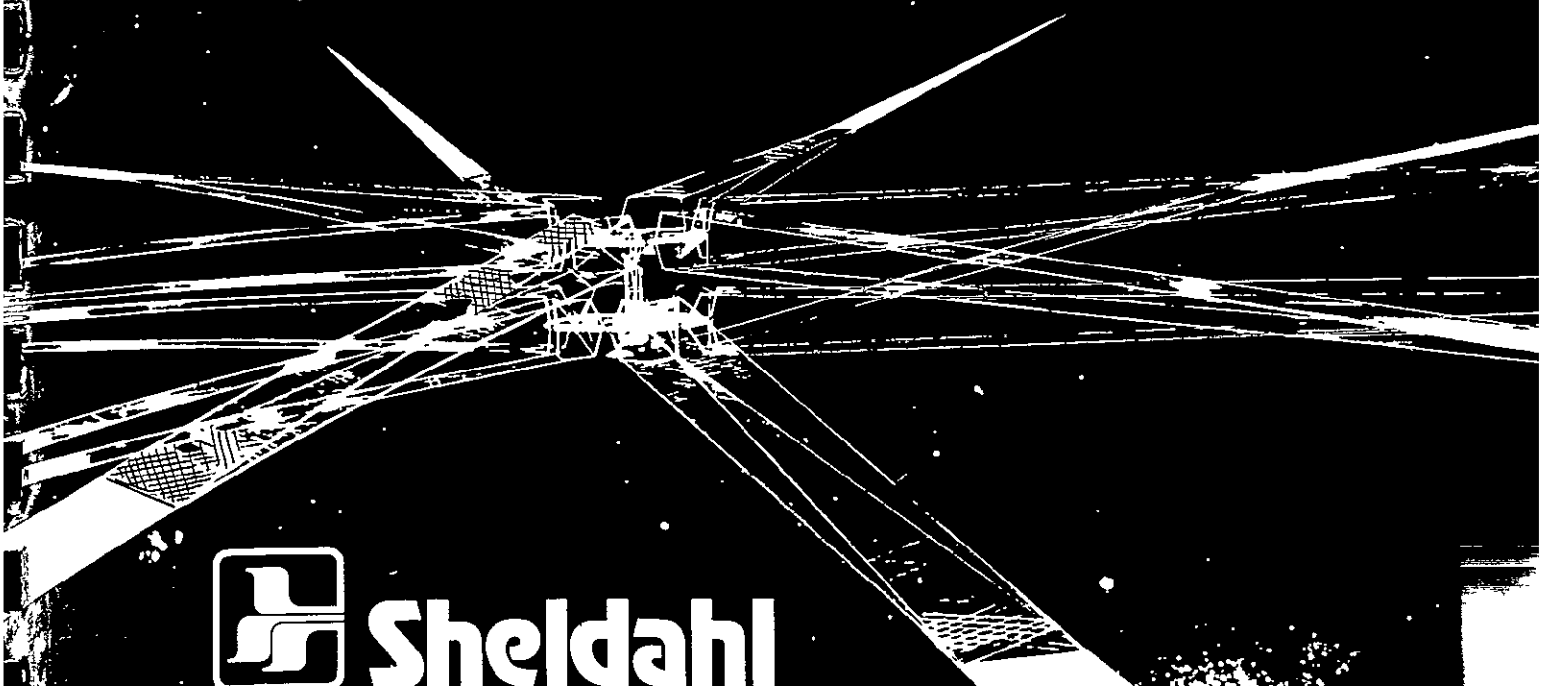


PRELIMINARY DESIGN & FABRICATION ASSESSMENT

- Spinning Sail Blade
- Square Sail Sheet



Sheldahl

PRELIMINARY SOLAR SAIL DESIGN AND FABRICATION ASSESSMENT

- SPINNING SAIL BLADE
- SQUARE SAIL SHEET

FINAL REPORT

AUTHORS:

J. B. Daniels
D. M. Dowdle
D. W. Hahn
E. N. Hildreth
D. R. Lagerquist
E. J. Mahagnoul
J. B. Munson
T. F. Origer

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Section I
Spinning Sail Blade

SECTION I
SPINNING SAIL BLADE DESIGN AND FABRICATION ASSESSMENT

INTRODUCTION AND SUMMARY

Sheldahl's efforts and activities under the original Statement of Work of Contract No. 954721 were directed to a study and evaluation of designs and fabrication methods, equipment, facilities, economics, schedules, etc., for the square sail sheet alternate. Those efforts and the work accomplished, until redirected to focus attention on the spinning sail blade alternate, are documented in Section II of this report.

Section I contains a report of Sheldahl's preliminary assessment of the Astro Research Corporation baseline for the spinning sail blade design and related fabrication issues, performed under the revised Statement of Work of Contract Unilateral Modification No. 1.

Four primary areas of interest were discussed:

1. Blade Design

Blade design aspects most affecting producibility and means of measurement and control of length, scallop, fullness and straightness requirements and tolerances were extensively considered. Alternate designs of the panel seams and edge reinforcing members are believed to offer advantages of seam integrity, producibility, reliability, cost and weight.

2. Manufacturing Methods and Processes

Analyses assumed that the base film (.1-mil Kapton or equivalent), battens and flight reels would be furnished by NASA.

Approaches to and requirements for unique and highly specialized metalizing methods, processes and equipment were studied and preliminarily identified.

Alternate methods of sail blade fabrication and related special machinery, tooling, fixtures and trade-offs were studied. A preferred and recommended approach is preliminarily identified.

Quality Control plans, inspection procedures, flow charts and special test equipment associated with the preferred manufacturing method were analyzed and are discussed.

3. Economic, Schedule, Facility Considerations

Special facilities requirements and ROM program plans, schedules and costs for the spinning sail blade were evaluated and are included in this report.

4. Areas Requiring Further Study

A number of areas requiring further study, refinement of definitions and requirements, conceptual or preliminary designs, and/or test and evaluation, etc., are identified.

Several are of particular importance from a schedule and lead time point of view. Others are presumed to be matters under study at JPL or other agencies, but are included so as, in any event, to avoid being overlooked. Sheldahl will be pleased to provide further particulars and furnish cost and schedule inputs for extension of the blade design and fabrication assessment areas suggested.

Some of the items are common to both the spinning sail blade and square sheet and are included in both Sections I and II.

MATERIALS STUDIES

While NASA JPL has prime responsibility for the design and specification of materials, bonding and seaming methods and is obtaining support from other NASA agencies and from other organizations under subcontract, Sheldahl also funded initial investigations of candidate adhesive systems, sealing equipment, methods and conditions; fabricated sample specimens; and conducted tests.

Two primary purposes were envisioned:

(1) To obtain preliminary working knowledge of materials and seaming equipment and methods as it pertained to the design and fabrications study; and

(2) To provide information and test data to JPL as a measure of support, to add to the total body of knowledge concerning candidate sail materials, seaming and bonding methods, etc., all ultimately for consideration in JPL material system design, development and specification purposes.

Results of the preliminary Sheldahl Materials Study to date are included as an appendix to this report.

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1.0 SPINNING SAIL BLADE DESIGN

Sheldahl's design and fabrication assessment was based upon a combination of baseline design data represented by current design drawings and background information developed by Astro Research Corporation and JPL guidance and direction with respect to exploration of alternate designs and manufacturing methods for certain aspects of the sail blade.

1.1 Baseline Design

Baseline designs referenced in this study comprise the following Astro Research Corporation background data and design drawings furnished by JPL:

(a) Description of Helio Gyro blades - narrative and Figures 1-6, undated.

(b) Helio Gyro Fundamentals, R. H. McNeal, March 7, 1977.

(c) Astro Research design drawings transmitted to Sheldahl June 8, 1977 including:

SK 1784 - Blade Configuration
SK 1791 - Blade Assembly
SK 1813 - Batten Assembly
SK 1810 - Panel/Batten Assembly
SK 1807 - Flap Hinge Brace
SK 1796 - Batten Hinge Assembly
SK 1814 - Tip Mass/Tie Down

1.2 Deviations From Baseline

As a result of a combination of JPL guidance and direction plus Sheldahl intiative, a variety of alterations to the Astro Research Corporation baseline design are considered and suggested by way of simplification, improved reliability, weight and cost reduction and generally enhanced producibility.

1.2.1 Manufacturing/Assembly, Packaging and Quality Assurance

1.2.1.1 Manufacturing/Assembly

Deviations from the Astro Research baseline are discussed in detail in Paragraphs 2.3 and 2.4.

Sheldahl does not recommend the use of a longeron subassembly. The baseline subassembly makes no provision for rip-stop along the longeron tape and down the blade. A tear could propagate and separate the longeron completely from the rest of the blade. It is recommended that the longeron tape be bonded directly to the blade panels during section fabrication.

It is suggested that the sail blade be built in 120 meter maximum sections and assembled in a separate operation to provide randomizing of thermal and weight properties and to provide for section alignment (blade straightness). Index marks on the longeron tapes do not in themselves guarantee a straight finished blade. By building the blade in sections (120 meters maximum), they can be aligned by lasers and then joined. During alignment and prior to joining, the sections can be tensioned under flight load. This will eliminate variations in the length, elongation and positioning of the longeron tapes.

1.2.1.2 Packaging

Packaging is discussed in detail in Paragraph 1.4. The recommendation is made that the blade be wound onto a reel approximately 8 1/2 meters wide and having a maximum O.D. of 0.6 meters. It is further recommended that the blade be level wound, under deployment tension, to spread the longeron tape build-up over a wide area.

1.2.1.3 Quality Assurance

To assure final blade straightness, Sheldahl recommends that the blade be built in sections, aligned and joined. Details are discussed in Paragraph 2.4.

1.2.2 Accuracy Requirements

Accuracy requirements are discussed in detail in Paragraph 2.4.1.4. As noted above, the suggested approach is for the blade to be built in sections, aligned and joined in order to assure blade straightness.

1.2.3 Batten Design

Baseline for the preliminary study assumes government supplied battens. A review of the baseline design indicates that the small hinges would be uacceptable. When the batten is folded and wound onto the reel, the corners of the hinges would protrude and become entangled in and tear the thin Kapton film.

1.2.4 Weight Estimates

Weight estimates are discussed in detail in Paragraph 1.5. Additional weight savings can be made in two areas - panel joints and longeron tapes.

1.2.5 Sealed Versus Sewn Seams

It is recommended that a tape butt-joined seam be used in place of the baseline sewn configuration.

The sewn seam does not visually guarantee seam integrity. Further the sewn seam concept requires that a tape reinforcement be applied to all adjoining edges. In turn, this tape must be reinforced with fibers to increase its tear resistance. It is this reinforcing tape which must be secure to transfer the stress into the adjoining film and which appears to be an unnecessary duplication.

Weight savings from use of the tape butt joint seam is discussed in Para. 1.5. The tape seam configuration is discussed in Paragraph 2.3.8 and is shown in Figure I-3.

1.2.6 Longeron Tapes

It is recommended that a single, wide longeron tape be considered in place of the baseline trifilar configuration.

The single tape concept will reduce packaging volume as described in Para. 1.4.

Weight savings can be made by tapering the single longeron tape as it progresses down the blade. This is discussed in detail in Paragraph 1.5.

1.3 Rip-Stop

For the purpose of this study, rip-stop is assumed to be inherent in the baseline design; the longeron tapes provide the rip-stop member along the edges and the panel splice tapes provide the reinforcing for rip-stop down the blade length.

This is an area recommended for further study to more specifically define requirements, analyze, test and evaluate rip-stop/tear propagation characteristics of the 0.1-mil film and preliminary blade design.

1.4 Packing Methods and Volumes

The baseline specifies that the completed blade be wound onto a reel having a maximum diameter of 0.6 meters. The following paragraphs review the Astro Research baseline calculations and two alternates - a single wide, thin longeron tape, in place of the trifilar tape, and the level winding method of winding the blade onto the reel.

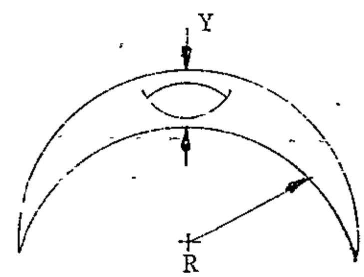
1.4.1 Baseline Design

If the blade is wound onto the reel with a straight edge, one thickness of film and one longeron tape thickness would always stack up. Using this baseline approach the estimated canister diameter would be as follows:

Film thickness - 2.54×10^{-6} meters
Longeron thickness - 1.80×10^{-4} meters
Blade length - 7,500 meters

Film and Longerons

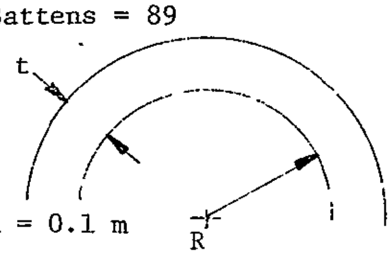
$$A_{F/L} = (2.54 \times 10^{-6} + 1.80 \times 10^{-4})\ 7{,}500$$
$$= 1{,}369\ m^2$$



y = 0.02 m
R = 0.2 m
Battens = 89

Battens

$$A_B = 2/3\ \sqrt{2\ Ry^3}$$
$$= 89\ (2/3)\ \sqrt{2(.2)\ (.02)^3}$$
$$= 0.106\ m^2$$



R = 0.1 m

Total Average Package Depth

$$t = \sqrt{\frac{A_{F/L} + A_B}{\pi} + R^2} - R$$

$$= \sqrt{\frac{1.475}{\pi} + .01} - 0.1$$

$$= 0.59\ m$$

Therefore reel diameter = 2 (0.1 + 0.59)

= 1.38 meters

The diameter (1.38 meters) calculated by the above method greatly exceeds the baseline goal of a 0.6 meter maximum diameter reel and makes no allowance for nesting of the trifilar longeron tapes.

The baseline uses a factor of 10 for the trifilar longeron tapes. This factor assumes some unknown amount of nesting. Using the baseline analysis, the estimated canister diameter would be as follows:

Film thickness	- 2.54×10^{-6} meters
Allowance for longerons	- factor of 10 x film thickness
Blade length	- 7,500 meters

Film and Longerons

$$A_{F/L} = 10 \times 2.5 \times 10^{-6} \times 7{,}500$$

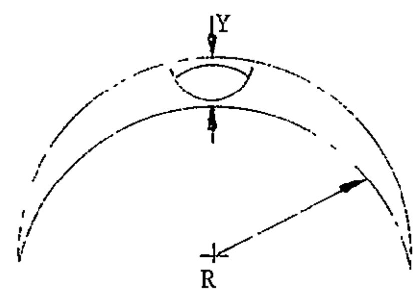
$$= 0.19 \text{ m}^2$$

Battens

$$A_B = 2/3 \sqrt{2 Ry^3}$$

$$= 89 \ (2/3) \sqrt{2 \ (.2) \ (.02)^3}$$

$$= 0.106 \text{ m}^2$$



y = 0.02 m

R = 0.2 m

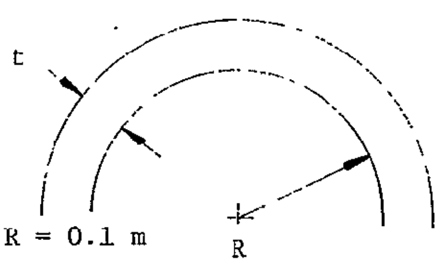
Battens = 89

Total Package Depth

$$t = \sqrt{A_{F/L} + A_B + R^2} - R$$

$$= \sqrt{\frac{0.296}{\pi} + .01} - 0.1$$

$$= 0.22 \text{ m}$$



R = 0.1 m

Therefore reel diameter = 2 (0.1 + 0.22)

= 0.64 meters

The diameter (0.64 meters) calculated by the above method also exceeds the baseline goal of 0.6 meters maximum reel diameter.

As can be seen by these two examples, the combination of the trifilar edge thickness and winding onto an 8-meter-wide reel produces unacceptable results. For these examples, a 0.2 meter (8 inch) reel I.D. was used. It is recommended that the reel I.D. not be less than 0.16 meters (6 inches).

1.4.2 Alternate Longeron Design

An alternate design, suggested for consideration, is to have a single, wide longeron on each edge. For this example, the trifilar longeron has been spread into a single 0.05 meter (2 inch) thin tape.

Therefore, a longeron 0.05 meter (2 inch) wide has the following thickness:

$$\frac{3\ (1.8 \times 10^{-4})\ (2.1 \times 10^{-3})}{0.05} = 2.27 \times 10^{-5} \text{ meters}$$
$$(\sim 0.9 \text{ mil})$$

Winding these in a straight edge, one thickness of film and one longeron tape per layer, we have the following:

Film thickness - 2.54×10^{-6} meters
Longeron thickness - 2.27×10^{-5} meters
Blade length - 7,500 meters

Film and Longerons

$$A_{F/L} = (2.54 \times 10^{-6} + 2.27 \times 10^{-5})\ 7{,}500$$
$$= 0.19 \text{ m}^2$$

Battens

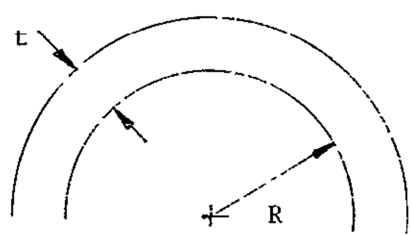
$$A_B = 0.106 \text{ m}^2 \text{ (same as previous examples)}$$

Total Average Package Depth

$$t = \sqrt{\frac{A_{F/L} + A_B}{\pi} + R^2} - R$$

$$= \sqrt{\frac{0.296}{\pi} + .01} - 0.1$$

$$= 0.22 \text{ m}$$



R - 0.1 m

Therefore reel diameter = 2 (0.1 + 0.22

= 0.64 meters

Thus, in this example also, spreading the trifilar tape into a single thin, wide tape is still not sufficient to obtain the goal of a 0.6 meter diameter reel.

1.4.3 Level Wind - Preferred Approach

The preferred packing method, in addition to the use of a single thin longeron tape, would be to level wind the sail blade and in turn the tape. This would spread the edge buildup over a greater area. It is estimated that an 8 1/2-meter-wide reel would be sufficient in this case.

The following example spreads the edge reinforcement over a 1/2 meter area as would result from using the level wind method.

Film thickness - 2.54×10^{-6} meters
Longeron thickness - 2.27×10^{-5} meters (single thin tape)
Blade length - 7,500 meters
Nesting factor due to level wind over 1/2 m - 8

Film and Longeron

$$A_{F/L} = \left(\frac{2.27 \times 10^{-5}}{8} + 2.54 \times 10^{-6}\right) 7{,}500$$

$$= 0.04 \text{ m}^2$$

Battens

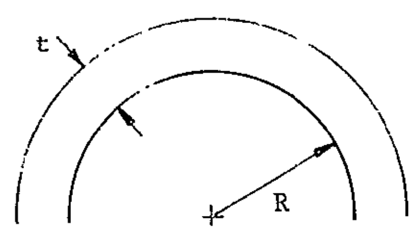
$$A_B = 0.106 \text{ m}^2 \text{ (same as previous examples)}$$

Total Average Package Depth

$$t = \sqrt{\frac{A_{F/L} + A_B}{\pi} + R^2} - R$$

$$= \sqrt{\frac{0.146}{\pi} + .01} - 0.1$$

$$= 0.14 \text{ m}$$



R - 0.1 m

Therefore reel diameter $= 2\ (0.1 + 0.14)$
$= 0.48$ meters

Using this method, the blade will easily wind onto a reel having a 0.6 meter maximum diameter. Even if the tape should be slightly thicker, there is sufficient space available.

1.5 Blade Weight Estimate

Weight estimates have been made for the coated film, seams and edge tendons for the blades. Blade dimensions used for the estimates are:

Total blade length - 7500 m (7326.25 m outboard of flap hinge)

Nominal chord length - 8 m

Edge cantenary sag (each side) - 0.24 m

The average section chord length is calculated to be approximately 7.68 m so the total area of reflective surface for 12 blades is about 675,187 m^2. Then the total weight for the coated film is:

Kapton (3.607 g/m^2) - 2435 kg

Coatings (0.36 g/m^2) - 243 kg

1.5.1 Seams (Panel Joints)

The proposed film seam construction is a butt joint with a 1 cm wide tape of metalized Kapton film 7.62 μm (0.3 mil) thick and 5.08 μm (0.2 mil) adhesive thickness.

The weight of this seam is about 0.184 g/m. With an approximate average panel seam length of 7.68 m and 7328 seams per blade, the total length of seams for 12 blades is about 675,348 m. Thus, the total weight of seams would be about 124 kg.

It may be possible to use a thinner film tape if testing were to prove that this tape provided adequate strength and rip-stop capabilities. For example, the use of 2.54 μm (0.1 mil) thick film for tapes would reduce the seam weight to 0.112 g/m. The total seam weight would then be about 76 kg.

For comparison purposes, the sewn seam construction in the ARC baseline design weighs 0.204 g/m. Also, the total length of seams is greater if the edge members are fabricated as separate assemblies and joined to the blade panels. This calculated length is about 826,568 m, making the total seam weight about 169 kg.

In summary, the comparisons of the three types of seams are as follows:

- ARC baseline sewn/tape seam	169 kg (total 12 blades)
- Proposed 0.3 mil tape seam	124 kg (total 12 blades)
- Alternate 0.1 mil tape seam	76 kg (total 12 blades)

1.5.2 Edge Tendons (Tapered edge alternative)

A weight of 1.77 g/m is assumed for a graphite-polyimide edge tendon for both the trifilar tape design and an alternate single wide tape of equivalent cross sectional area. The length of an edge is about 7493 m per blade for a total length of 179,832 m for all tendons. Thus, the total weight is about 318 kg.

Since the blade tension decreases outboard from the root, it is perhaps possible to decrease the tendon weight by tapering the tape area from the root to the tip. Calculations indicate that a weight reduction of almost one-third of the total (104kg) could be realized by making the tendon cross section proportional to the blade tension. This concept, of course, would affect the blade stiffness, mass distribution and dynamic behavior which has not been evaluated and should be an area of further study.

2.0 HANDLING AND FABRICATION PLAN

2.1 Government Furnished Equipment

Baseline for this preliminary study assumes government supplied Kapton (or similar) film and battens. The baseline also assumes that the government supplies the flight reel and associated hardware.

2.2 Film Metalizing

The question of proper equipment to produce the metalizations required for the sail fabric is critical. Tightly controlled deposits of both aluminum and chromium are required which are uniform in thickness and density.

In addition, the aluminum thickness, as compared to the substrate thickness, is substantial and is also high in relationship to commercial practice. Chromium deposits present distinct problems with deposition methods and control. The following discussion will outline some of the parameters currently recognized as in need of much further refinement and definition. It is felt that equipment available in the industry at the present time cannot fulfill the special requirements of this product. Suitable, specialized equipment will need to be designed and constructed to ensure timely deliveries of "on spec" material, minimizing expensive scrap losses.

2.2.1 Key Equipment and Process Considerations

Some very basic questions must be addressed before progress can be made on design of suitable equipment. Many of these revolve around the nature of the candidate sail material itself. Polyimides absorb high percentages of moisture. There is also an opinion that a lot-to-lot variation exists in the amount of unreacted polymerization charge materials and/or by-products. Both of these contribute to loads on the pumping system and possible contamination of the vapor deposit. A vacuum pretreatment may be necessary to thoroughly remove these potential sources of trouble.

Further, the behavior of .1 mil polyimide in vacuum systems when exposed to high heat, vacuum, and tension could result in physical changes from the nominal. General shrinkage of the material is expected; how much shrinkage needs to be determined. Edge curling due to induced stresses is expected; again, how much occurs, how much is tolerable, and how we minimize or eliminate it are questions needing answers (slitting after metalization and edge banding during metalization are possible solutions).

The heat of condensation of the metals on the polymer could lead to severe problems, up to and including the physical destruction of the plastic film. Therefore, the "flux density" allowable must be firmly established early and adhered to during production phases.

Several other details must be exercised early to provide essential input to design stages. The suitability of the various types of sources to produce acceptable material from an optical standpoint should be determined. The question of perforations before or after metalization must be thoroughly discussed and resolved. Perforating before metalization presents problems in web handling such as tears, poor handling characteristics, "ridge" formation (similar to gauge bands), loose "divots" from the punching operation in the metalizer, etc. Laser perforating on a random pattern should preclude most of these problems but must be investigated as a production method.

2.2.2 Major Equipment Design Areas

For ease of discussion, the major design areas of consideration will be broken down into six major categories as follows:

A. Sources - The various means of producing metal vapor for subsequent condensation on the plastic web.

B. Pumping - The types and suitability of different means of achieving adequate vacuum.

C. Web Handling - The carriage assembly for transporting the plastic web from place to place within the vacuum chamber.

D. Sensing - All the devices needed to insure the production of "on spec" deposits from:

1. a material property standpoint and
2. a source control standpoint.

E. Controls and system integration - The various gauges and monitors to verify system performance.

F. Single or multi-tank considerations - The desirability, or lack thereof, of splitting deposition into two separate and definable systems.

2.2.2.1 Sources

Several means are available for producing aluminum deposits in the vacuum chamber. Among these are resistance heating, induction, electron beam, and ion plating. Each has advantages and disadvantages. Questions must be answered in regard to uniformity, controllability, reliability, and deposit properties.

Chromium deposition is also possible by several methods. Among these are induction, electron beam, ion plating, and sputtering. Again, each method has advantages and disadvantages, with sputtering requiring a two-tank configuration.

2.2.2.2 Pumping

Rough pumping can be accomplished reliably with commercially available and universally used mechanical pumps and blower combinations (in the U. S. the most frequently utilized units are Stokes pumps and Roots blowers). These can be "gaged" if pumping speed so dictates.

Due to the volatiles present in the substrate, cryogenic pumping will most likely be required. This should include traps above all diffusion pumps and cold plates or "fingers" on both sides of the moving web in suitable locations.

High vacuum pumping would most likely be accomplished by oil diffusion pumps of 36" to 48" size singly or in multiples as required by capacity considerations.

Capacities of all pumps must be determined by the anticipated gas load, desired vacuum levels, and pumping speed considerations.

2.2.2.3 Web Handling

This is a very critical area of processing and is highly dependent upon the quality of the film material. Many devices are built to facilitate moving a web of material from place to place. Among these devices are specialized rolls and roller assemblies such as bowed rolls, flex spreaders, herringbone spreaders, slotted expanders, and Slimb [R] devices (gimballing rollers). Thought must be given to the use of tension sensors, very fine clutches and brakes, low drag bearings, and tendency driven rollers. The use of multiples of these units to handle this thin material will probably preclude bidirectional web travel in favor of a uniderectional approach. Provision will also have to be made for shadow bonding the edges of the material should this prove necessary.

All the web handling questions must begin to be addressed as soon as the first prototype film becomes available.

2.2.2.4 Sensing

Systems must be incorporated to give ready answers to the machine operators verifying the production of quality material. Among these should be:

A. Continuous resistance monitoring - A readout indicating electrical resistance as an indication of thickness;

B. CO_2 laser (at 10.2μ) - A continuous reflectivity measurement in tank as material is processed;

C. Fast scan spectrophotometer - Set to operate at 4 or 5 predetermined wavelengths to give an indication of reasonable α values; this unit could give a continuous, permanent record of values if desired;

D. Closed circuit internal TV - To monitor web travel and verify operation of web handling devices.

In addition, sensors should be incorporated to monitor source operation and deposition parameters. These should include:

A. Rate monitors - One per source to give indication of the operating efficiency of that source;

B. Thickness monitors - Multiple heads located at strategic spots to validate continuous readings;

C. "Stand Alone" control computer - Accepts inputs from sensors, sorts data and records, updates program for control purposes.

2.2.2.5 Controls and System Integration

The operator control console (s) must contain all the sensor and gauge output for the total system. This allows for central accumulation and readout with potential operator override of primarily automatic operation in case of malfunction. The environmental readouts (e.g. vacuum tank proper) should include residual gas analysis capable of automatic sequential scanning of several head placements with demand isolation of a single head. In addition, thermocouple and ion gauges must be used to monitor vacuum levels and can be used in multiples. Functional interlocks are essential to prevent inadvertent miscycling of the machine. Various visual and audible warning devices can indicate lack of water flow, improper intermediate vacuum levels, and similar variables to "flag" them for the operator (s).

All monitoring and readouts from the sources, as previously discussed, would feed to this central control. Material property measurements would be reported to this same area with visual readouts and auto recording of values with computer interface for automatic shutdown or a manual override decision point. All web handling readouts would be reported to this location, including the closed circuit TV monitoring. Again, preset values could signal shutdown or demand manual override within a pre-programmed time frame All sensor data would be coordinated in this area for computer stock generation as well as updating control algorithms.

2.2.2.6 Single or Multi-Tank Decision

A choice inherent in the new equipment concept is that of whether a single, extremely complex unit or two or more somewhat simpler versions should be designed. There are trade-offs in both directions:

A. Single Tank

1. Less web handling;
2. Probably less capital cost;
3. Significantly more complex;
4. Downtime means nothing gets coated;

5. Limits source types; and
6 Balancing two deposit zones extremely tricky.

B. Multiple Tanks

1. One system down does not result in total shutdown (operate other unit);
2. Control only one deposit at time - easier;
3. Does not limit source configurations;
4. Could be somewhat more capital intensive; and
5. More web handling.

2.2.2.7 Conceptual Designs

Operating from sail material baselines, it is important that very early attention be given the means of metalizing this material. The requirements are currently on the extreme fringe of producibility and will require specialized equipment for conformance. It is suggested that as many answers as possible to points raised here be found quickly, that further efforts to more fully define requirements be undertaken and that at least two manufacturers of sophisticated metalizing equipment be funded or partially funded to develop conceptual equipment designs. Fabrication time of this item(s) from *finished* drawings indicates that no time be lost developing and approving the initial design.

2.3 Sail Blade Manufacture

2.3.1 Fabrication Concepts

The blade manufacturing concepts are shown in Figures I-1 and I-2. As summarized under Paragraph 1.2, some departure has been taken from the baseline design. The Sheldahl concept, outlined in the figures, does not use an edge subassembly and uses sealed tape joints instead of a tape/sewn joint.

The Sheldahl manufacturing concept is divided into two operations - section fabrication and blade assembly. Under this plan, sections of the blades (each 120 meters long maximum) are fabricated, randomized and then assembled

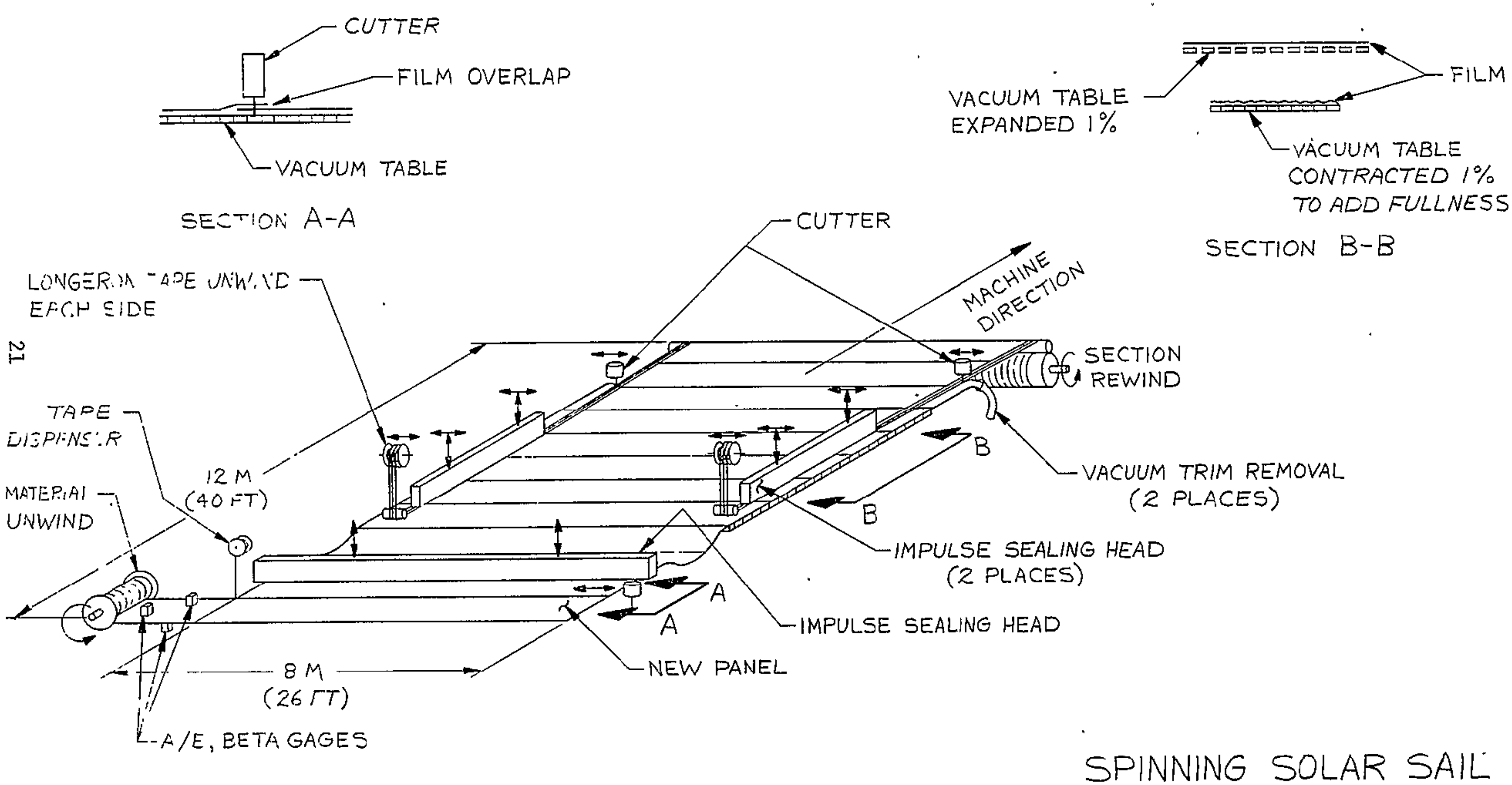

CUTTER
FILM OVERLAP
VACUUM TABLE
SECTION A-A
VACUUM TABLE EXPANDED 1%
FILM
VACUUM TABLE CONTRACTED 1% TO ADD FULLNESS
SECTION B-B
CUTTER
LONGERON TAPE UNWIND EACH SIDE
MACHINE DIRECTION
SECTION REWIND
TAPE DISPENSER
12 M (40 FT)
MATERIAL UNWIND
VACUUM TRIM REMOVAL (2 PLACES)
B
B
IMPULSE SEALING HEAD (2 PLACES)
A
A
IMPULSE SEALING HEAD
NEW PANEL
8 M (26 FT)
A/E, BETA GAGES
SPINNING SOLAR SAIL
SECTION FABRICATION

Figure I-1

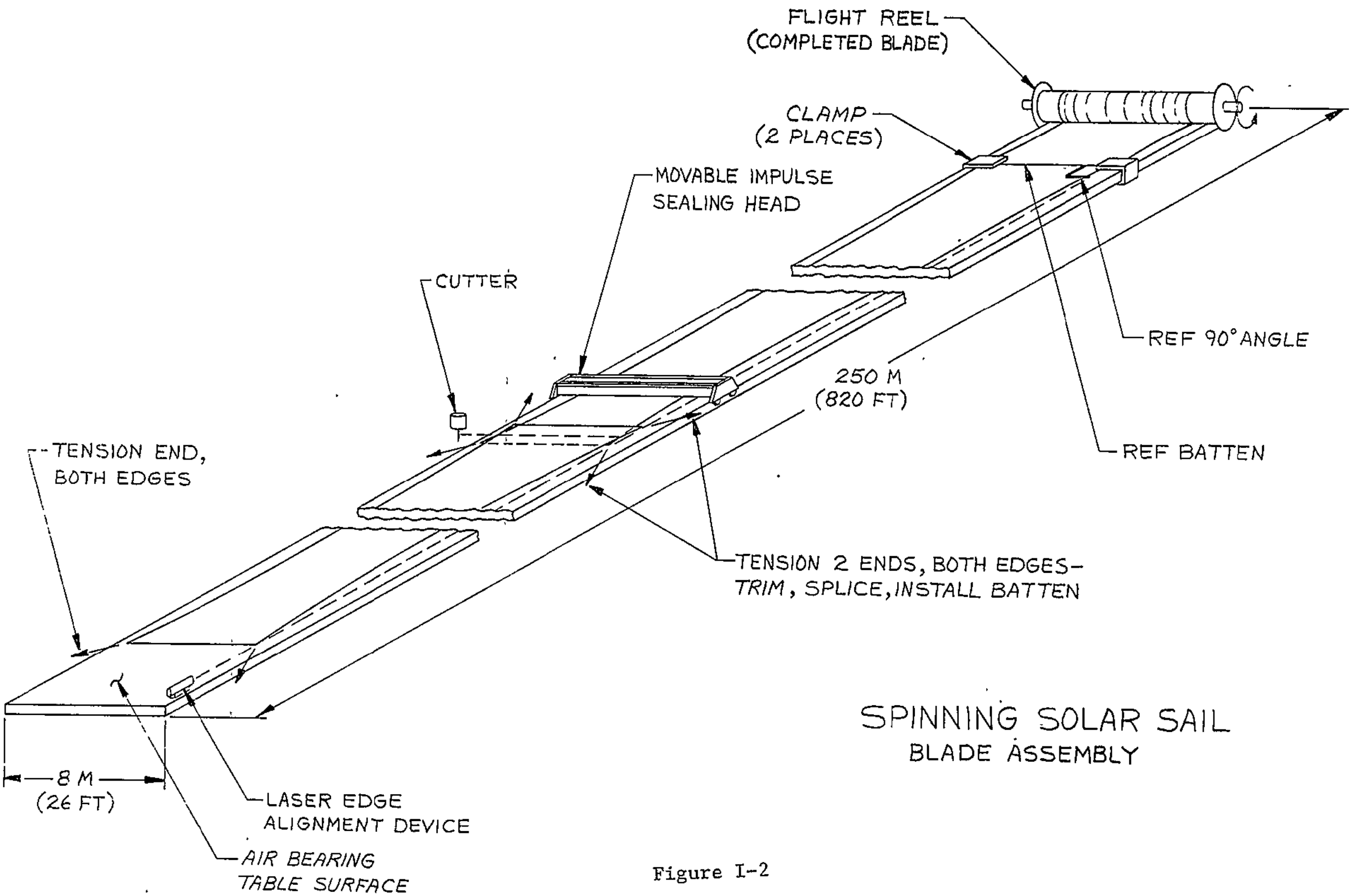

FLIGHT REEL
(COMPLETED BLADE)
CLAMP
(2 PLACES)
MOVABLE IMPULSE
SEALING HEAD
CUTTER
REF 90° ANGLE
250 M
(820 FT)
REF BATTEN
TENSION END,
BOTH EDGES
TENSION 2 ENDS, BOTH EDGES-
TRIM, SPLICE, INSTALL BATTEN
SPINNING SOLAR SAIL
BLADE ASSEMBLY
8 M
(26 FT)
LASER EDGE
ALIGNMENT DEVICE
AIR BEARING
TABLE SURFACE

Figure I-2

together to make each blade assembly. Provision has been made to add 1% fullness in the Kapton in the machine direction. Special care is taken to tension and locate the longeron tapes with precision when they are installed. At final assembly (Figure I-2), the sections are carefully aligned to produce a straight blade.

The material (metalized Kapton film or similar) is randomized three times during fabrication and assembly of the blades to the spacecraft. The material is first selectively randomized after vacuum metalizing when it is dispensed and cut into 1- by 8-meter panels as shown in Figure I-1. Twelve sections are then built and randomized before being assembled into the blades. This allows the twelve blades to be as equal as possible in thermal control properties and weight distribution. A final randomizing can be done when the blades are completed and being attached to the spacecraft.

The following sections outline the manufacturing procedure in greater detail. The primary concern in development of this manufacturing concept has been to produce twelve blades as straight and equal in properties as possible. With this in mind, provision has been made throughout the manufacturing process to allow and correct for materal and fabrication variances.

2.3.2 Panel (1 m x 8 m) Seaming

The first step in the manufacturing process is to seam together the 1- by 8-meter panels. This is done on the section fabrication machine shown in Figure I-1.

The material, as received from vacuum metalizing, is dispensed across the machine and between A/E and Beta (thickness) gages as shown. The good section is then cut from roll and held in place on a vacuum table as shown in Figure I-1, Section A-A.

The new panel has been positioned to overlap the edge of the previously attached panel as shown in Figure I-1, Section A-A. A cutter then traverses the 8 meters and trims the two edges to provide a precise butt joint gap. The trim is manually removed. During this and the subsequent sealing operation, the material is constantly held by the vacuum table.

The butt joint splice tape is then dispensed and tacked into place. After the splice tape has been positioned, the vacuum table, holding the edges of the two panels, indexes ahead and under the 8-meter impulse-sealing head. The butt joint splice tape is then impulse-sealed in place. The impulse sealing method is preferred to provide precise pressure, temperature and dwell.

After the sealing cycle has been completed, the vacuum table releases the two joined pieces and indexes back to the original position. It is then ready for the addition of the next panel.

All machine operating conditions, as well as the A/E, Beta gage measurements, are recorded into a computer log for future reference and use. In addition, equipment is provided at this step to scan and monitor the butt joint gap and to scan the completed seal for voids and unbonds.

2.3.3 Edge Reinforcement - Dispenses and Bond

As shown in Figure I-1, the next process step is to install the longeron tapes along both edges. They are located and bonded directly to the joined Kapton panels on the same section fabrication machine.

Prior to being installed in this step, the unidirectional longeron tapes have been made, index marks located and then slit into matching rolls. It is recommended that the longeron tape be made as a wide web, index marks located across and down the web, and the web slit into individual rolls of pre-preg tape. These matched rolls of tape will then be used on each blade. This will assure that the same amount (length) of tape has been dispensed and installed down both edges of a blade.

This is also the step where 1% fullness is added to the Kapton film in the machine direction. This is done as shown in Figure I-1, Section B-B. The film is held on a vacuum table in the expanded position. The table then contracts 1% to add the fullness. Three meters are gathered per cycle of the machine. The vacuum table is divided into sufficient sections to prevent irregular gathering and fold-overs.

After the material has been located, smoothed out, held by the vacuum table, and gathered to add fullness, the longeron tapes are bonded in place. Three meters of tape are installed per cycle. If a single longeron tape is used, it is dispensed from the reel, located on the blade, tensioned, and impulse sealed in place. If a trifilar tape is used, each tape is dispensed from a reel and its position located and held by retractable locating pins; then all three tapes are tensioned and impulse-sealed in place. Approximately the last foot of each longeron tape is left unbonded on each end of the section. This will be used and bonded in place when the sections are joined together: As shown in Figure I-1, the longeron tape dispensers, locating pins and impulse-sealing heads move in and out to provide the 0.24-meter cantanary edge shape. Their position is computer-controlled from the location along the section.

After the longeron tapes are installed, the machine indexes ahead three meters. During this indexing step, cutters trim the excess Kapton film off as shown in Figure I-1.

Finished sections (120 meters maximum) are wound onto cores ready for randomizing and joining into blade assemblies. A completed section may contain one or more bays of blade.

2.3.4 Tailoring (fullness and scallop)

2.3.4.1 Preferred Method - Spanwise Fullness

As described in Para. 2.3.3 and shown in Figure I-1, Section B-B, the machine direction fullness is added prior to bonding the longeron tapes in place. This is accomplished by expanding and contracting the vacuum table which is holding the film.

2.3.4.2 Alternate Method - Spanwise Fullness

An alternate method of fabricating a blade section with spanwise fullness built into the film is to tension the edge longerons so they are elongated the proper amount while being bonded to the film. Then when the edge members are unloaded, the film will be compressed and the extra length (1%) will be contained in the resulting small wrinkles. The amount of pre-load required depends on the properties of the edge tendons.

Based on Astro Research Corp. preliminary design data, material properties for the proposed graphite - polyimide composite ribbons are assumed to be as follows:

Modulus - $E = 125\ GN/m^2$ (18×10^6 psi)

Area - Trifilar tapes each 2.1 x 0.18 mm
$A = 1.13 \times 10^{-6}\ m^2$, total one edge

Ultimate Tensile Strength - $F_{tu} = 1.73\ GN/m^2$ (250 ksi)

The elongation per unit length, ε, is related to the load P by the equation

$$\varepsilon = \frac{P}{EA}$$

Thus to produce 1% elongation, the load required is

$$P = 0.01\ EA = 1400\ N \quad (320\ lbs.)$$

The corresponding stress is about 1.25 GN/m^2, which is about 70% of ultimate, assuming linear-strain behavior.

The tension required to produce 1% elongation is rather high and would stress the material to a relatively high proportion of its ultimate. The recovery characteristics in this load range are not known. Also, the edge members would have to be held in the cantanary shape while under tension. For these reasons, indications are that this potential fabrication method may not be desirable or practical.

Further investigation is recommended to verify these tentative conclusions. Materials properties, including recovery characteristics should be ascertained from manufacturer's data, if available, or by test before final conclusions as to the preferred method of providing for 1% section length fullness.

2.3.4.3 Catenary Scallop

As described in Para. 2.3.3, the catenary scallop (0.24 meter) is built into the blade during longeron tape installation. After the tape is bonded, cutters, guided from the edge of the longeron tape, trim off the excess Kapton film.

2.3.5 Section Joining and Batten Installation

Prior to the start of blade assembly, 24 sections are made, randomized and matched into 12 pairs. Subsequently, 12 sections are always completed, randomized and then matched to the 12 blades being assembled. This allows for controlled distribution of weight and thermal control properties.

Figure I-2 shows the prefabricated sections being joined together to make a blade and shows the battens being installed. This step allows the sections to be tensioned and aligned to eliminate variations in the length, elongation and positioning of the longeron tapes. Each section is tensioned as it will be when deployed in flight.

The end of the previous blade section and the last batten installed is located and clamped to the table as shown in Figure I-2 , A laser is used to locate the blade edge at this point and to verify the 90° angle. The other end of the previously joined section is then stretched down the table and tensioned. Electronic load cells are used to tension each as it would be when deployed in space.

The new section (120 meters maximum) is then unrolled onto the table from its temporary storage core. It is positioned to slightly overlap the end of the other section and then is attached to electronic load cells at all four corners. It is also tensioned as it would be when deployed in space. A laser is used to align both ends of the new section with the reference end of the previous section as shown in Figure I-2. Where the two sections overlap, the laser is used to locate and establish a 90° perpendicular line. At this point, the overlapped ends will be trimmed and the two sections joined. The table is equipped with an air bearing surface to reduce sliding friction and abrasion of the metalized surface when the two sections are tensioned.

A cutter traverses the table and cuts the overlapping end from each section. This provides a precise butt joint gap. The overlapped ends are held by a vacuum clamp during the cutting and splicing operation.

After cutting, the Kapton (or similar) splice tape is dispensed, located on the blade film and tacked in place. At this time, the unbonded ends of longeron tape are positioned and tacked in place. An additional piece of longeron unidirectional tape is positioned across each cut to provide a butt joint splice. An impulse sealing head is then moved into position and the film and longeron tape splices are made. After sealing, equipment is provided to scan and monitor the butt joint gap and to scan the completed seal for voids and unbonds.

The batten is installed by a combination of bonding and rivets. Reinforcing metal plates are located and bonded to and across the longeron tapes. The metal plates are coated with adhesive and impulse-bonded in place. This operation may be done in conjunction with the previous splicing step or as a separate step. After the plates are installed, the batten is riveted in place.

The completed section is unclamped and wound onto the flight reel. The blade is level wound to provide a compact package. Surface winding rolls are provided to control tension as the blade is wound onto the reel. The blade is wound onto the reel under the same tension as it will encounter when being unwound and deployed in space.

2.3.6 Tensioning - Variations by Section

When the blade is being assembled (Figure I-2) each section (approximately 120 meters) is tensioned as it will be when deployed in space. This allows for correction of variations in the length, elongation and positioning of the longeron tapes.

2.3.7 Measurement and Control

2.3.7.1 Longeron Tape Length

It is recommended that the longeron tape be made as a wide web, index marks located across and down the web and the web then slit into individual rolls of pre-preg tape. These matched rolls of tape will then be used on each blade. If splices in the tape are required, the position of these index marks along each edge of the blade can be maintained. By using this method of matched rolls, the relationship of individual index marks can be allowed to vary while still assuring that the same amount (length) of tape is being installed along each edge. If a single longeron tape is used along each edge, the index mark alignment can be easily maintained. If the trifilar longeron tapes are used, the alignment of six index marks will be maintained. A computer program will be used to identify each mark location as the three tapes on each side weave back and forth down the section of blade being fabricated.

In addition to the index marks, tension control devices will be provided on each of the tape dispensing reels. This will minimize the length variations due to tape elongation.

The catenary position of the tapes will be located and computer-controlled. As described in Para. 2.3.3, retractable alignment pins will be used and three meters of tape will be positioned and bonded per machine cycle.

2.3.7.2 Blade (section to section) Straightness

As described in Para. 2.3.5 and shown in Figure I-2, a laser is used to provide final blade straightness and section alignment.

Also as described in Para. 2.3.5, the sections of the blade are tensioned under flight load. This allows variations in the blade to be "pulled out" and corrections made for variances in the longeron tape length, location and elongation.

While under flight tension, two sections (120 meters maximum) at a time are laser aligned. Laser alignment equipment is very precise in the horizontal direction and special attachments are available to find and integrate the exact center of the beam. Optical accessories are also available to provide the 90° angles for reference and at the section splice.

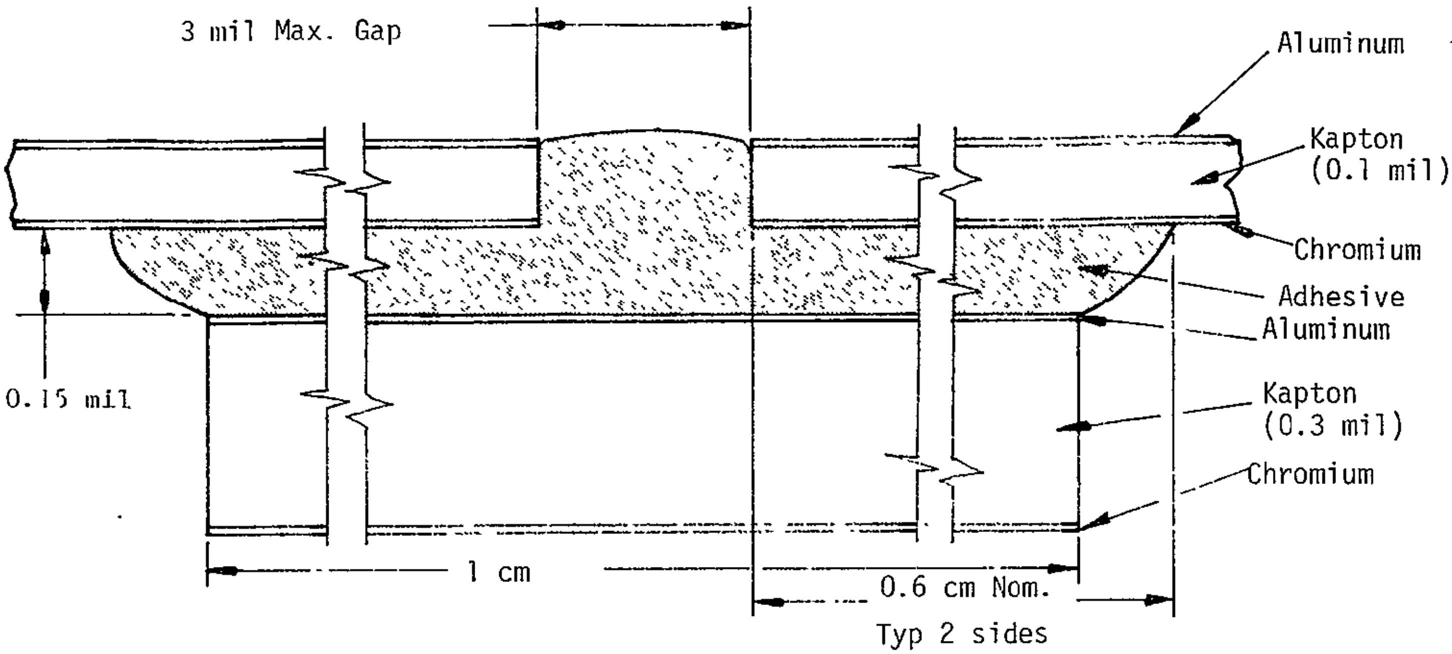
2.3.8 Repair, Splicing Techniques

Figure 1-3 shows a typical splice in the film and in the longeron tape. A repair would be similar. A special, portable cutter impulse-sealer would be built and used for repair work. The same piece of equipment would be used for splicing other than where the sections are joined. At this location, a special 8-meter cutter/sealer is provided and used as shown in Figure I-2.

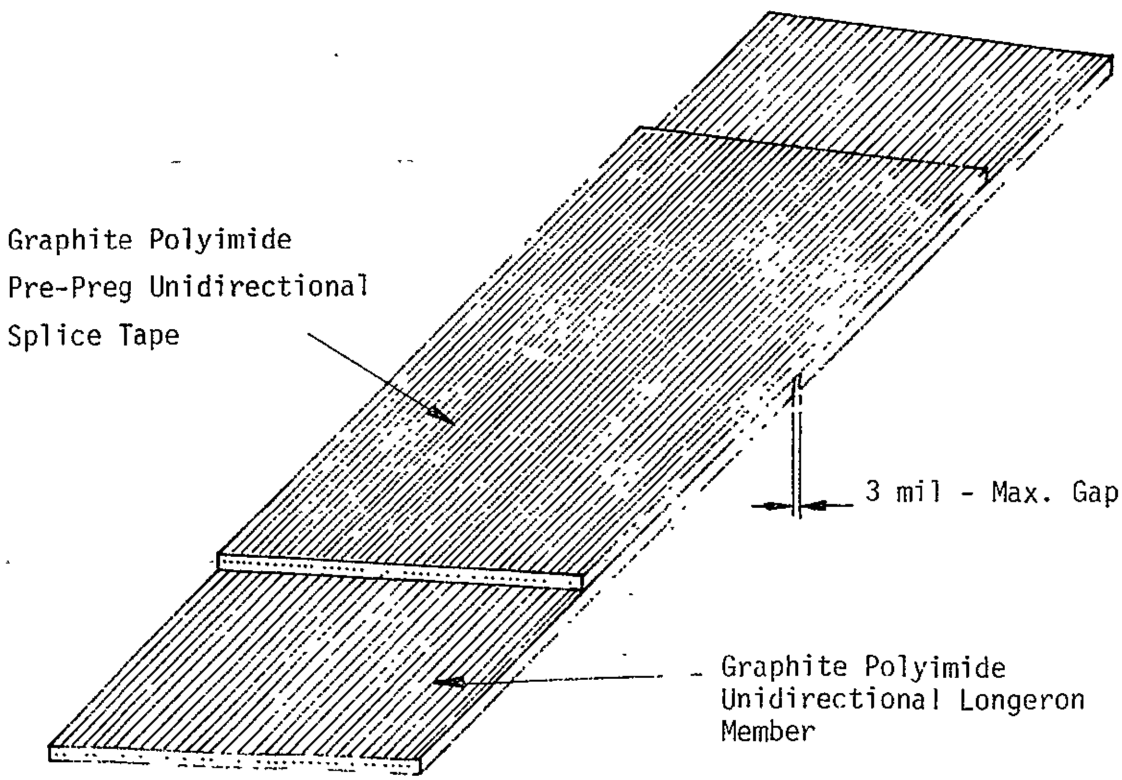
If there is a tear in the material, the defective area would be held in a vacuum clamp, the repair tape positioned and the tape impulse sealed in place.

If it should be necessary to remove the defective area and a new piece added, the following procedure would be followed. The same equipment would be used for adding a new piece as was used for repairing the tear. The defective area would be cut out, leaving a narrow salvage edge. The new piece of material (slightly oversize) would be positioned slightly overlapping the salvage edge. While being held by a vacuum clamp, a laser cutter would cut the two pices providing an exact butt joint gap. The tape would be positioned and the seal made. An impulse sealer would be used. The portable cutter/sealer would then be repositioned and the process repeated until all sides of the rework area had been resealed.

Splicing of the longeron tape is done in a similar manner. A piece of longeron pre-preg tape is used and a butt joint splice is made using the impulse sealer. When splicing the longeron tapes, special care is taken to maintain index mark increments and alignment.



TYPICAL PANEL JOINT



TYPICAL LONGERON JOINT

Figure I-3

2.3.9 Film Cutting Methods

Three methods of cutting the 0.1-mil Kapton (or similar) plastic film were investigated. They were as follows:

- Fluid-jet - High-pressure water cutters manufactured by McCartney Mfg. Co;
- Laser cutters - Manufactured by Hughes Aircraft Co.; and
- High-speed rotary knife - Presently used by Sheldahl.

Samples of the following plastic film were used for the evaluation:

- 1/3 mil Kapton (plain);
- 1/10 mil Kapton (chem. milled by JPL), metalized on one side with 1000Å aluminum and on the other side with 125Å chrome.
- 1/10 mil Mylar metalized on one side with 1000Å aluminum.

The 1/10 mil Mylar and 1/3 mil Kapton were used for equipment set-up and initial evaluation. Final samples were made using the 1/10 mil, metalized Kapton.

Fluid-jet high-pressure water cut samples were made by the manufacturer (McCartney Mfg. Co.) and the typical result is shown in Picture A of Figure I-4. Cutting was done at 45,000 psig using a 5-mil diameter jet. Results were quite good and although the edge appears quite ragged, the tear resistance seemed excellent. Some removal of the metalizing is apparent due to overspray adjacent to the cut. The irregularity of the present cut would also exceed the 3-mil maximum gap if two pieces were butt joined. While no corrosion of the metalized surfaces has been noted, there is concern that the water and chemical additives may have a long-term detrimental effect.

Laser cut samples were made by the manufacturer (Hughes Aircraft Co.) and the typical result is shown in Picture B of Figure I-4. Cutting was done using a 5-mil diameter beam. Results were very good and the edge irregularity seems within acceptable limits. Some discoloration of the adjacent metalizing was noted. This is caused by beam spread and modifications are available to eliminate this. Discussions with the manufacturer also indicate a cut width of 1 to 2 mils is possible.

High-speed, rotary knife cut samples were made by Sheldahl. This was done using current production cutters. The typical result is shown in Picture C of Figure I-4. Results were acceptable.

A – Fluid-jet,
McCartney Mfg. Co.
125 x

B – Laser,
Hughes Aircraft Co.
125 x

C – High-speed rotary
knife, Sheldahl
125 x

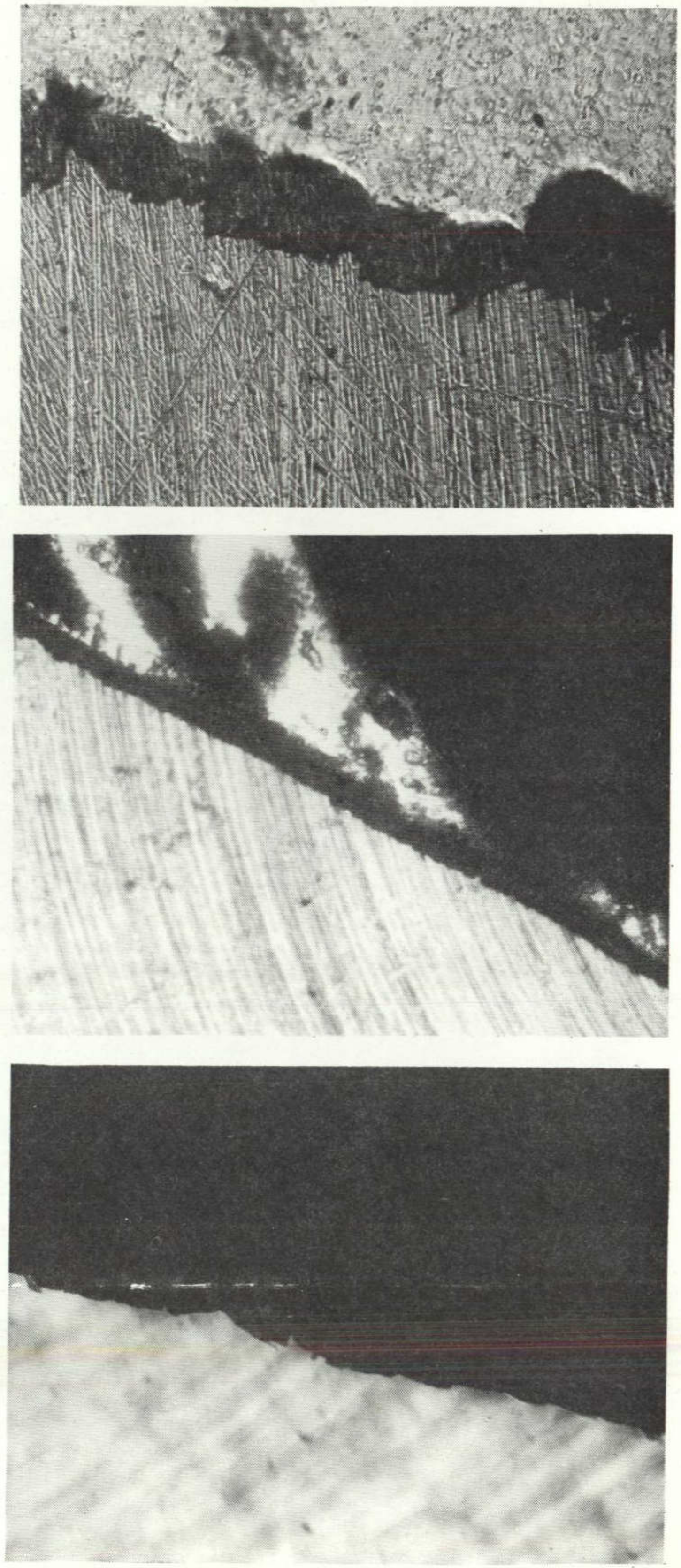
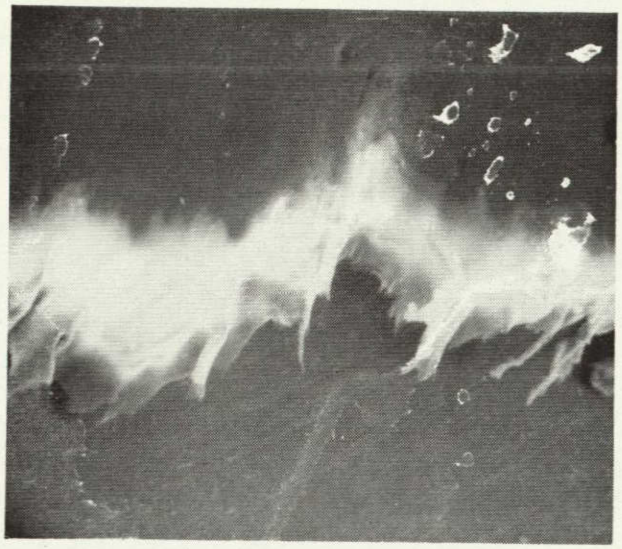
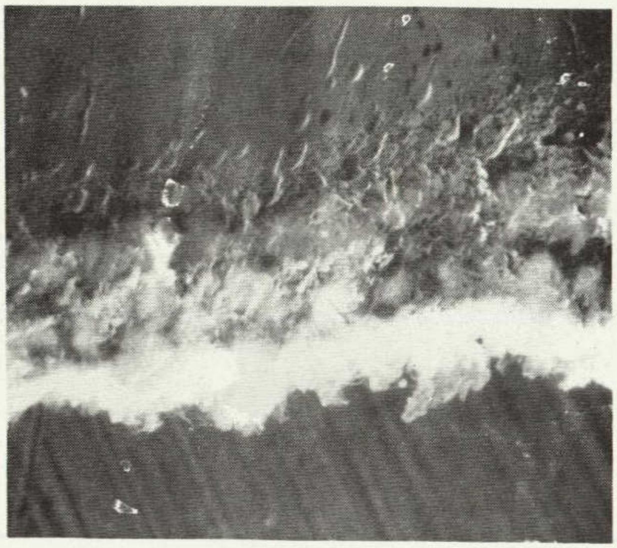


Figure I-4. Film Cutting Methods



A — Fluid-jet
McCartney Mfg. Co.
200 x



B — Laser,
Hughes Aircraft Co.
560 x

C — High-speed rotary
knife, Sheldahl
540 x

Figure I-4. Film Cutting Methods

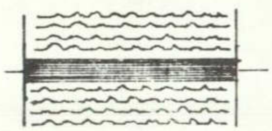
As a result of this preliminary evaluation, it is felt the laser cutter offers the most advantages and is the preferred method. Modifications are available to provide a 1- to 2-mil cut, thereby eliminating the need to reposition the material to obtain the 3-mil maximum gap. The high-speed rotary knife would be the best alternate choice.

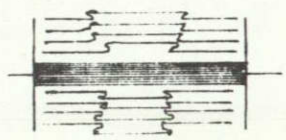
2.3.10 Flight Reel, Canister Packing

As sections are joined together, the completed portion of the blade is wound onto the flight reel, as shown in Figure I-2, and described in Para. 2.3.5. The blade is wound onto the reel under the same tension as it will encounter when being unwound and deployed in space. Surface winding rolls are provided to control tension as the blade is being wound onto the reel.

It is recommended that the blade be level wound onto the reel by one of two methods, either by gathering or folding the film or by using a reel wider than 8 meters.

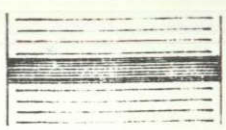
The first method of level winding would be to weave the longeron tapes back and forth, gathering or folding the film between.





By using this technique, the longeron tapes would nest, making a wider, thinner stack along both edges. While this method would provide the necessary compactness, some degradation of the thermal control coatings would probably occur.

The preferred method would be to use a reel wider than the 8-meter blade. A reel of approximately 8 1/2 meters would be suitable.



By using this method, the longeron tapes could weave back and forth and nest while the film between remained smooth and flat.

2.4 Quality Assurance and Inspection

2.4.1 Quality Assurance Plan

To assure adherence to all specifications, an extensive quality assurance plan must be developed. Figures I-5 and I-6 indicate suggested process control points and measured inspection characteristics at each. Figure I-5 represents a flow plan if the base material, Kapton, is metalized and the sail blade fabricated at the same vendor. Figure I-6 is an optional flow plan if the metalized Kapton is purchased or supplied GFE.

2.4.1.1 Material Receiving

Inspection characteristics of incoming materials, as shown in Figure I-5 are fairly standard. the common points of identification, certification and packaging will be checked. In addition, a portion of the beginning of each perforated Kapton roll will be verified for weight (thickness) and dimensions of perforations. If material is purchased already metalized, source inspection personnel may be based at the material vendor to verify material properties being shipped. With each metalized roll shipped to the blade fabricator, a thermal/material properties computer data tape (as a function of footage) will be required to facilitate selective panel cutting/sealing during fabrication.

2.4.1.2 Metalizing Process

If the vacuum deposition process is performed at Sheldahl (Figure I-5). machine/process settings will be verified by quality control. In addition, surface resistance in ohms/square and a deposition crystal monitor system will be used inside the deposition chamber to control metalizing thickness. Past experience indicates that resistance is a verification of metallic coating thickness and will be helpful in flagging possible bad footage. Solar reflectance will also be measured at this time and will be used with the surface resistance to determine selective footage for future fabrication. All data will be recorded as a function of footage to assist in removing reject material and provide a record for all material used in the flight system.

If required, it is also possible to measure emissivity of the deposited surfaces in the vacuum deposition tank. ε may be measured at one wavelength using a low power CO_2 laser scan. Since the reflectance curve for aluminum is

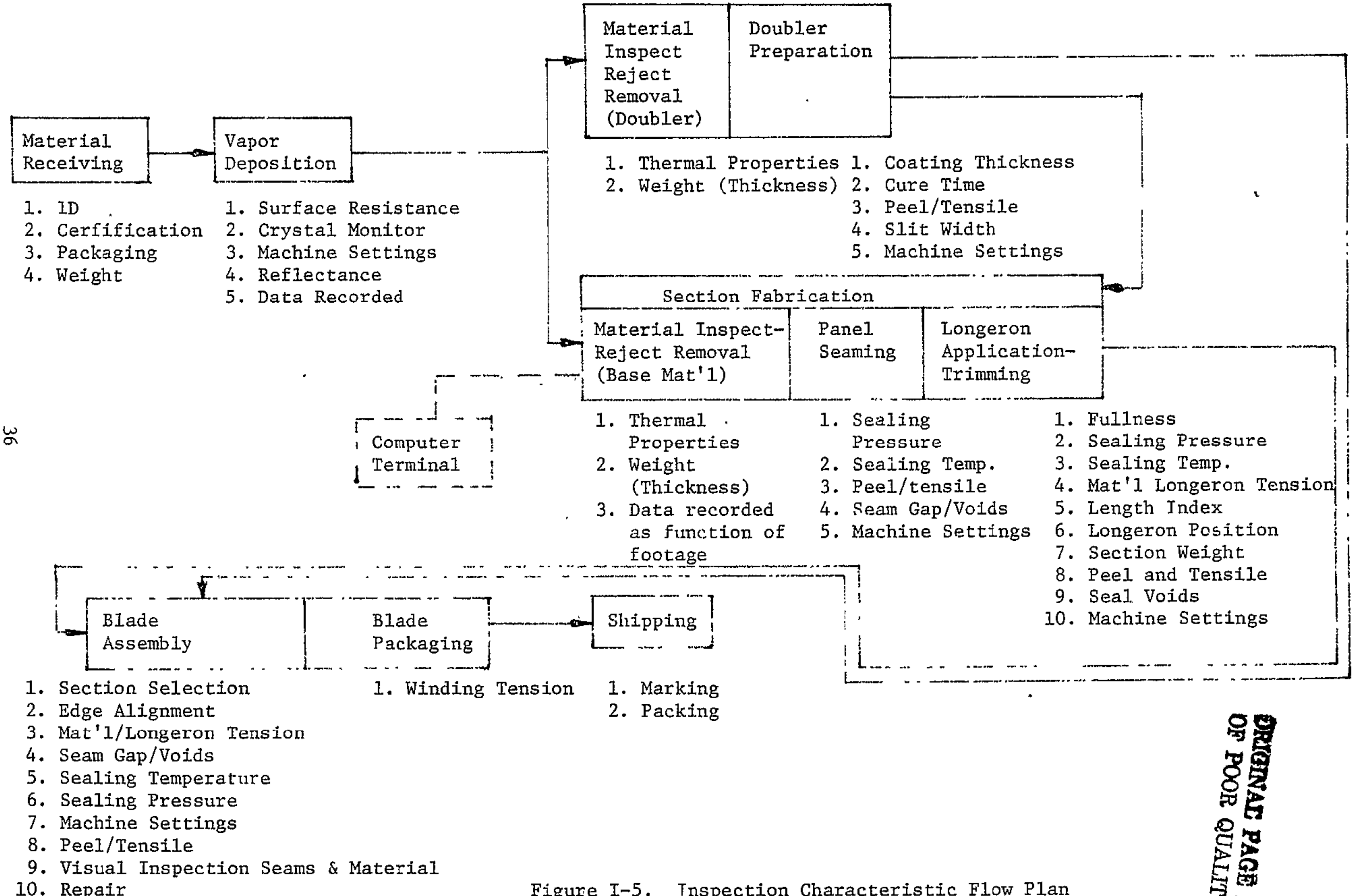


Figure I-5. Inspection Characteristic Flow Plan
Vapor deposition/Fabrication, same vendor

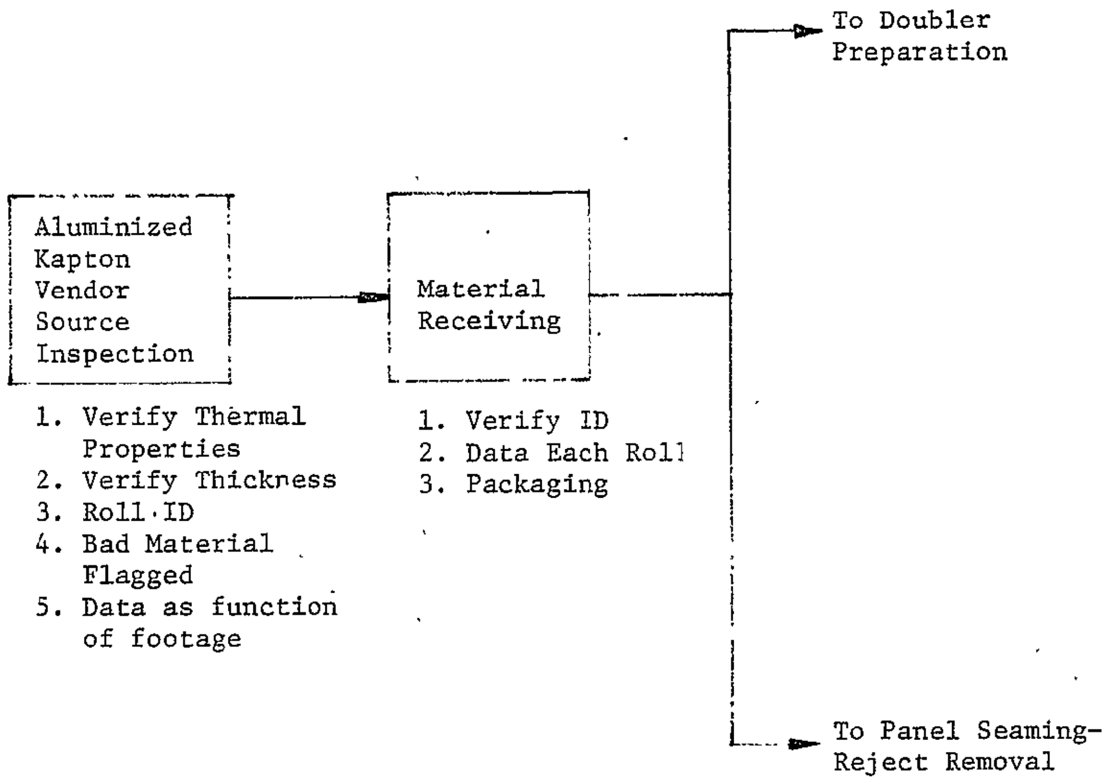


Figure I-6. Inspection Characteristic Flow Plan (Optional Purchase of Metalized Kapton) fairly flat, this system could be used as a go, no-go acceptance criteria for the thermal property. Correlation runs would initially be required to establish both emissivity and surface resistance acceptance levels.

An optical monitoring system (light transmission) to control uniformity of the coatings across the web could be added to the deposition process if required. But, it is suggested that as much instrumentation as possible be kept out of the vacuum tank itself. Only those monitors required for direct machine control of the metalizing thickness are recommended. This is to reduce the material run length and any extra rollers, resulting in less handling of the material. This will also reduce instrumentation interference from the many power sources and electrical fields expected to be encountered in and around the vicinity of the vacuum tank. In addition, less instrumentation and equipment in the tank will reduce tank size, space, complexity and vacuum pump down time. Since final inspection and removal of reject material is planned prior to section fabrication, that appears the best time to measure material properties in a "hands on" environment, eliminating the majority of coordination of computer-recorded data versus footage during vapor deposition.

2.4.1.3 Section Fabrication

Section fabrication involves sub-panel sealing, longeron application and section trimming to a catenary curve. At the beginning of the section fabrication cycle, a material inspection and reject removal will take place. Since some time is involved in sealing panels of 8 meters long (blade width) this affords an ideal time to measure thermal properties, weight (thickness) and to remove reject material. This removes the problem of measuring thermal properties on a moving web of material such as during Kapton metalization. A computer terminal would be located at this process point to record all data as a function of footage. This data will be used for selectively assigning the completed section to a specific sail blade after twelve such sections are made. A computer program will be required to average the properties of each section inspected and choose which section is to be used for each blade to equalize sail dynamic stability.

After 1- by 8-meter panels are cut and inspected, the panels are sealed into sections 120 meters long. Sealing process characteristic measurements at this point are common standard techniques in the thin film industry. Machine settings of cure and sealing temperatures, dwell time, and sealing pressure will be monitored by manufacturing and quality personnel. Peel/tensile samples of seals are usually cut from a number of the bonds for test specimens. Either an extra 2 to 3 feet of panel material can be sealed or bond samples can be made on the same sealing head at each end of the doubler being layed down. All seals will be automatically monitored for a 3-mil maximum butt joint gap and for 10 mil maximum diameter voids and unbonds. The gap can be measured using a Beta particle transmission technique which for this application would probably require a specially designed instrument (United Process Assemblies, Syosett, N.Y.). Voids would be monitored using ultrasonics. Krautkramer-Branson of Stratford, Connecticut can supply an ultrasonic instrument after verification of a sample seam first. The butt joint gap will be checked twice on each seam, once after cutting by the laser beam and once after the doubler tape is sealed on. An alternate method to check voids and gap width would be to "paint" the seal area with an artificial sun after bonding. Burn through of gaps and voids could then be detected with a light transmission sensor system. This technique has the advantage of guaranteeing that the final seal will actually perform under operational conditions.

Following panel sealing, longeron edge reinforcements are added. Addition of 1% fullness in the blade material is accomplished at this time. A predetermined table movement to accomplish this will be checked daily. Longeron tensioning devices will be monitored and longeron tape voids will be checked if required. Index marks on the longeron tapes indicating distance dispensed will be monitored with an optical scanner system on both edges of the blade sections. These marks will be required to lie within a predetermined tolerance when compared across the blade. Longeron position on the blade edge forming a cantenary curve will be computer-controlled. A check of these dimensions will be verified by scale. A laser cutting system will then trim the excess edge off, using the sealed longeron as an edge guide. The finished section is then weighed to assist in choosing which of 12 blades the 120-meter section should be used in. It should be noted that throughout section fabrication a post sealing inspection can be included to observe for unbonded seals, misaligned seals and damages to sail material during fabrication (holes and tears). Inspection and repairs can be made without interfering with the sealing process.

2.4.1.4 Blade Assembly/Packaging

Fabrication of the final blade assembly is accomplished by joining the selected prefabricated sections from the previous step and installing battens. To control straightness of the blade and edge length, two prefabricated sections (120 m maximum each) may be aligned together in a 240 m length by using a laser alignment device. A rotating laser beacon (rotating in the vertical plane) can be located at the halfway point or seal line, and the edges of the sections aligned within 1 mm in 120 m. This error could result in an edge length difference of approximately 5 mm over 7500 m which is well within the requirements of 15 cm/7500 m. This is analogous to a 3-mil gap along one edge in each seal across the 8-meter blade. It can be concluded that the majority of edge length error will occur due to material cast-off, built in tension, and material elongation differences rather than overall section alignment. The laser system above is an off-the-shelf construction tool; more sophisticated laser systems are available if higher resolution is required.

After alignment of sections, the sections are match cut with a laser beam, sealed with a doubler tape, and battens added as required. Seals and battens may be aligned exactly 90^{o} to the blade edge by using the same laser applied to edge alignment and interrupting the beam with a 90^{o} pentaprism. During sealing of the sections, each bond line is surveyed for gap width and voids or unbonds using Beta transmission and ultrasonic techniques. Material tension to control variations in length, elongation and longeron tape tension will be monitored by quality control and manufacturing personnel.

Packaging is accomplished by level winding the completed blades immediately onto the flight reels. The winding tension will be controlled and monitored to equal the expected deployment tensions.

2.4.2 Test Equipment/Problems

Table I-1 lists inspection characteristic, measurement method and a typical instrument now available on the market for performing inspection. The major area of additional study will be to finalize in more detail the equipment that will do the job of measuring all the characteristics require. For instance, speed of measurement required may become of some concern. The Gier Dunkle IR Reflectometer is portable and capable of measuring and delivering emissivity in 3 seconds. The Lions Solar Reflectometer will give immediate measurement, but only at one wavelength. It is dialable over 11 or 12 wavelengths. Lions' personnel indicate that for a few thousand dollars, a machine could be modified to quickly scan all wavelengths and print a computer averaged reflectance over the waves required. As shown in Table 1-1, weight could be monitored as a measured function of thickness by using either a Beta backscatter or a linear non-contact comparison technique.

Another major area of further equipment study and the area most likely to be a problem is the continuous monitoring of bonding efficiency of the doubler tape. It is questionable whether instrumentation and a technique can be attained for measuring the small gap width and voids in the seals. The method and instrumentation will definitely have to be proven on sample seals by the instrument manufacturer first. As stated previously, measurement of the gap width may be accomplished with Beta-particle transmission using an instrument designed and tested specifically for this purpose.

Some trouble may be encountered in the correlation of measured data with footage on each roll of final sail. An extensive computer program must be written with the ability to remove that footage not used and to renumber all the footage remaining throughout all processes and inspections.

Although the above problems are foreseen in the equipment area of inspection and quality control, none appear insurmountable with the technology available today.

Table I-1. Fabrication and Test Equipment

FABRICATION OPERATION	INSPECTION CHARACTERISTIC	MEASUREMENT METHOD	TYPICAL EQUIPMENT	COMMENTS
Material Receiving	Weight	Gram Balance	Mettler Balance	
Vapor Deposition	1. Deposition 2. Thickness 3. Reflectance	1. Digital Ohhmmeter 2. Deposition Crystal Monitor 3. Solar Reflectometer	1. Simpson Digital Ohmmeter 2. Inficon XTM System 3. Lions R25C	1. In-vacuum Surface Resistance (Ω/□) All Data Computer Recorded
Doubler & Ripstop Preparation	1. Coating Thick-ness 2. Cure Temperature 3. Peel/Tensile 4. Tape Width	1. Analytical Balance 2. Thermocouple 3. Force-Deflection Tester 4. Rule	1. Mettler Balance 2. Standard Machine Control 3. Instron Model 1130	
Material Inspection-Reject Removal	1. Emittance 2. Weight(thick-ness)	1. IR Reflectometer 2. Beta Backscatter or Linear Comparison Gauge	1. Gier Dunkle DB-100 2. Compuderm and Beta Scope, or Microsense 3046 (ADE Corp.)	All Data Cumpter Recorded
Panel Sealing	1. Sealing Pressure 2. Sealing Temp. 3. Peel/Tensile 4. Seam Gap Width 5. Seam Voids	1. Air Pressure Gauge 2. Thermocouple 3. Force-Deflection Tests 4. Beta Transmission 5. Ultrasonics	1. Standard Machine Control 2. Standard Machine Control 3. Instron Model 1130 4. Special Design (UPA Inc.) 5. Krautkramer-Branson Ultrasonic Flaw Detector	Alternate for 4 & 5 is artificial burn-through followed by light transmission detection

(Table continued on next page.)

Table I-1. Fabrication and Test Equipment (Continued)

FABRICATION OPERATION	INSPECTION CHARACTERISTIC	MEASUREMENT METHOD	TYPICAL EQUIPMENT	COMMENTS
Longeron Application -Trimming	1. Fullness 2. Sealing Pressure 3. Sealing Temp. 4. Mat'l-Longeron Tension 5. Length Index 6. Tape Voids 7. Peel/Tensile 8. Longeron Position 9. Section Weight	1. Rule 2. Air Pressure Gauge 3. Thermocouple 4. Load Cell 5. Optical Scanner of Index Marks 6. Ultrasonics 7. Force Deflection Tester 8. Computer Controlled 9. Beam Scale	2-4. Standard Machine Control 5. Reticon LC-64P Camera Measuring System 6. Krautkramer-Bronson Ultrasonic Flaw Detector 7. Instron Model 1130 8. Fairbanks Morse	
Blade Assembly	1. Edge Alignment 2. Mat'l Longeron Tension 3. Seam Gap Width 4. Seam Voids 5. Sealing Pressure 6. Sealing Temp. 7. Peel/Tensile	1. Laser Alignment 2. Load Cell 3. Beta Transmission 4. Ultrasonics 5. Air Pressure Gauge 6. Thermocouple 7. Force-Deflection Tests	1. Spectra-Physics Laser level Model 944SL 2. Standard Machine Control 3. Special Design (UPA Inc.) 4. Krautkramer-Branson Ultrasonic Flow Detector 5. Standard Machine Control 6. Standard Machine Control 7. Instron Model 1130	Alternate for 3&4 is artifical sun burn-through followed by light transmission detection
Blade Packaging	Winding Tension	1. Surface Winding Rollers	1. Standard Machine Control	

3.0 ECONOMIC, SCHEDULE AND FACILITY CONSIDERATIONS

3.1 Existing Facilities and Equipment

Factory space and capacity required for either or both of film metalizing and sail fabrication are not available at Sheldahl at this time and is not foreseen to be in the time periods required for performance as contemplated by preliminary program plans and schedules discussed in Paragraph 3.3.

Similarly, machinery, equipment, tooling and fixturing are necessarily highly specialized and unique to the purpose. Neither at Sheldahl nor, to our knowledge, any place else in the world does equipment of the type required exist.

3.2 New Facilities and Equipment

3.2.1 Factory Facilities

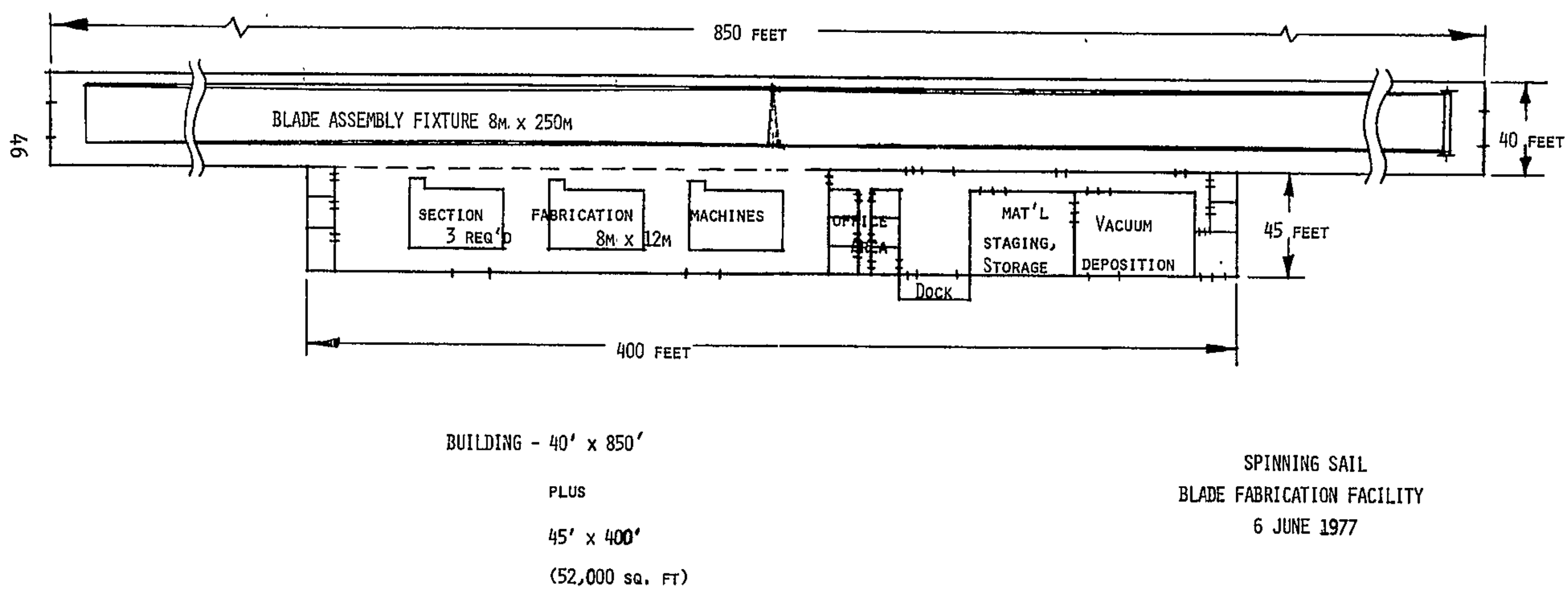
Preliminary analyses of factory space and related requirements for both film metalizing and sail blade fabrication have been performed.

Figure I-7 illustrates overall building dimensions and a tentative physical layout to house office, receiving, material staging, metalizing, sail section fabrication and blade assembly areas.

For the fabrication program comprising prototype materials plus five DTM and twelve flight blades, three fabrication machines are contemplated. Should requirements exceed these, the building dimensions would accommodate a fourth sail section fabrication machine. Capacity of the final blade assembly fixture and other facilities and equipment remain adequate.

3.2.2 Manufacturing Equipment

Special machinery, equipment, tooling and fixturing requirements are discussed and illustrated in the narrative and figures contained in Paragraph 2.3 and subparagraphs.



850 FEET
BLADE ASSEMBLY FIXTURE 8M x 250M
46
40 FEET
SECTION 3 REQ'D
FABRICATION 8M x 12M
MACHINES
OFFICE AREA
MAT'L STAGING, STORAGE
VACUUM DEPOSITION
45 FEET
DOCK
400 FEET
BUILDING - 40' x 850'
PLUS
45' x 400'
(52,000 SQ. FT)
SPINNING SAIL
BLADE FABRICATION FACILITY
6 JUNE 1977

Figure I-7

Primary special machinery and tooling equipment requirements are:

- Vacuum Metalizing chamber(s) and related equipment;
- Blade section fabrication machines - three each;
- Final blade assembly fixture - one each; and
- Portable sealer - repair, splicing, etc. - one each.

Special test equipment requirements are tabularized and discussed in Paragraph 2.4.

3.3 Program Plan and Schedule

Figure I-8 is a master program plan and overview of the time phasing of key events and activities for the spinning sail blade program.

This planning and phasing is generally compatible with key constraints and milestones furnished by JPL as to end dates and front-end definition of requirements, contract(s) let, completion of sail blade designs and release of material specs. The overall elapsed time, production rates and blade section fabrication machine needs are essentially tailored to fit JPL project start and sail delivery dates as presently understood. The general intent and scope of effort contemplated in each of the phases is as follows:

ϕ 0 - Extension of spinning sail blade design and/or manufacturing studies through September 30 (Government FY 77). Areas requiring further attention are suggested in Paragraph 4.0.

ϕ I - Preliminary designs and specifications - vacuum metalizing, and blade manufacturing equipment, facilities and methods.

ϕ II - Final, detail machinery and equipment designs; fabrication of machinery, equipment, tooling and fixtures; detail metalizing and fabrication process and QC specs; perforate, metalize, fabricate and delivery prototype, DTM and flight sail blades.

3.4 ROM Cost Estimates

Table I-2 presents a preliminary ROM estimate of costs for the spinning sail blade program of the general scope indicated and based on the go-ahead date and general phasing of events and activities embodied in Figure I-8.

FOLDOUT FRAME

SOLAR SAIL (SPINNING SAIL CONF

PROGRAM PLAN

FY 77 | F

1978

J F M A M J J A S O N D J F M A M

PHASE	
MATERIALS	
Prelim Mat'ls Properties Spec	JPL
Mat'ls Process Spec (Draft, Prelim, Final)	JPL
RFP (Film) Out	JPL
Film Contract Executed	
Design, Fab, Shakedown - Film Facility & Equip	Film Mfr.
RFP (Metalizing) Out	JPL
Metalizing Contract Executed	
Des, Fab, Shakedown Metalizing Facility & Equip	S.I.
Coating Process, QC Specs, Procedures	S.I.
Manufacture Film	Film Mfr.
Perforate and Metalize	S.I.
FABRICATIONS	
Prelim Des, Fab, Facil Equip Studies	JPL, S.I.
RFP Contract - Blade Fab	JPL, S.I.
Blade Design (Prelim, Final)	JPL
Fab Equip, Des, Fab, Shakedown	S.I.
Fab Facility Des, Build, Equip Install	S.I.
Detail Blade Des, Dwgs, Process - QC Specs	S.I.
Fab Blades and Deliver	S.I.
First Article Inspection	JPL, S.I.
ETR Ops Prop Module Mate - Launch	
FACILITIES EQUIPMENT SUMMARY	
Design Metalizing Equipment (Prelim)	S.I.
Fab, Install, Shakedown Metalizing Equip	S.I.
Fabrication Equipment:	S.I.
Design, Build, install Blade Section Fab Machines	
Design, Build Install Final Blade Assy Fixture	
Design, Build Portable Sealer	
Design, Construct/Upgrade Facility	
Install, Shakedown Equipment	

Phase markers: Φ 0, Φ I. Milestones: D, D, RFP, CO, P.

Figure I

Table I-2

ROM COSTING - SOLAR (SPINNING) SAIL BLADE

(Phase I-II Combined)

HALEY'S MISSION

(1977 Dollars - 000's)

I.	MATERIALS		
	A.	MACHINERY AND EQUIPMENT - VACUUM DEPOSITIONS	
		1. Conceptual Designs	$ 90
		2. Detail Design, Fabrication, Install C/O	$1,600
			$1,690
	B.	METALLIZING	
		1. Non-recurring	$ 15
		2. Coatings (GFE Film)	1,475
			$1,490
	*C.	DEDICATED FACILITY	$ 60
		Subtotal, Materials	$3,240
II.	FABRICATIONS		
	A.	PROGRAM MANAGEMENT	$ 480
	B.	MACHINERY AND EQUIPMENT	
		1. Blade Section Fab Machine 3 ea @ $150	450
		2. Final Blade Assy Fixture	250
		3. Special Sealer - Repair, etc.	35
			$ 735
	C.	FABRICATIONS	
		1. Non-recurring	$ 25
		2. Fabrications	3,700
			$3,725
	*D.	DEDICATED FACILITY	720
		Subtotal, Fabrications	$5,660
		TOTAL PROGRAM	$8,900

*Approximate allocations by space utilization. A single dedicated facility is planned. The materials and fabrications facility prices do not stand alone.

Further general assumptions as to the scope of effort contemplated are that:

1) NASA will retain blade design responsibility and ultimately will contract on the basis of supplier fabrication to JPL drawings and specifications. Only a modest non-recurring effort for preparation of internal detail drawings, process specifications, quality and inspection specifications and procedures, etc., is provided for.

2) NASA will furnish GFE the following blade elements:

- Base film in quantities sufficient for metalizing and blade fabrication with due allowance for reasonable yield factors.
- Battens of a design yet to be determined but which may be installed by techniques compatible with fabrication methods and and equipment described in Paragraph 2.3.
- Flight reels onto which the fabricated blades will be wound.

3) Costs shown encompass Phases I and II activity only, excluding any extension of pre-project studies or experimental work. Spare considerations are excluded.

The allocation of facility costs between materials and fabrications is arbitrary. A single facility is planned for both operations and allocated costs do not stand alone.

Although not fully explored, among alternatives that may be considered for providing factory space is an existing Government-owned facility. In addition, lease of facilities of the type needed, if available when required under suitable terms and satisfactorily located, could be investigated. A further option, preferred by Sheldahl, would be the construction of a facility to our specifications, in reasonable proximity to Northfield. This option contemplates financing by the contractor or other agency and lease to Sheldahl for the period and under other terms compatible with needs.

Financial trade-off of costs to the government of construction of a new facility versus lease of existing or new facilities over an extended period have not been performed.

4.0 AREAS REQUIRING FURTHER ATTENTION

This section contains a suggested list of areas requiring further attention by either Sheldahl or JPL and one or another of its supporting agency contractor team members. All are believed to be required with varying degrees of urgency, prior to project start in the period from the present to approximately December 31, by which time it is understood JPL draft specifications and RFQs for materials metalizing and sail blade fabrications will be issued.

Some of these items are applicable also to the square sail sheet design and are accordingly included in Section II, Paragraph 5.0 of this report.

Further particulars, plus cost and schedule information for an extension of these sail blade design and fabrication study areas can be furnished promptly on request.

4.1 Metalizing Chambers and Equipment

Requirements, characteristics, conceptual designs and refinement of schedules and cost estimates (please refer to paragraph 2.2 of this report).

4.2 Sail Blade Fabrication Equipment

Requirements, characteristics, preliminary designs and refinement of schedules and cost estimates.

4.3 Thermal Control Coating Degradation - Test and Evaluation

The degradation effects of manufacturing, packaging and deployment should, in particular, be addressed.

4.4 Facilities

Further definition of special requirements, availabilities, alternate methods of financing, etc. will need to be assessed in greater detail.

4.5 Seam Quality/Integrity, Monitoring Methods Equipment

Explore techniques with special reference to the butt joint gap and adhesive voids and unbonds.

4.6 Continued Materials Test and Evaluation, Including:

- Adhesive Systems, including methods and control of adhesive application;
- Seaming equipment,methods, conditions;
- Sample fabrication; and
- Test and evaluation - among tests required are long-term heat/vacuum/ UV radiation environment tests, as well as long-term dead load (creep) test in high-temperature conditions for the purpose of supplementing, complementing or corroborating JPL, Langley, etc., work and findings.

4.7 Precision Measurement and Control Equipment

With particular reference to laser techniques for achieving blade straightness and longeron length requirements and tolerances.

4.8 Butt Joint Cutting and Seaming Techniques

Including modification of existing laser devices plus special fixturing required to fabricate samples, test and verify methods and capability to hold within the maximum 3.0-mil tolerance.

4.9 Weights Analysis

Verify preliminary analysis of weight savings (Para. 1.5) resulting from Sheldahl proposed alterations to the baseline design and manufacturing methods, with particular reference to:

- Panel seam design;
- Longeron design (tapering, etc.) n analysis of the effect on blade stiffness, mass distribution and dynamic behavior would also be required;
- Alternate seam thicknesses (see Paragrpah 4.10).

4.10 Optimum Tape Thickness

Experiment with optimum tape thickness from a handling, producibility, weight savings, rip-stop and tear propagation point of view. Fabricate multiple panel (partial blade sections) samples with .1, and .3-mil tape thickness, test and evaluate.

4.11 Spanwise Fullness

Experiment with alternate methods of adding 1% fullness and verify preference for proposed method. Alternates under consideration are:

- Gather 1% and seal over (proposed method per Para. 2.3.3; and
- Stretch longeron 1% and seal (per alternate method, Para. 2.3.4.2)

4.12 Blade Deployment Test

Consider and define a meaningful blade deployment test using .1-mil coated Mylar. The primary purpose being to assess the effect of level winding and batten "unfolding" during deployment.

4.13 Advantages and Requirements for Blade Spares

Consider advantages and requirements for blade spares taking into account radomizing processes and blade interchangeability needs.

SECTION II

SQUARE SAIL SHEET DESIGN AND FABRICATION ASSESSMENT

Introduction and Summary

Sheldahl's efforts and activities under the original statement of work of NASA Jet Propulsion Laboratory Contract No. 954721 have been concerned primarily with five areas of interest:

1. Sail Sheet Design

Sail sheet design elements as affected by analyses of loads and stress factors entailed in the JPL baseline designs and Benchmark Sail Material System were considered.

Primary concerns examined were the sail corner and center sections and the attachment and reinforcement requirements resulting from sail deployment and attitude control methods contemplated. Several alternatives were identified, and weight, strength, producibility trade-off information presented.

Support was also provided to the JPL Structures and Dynamics Group in the area of gore tailoring and sail shaping as a function of apex height and desired/required sail quadrant billowing and edge scalloping. This work was cut short by redirection of the study to the helio gyro configuration. Further study would be required in this area as would be the case with means of eliminating the "wrinkling" effect inherent in the current JPL baseline design.

Past and related experience contributed to analyses and recommendations on stowage/packing methods and factors and canister design.

2. Sail Handling and Fabrications

Planning assumed that the base film (.1 mil Kapton or equivalent) would be procured by NASA and furnished GFE.

Approaches to and requirements for unique and highly specialized metalizing methods, processes and equipment were studied and preliminarily identified.

Alternate methods of fabrication with attendant machinery, equipment, space,schedule and cost implications, and trade-offs were studied. Preferred approaches were tentatively identified.

Quality Control plans, inspection procedures, and flow charts associated with preferred manufacturing methods were analyzed and are discussed.

3. Economic, Schedule, Facility Considerations

Special facilities requirements and ROM program plans, schedules and costs were evaluated and are included in this report.

4. Areas Requiring Further Study

A topical "shopping" list of areas tentatively identified as requiring further attention, in terms of enlarged definition of requirements, designs equipment, facilities and economic factors, is included. Due to the shift in focus from the square to spinning sail configuration, no attempt was made to detail the nature and scope of proposed study extensions. Several items, equally applicable to the spinning sail configuration, are discussed in Section I of this report.

5. Verification of Concepts and Fabrication Technique

The project to demonstrate recommended fabrication techniques using .1-mil coated Mylar to simulate a reel-to-reel manufacturing process and to prepare a documentary film was initiated on May 12 and terminated on May 18 upon receipt of advance notice of program redirection. Costs expended on the project were nominal.

MATERIALS STUDIES

While NASA JPL has prime responsibility for the design and specification of materials, bonding and seaming methods, and is obtaining support from other NASA agencies and from other organizations under subcontract, Sheldahl has funded initial investigations of candidate adhesive systems, sealing equipment, methods and conditions; fabricated sample specimens and conducted tests.

Two primary purposes were envisioned:

(1) To obtain preliminary working knowledge of materials and seaming equipment and methods as it pertains to the design and fabrications study; and

(2) To provide information and test data to JPL as a measure of support and to add to the total body of knowledge concerning candidate sail materials, seaming and bonding methods, etc., all ultimately for consideration in JPL material system design, development and specification purposes.

Results of the preliminary Sheldahl Materials Study to date are included as an appendix to this report.

Square Sail Sheet

1.0 SAIL SHEET DESIGN

1.1 JPL Baseline Design

Sheldahl's design and fabrications study was based on and conducted within the framework of the JPL baseline design information as described below:

(a) JPL Benchmark Sail Material System dated 4/8/77, modified to the extent necessary to accommodate a sail sheet size increase from 800 m^2 to 850 m^2 and a change in apex height to 8.8 meters. While the Benchmark System specifies that both surfaces shall be coated with adhesive, subsequent study and discussion by and with JPL indicates a bonded joint with only the tape coated would be adequate.

(b) JPL Drawing No. 10082706, Solar Sail Module configuration - Back Side Structure - third approximation dated 4/7/77.

(c) JPL mast, boom, stay, deployment and attitude control configuration and mechanizations as illustrated in J. Stevens conceptual designs (viewgraphs) dated 3/7/77.

1.2 Reinforcement and Attitude Control

The sail sheet is attached to the structure only at the four corners where outhaul lines are attached to the boom ends and at the center cutout which is attached to the center mast. These attachment areas must be designed to withstand the concentrated loadings introduced during deployment and all flight configurations, including the translated case used for attitude control. The design goal is to distribute the concentrated loads into the sail sheet without causing high stress locally and to avoid large weight increases from reinforcement. Several designs for reinforcing the corners and center have been studied, and the results of these evaluations are reported in this section.

1.2.1 Corner Design

The design concept for the corner outhaul line includes a load sensing and regulating mechanism to maintain a constant corner force even when the sail is translated for attitude control. For design, it is assumed that this constant force magnitude is 33 Newtons directed outward along the diagonal. Analyses of this region have been done considering only this corner loading and not the solar pressure loading on the surface. Thus, the stress results are valid only in the immediate corner region.

The first method presented a "brute force" reinforcement scheme in which the sail sheet material is made increasingly thicker toward the corner to keep the unit film stress below a limit value, which is 20 psi (138 kPa) in this example. As shown in Figure II-1, the corner must be over 40 times thicker than the base sheet material to accomplish this and the reinforced region extends out more than 60 meters from the corner. The estimated weight increase is about 70 kg for four corners, assuming 3.6 g/m^2 for the base sheet.

An alternate approach is to use stiff edge tendons to carry the corner force and to distribute the load more gradually into the sheet. A modified corner scallop on the sheet may be desirable to reduce the angle that the tendons make with the force line of action. The concept is illustrated schematically in Figure II-2.

The benefits of a deeper scallop are shown in Figure II-3 where stresses are compared for a square corner, the nominal scallop in the current design and for a modified corner scallop with a 20 m corner extension. A modified scallop with a 10 m extension is nearly as effective in reducing the sheet stress as shown in Figure II-4.

Stress contours for a typical model are illustrated in Figure II-5. It is noted that stresses in the corner do exceed the design goal 0.35 N/m (20 psi). Therefore, it may still be necessary to use double thickness film in this region.

It may not be possible to extend the corner scallop because of design restrictions on the boom connection. Thus, the nominal design scallop was studied with increasing stiffness of the edge tendon. Results presented in Figure II-6 show that the corner film stress can be reduced to a safe level

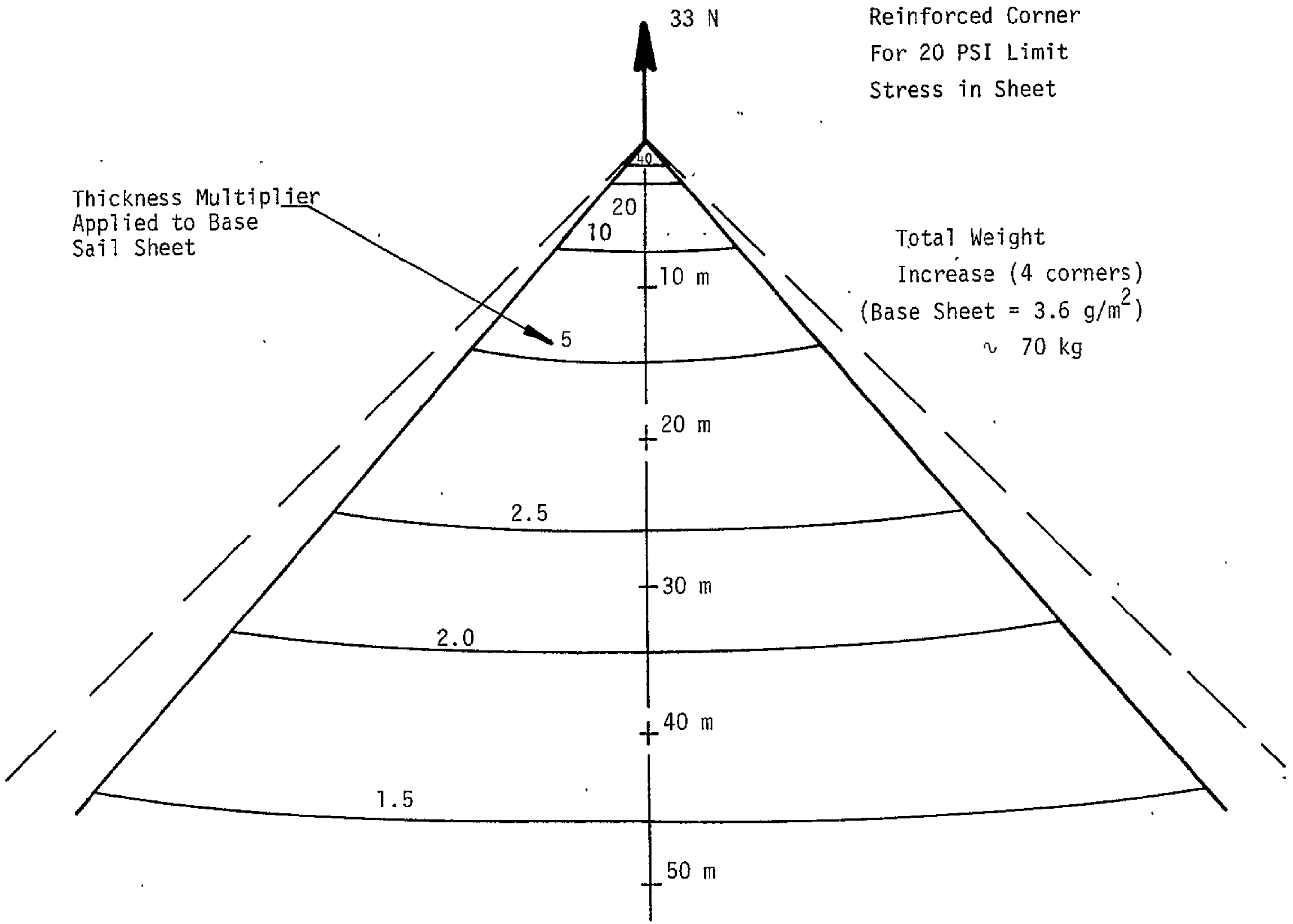

33 N
Reinforced Corner
For 20 PSI Limit
Stress in Sheet
Thickness Multiplier
Applied to Base
Sail Sheet
40
20
10
5
2.5
2.0
1.5
10 m
20 m
30 m
40 m
50 m
Total Weight
Increase (4 corners)
(Base Sheet = 3.6 g/m2)
∿ 70 kg

Figure II-1

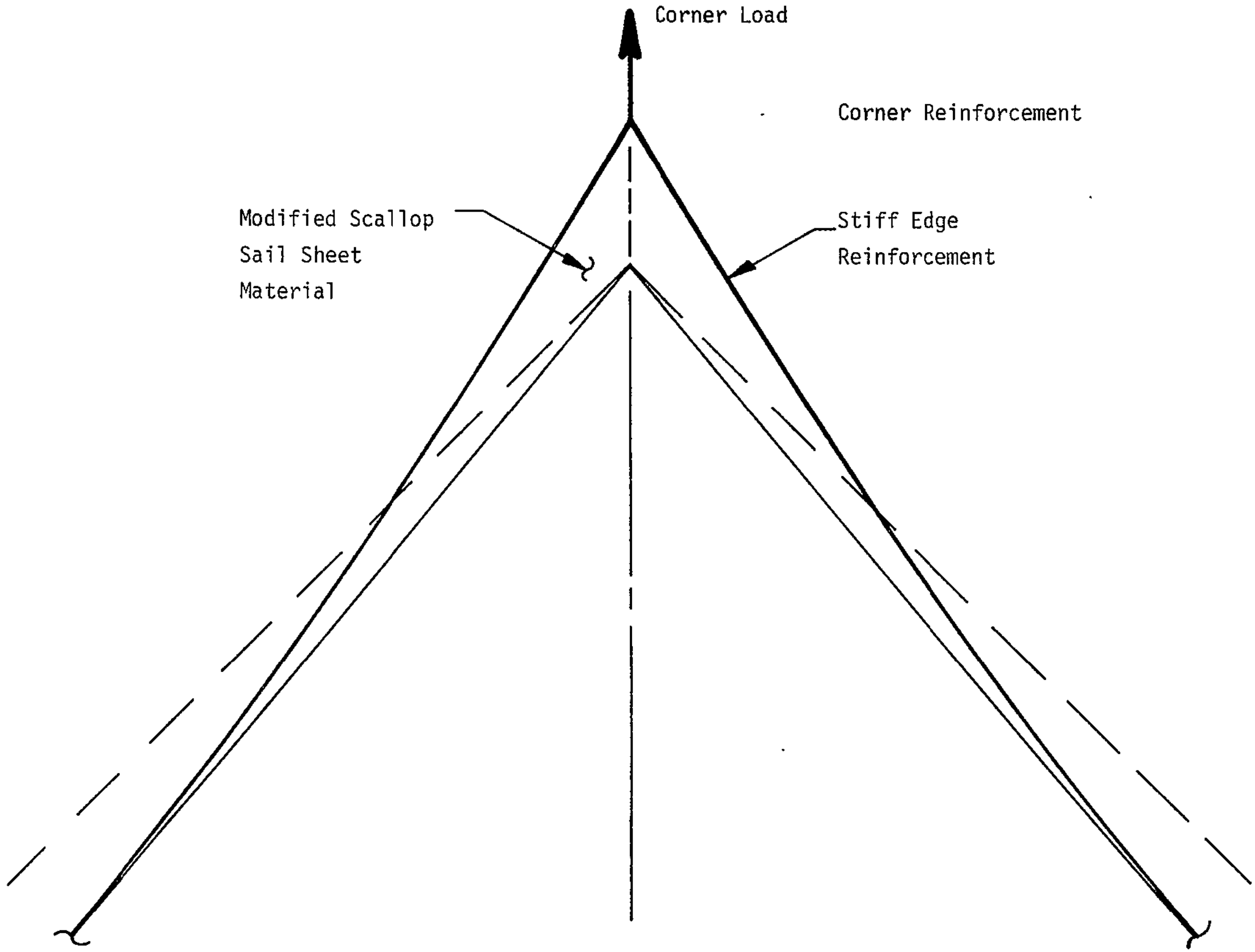

Corner Load
Corner Reinforcement
Modified Scallop
Sail Sheet
Material
Stiff Edge
Reinforcement

Figure II-2

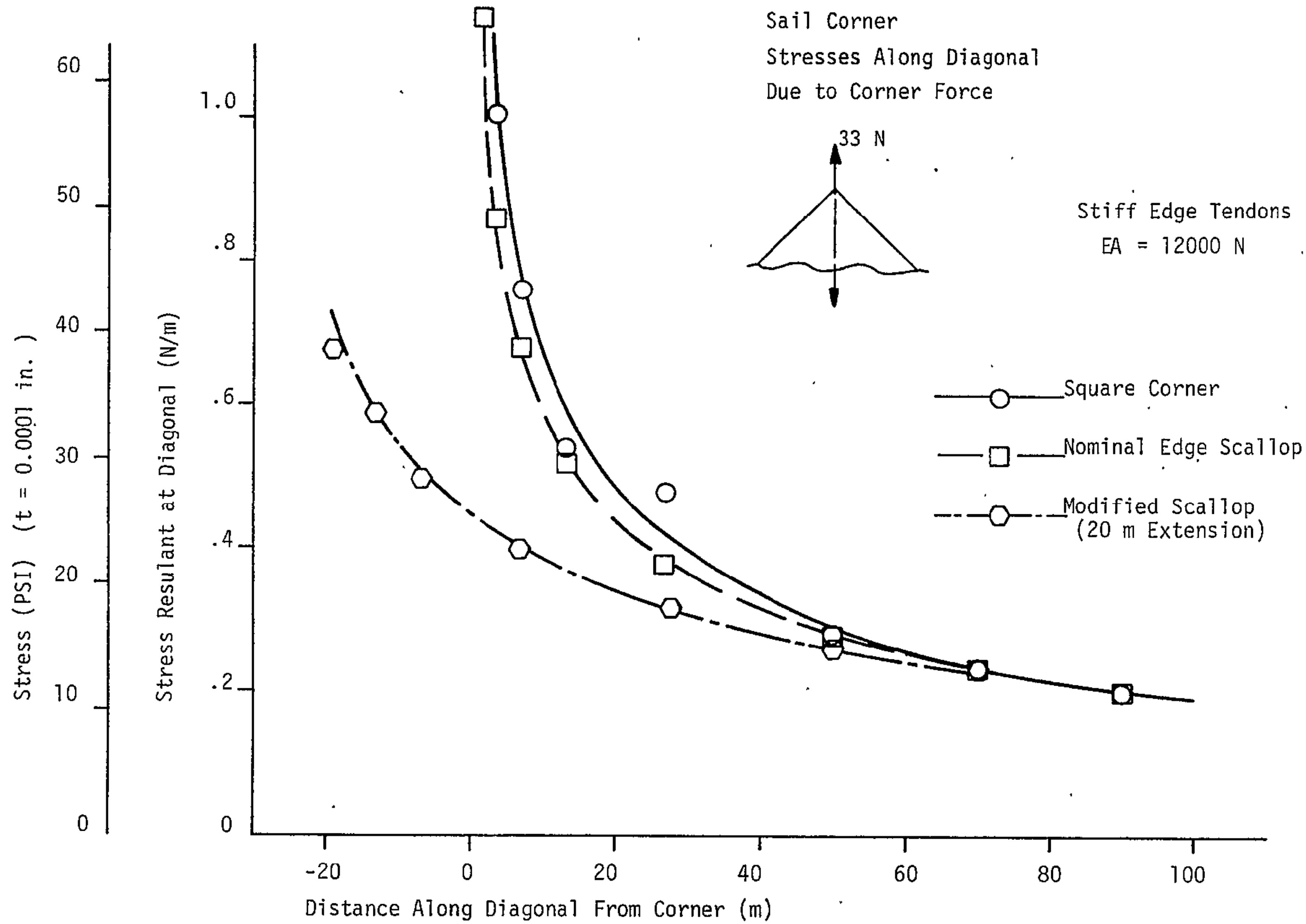

Sail Corner
Stresses Along Diagonal
Due to Corner Force
33 N
Stiff Edge Tendons
EA = 12000 N
Square Corner
Nominal Edge Scallop
Modified Scallop
(20 m Extension)
Stress (PSI) (t = 0.0001 in.)
Stress Resulant at Diagonal (N/m)
Distance Along Diagonal From Corner (m)
60
50
40
30
20
10
0
1.0
.8
.6
.4
.2
0
-20
0
20
40
60
80
100

Figure II-3

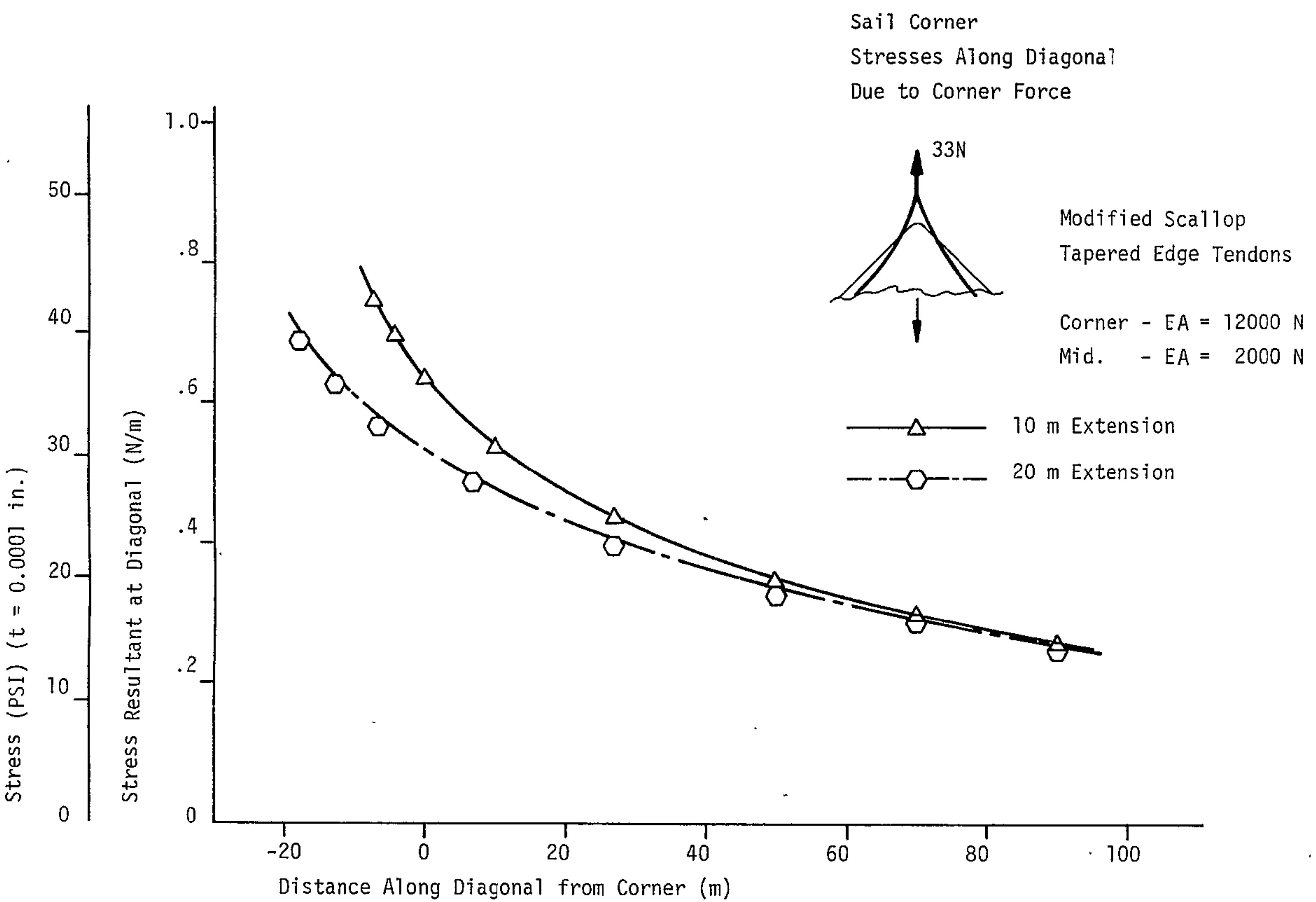

Sail Corner
Stresses Along Diagonal
Due to Corner Force
33N
Modified Scallop
Tapered Edge Tendons
Corner - EA = 12000 N
Mid. - EA = 2000 N
10 m Extension
20 m Extension
Stress (PSI) (t = 0.0001 in.)
Stress Resultant at Diagonal (N/m)
0
10
20
30
40
50
0
.2
.4
.6
.8
1.0
-20
0
20
40
60
80
100
Distance Along Diagonal from Corner (m)

Figure II-4

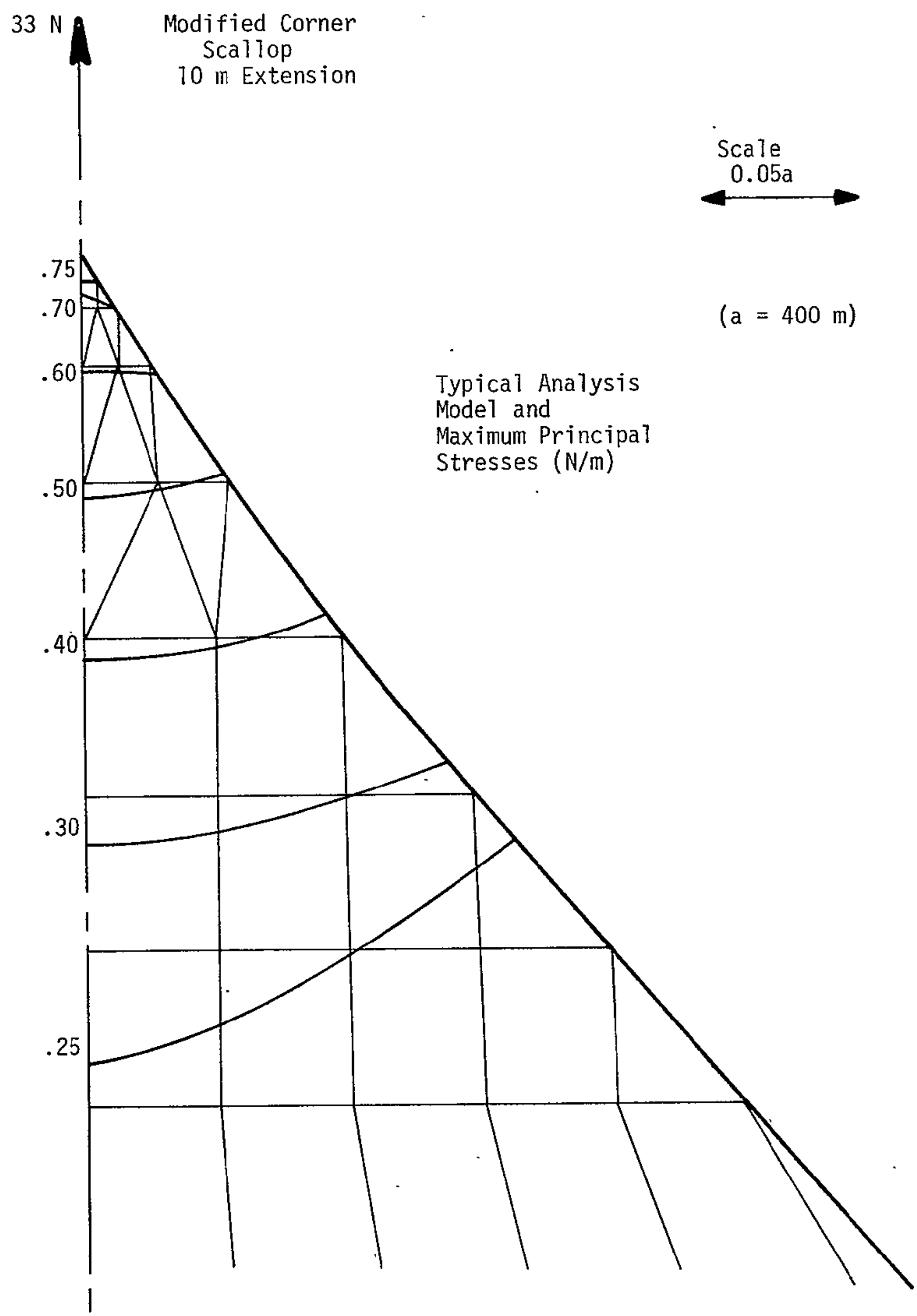

33 N
Modified Corner
Scallop
10 m Extension
Scale
0.05a
(a = 400 m)
Typical Analysis
Model and
Maximum Principal
Stresses (N/m)
.75
.70
.60
.50
.40
.30
.25

Figure II-5

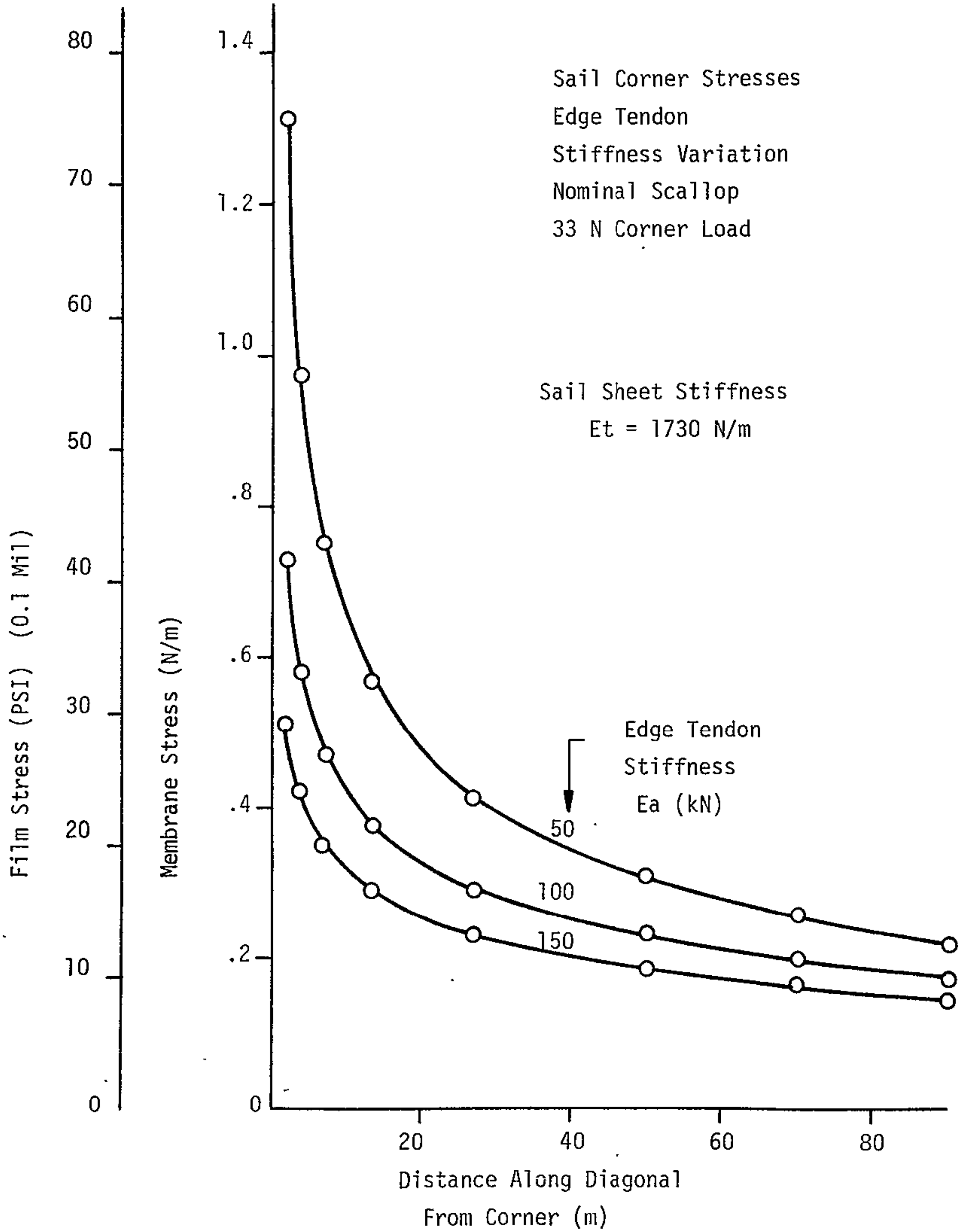

Sail Corner Stresses
Edge Tendon
Stiffness Variation
Nominal Scallop
33 N Corner Load
Sail Sheet Stiffness
Et = 1730 N/m
Edge Tendon
Stiffness
Ea (kN)
50
100
150
Film Stress (PSI) (0.1 Mil)
Membrane Stress (N/m)
80
70
60
50
40
30
20
10
0
1.4
1.2
1.0
.8
.6
.4
.2
0
20
40
60
80
Distance Along Diagonal
From Corner (m)

Figure II-6

by making the edge tendon very stiff compared to the base sheet stiffness.

The concept of a stiff edge tendon to reduce corner film stresses appears to be promising if a suitable material could be selected. The tendon material must have high modulus and strength and low density and yet be compatible with the film at elevated temperatures. Properties of a titanium ribbon are used herein for example weight comparisons.

Estimated Weight Increases (kg)
(Four Corners)

	Mod. Scallop, 10 m Ext.	Nominal Scallop
Edge Tendons	8	16
Attach. Tape	3	3
Added Sail Sheet	4	-
Corner Sheet Doubler	12	12
Total	27	31

Thus, the edge tendon approach would probably add less than half the weight of the increased film thickness approach. Also, there is some evidence that a stiff edge tendon is desirable for overall sail shape characteristics (Sect. 1.3). The differential thermal expansion problem perhaps could be reduced by using other materials or by a tendon attachment method which allows some differential expansion.

1.2.2 Center Design

The sail design has a 40-m diameter center cutout to allow sail translation and clearance for the mast, attachment cables and winches. This configuration is schematically illustrated in Figure II-7. The sail sheet must be attached to the four radial cables in such a way that the stress field is fairly uniform surrounding the cutout, in both the symmetrical and translated configuration.

One design approach, presented in Figure II-8, is to scallop the cutout perimeter and use a series of attachment lines from the scallops to the cables. The edges of the scallops would have to be reinforced to avoid overstressing

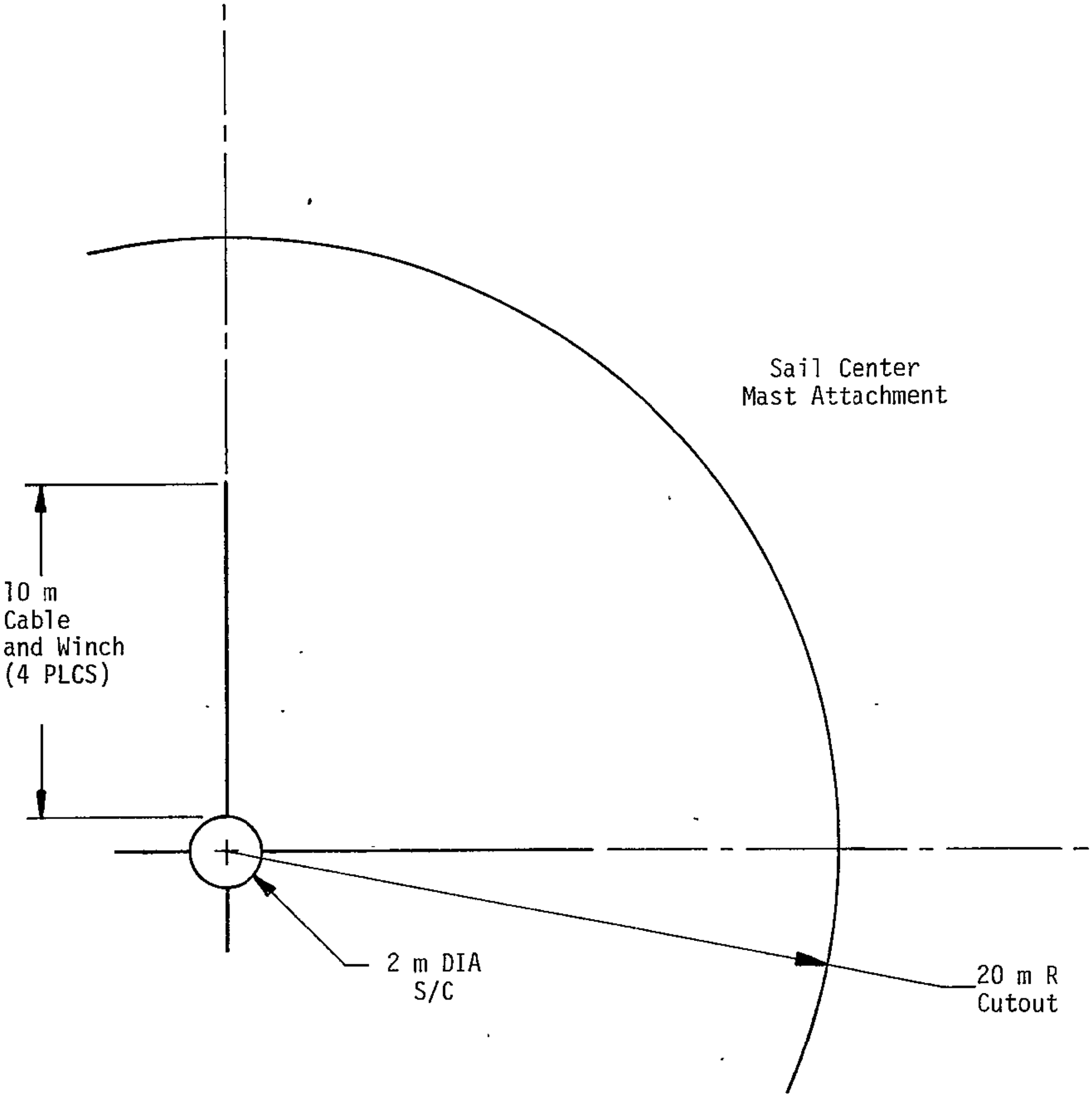

Sail Center
Mast Attachment
10 m
Cable
and Winch
(4 PLCS)
2 m DIA
S/C
20 m R
Cutout

Figure II-7

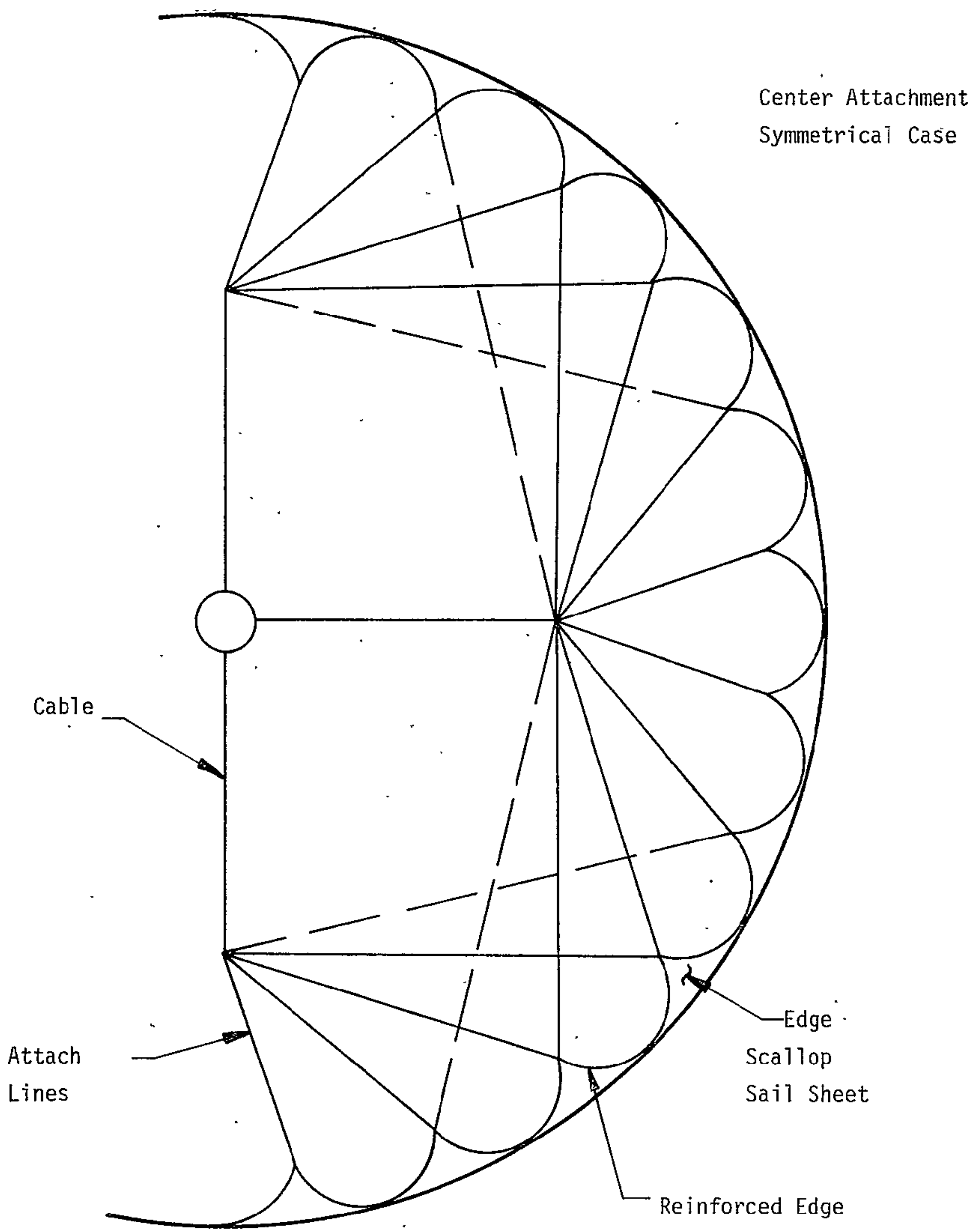

Center Attachment
Symmetrical Case
Cable
Attach
Lines
Edge
Scallop
Sail Sheet
Reinforced Edge

Figure II-8

the sail sheet locally.

Preliminary design analyses have been performed on this center attachment concept. Figure II-9 shows the results of an analysis to determine the load distribution in the attachment lines when a uniform stress field of 0.35N/m was applied to the sail sheet surrounding the cutout. These results suggest a fairly good distribution of loads for this symmetrical case.

Next, a more detailed look at an individual scallop is presented. The example scallop shape used is shown in Figure II-10. Stress analyses results are summarized in Figure II-11 for varying edge reinforcement stiffness. A stiffer edge reinforcement causes a decrease in peak stress at the scallop apex but an increase in stress at the valley. Thus, an optimum edge stiffness could be selected to minimize stresses in the scallop sheet.

The sail sheet is translated by outhauling and inhauling the four attachment cables. It has been assumed that the lengths of the individual attachment lines are not variable so the ends of the cables remain fixed relative to the sail sheet. The configuration of the attachment lines and cables with the sail translated 10 m is illustrated in Figure II-12.

A preliminary investigation of the load distribution in the attachment lines was conducted for the translated configuration. Results are shown in Figure II-13. It is noted as expected that the load distribution is not as uniform as for the symmetrical case. However, the maximum scallop load is only on the order of twice the minimum load.

The center attachment design study was concluded because of time limitations without further detailed evaluations. However, the design approach explored does appear to be feasible.

1.3 Gore Tailoring

The shape of the sail sheet in flight is selected to give a good balance between performance and stresses. Then the deflection characteristics under load must be determined so that the fabricated shape can be defined. Individual panels of the film material, called gores, are tailored such that when joined together, they form the desired fabricated shape.

A limited analytical effort was expended in support of the shape study performed by JPL. The objectives of the study were to find a shape acceptable

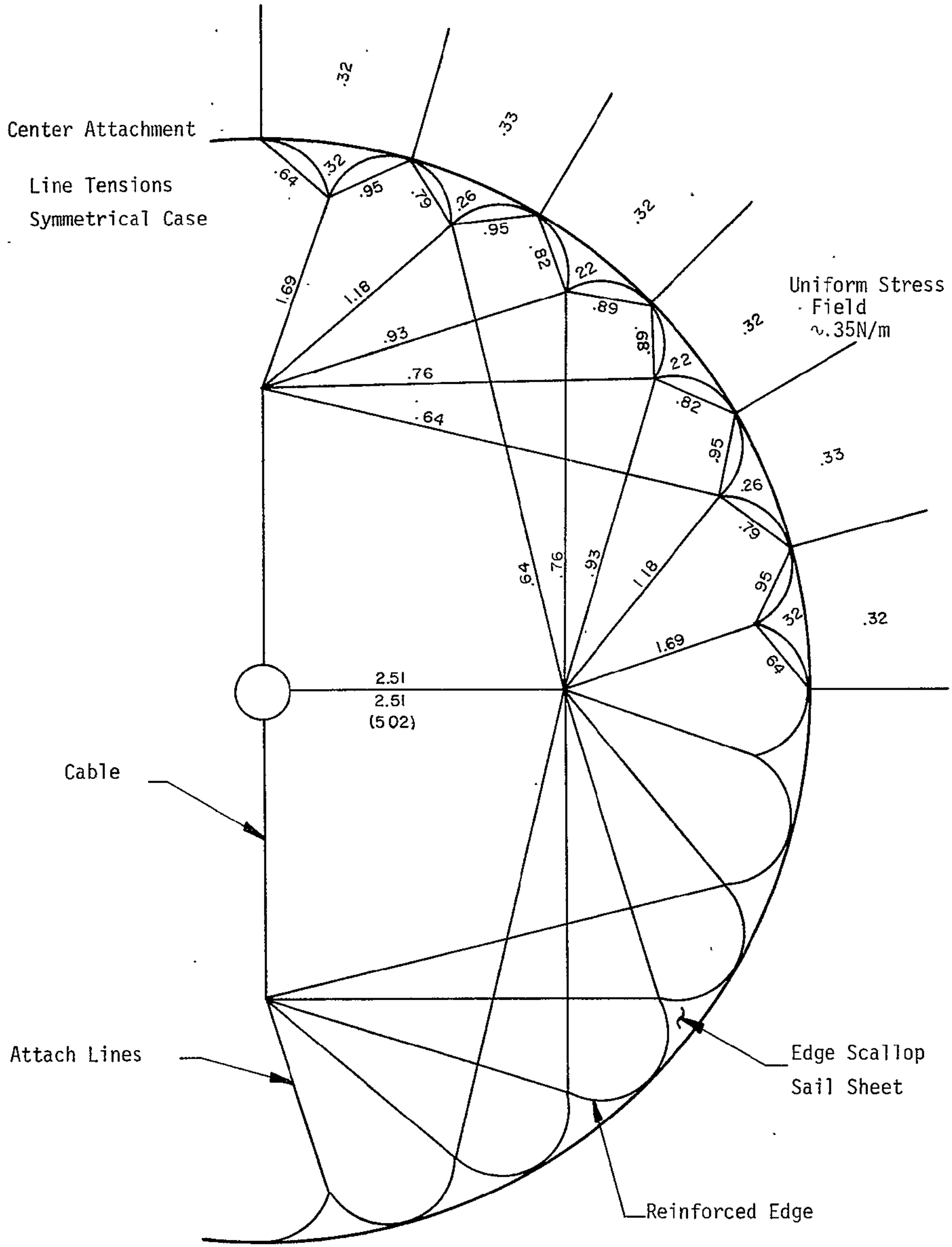

Center Attachment
Line Tensions
Symmetrical Case
Uniform Stress Field ∿.35N/m
.32
.33
.32
.32
.33
.32
.64
.32
.95
.79
.26
.95
.82
.22
.89
.89
.22
.82
.95
.26
.79
.95
.32
.64
1.69
1.18
.93
.76
.64
.64
.76
.93
1.18
1.69
2.51
2.51
(5.02)
Cable
Attach Lines
Edge Scallop
Sail Sheet
Reinforced Edge

Figure II-9

Example Center Cutout Scallop Design

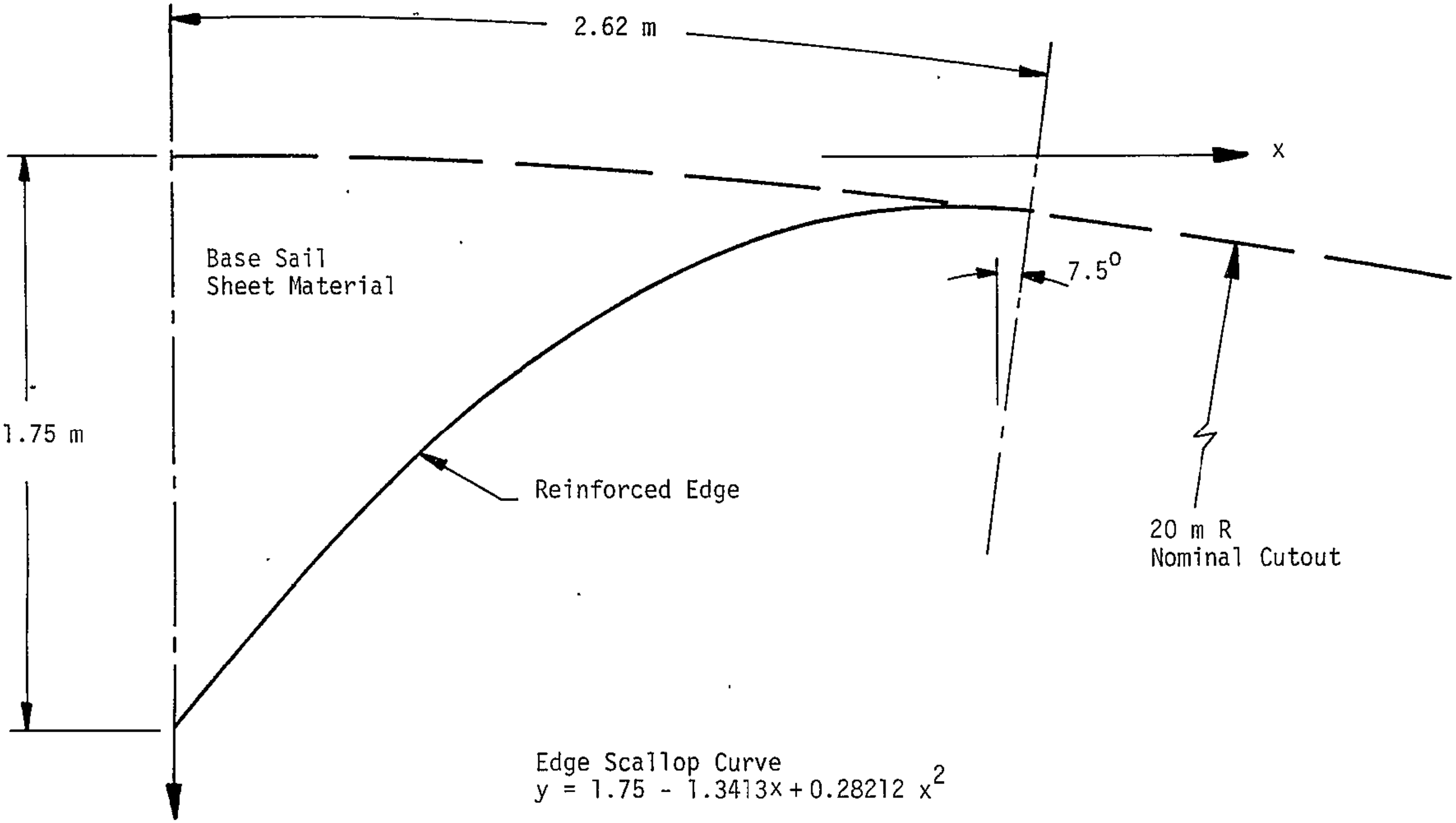


Figure II-10

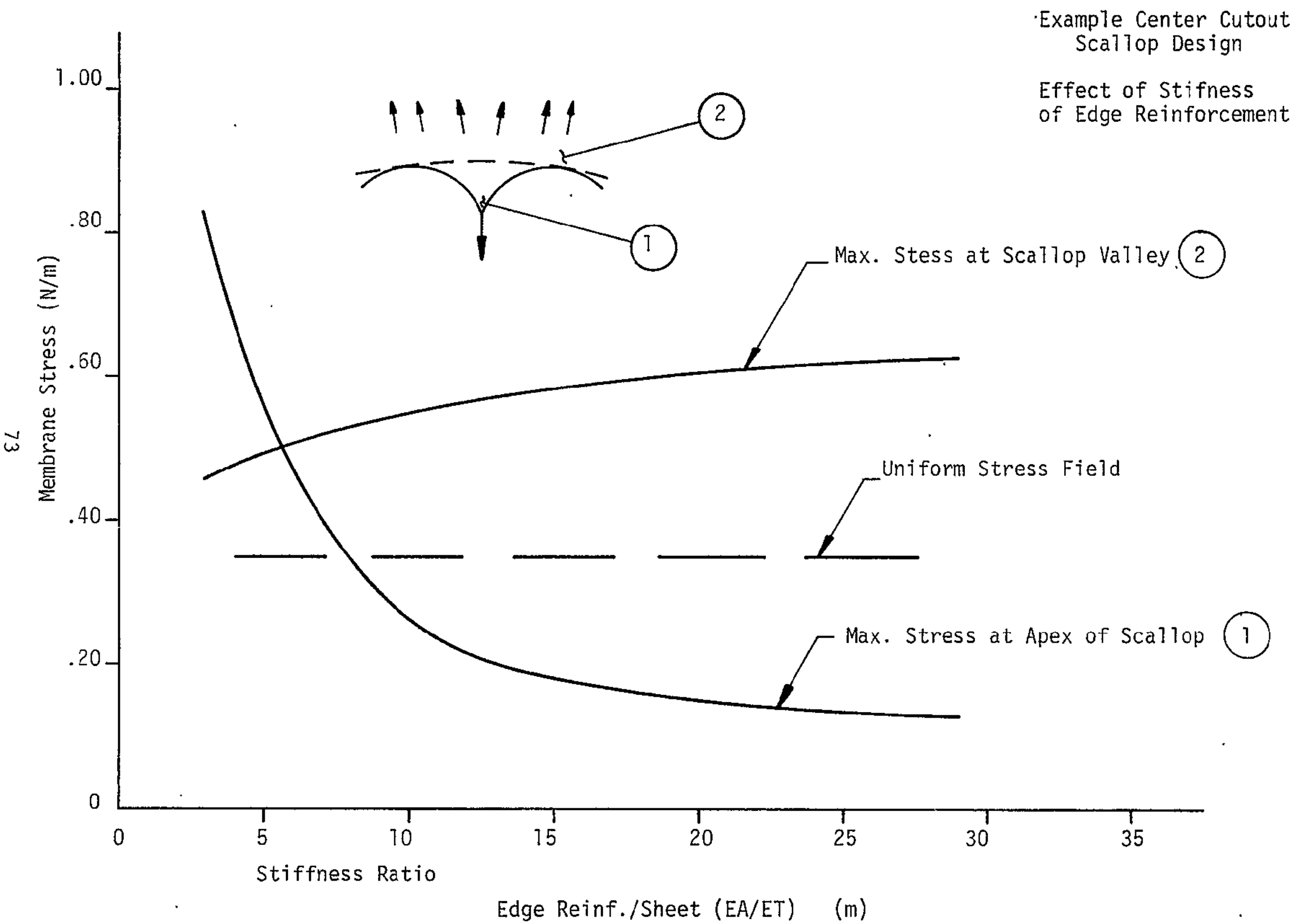

Example Center Cutout
Scallop Design
Effect of Stifness
of Edge Reinforcement
1.00
.80
.60
.40
.20
0
Membrane Stress (N/m)
2
1
Max. Stess at Scallop Valley 2
Uniform Stress Field
Max. Stress at Apex of Scallop 1
0
5
10
15
20
25
30
35
Stiffness Ratio
Edge Reinf./Sheet (EA/ET) (m)

Figure II-11

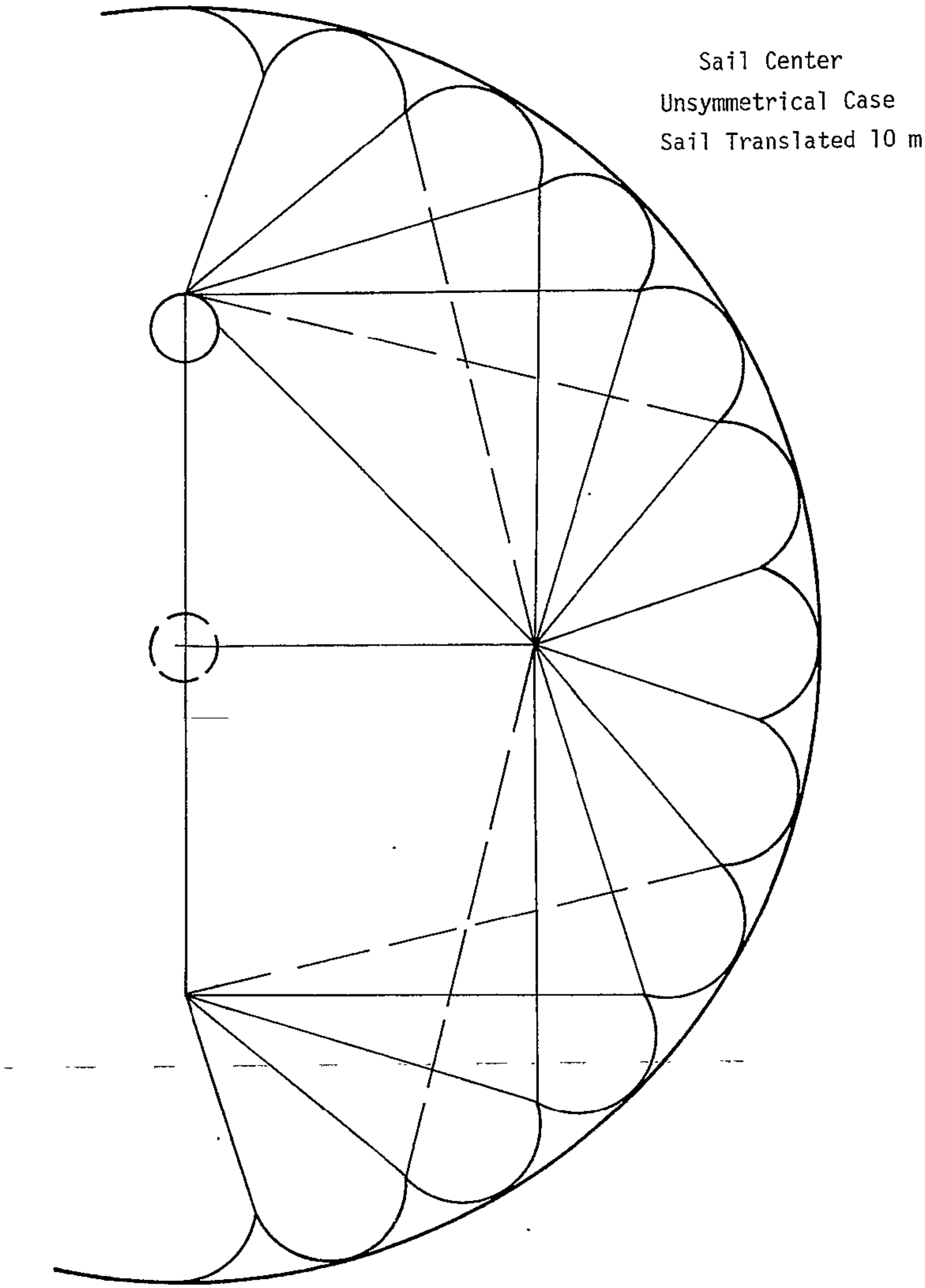


Figure II-12

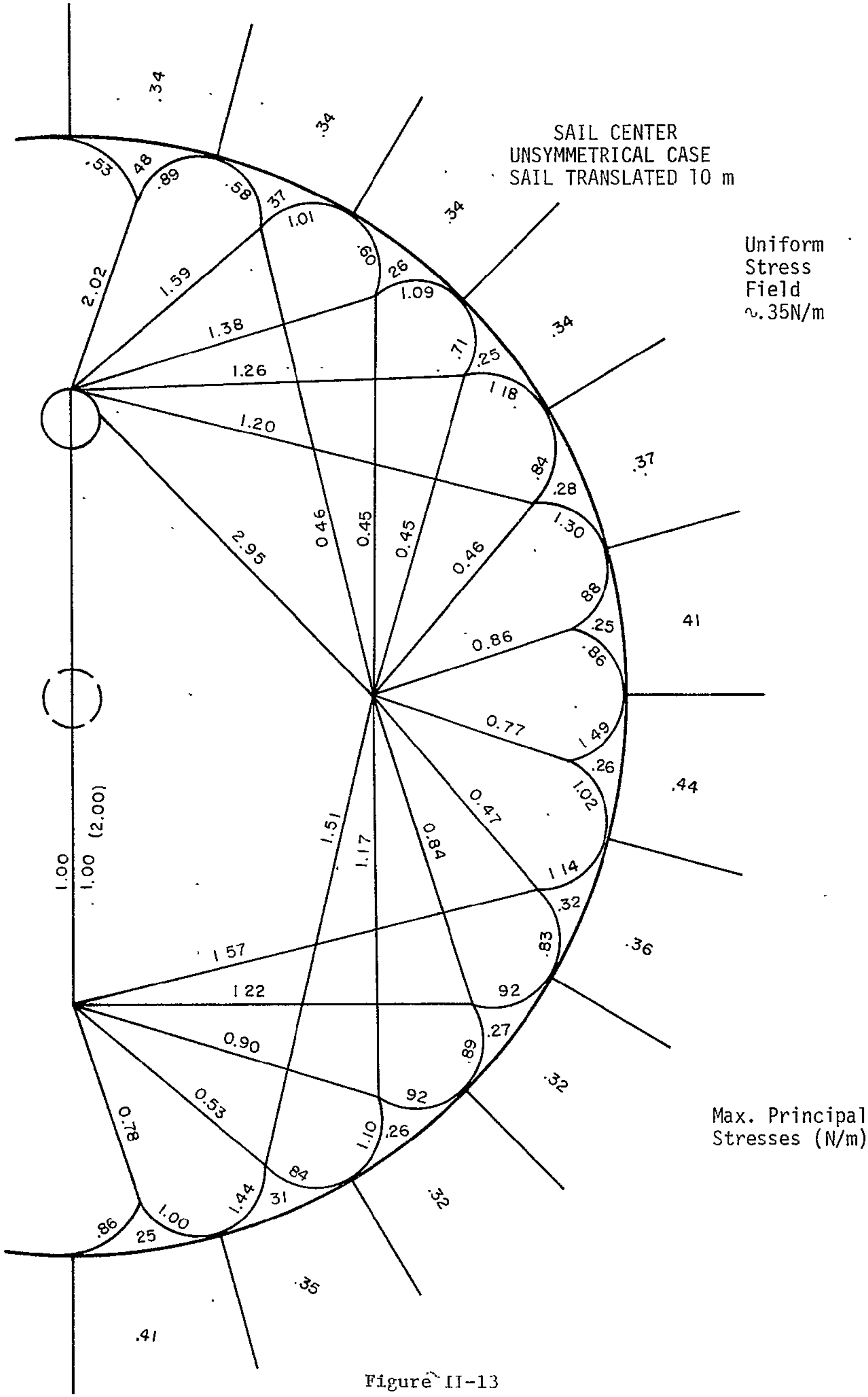

SAIL CENTER
UNSYMMETRICAL CASE
SAIL TRANSLATED 10 m
Uniform
Stress
Field
∿.35N/m
Max. Principal
Stresses (N/m)

Figure II-13

for performance and control which would also result in a fairly uniform stress distribution with no wrinkles.

The first shapes studied were variations of a pyramidal shape with 63 m apex height with draft limitations of 20 m and 40 m on the diagonals and apothems, respectively. It was found that extremely stiff diagonal and edge tendons were required in order to reduce the amount of wrinkling.

The second basic shape had an apex height of 10 m and draft limits of 10 m and 20 m for the diagonals and apothems, respectively. In an attempt to eliminate the diagonal tendons, the diagonal ridge curve was reduced. An initial shape formed from hyperbolic paraboloid (hypar) quadrants was assumed for convenience because of the straight line generators parallel to the edges. Example initial and deflected shapes are shown in Figure II-14. Some wrinkling still occurred in this case and a stiff edge tendon is required. It appears, however, that the diagonal tendon could be eliminated and this type of shape could perhaps be explored further.

Since the final sail shape has not been selected, the exact gore-tailoring requirements can not be specified. However, general requirements can be discussed.

For fabrication reasons, gores of about 1 m width would be oriented perpendicular to a diagonal axis starting from a corner. The length of each gore would have to be determined and the ends trimmed to give the proper shape, considering the diagonal draft and the edge scallop and sag. Gore-width tailoring requirements depend on the surface shape. As examples, the total gore width difference along the diagonal for a half sail for the hypar and pyramid shapes are shown in Figure II-15 as a function of apex height. Also shown in the figure is the point for the JPL shape with 10 m apex height. It is noted that the additional gore width to be added along a diagonal is less than one gore (1 m) if the apex height is kept below about 20 to 30 m. Similarly, the additional gore width required due to edge sag is small if the edge sag is restricted to this range. Therefore, all gores, except perhaps one or two per half sail, could probably be made a constant width. Then, only one or two gores per side would need to be specially tailored in width to give the proper fabricated shape.

EXAMPLE SHAPE
INITIAL HYPAR QUADRANT

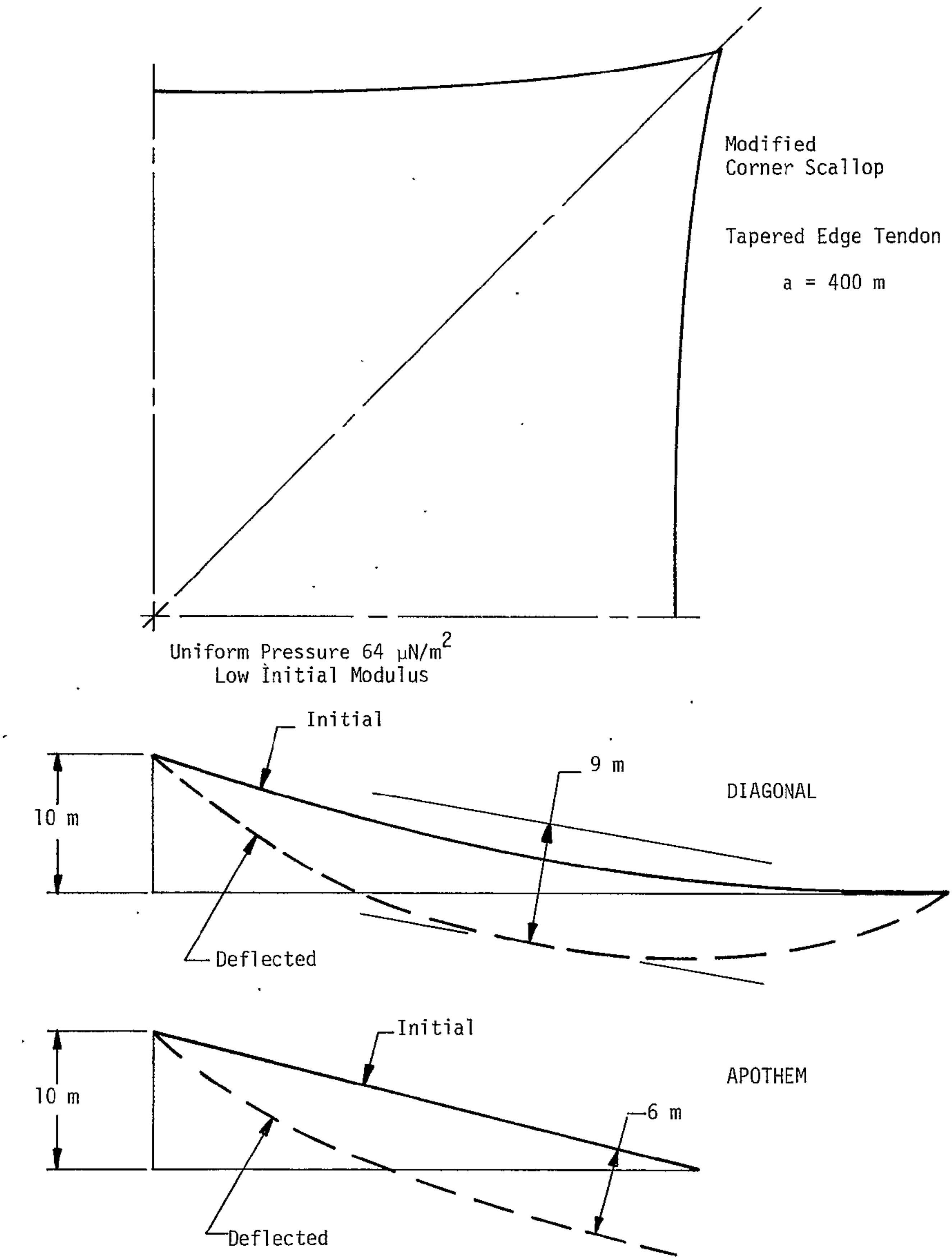


Figure II-14

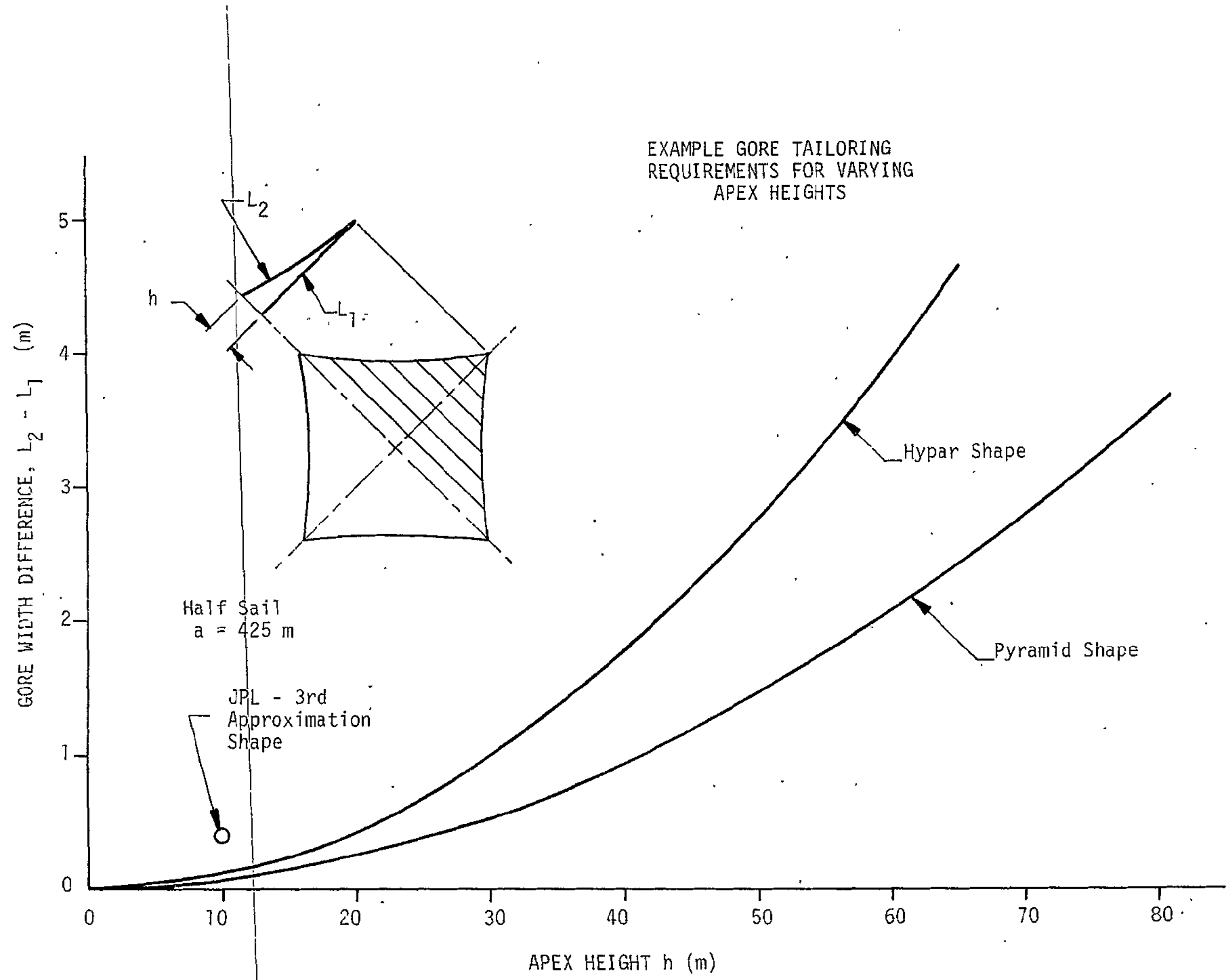

EXAMPLE GORE TAILORING
REQUIREMENTS FOR VARYING
APEX HEIGHTS
L_2
h
L_1
Half Sail
a = 425 m
JPL - 3rd
Approximation
Shape
Hypar Shape
Pyramid Shape
GORE WIDTH DIFFERENCE, $L_2 - L_1$ (m)
0
1
2
3
4
5
0
10
20
30
40
50
60
70
80
APEX HEIGHT h (m)

Figure II-15

1.4 Stowage and Deployment

1.4.1 Packing Configuration

The primary purpose of the chosen folding geometry, packing method and container design should be to preclude damage to the panels, seams and surface coatings of the sail during packaging, transport, storage, launch and deployment. For thin, thermoplastic films, like Kapton, tensile strength does not appear to be significantly affected by folding and creasing at room temperature. There is evidence that thermal radiation properties (e.g. reflectance) of a vacuum-deposited metal coating on KAPTON film may be significantly changed in areas where film buckling occurs, like the inside of a folded stack of film layers. To protect the surface coatings, folding and packaging techniques which result in compressive forces in the film plane should be avoided to the maximum possible extent.

The folding configuration in Figure II-16 favors sail deployment and minimizes stowed dimensions at the expense of additional folds. A pair of rectangular packs each containing half of the sail on either side of the central, cylindrical bay would reduce the number of folds required, but this arrangement would require considerably more space.

1.4.2 Packing Factors

Since the sail is of approximately uniform thickness and is folded in an orderly manner, the packing factor (ratio of packed volume to "molten" volume) can be compared with that of parachutes and large balloons, Figure II-17. The porosity and flexibility of parachute panels and lines permit application of high mechanical pressures during packing to achieve high packing factors. The sail will be perforated at relatively small, regular intervals and adjacent folds will be in alternate directions. Therefore, the distance that entrapped air must travel from the interior to the surface of the pack will be on the order of the finished pack dimensions, 2 - 3 m or less. To remove air entrapped during final folding, it would be preferable to reduce ambient pressure around the folded sail in a chamber as was the case with the PAGEOS satellite, rather than to force out the air by externally applied, mechanical or fluid pressure.

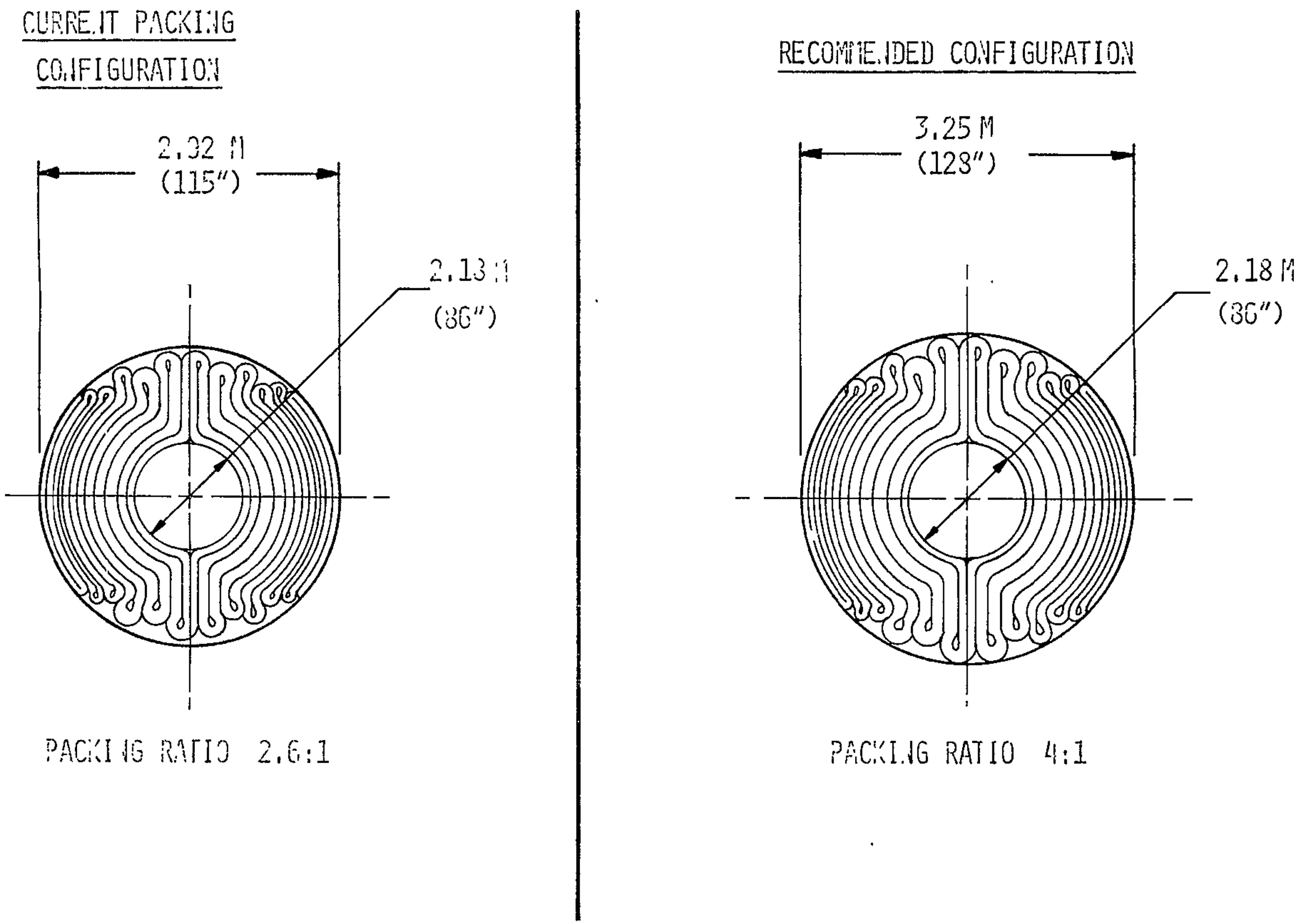


Figure II-16. Solar Sail Packing Configuration

EFFECT OF PACKING PRESSURE ON PACKING FACTOR

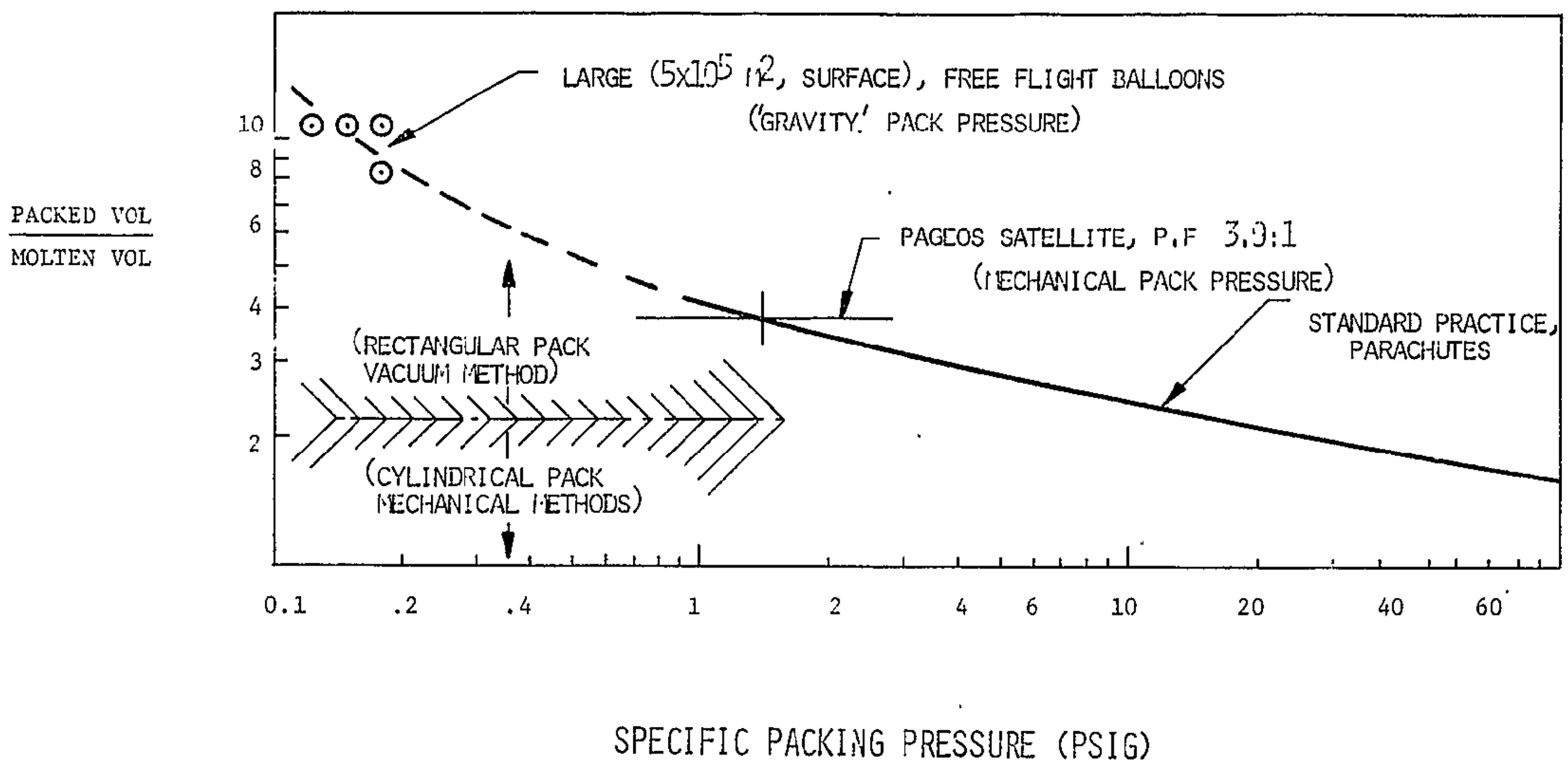


Figure II-17. Solar Sail Packing Configuration

1.4.3 Canister Design - Vacuum Pads vs Venting

It has been suggested that the curved surfaces of the external canister be made of two halves lapped at the free edges so the normal forces caused by atmospheric pressure could be supported by the packed sail. This arrangement is probably undesirable for the reasons cited in 1.4.1. A canister designed to support one atmosphere of external pressure would be prohibitively heavy. It is recommended that a canister pressurized with an inert gas be investigated. Differential pressure loads on the canister and canister weight could be made quite small by controlled venting of the gas during shuttle ascent. A similar design was used on the VIKING bioshield to prevent entrance of airborne micro-organisms during storage and launch.

2.0 HANDLING AND FABRICATION PLAN

2.1 Materials Procurement

Baseline for this preliminary study assumes Government supplied Kapton (or similar) film.

2.2 Film Metalizing

The question of proper equipment to produce the metalizations required for the sail fabric is critical. Tightly controlled deposits of both aluminum and chromium are required which are uniform in thickness and density.

In addition, the aluminum thickness, as compared to the substrate thickness, is substantial and is also high in relationship to commercial practice. Chromium deposits present distinct problems with deposition methods and control. The following discussion will outline some of the parameters currently recognized as in need of much further refinement and definition. It is felt that equipment available in the industry at the present time cannot fulfill the special requirements of this product. Suitable, specialized equipment will need to be designed and constructed to ensure timely deliveries of "on spec" material, minimizing expensive scrap losses.

2.2.1 Key Equipment and Process Considerations

Some very basic questions must be addressed before progress can be made on design of suitable equipment. Many of these revolve around the nature of the candidate sail material itself. Polyimides absorb high percentages of moisture. There is also an opinion that a lot-to-lot variation exists in the amount of unreacted polymerization charge materials and/or by-products. Both of these contribute to loads on the pumping system and possible contamination of the vapor deposit. A vacuum pretreatment may be necessary to thoroughly remove these potential sources of trouble.

Further, the behavior of .1 mil polyimide in vacuum systems when exposed to high heat, vacuum, and tension could result in physical changes from the nominal. General shrinkage of the material is expected; how much shrinkage needs to be determined. Edge curling due to induced stresses is expected; again, how much occurs, how much is tolerable, and how we minimize or eliminate it are questions needing answers (slitting after metalization and edge banding during metalization are possible solutions).

The heat of condensation of the metals on the polymer could lead to severe problems, up to and including the physical destruction of the plastic film. Therefore, the "flux density" allowable must be firmly established early, and adhered to during production phases.

Several other details must be exercised early to provide essential input to design stages. The suitability of the various types of sources to produce acceptable material from an optical standpoint should be determined. The question of perforations before or after metalization must be thoroughly discussed and resolved. Perforating before metalization presents problems in web handling such as tears, poor handling characteristics, "ridge" formation (similar to gauge bands), loose "divots" from the punching operation in the metalizer, etc. Laser perforating on a random pattern should preclude most of these problems but must be investigated as a production method.

2.2.2 Major Equipment Design Areas

For ease of discussion, the major design areas of consideration will be broken down into six major categories as follows:

A. Sources - The various means of producing metal vapor for subsequent condensation on the plastic web.

B. Pumping - The types and suitability of different means of achieving adequate vacuum.

C. Web Handling - The carriage assembly for transporting the plastic web from place to place within the vacuum chamber.

D. Sensing - All the devices needed to insure the production of "on spec" deposits from:

1. a material property standpoint and
2. a source control standpoint.

E. Controls and system integration - The various gauges and monitors to verify system performance.

F. Single or multi-tank considerations - The desirability, or lack thereof, of splitting deposition into two separate and definable systems.

2.2.2.1 Sources

Several means are available for producing aluminum deposits in the vacuum chamber. Among these are resistance heating, induction, electron beam, and ion plating. Each has advantages and disadvantages. Questions must be answered in regard to uniformity, controllability, reliability, and deposit properties.

Chromium deposition is also possible by several methods. Among these are induction, electron beam, ion plating, and sputtering. Again, each method has advantages and disadvantages, with sputtering requiring a two-tank configuration.

2.2.2.2 Pumping

Rough pumping can be accomplished reliably with commercially available and universally used mechanical pumps and blower combinations (in the U. S. the most frequently utilized units are Stokes pumps and Roots blowers). These can be "gaged" if pumping speed so dictates.

Due to the volatiles present in the substrate, cryogenic pumping will most likely be required. This should include traps above all diffusion pumps and cold plates or "fingers" on both sides of the moving web in suitable locations.

High vacuum pumping would most likely be accomplished by oil diffusion pumps of 36" to 48" size singly or in multiples as required by capacity considerations.

Capacities of all pumps must be determined by the anticipated gas load, desired vacuum levels, and pumping speed considerations.

2.2.2.3 Web Handling

This is a very critical area of processing and is highly dependent upon the quality of the film material. Many devices are built to facilitate moving a web of material from place to place. Among these devices are specialized rolls and roller assemblies such as bowed rolls, flex spreaders, herringbone spreaders, slotted expanders, and Slimb ^{R} devices (gimballing rollers). Thought must be given to the use of tension sensors, very fine clutches and brakes, low drag bearings, and tendency driven rollers. The use of multiples of these units to handle this thin material will probably preclude bidirectional web travel in favor of a uniderectional approach. Provision will also have to be made for shadow bonding the edges of the material should this prove necessary.

All the web handling questions must begin to be addressed as soon as the first prototype film becomes available.

2.2.2.4 Sensing

Systems must be incorporated to give ready answers to the machine operators verifying the production of quality material. Among these should be:

A. Continuous resistance monitoring - A readout indicating electrical resistance as an indication of thickness;

B. CO_2 laser (at 10.2μ) - A continuous reflectivity measurement in tank as material is processed;

C. Fast scan spectrophotometer - Set to operate at 4 or 5 predetermined wavelengths to give an indication of reasonable α values; this unit could give a continuous, permanent record of values if desired;

D. Closed circuit internal TV - To monitor web travel and verify operation of web handling devices.

In addition, sensors should be incorporated to monitor source operation and deposition parameters. These should include:

A. Rate monitors - One per source to give indication of the operating efficiency of that source;

B. Thickness monitors - Multiple heads located at strategic spots to validate continuous readings;

C. "Stand Alone" control computer - Accepts inputs from sensors, sorts data and records, updates program for control purposes.

2.2.2.5 Controls and System Integration

The operator control console (s) must contain all the sensor and gauge output for the total system. This allows for central accumulation and readout with potential operator override of primarily automatic operation in case of malfunction. The environmental readouts (e.g. vacuum tank proper) should include residual gas analysis capable of automatic sequential scanning of several head placements with demand isolation of a single head. In addition, thermocouple and ion gauges must be used to monitor vacuum levels and can be used in multiples. Functional interlocks are essential to prevent inadvertent miscycling of the machine. Various visual and audible warning devices can indicate lack of water flow, improper intermediate vacuum levels, and similar variables to "flag" them for the operator (s).

All monitoring and readouts from the sources, as previously discussed, would feed to this central control. Material property measurements would be reported to this same area with visual readouts and auto recording of values with computer interface for automatic shutdown or a manual override decision point. All web handling readouts would be reported to this location, including the closed circuit TV monitoring. Again, preset values could signal shutdown or demand manual override within a pre-programmed time frame. All sensor data would be coordinated in this area for computer stock generation as well as updating control algorithms.

2.2.2.6 Single or Multi-Tank Decision

A choice inherent in the new equipment concept is that of whether a single, extremely complex unit or two or more somewhat simpler versions should be designed. There are trade-offs in both directions:

A. Single Tank

1. Less web handling;
2. Probably less capital cost;
3. Significantly more complex;
4. Downtime means nothing gets coated;

5. Limits source types; and
6 Balancing two deposit zones extremely tricky.

B. Multiple Tanks

1. One system down does not result in total shutdown (operate other unit);
2. Control only one deposit at time - easier;
3. Does not limit source configurations;
4. Could be somewhat more capital intensive; and
5. More web handling.

2.2.2.7 Conceptual Designs

Operating from sail material baselines, it is important that very early attention be given the means of metalizing this material. The requirements are currently on the extreme fringe of producibility and will require specialized equipment for conformance. It is suggested that as many answers as possible to points raised here be found quickly, that further efforts to more fully define requirements be undertaken and that at least two manufacturers of sophisticated metalizing equipment be funded or partially funded to develop conceptual equipment designs. Fabrication time of this item(s) from *finished* drawings indicates that no time be lost developing and approving the initial design.

2.3 Sail Fabrication

2.3.1 Fabrication Concepts

A number of fabrication concepts were considered and studied. Figure II-18 shows three of these which showed particular advantages in either folding and packaging, size of facilities or gore tailoring.

The most straightforward concept would be to build the entire sail as one large single sheet as shown in Figure II-18 - Single Sail Sheet. As each new panel is added, this concept would allow folding it over on top of the stack of previous seamed panels. The result would be a long narrow stack of seamed panels which, when completed, could then be folded directly into the canister. This concept allows access to the center and all corners for making attachments. The primary disadvantage of this concept is that it greatly restricts the fabrication methods, seaming speeds and inspection time available.

The second concept shown in Figure II-18 is the Half Sail Sheet. This has the same advantages as the Single Sail Sheet of folding and packaging into the canister while giving access to the center and corners. Depending on the method of fabrication, the facilities could be much smaller. Also, building two halves simultaneously allows great flexibility in sealing speeds and inspection time. Fabricating the sail sheet in two halves and joining the halves prior to packing in the canister is clearly the preferred choice.

The third concept shown in figure II-18 is the Quarter Sail Sheet. This concept would allow the fabrication of the sail in four sections simultaneously. The advantage of this concept is easier gore tailoring. The width of each panel could be slightly altered along the diagonals and outer edges to build in fullness. This concept is not recommended since, due to the orientation of the panels and seams, the sail sheet must be unfolded and refolded along the diagonals in order to package it into the canister.

Of the methods considered, building the sail in two halves offers the greatest flexibility of fabrication methods, seaming speeds and inspection time.

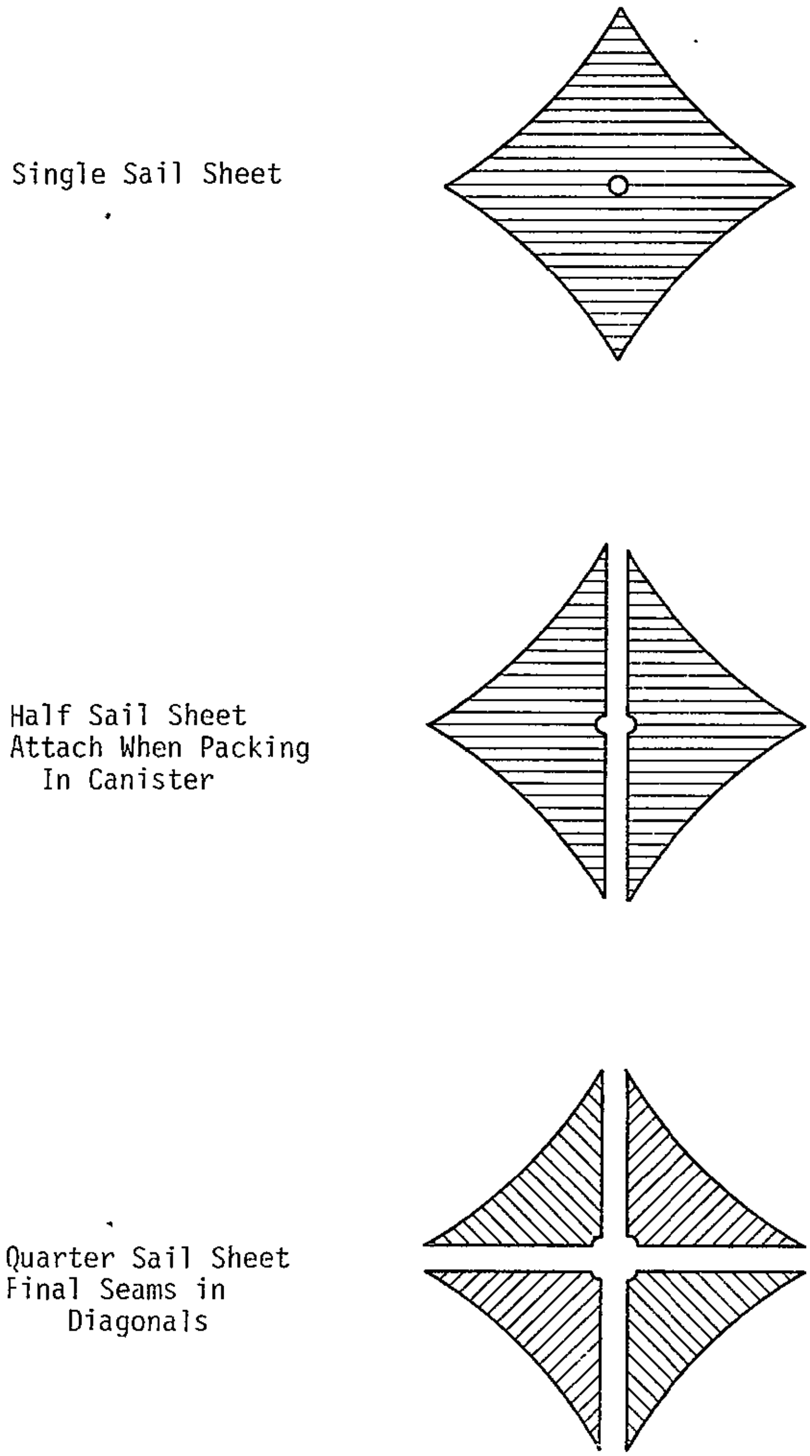


Figure II-18. Solar Sail Fabrication Concepts
850 Meter Square Sail

2.3.2 Fabrication Methods

Five fabrication methods are shown in Figure II-19. The Half Table method lends itself particularly well to the Half Sail Sheet concept. The Reel-to-Reel method is compact and fits well with the Full Sail Sheet concept.

The first method shown is the Long Table. While this would allow fabrication of the sail sheet in one piece, it is not very compact and would require an unusually long facility. It also limits the time available for seaming and inspection.

The Half Table method is more compact and requires a smaller facility than the Long Table method. It is the preferred method and allows the fabrication of the two sail halves simulaneously. It offers great flexibility in sealing speeds, inspection time, time available for repairs, and the addition of reinforcements at the corner, edges and center.

The Reel-to-Reel method allows the fabrication of the sail in a single sheet while still being very compact and requiring a small facility. This method greatly restricts the sealing speed and inspection time.

The Serpentine method is compact and could be used with either the Single or Half Sail Sheet concepts. The primary disadvantages of this method is that the material traverses back and forth as each new panel is added. The flexing of the material always occurs at the same location. This would cause severe localized degradation of the material coated surfaces.

The U-shape method, while allowing fabrication of a single sail sheet, is not very compact. In addition, excess material degradation would occur at the U.

Of the methods shown in Figure II-19 and discussed here, the Half Table (Half Sail Sheet) and the Reel-to-Reel (Single Sail Sheet) methods are preferred and will be further discussed and compared in the next sections.

2.3.2.1 Reel-to-Reel vs Half Table - Trade-off Analysis

Table II-1 compares the Half Table and Reel-to-Reel methods. It should be noted that the Half Table method is used to fabricate two half sail sheets simultaneously on two adjoining, parallel tables. The Reel-to-Reel method is used to fabricate the single sail sheet.

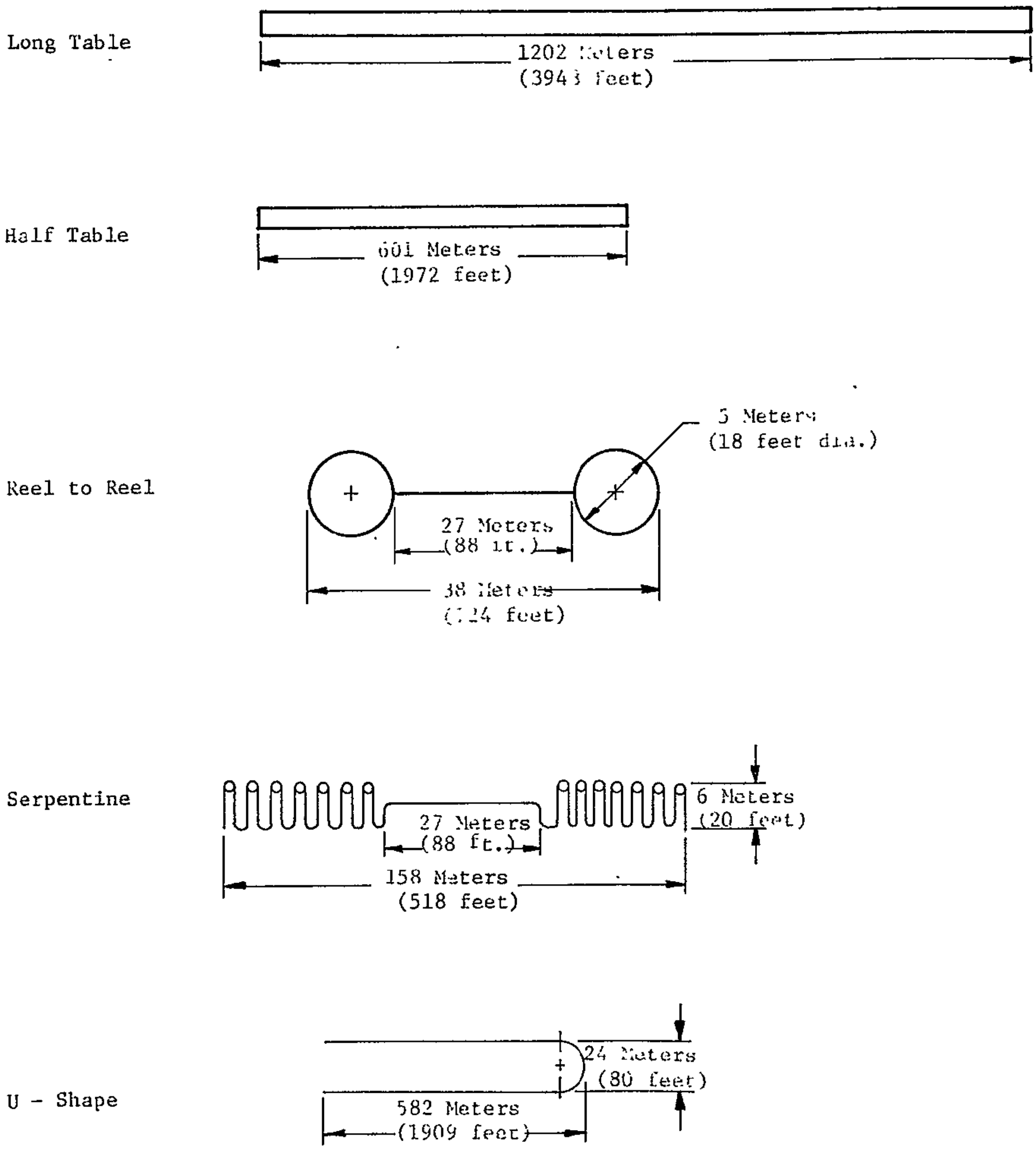


Figure II-19. Solar Sail Fabrication - 850 meter square sail.

Table II-1. Solar Sail Sheet
Fabrication Concepts/Methods
850 Meter Square Sail
3 May 1977

Half Table
(Half Sail Sheet)

Advantages

- Minimum Degradation of Thermal Control Surfaces
- Flexibility in Sealing Speed
- Easy to Make Repairs on Sail
- Easy to Add Edge Reinforcement
- Maximum Inspection Time
- Cost Effective (Lower Cost Equipment)

Disadvantages

- Long Building Required
- Increased Energy Consumption (long, large facility)

Reel-to-Reel
(Single Sail Sheet)

Advantages

- Compact Machine
- Small Facility
- Lower Energy Consumption (Small facility)

Disadvantages

- Increased Degradation of Thermal Control Surfaces
- Limited to a Minimum Sealing Speed
- Must Stop Entire Machine To Make Repairs
- Must Stop Entire Machine To Add Edge and Center Reinforcements
- Minimum Inspection Time
- Very Expensive Equipment

The advantages of the Half Table method are given in Table II-1. Minimum degradation of the thermal control surfaces occurs because each panel is only handled once during seaming. It is attached, folded onto the stack of previous panels and not moved again until the sail halves are joined and packaged into the canister. The table method also allows greater flexibility in sealing speeds since, while one crew is seaming on a new panel, other crews can make repairs and add edge, corner and center reinforcements as required. The table method also allows maximum inspection time since the panels and seams can be inspected both ahead of and behind the sealer. The table method is also cost effective, as shown in detail in another section of this report.

The Reel-to-Reel method, as shown in Table II-1, has one primary advantage - compactness. The machine is compact and requires a small facility even while fabricating the sail as a single sheet. It has many disadvantages, as shown, which makes it less attractive. Some degradation of the metalized thermal control surfaces will occur since the stack of panels will fluff up and, as they are wound onto the reel each time, will compress and shift against each other causing some mechanical abrasions. The Reel-to-Reel method also places a severe limitation on seaming speed since an average of 20 fpm must be maintained in order to fabricate a sail sheet in six months using three shifts per day. This means when a repair must be made or reinforcements added at the center, corners and edges, the machine and seaming operation must be stopped. Therefore, while seaming, a much higher speed must be maintained (40 - 50 fpm). This puts critical restraints on the time and methods available for quality inspection. As shown in later sections of this report, the Reel-to-Reel equipment is also very expensive.

2.3.2.2 Preferred and Recommended Approach

As reviewed in the previous sections and Table II-1, it is recommended that the Half Table method be used to fabricate the two sail sheet halves simultaneously. As noted, this method causes the least amount of material degradation while offering the greatest flexibility and amount of fabrication and inspection time at no greater overall cost.

2.3.3 Inspection, Splicing, Rip Stop Installation

Figure II-20 shows the concept for a machine which would be used to inspect the coated film, splice sections together and add the rip-stop reinforcement tapes.

Key components are indicated on Figure II-20 and are as follows:

- Edge guide system;
- Equipment to measure and record thermal control properties on both sides of the web;
- Equipment to measure and record film thickness;
- Cutting equipment for cutting the web to remove defective material;
- Impulse sealer for splicing the web or sealing on rip-stop;
- Drive roll system with footage pick off; and
- Web handling equipment including tension control equipment.

Also included on the machine, but not shown, would be necessary static elimination devices. A large variety of these are available commercially for use in the vacuum metalizing and laminations industries which could be used with no special modifications.

As shown in Figure II-20, the material unwinds and proceeds through a series of rolls which monitor and control web tension. The web is then scanned on both sides by a series of instruments which measure and record into a computer the thermal control properties, film thickness, footage, room temperature and humidity. If no defective material is to be removed or rip-stop added, the material passes through a series of drive rollers where a footage signal is picked off and recorded in the computer to match up with the previously taken measurements. The web is then carefully wound into a roll and is available to be seamed into the sail.

If a rip-stop tape is to be added, the operator would stop the machine, position the rip-stop tape across the web, move the web and tape under the impulse sealing head and seal the tape in place.

As shown in Figure II-20, a cutting device is provided if defective material is to be removed or additional rolls spliced together. For cutting, C-2

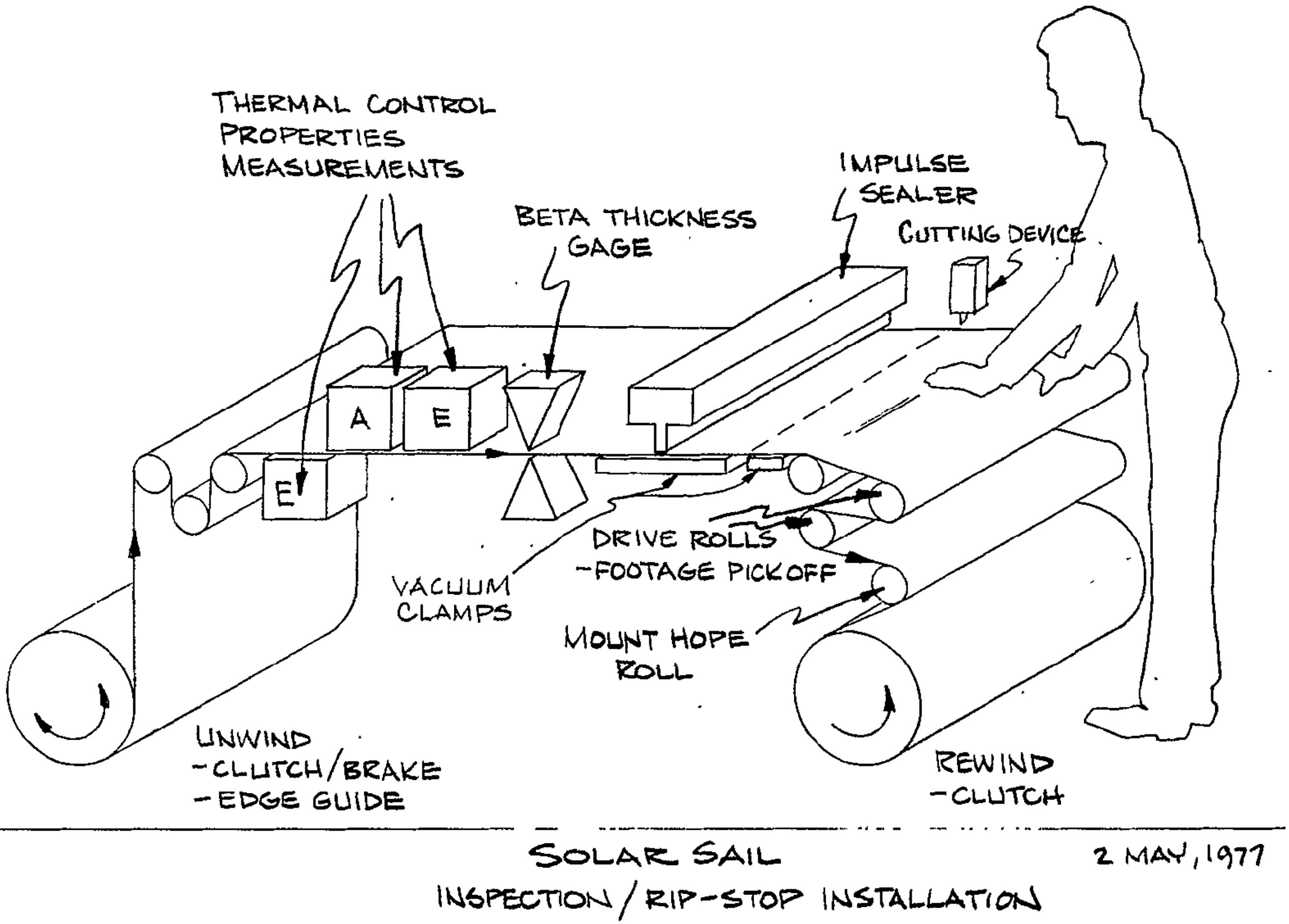


Figure II-20

the material would be held by vacuum clamps and the cutter would traverse the web cutting it into two pieces. The defective material would be removed manually. When good material is again available, or the good end of a new roll, the two ends would be overlapped and the cutter would again traverse the web. This time, a small piece would be cut from each of the two ends and discarded. Since the ends of both pieces are being held by vacuum clamps a precise butt joint is obtained and maintained. The splice tape would then be positioned, the web and tape moved under the impulse sealing head and the tape sealed in place.

As noted previously, the computer monitors and records all operations and machine conditions. This provides a complete record of material properties within the completed roll as well as a complete record of all defective material.

2.3.4 Gore Tailoring

Figure II-21 shows the concept for a machine which would be used for tailoring the gores when required. Material processed by this machine would have been inspected and have had rip stop added by the machine shown in Figure II-20 and described in Section 2.3.3.

Key components are indicated on Figure II-21 and are as follows:

- Edge guide system;
- Two cutting devices (tape or computer controlled);
- Vacuum trim removal;
- Drive roll system with footage pick off; and
- Web handling equipment including tension control equipment.

Also included on the machine, but not shown, would be necessary static elimination devices. A large variety of these are available commercially which could be used with no special modification.

As shown in Figure II-21, the material unwinds and proceeds through a series of rolls which monitor and control web tension. The web then passes under the cutting devices whose transverse positions are tape or computer controlled in relation to the linear footage. After having the edges cut, as required, the web passes through a series of drive rolls where the footage signal is picked off which is used to control the cutter positions. The web is then carefully wound into a roll and is available to be seamed into the sail.

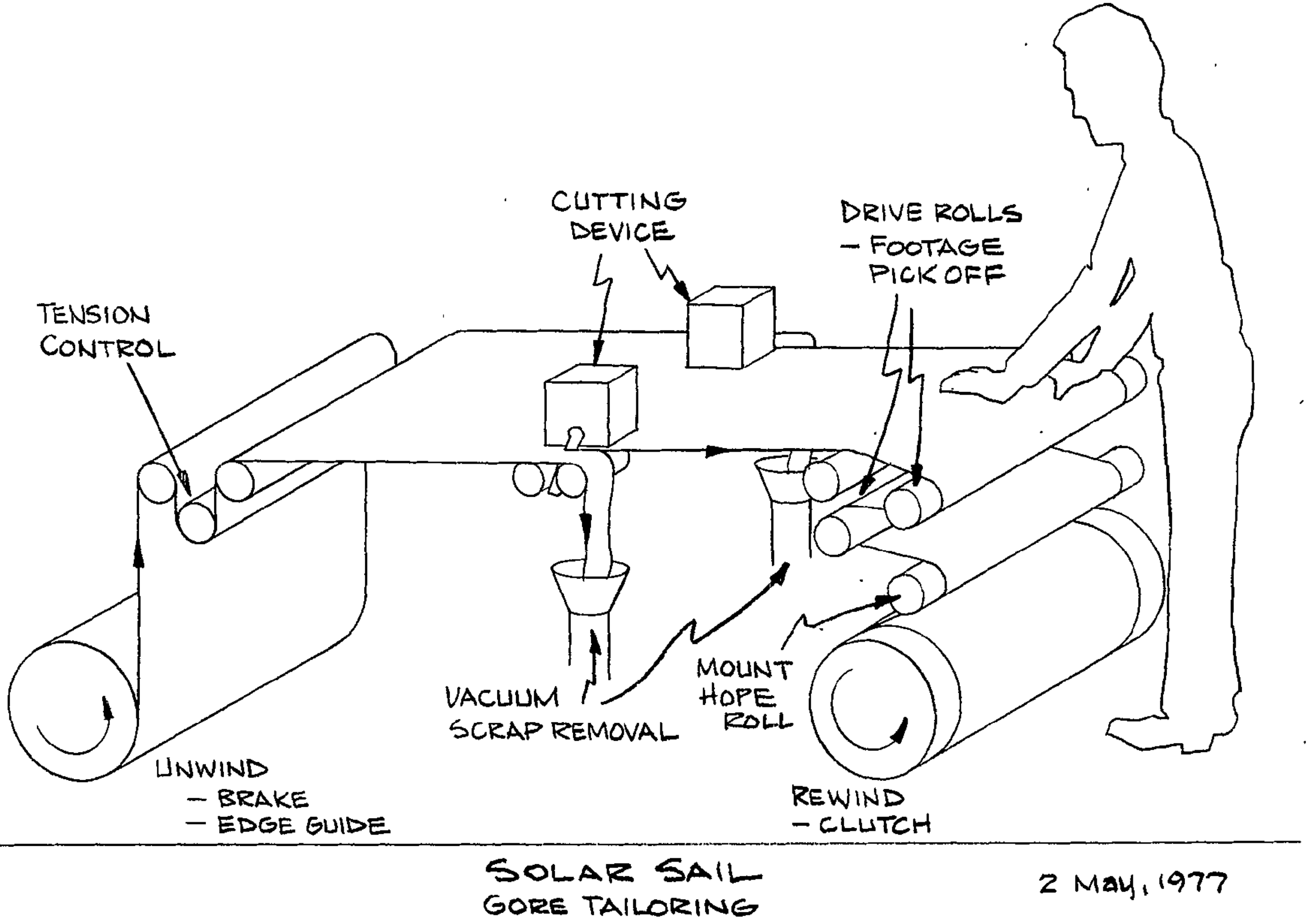

CUTTING DEVICE
DRIVE ROLLS
— FOOTAGE PICK OFF
TENSION CONTROL
VACUUM SCRAP REMOVAL
MOUNT HOPE ROLL
UNWIND
— BRAKE
— EDGE GUIDE
REWIND
— CLUTCH
SOLAR SAIL
GORE TAILORING
2 May, 1977

Figure II-21

2.3.5 Sealing and Folding

As shown and described in Section 2.3..2.1, two methods have been studied in detail. They are the Reel-to-Reel and Half Table methods. A conceptual design for equipment is shown in Figures II-22 and II-23 and are also described in the following sections for each method. As discussed in Section 2.3.2.1 and 2.3.2.2, the Half Table (Half Sail) is the preferred method.

2.3.5.1 Reel-to-Reel Method

Figure II-22 shows a machine for the Reel-to-Reel concept. Key components are indicated on Figure II-22 and as follows:

- Two reels for storage of already seamed and folded sail material;
- A belt which supports the fabricated sail sheet and is attached on either end to a reel;
- Tension control equipment which controls the reel drive systems;
- Edge guide system for positioning the top gore in the sealed stack;
- Sealer with new gore unwind plus edge guiding and tension control equipment; and
- Double spiral folder with air bearing surfaces.

As shown in Figure II-22, the machine is designed to run both directions. Therefore, it is equipped with two sealers and folders which are alternately used.

In practice, as shown in Figure II-22, the previously sealed together gores would be folded and stored in the left reel. They are laying on the belt which is also wound onto the reel. The other end of the belt is attached to the right reel. Spacer pins index into place and provide the 0.685 inch space between turns. As the belt and stack of gores unwind, the belt passes through a tension monitoring device which controls the motors, clutches and brakes of both reels. The top gore is then picked up by the edge and held by the edge guide/tension monitor device. This positions the edge as it goes into the sealer. The sealer then dispenses the new gore, to be added, and seals it onto the gore already folded onto the stack. The sealer is equipped with edge guide/tension monitoring equipment as well as necessary tape dispensers. To provide an exact butt joint, the two edges to be sealed are overlapped and a laser is used to cut both edges simultaneously. After the trim is removed, a controlled butt joint

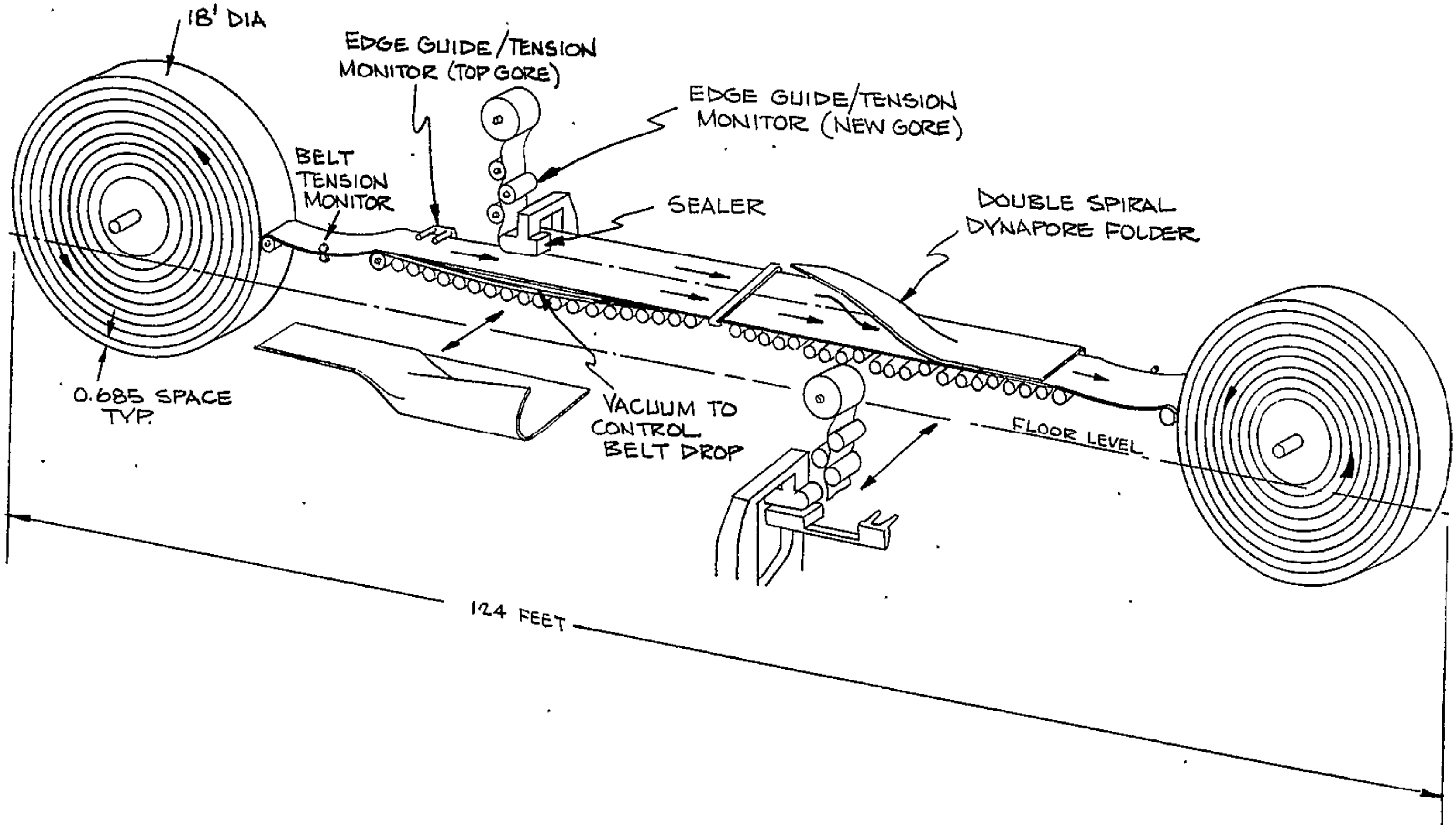


Figure II-22. Solar Sail Sheet,
Reel to Reel Concept

gap is the result. At the sealer, the belt and all but the top gore of the stack, drop down and under the bottom sealing device as shown. After sealing, the web then enters the double spiral folder. This device has low pressure air bearing surfaces and folds the new gore onto the stack. The stack of gores, laying on the belt, are then wound onto the right reel. To add the next gore the process is reversed and the alternate sealer/folder moves into position while the previously used sealer/folder retracts out of the way.

The reels are designed to maintain 0.685 inch space between turns. This is important so that subsequent turns do not slide and crush the previous layers of material.

The sealer can be of a number of different types, depending on finally selected adhesive and sealing parameters. Possible ones are the wheel sealer, long band sealer and the step/impulse sealer.

The belt, as envisioned, is a laminate comprised of aluminum foil with a polyester film on both sides. This provides a strong belt with smooth, clean surfaces where contact with the sail is made.

The folder is a double spiral, made of porous sheet metal. Each spiral is double walled so the annular space can be pressurized. The result is a folder where both surfaces that contact the sail material have an air bearing surface. With this design, the thermal control surfaces of the material never slide against any part of the machine.

As shown in Figure II-22, this machine is quite compact. It also allows the fabrication of the sail as a single sheet.

There are a number of disadvantages associated with this method which should be highlighted. First, some degradation of the thermal control surfaces is anticipated because of the number of times the material is run through the machine. As a new gore is added, the stack of previously sealed gores is expected to "fluff" up. As the stack is then wound onto the reel, it will crush down each time. This will cause some mechanical abrasion due to the two metalized surfaces rubbing together. The second disadvantage is that any time a repair must be made or a reinforcement added, the machine must be stopped, interrupting the sealing process. This complicates the web handling problem and also requires a much higher sealing speed. To fabricate the sail in six months, an average speed of 20 fpm must be maintained. The third disadvantage is limited inspection time. Once a gore is sealed, it is folded onto the stack and wound onto the reel. With this process, inspection must be done while sealing, at the average speed to 20 fpm.

As envisioned by this method, one gore is added each time through the machine. It is not recommended that multiple gores be added per pass since the folding operation would be greatly complicated resulting in additional degradation of the material.

In summary, this is a very compact fabrication method requiring minimal factory space and facilities. The disadvantages are high sealing speed, minamal inspection time, some expected degradation of the material and complex, costly machinery. For these reasons, this is not the preferred method.

2.3.5.2 Long Table (Half Sail) Method

Figure II-23 shows the Half Table (Half Sail) fabrication concept. As noted and discussed in the previous sections, this is the preferred method. The sail is fabricated in two halves, simultaneously, on two parallel tables. Two sealers are used and are guided down tracks on both sides of each table. Key components are indicated on Figure II-23 and as follows:

- Two long, parallel tables with tracks in the floor adjacent to both sides of each table;
- Two traveling sealers/folders guided in the floor tracks;
- Edge guide system for positioning the top gore in the sealed stack;
- Sealer with new gore unwind plus edge guiding and tension control equipment; and
- Double spiral folder with air bearing surfaces.

In practice, as shown in Figure II-23, the previously sealed gores would be folded and stored on the table. As a new gore is added, the top gore of the stack is picked up by the edge and held by the edge guide/tension monitor device. This positions the edge as it goes into the sealer. The sealer then dispenses the new gore and seals it onto the gore already folded onto the stack. The sealer is equipped with edge guide/tension moitoring equipment as well as necessary tape dispensers. To provide an exact butt joint, the two edges to be sealed are overlapped and a laser is used to cut both edges simultaneously.

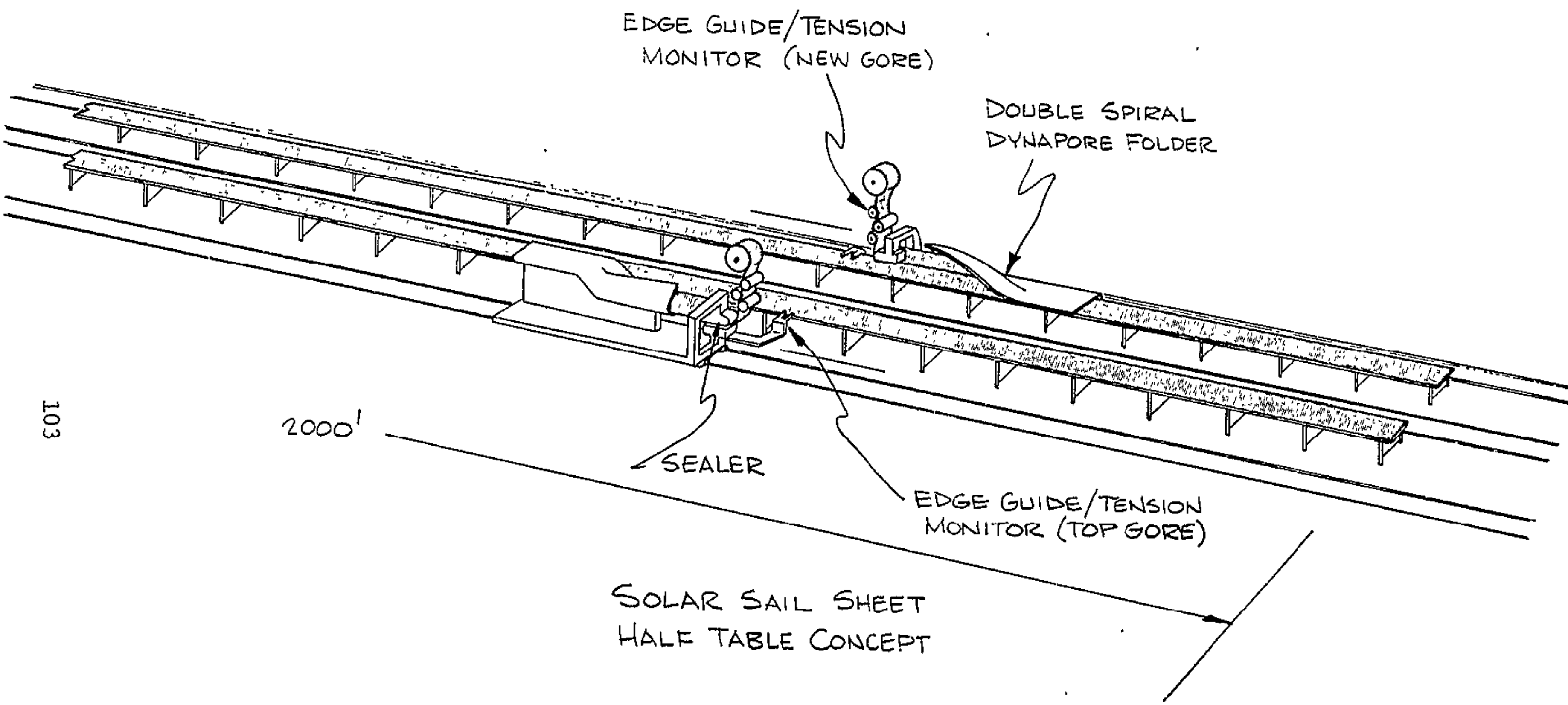

EDGE GUIDE/TENSION MONITOR (NEW GORE)
DOUBLE SPIRAL DYNAPORE FOLDER
2000'
SEALER
EDGE GUIDE/TENSION MONITOR (TOP GORE)
SOLAR SAIL SHEET HALF TABLE CONCEPT

Figure II-23

After the trim is removed, a controlled butt joint gap is the result. As the sealer travels down the table, all but the top gore of the stack goes under the bottom sealing device as shown. After sealing, the web enters the double spiral folder. This device has low pressure air bearing surfaces and folds the new gore onto the stack. The stack of gores on the table are then ready for the addition of the next gore from the other side of the table.

The sealer can be of a number of different types, depending on finally selected adhesive and sealing parameters. Possible ones are the wheel sealer, long band sealer, and the step/impulse sealer.

The folder is a double spiral made of a porous sheet metal. Each spiral is double walled so the annular space can be pressurized. The result is a folder where both surfaces that contact the sail material have an air bearing surface. With this design, the thermal control surfaces of the material never slide against any part of the machine.

After the two sail halves are complete, they are joined together along the diagonal while the sail is being folded and packaged into the flight canister. Figure II-24 shows this final step. After all but approximately 30 feet have been packaged, the two halves are brought together for joining.

Figure II-25 shows one method of making the final seam using an impulse sealer. As envisioned, the two edges to be joined would be brought together and overlapped. While being held by a vacuum clamp, a laser cutter would cut the two pieces providing an exact butt joint gap. The tape would be positioned and the seal made. This process would be repeated on alternate sides, as shown in Figure II-25.

As shown in Figure II-23, this method requires a very long fabrication facility. It also allows for the simultaneous fabrication of the sail in two halves.

There are a number of advantages with this method which should be highlighted. First, minimum degradation of the thermal control surfaces is expected. As each gore is added, it is folded onto the stack and not moved until the sail sheet is completed and ready for packaging. The second advantage is that any time a repair must be made or a reinforcement added, the sealing process need not be interrupted. Other crews can perform these operations both ahead of

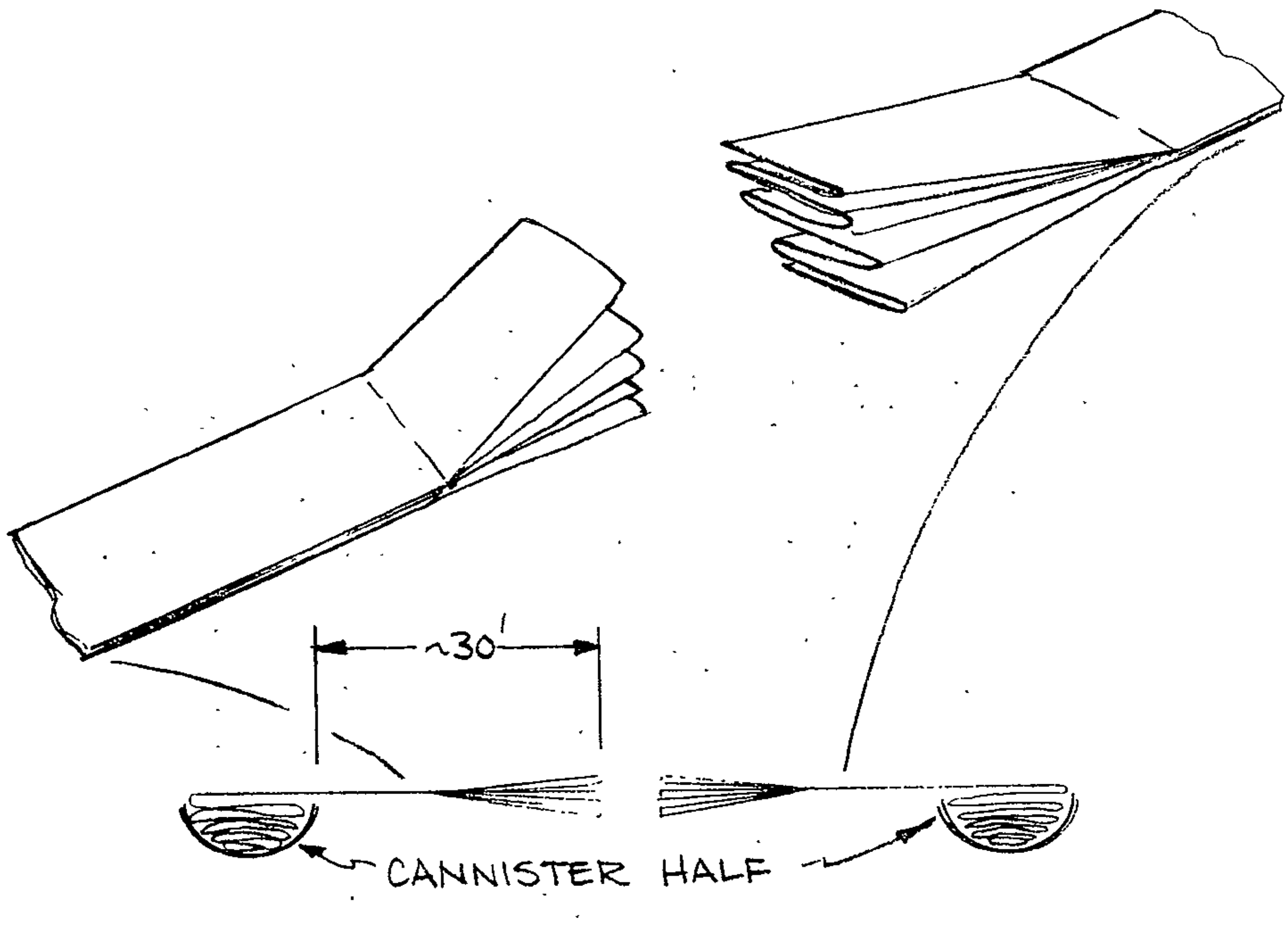


Figure II-24. Solar Sail Final Diagonal Seam Sealer Concept, Folding and Preliminary Packing

Figure II-24

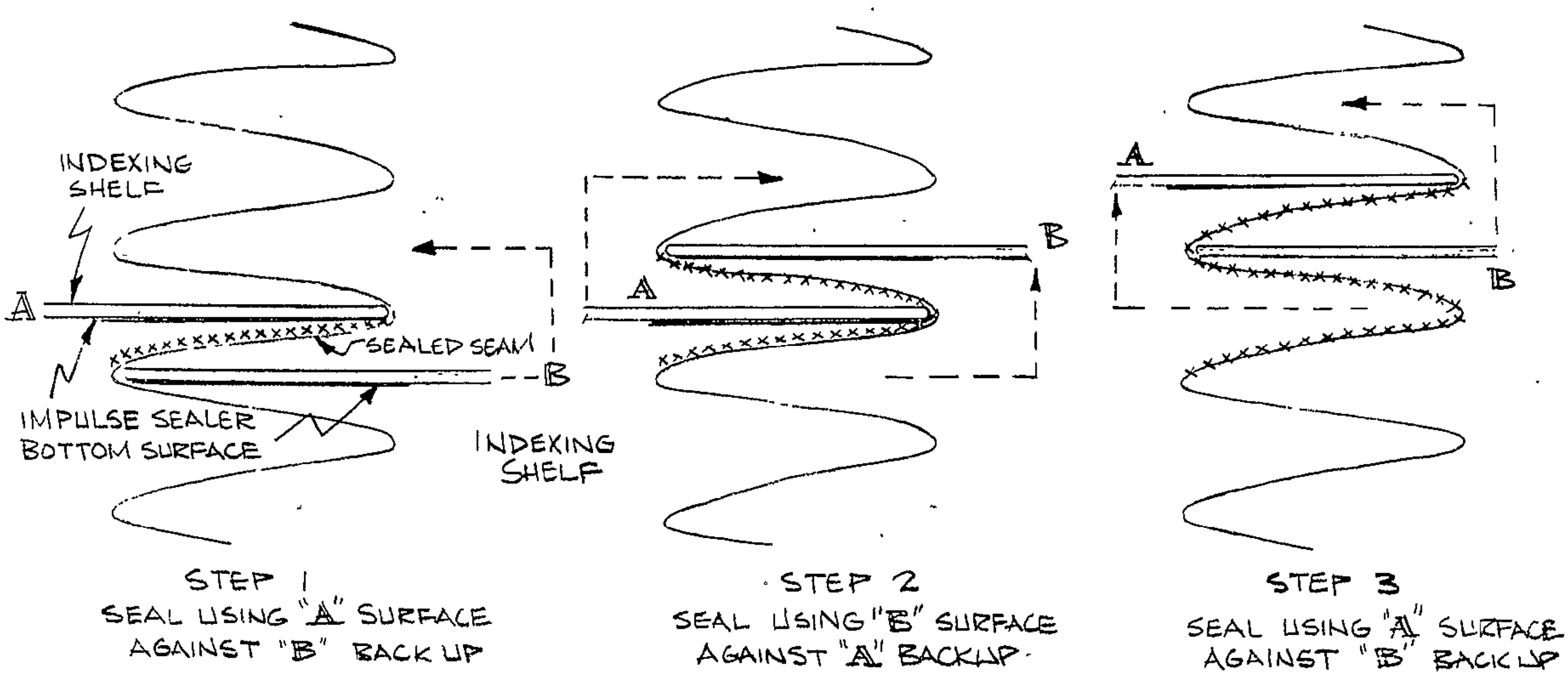


Figure II-25. Solar Sail
Final Diagonal Seam Sealer Concept

or behind the traveling sealers. The third advantage is inspection time. Gore material and seams can be inspected both ahead of and behind the sealers. Finally, as envisioned, this method requires that only a 10 fpm sealing speed be maintained. This is easily attainable since all other operations can be performed simultaneously with the seaming.

As envisioned by this method, one gore is added at a time. It is not recommended that multiple gores be added per pass since the folding operation would be greatly complicated, resulting in additional degradation of the material.

In summary, this method provides for fabrication of the sail with minimum material handling and degradation. It also provides for a low sealing speed and maximum inspection time. For these reasons, this is the preferred method.

2.3.6 Repair and Rework Techniques

As mentioned in Section 2.3.5, time has been allowed for repair and rework. For the Reel-to-Reel method, the entire seaming operation must be stopped while the work is performed. For the preferred Half Table (Half Sail) method, the work can be performed without interrupting the seaming. The equipment required for repair work would be the same as needed for adding the edge, corner, and center reinforcements.

If there is a tear in the material to be repaired, the defective area would be held by a vacuum clamp; the repair tape positioned and the tape impulse sealed in place.

If it should be necessary to remove the defective area and a new piece added, the same equipment would be used for adding a new piece as was used for repairing the tear. The defective area would be cut out, leaving a narrow salvage edge. The new piece of material (slightly oversize) would be positioned, slightly overlapping the salvage edge. While being held by a vacuum clamp, a laser cutter would cut the two pieces providing an exact butt joint gap. The tape would be positioned and the seal made. An impulse sealer would be used. The portable cutter/sealer would then be repositioned and the process repeated until all sides of the rework area had been resealed.

2.3.7 Film Cutting Methods

Three methods of cutting the 0.1 mil Kapton (or similar) plastic film were investigated. They were as follows:

- Fluid-jet, high-pressure water cutters manufactured by McCartney Mfg. Co.;
- Laser cutters manufactured by Hughes Aircraft Co.; and
- High speed rotary knife as presently used by Sheldahl.

Samples of the following plastic films were used for the evaluation:

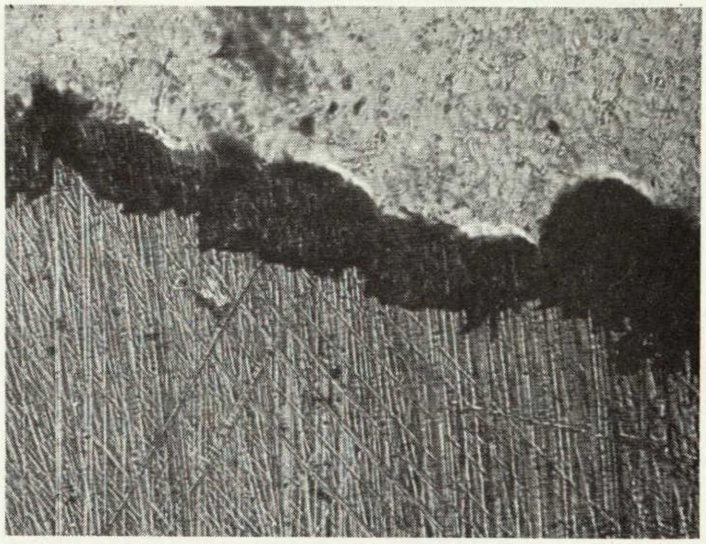
- 1/3 mil Kapton (plain)
- 1/10 mil Kapton (chem. milled by JPL) metalized on one side with 1000 Å aluminum and on the other with 125 Å chrome; and
- 1/10 mil Mylar metalized on one side with 1000 Å aluminum.

The 1/10 mil Mylar and 1/3 mil Kapton were used for equipment set-up and initial evaluation. Final samples were made using the 1/10 mil metalized Kapton.

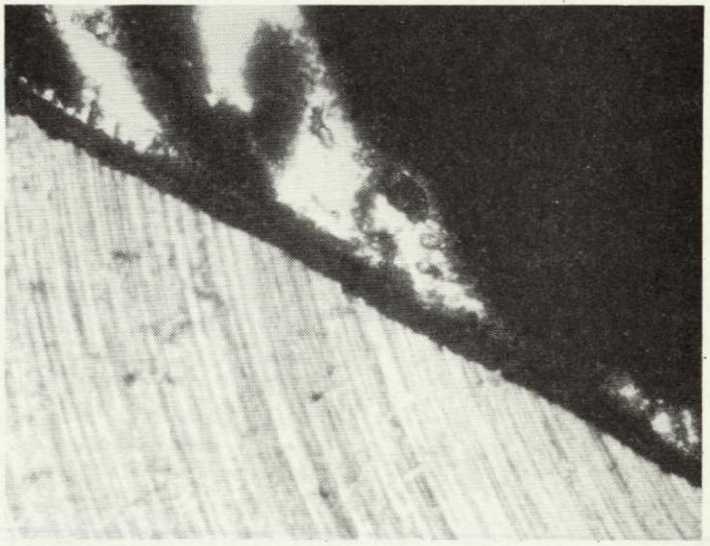
Fluid-jet, high-pressure water cut samples were made by the manufacturer (McCartney Mfg. Co.) and the typical result is shown in Picture A of Figure II-26. Cutting was done at 45,000 psig using a 5 mil diameter jet. Results were quite good and although the edge appears quite ragged, the tear resistance seemed excellent. Some removal of the metalizing is apparent due to overspray adjacent to the cut. The irregularity of the present cut would also exceed the 3 mil maximum gap if two pieces were butt joined. While no corrosion of the metalized surfaces has been noted, there is concern that the water and chemical additives may have a long term detrimental effect.

Laser cut samples were made by the manufacturer (Hughes Aircraft Co.) and the typical result is shown in Picture B of Figure II-26. Cutting was done using a 5 mil diameter beam. Results were very good and the edge irregularity seems within acceptable limits. Some discoloration of the adjacent metalizing was noted. This is caused by beam spread. Modifications are available to eliminate this. Discussions with the manufacturer also indicate a cut width of 1 to 2 mils is also possible.

A – Fluid-jet,
McCartney Mfg. Co.
125 x



B – Laser,
Hughes Aircraft Co.
125 x



C – High-speed rotary
knife, Sheldahl
125 x

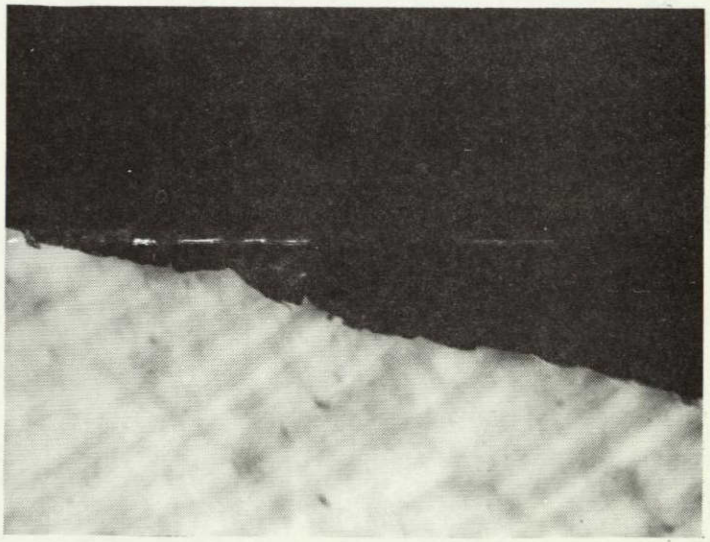
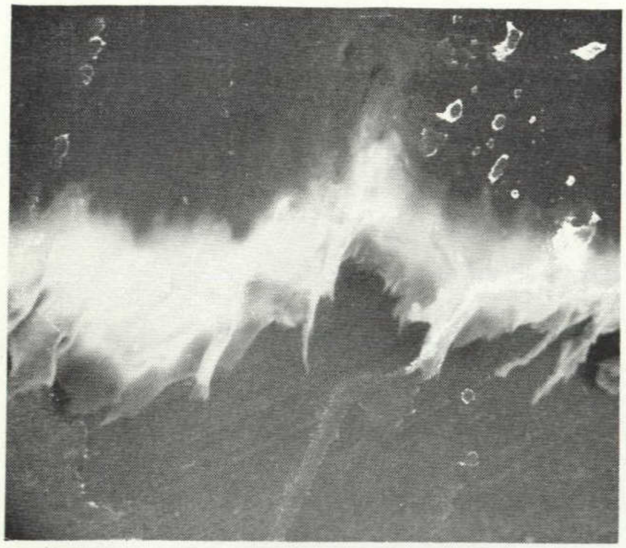
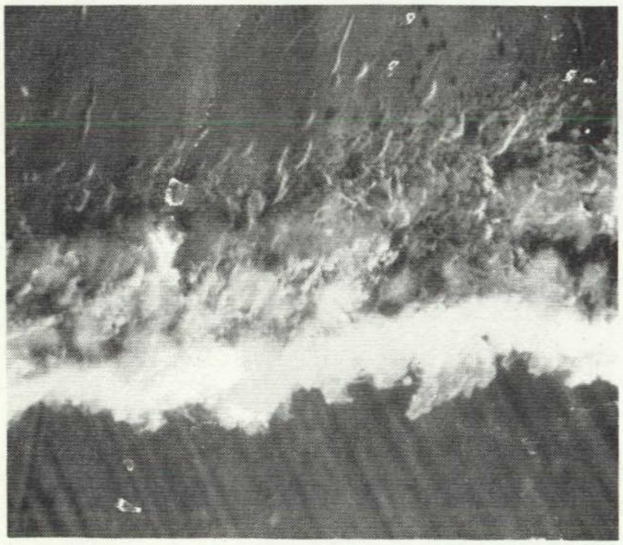


Figure II-26. Film Cutting Methods



A – Fluid-jet
McCartney Mfg. Co.
200 x



B – Laser,
Hughes Aircraft Co.
560 x

C – High-speed rotary
knife, Sheldahl
540 x

Figure II-26. Film Cutting Methods

High-speed, rotary knife cut samples were made by Sheldahl. This was done using current production cutters. The typical result is shown in Picture C of Figure II-26. Results were acceptable.

As a result of the preliminary evaluation, it is felt the laser cutter offers the most advantages and is the preferred method. Modifications are available to provide a 1 to 2 mil cut, thereby eliminating the need to re-position the material to obtain the 3 mil maximum gap. The high-speed rotary knife would be the best alternate choice.

2.3.8 Canister Packing

Reference has been made to packing in some of the previous sections, particularly in Figure II-24 for the Half Table (Half Sail) fabrication method.

For the reel-to-reel method, the canister half would be placed adjacent to the belt. The material would then be fed and folded into the canister. Manual folding with mechanical aids would be used. If necessary, a fixture could also be made which would cradle one half of the canister and control wrap-around length of the sail as it is folded up.

Packing for the Half Table (Half Sail) method is shown, in part, in Figure II-24. Each half would first be packaged into a canister half. Folding would be manual with mechanical aids. After the final seal was completed, the remaining material would be folded into the appropriate canister half. With mechanical aids, the two halves would be placed together and the canister closed.

Note: See Paragraph 1.4 concerning packing considerations.

2.4 Quality Assurance and Inspection

2.4.1 Quality Assurance Plan

To assure adherence to all specifications, an extensive quality assurance plan must be developed. Figures II-27 through II-29 indicate suggested process control points and measured inspection characteristics at each. Figure II-27 represents a flow plan if the base material, Kapton, is metalized and the sail fabricated at the same vendor under the Half Table (Half Sail) method. The Half Table method is the preferred choice of sail fabrication. Figure II-28 represents the flow plan if the metalized Kapton is purchased or furnished GFE. Figure II-29 is an optional panel sealing technique representing the reel-to-reel sealing method.

2.4.1.1 Material Receiving

Inspection characteristics of incoming materials, as shown in Figure II-27, are fairly standard. The common points of identification, certification and packaging will be checked. In addition, a portion of the beginning of each perforated Kapton roll will be verified for weight (thickness) and dimensions of perforations. If material is purchased already metalized, source inspection personnel may be based at the material vendor to verify material properties being shipped. With each metalized roll shipped to the sail fabricator, a thermal/material properties computer data tape (as a function of footage) will be required to facilitate selective panel cutting/sealing during fabrication.

2.4.2.2 Metalizing Process

If the vacuum deposition process is performed at Sheldahl, machine/process settings will be verified by quality control. In addition, surface resistance in ohms/square and a deposition crystal monitor system will be used inside the deposition chamber to control metalizing thickness. Past experience indicates that resistance is a means of verifying metallic coating thickness and will be helpful in flagging possible bad footage. Both surface resistance and crystal deposition thickness will be recorded as a function of footage for use in removing reject material later in the fabrication cycle.

If required, it is also possible to measure emissivity of the deposited surfaces in the vacuum deposition tank. ε may be measured at one wavelength

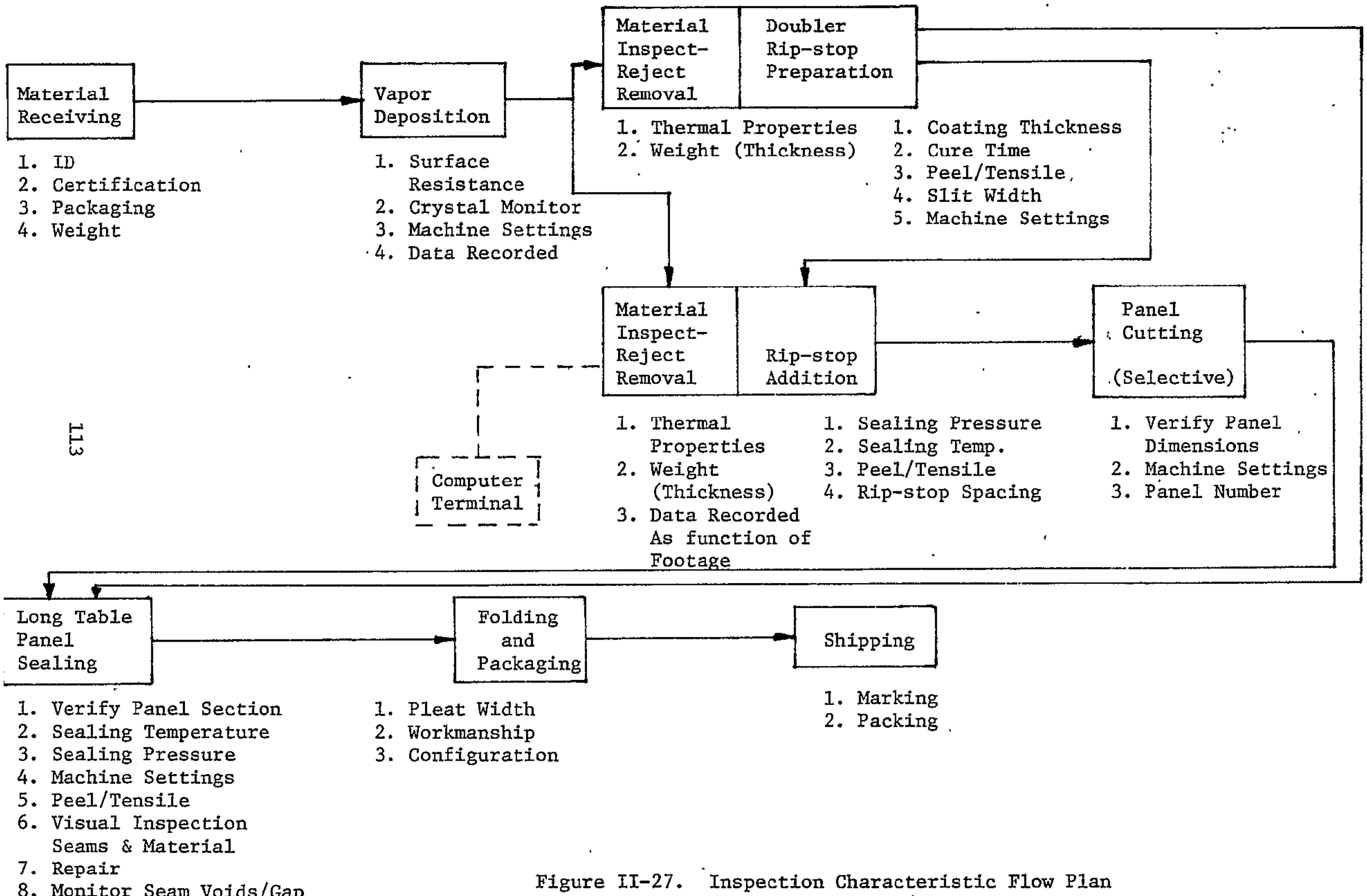


Figure II-27. Inspection Characteristic Flow Plan (Vapor Deposition/Fabrication, Same Vendor

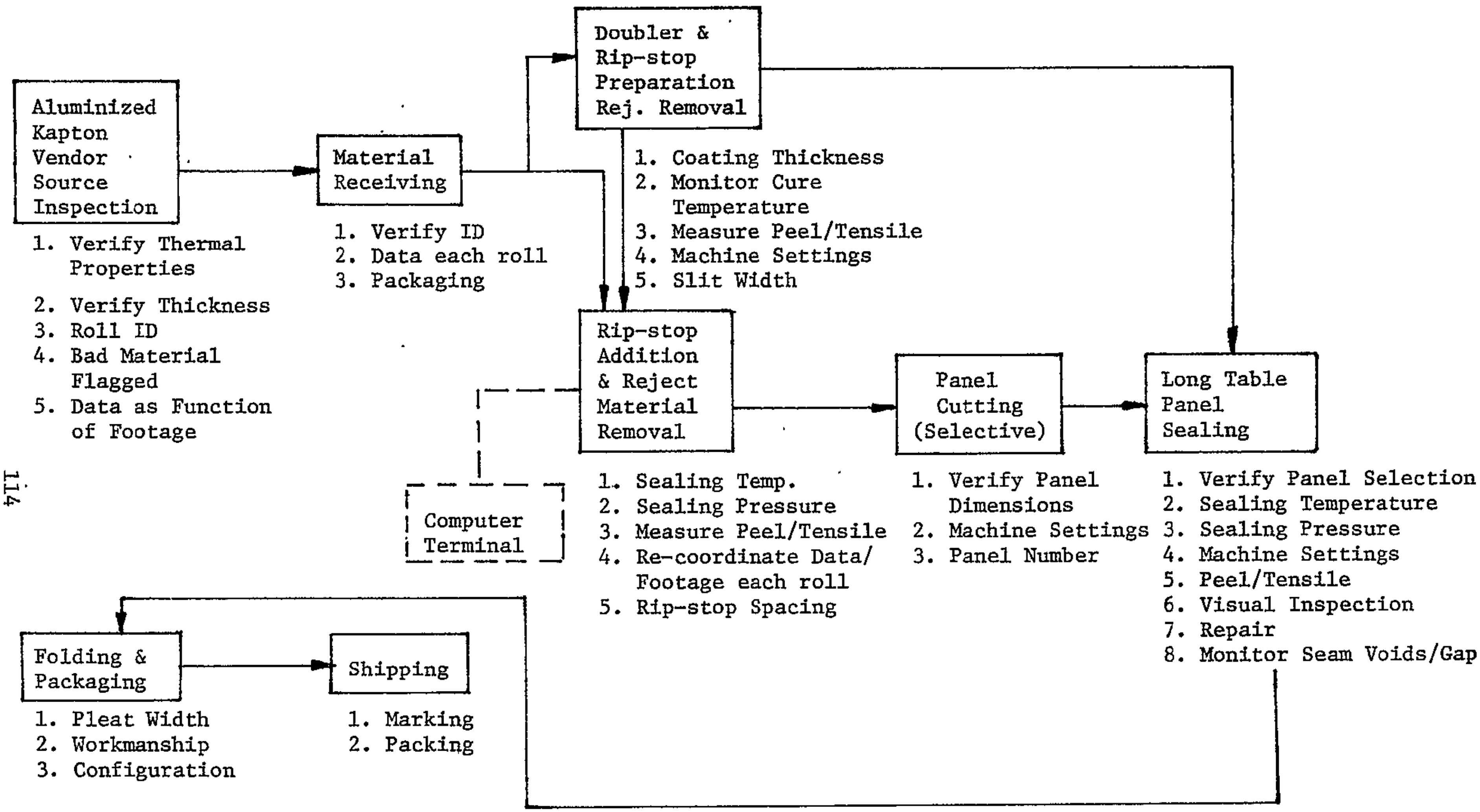


Figure II-28. Inspection Characteristic Flow Plan (Base Material Purchased)

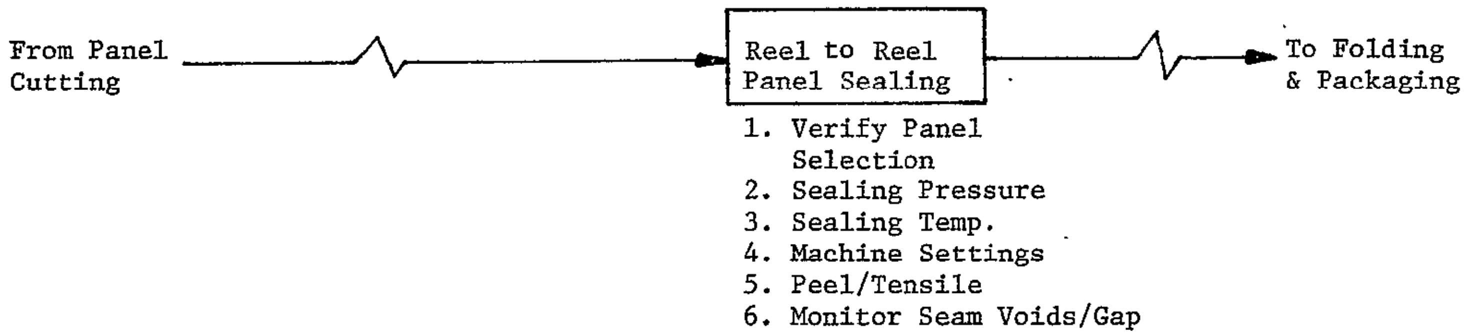


Figure II-29. Inspection Characteristic Flow Plan Reel-to-Reel (Optional Sealing) Method using a low power CO_2 laser scan. Since the reflectance curve for aluminum is fairly flat, this system could be used as a go, no-go acceptance criteria for the thermal property. Correlation runs would initially be required to establish both emissivity and surface resistance acceptance levels.

Both measurement of solar reflectance and an optical monitoring system (light transmission) to control uniformity of the coatings across the web could be added to the deposition process if required. But, it is suggested that as much instrumentation as possible be kept out of the vacuum tank itself. Only those monitors required for direct machine control of the metalizing thickness are recommended. This is to reduce the material run length and any extra rollers, resulting in less handling of the material. Second, from past experience, this will reduce instrumentation interference from the many power sources and electrical fields expected to be encountered in and around the vicinity of the vacuum tank. Third, less instrumentation and equipment in the tank will reduce tank size, space, complexity and vacuum pumpdown time. Since final inspection and removal of reject material is planned immediately after vapor deposition, this appears the best time to measure material properties in a "hands on" environment, eliminating most of the requirement for coordination of computer-recorded data versus footage during vapor deposition.

2.4.1.3 Material Inspection/Reject Removal/Rip-Stop Addition

At the beginning of fabrication, rolls of metalized sail film will require rip-stop addition at predetermined intervals. This affords an ideal time to measure thermal properties, weight (thickness) and remove reject material, since a pause is required in the rolling stock to apply the rip-stop. This removes the problem of measuring thermal properties on a moving web of material, especially solar reflectance which requires a long time measurement. A computer terminal would be located at this process point to record all data as a function of footage. This data will be used for selectively choosing rolls and subsequent panel location in the final sail. A computer program will be required to average the properties of each roll inspected and choose which roll is to be used for each panel/sail location to equalize sail dynamic stability. Measurements to be made at this point will consist of emissivity on the aluminum and chrome sides, solar reflectance on the aluminum side and material weight (thickness).

In addition to periodic weight measurements of the web, each finished roll will be weighed to verify the final computer average.

It should be noted that the property measurements would not be done if metalizing is completed at another vendor other than the sail fabricator. The required computer data tape of properties/footage from the metalizer would be used at this point to accept and reject in-process material (Ref. Figure II-28).

After the base material has been inspected, accepted film is either routed to doubler/rip-stop adhesive coating and slitting, or to rip-stop addition of main sail material. Process characteristic measurements at this point are common standard techniques in the thin film industry. Machine settings of cure and sealing temperatures and sealing pressure will be monitored by manufacturing and quality personnel. Manual measurements of coating thickness, peel/tensile samples and rip-stop spacing will be taken. The rip-stop will then be checked for unbonds or voids in the sealed tape of greater than 0.010 diameter. This can be accomplished using ultrasonic techniques. Krautkramer-Branson of Stratford, Connecticut, can supply the instrument after verification of a sample seam first.

2.4.1.4 Panel Cutting, Panel Sealing

As shown in Figure II-27, cutting of panels will be done on materials selectively picked by computer. Panel contour (tailored gores) can be controlled easily be computer tape input driving the slitting heads. Machine settings will be monitored by manufacturing personnel. A check of cutting dimensions will be performed by prepunched tape or by key and the distance between cutters verified by scale. Each panel should be numbered for identification and sail location prior to panel-to-panel sealing. Increment marks will be added along the edges of each cut panel at a predetermined repeated distance. These will be used during sealing to verify panel footage, monitor material stretch and align successive panels with each other.

Two methods of panel sealing are proposed; reel -to- reel and long-table sealing. The long-table method is the preferred system. In both methods, panel ID, sealing temperatures and pressures, machine settings and peel/tensile samples should be verified. These are again standard measurements now performed on similar thin film fabrication items and no problems with technique or method are expected. Peel/tensile samples of seals are usually cut from the ends of panels in thin film fabrication. An extra 3 to 6 feet of panel material is sealed and then removed for test specimens. Samples could also be made on the same sealing head immediately next to the seal in process.

All seals will be automatically monitored for a 3-mil butt joint gap, and for 10-mil maximum diameter voids and unbonds. The gap can be measured using a Beta particle transmission technique which for this application would probably require a specially designed instrument (United Process Assemblies, Syosset, New York). Voids would be monitored using ultrasonics. An alternate method to check voids and gap width would be to "paint" the seal areas with an artificial sun after bonding. Burn though of gaps and voids could then be detected with a light transmission sensor system. This technique has the advantage of guaranteeing that the final seal will actually perform under operational conditions.

Since the reel-to-reel method could be sealing up to 60 fpm and the long-table method 10 fpm, the table method offers an extra "last chance" inspection of the sail before folding and packaging. A post sealing inspection would include observing for unbonded seals, misaligned seals, and damage to sail material during fabrication (holes and tears). Unlike the reel-to-reel method, inspection and repairs in the table method could be made without interfering with the sealing process. It can be expected that there will be much less handling and mutilation of the material in the table method of fabrication.

2.4.1.5 Packing

One major problem throughout the manufacturing cycle will be handling and damage from handling. This will also become apparent during folding and packaging of the unit when many layers of the thin base material will be pleated and folded into the launch container. Inspection of pleat width, workmanship, and configuration should be performed. Pleat width may be controlled with a simple trough equal to the maximum width allowable to hold the sail before packing into the canister. A fixture could also be made which would cradle one half of the canister and control wrap-around length of the sail as it is folded in.

2.4.2 Test Equipment/Problems

Table II-2 lists inspection characteristic, measurement method and a typical instrument now available on the market for performing inspection.

One major area of additional equipment study will be for the material inspection, reject-removal procedure. Speed of measurement required may become of some concern. The Gier Dunkle IR Reflectometer is portable and capable of measuring and delivering emissivity in 3 seconds. The Lions Solar Reflectometer will give immediate measurement, but only at one wavelength. It is dialable over 11 or 12 wavelengths. Lions' personnel indicate that for a few thousand dollars, a machine could be modified to quickly scan all wavelengths and print a computer-averaged reflectance over the waves required. As shown in Table II-2, weight could be monitored as a measured function of thickness by using either a Beta backscatter or a linear non-contact comparison technique.

Another major area of further equipment study and the area most likely to be a problem is the continuous monitoring of bonding efficiency of the doubler tape. It is questionable whether instrumentation and a technique can be attained for measuring the small gap width and voids in the seals. The method and instrumentation will definitely have to be proven on sample seals by the instrument manufacturer first. As stated previously, measurement of the gap width may be accomplished with Beta-particle transmission using an instrument designed and tested specifically for this purpose.

Some trouble may be encountered in the correlation of measured data with footage on each roll of final sail. An extensive computer program must be written with the ability to remove that footage not used and to re-number all the footage remaining throughout all processes and inspections.

Although the above problems are foreseen in the equipment area of inspection and quality control, none appear unsurmountable with the technology available today.

Table II-2. Fabrication Test Equipment

FABRICATION OPERATION	INSPECTION CHARACTERISTIC	MEASUREMENT METHOD	TYPICAL EQUIPMENT	COMMENTS
Material Receiving	Weight	Gram Balance	Mettler Balance	
Vapor Deposition	Deposition Thickness	1. Digital Ohmeter 2. Deposition Crystal Monitor	1. Simpson Digital Ohmeter 2. Inficon XTM System	1. In-Vacuum Surface Resistance (Ω/□) All Data Computer Recorded
Material Inspection-Reject Removal	1. Thermal properties: -emittance -reflectance 2. Weight (Thickness)	1. IR reflectometer Solar reflectometer 2. Beta Backscatter or Linear Comparison Gage	1. Gier Dunkle Model DB-100, Lions R25C 2. Compuderm, Beta Scope, or Micro-sense - 3046 (ADE Corp.)	All Data Computer Recorded
Doubler & Ripstop Preparation	1. Coating Thickness 2. Cure Temperature 3. Peel/Tensile 4. Tape Width	1. Gram Balance 2. Thermocouple 3. Force-Deflection Tester 4. Rule	1. Mettler Balance 2. Standard Machine Control 3. Instron Model 1130	
Panel Cutting	Panel Dimension	Computer Controlled		
Panel Sealing	1. Sealing Pressure 2. Sealing Temp. 3. Peel/Tensile 4. Seam Gap Width 5. Seam Voids	1. Air Pressure Gauge 2. Thermocouple 3. Force-Deflection Tests 4. Beta Transmission 5. Ultrasonic	1. Standard Machine Control 2. Standard Machine Control 3. Instron Model 1130 4. Special Design (UPA Inc.) 5. Krautkramer-Branson	Alternate for 4 & 5 is artificial sun burn-through followed by light transmission detection
Folding and Packaging	Pleat Width	Rule, Template/Fixture		

3.0 ECONOMIC, SCHEDULE, FACILITY CONSIDERATIONS

3.1 Existing Facilities and Equipment

Factory space and capacity required for either or both of film metalizing and sail fabrication are not available at Sheldahl at this time and is not foreseen to be in the time periods required for performance as contemplated by preliminary program plans and schedules discussed in Paragraph 3.3.

Similarly, machinery, equipment, tooling and fixturing are necessarily highly specialized and unique to the purpose. Neither at Sheldahl, nor to our knowledge, any place else in the world does equipment of the type required exist.

3.2 New Facilities and Equipment

3.2.1 Factory Facilities

Preliminary analyses of factory space and related requirements were performed for both the Reel-to-Reel and Half Sail (Long Table) manufacturing methods.

Figure II-30 illustrates the overall building dimensional aspects of the two methods. The preferred and recommended fabrication method (see Paragraphs 2.3.2.1 and 2.3.2.2) would require a building of approximately 87,875 square feet of rather unusual proportions for the Half Sail method as compared to a smaller building of approximately 15,750 square feet and more conventional proportions for the Reel-to-Reel method.

Figure II-31 is a layout indicating space needs and utilization of the larger facility required for the Half Sail (Long Table) approach.

Figure II-32 provides a further detailed layout of the smaller facility indicating space utilization intended, should the Reel-to-Reel fabrication method ultimately be selected.

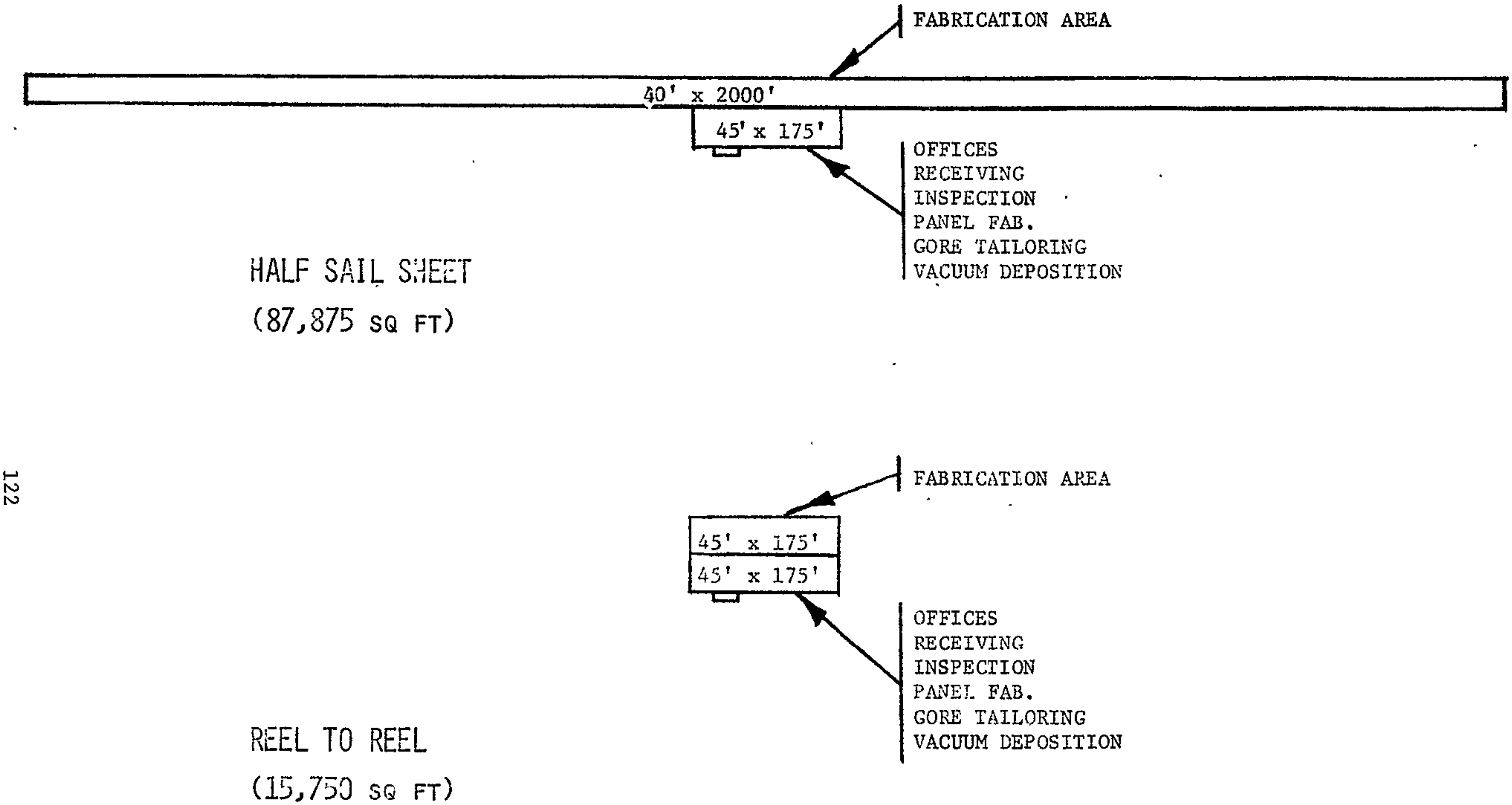
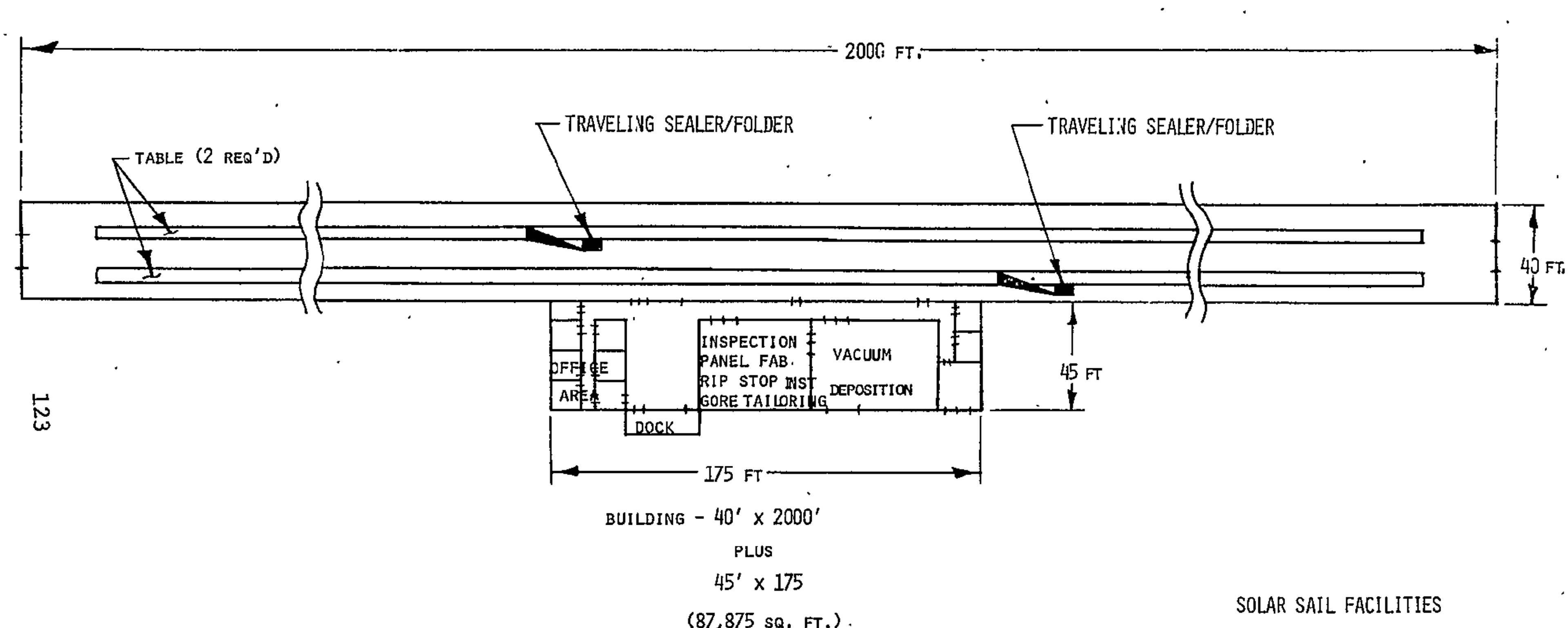
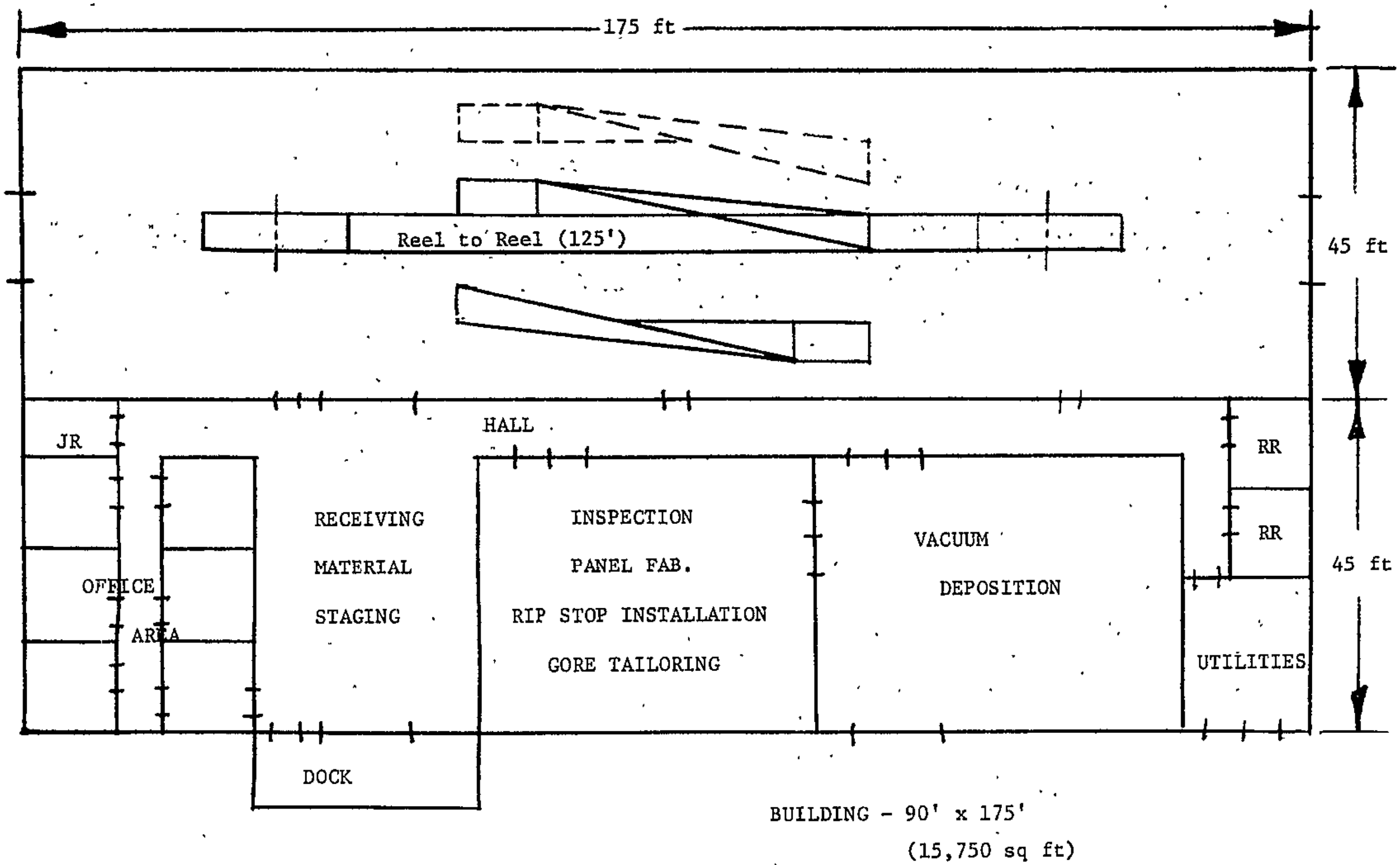


Figure II-30. Solar Sail Facilities
- Half Sail Sheet
- Reel to Reel



SOLAR SAIL FACILITIES
_ HALF TABLE FABRICATION
_ WITH VACUUM DEPOSITION

Figure II-31



SOLAR SAIL FACILITIES

- REEL TO REEL FABRICATION
- WITH VACUUM DEPOSITION

8 MAY 1977

Figure II-32

The bottom half of both layouts, illustrating office, receiving, inspection, panel fabrication, gore tailoring and vacuum-deposition space requirements would be the same in either instance.

Despite appearances and significant building size differentials, Sheldahl's preliminary evaluation, reflected in the trade-off analysis, Paragraphs 2.3.2.1 and 2.3.2.2, and in total ROM program costs, Paragraph 3.4, indicate cost-effectiveness and technical preference for the larger facility.

3.2.2 Manufacturing Equipment

Special machinery, equipment, tooling and fixturing requirements are discussed and illustrated in the narrative and figures contained in Paragraph 2.3 and subparagraphs.

In summary, requirements for the Reel-to-Reel versus preferred Half Sail (Long Table) methods are as follows:

	Reel-to-Reel	Half Sail (Long Table
1) Sail fabrication machine	X	X
2) Gore tailoring machine	X	X
3) Panel inspection, splicing Rip-stop application, etc.	X	X
4) Special sealer - repair, splicing, etc.	X	X
5) Canister packing, incl. vacuum packing, etc.	X	X
6) Final seam sealer		X

Primary differences in the above equipment requirements are twofold: First, sail fabrication (sealing, folding, etc.) machinery for a Reel-to-Reel manufacturing method is significantly more complex and costly than for the traveling sealer/folders required for the Half Sail approach.

Second a final seam sealer is, of course, not required in a Reel-to-Reel manufacturing method.

In terms of equipment costs, the advantage is significantly in favor of the Half Sail method to the extent that higher costs for a larger facility are offset. The ROM cost data presented in Paragraph 3.4 are in sufficient detail to assess this cost trade-off.

3.3 Program Plan and Schedule

3.3.1 Half Sail (Long Table)

Figure II-33 depicts the overall program phasing of key events and activities for carrying out the program assuming the use of long tables and fabricating two half sails simultaneously. This planning and phasing is generally compatible with key constraints and milestones furnished by JPL in terms of end dates and front end definition of requirements, contracts let, completion of sail sheet designs and release of material specifications.

The general intent and scope of effort contemplated in each of the phases is as follows:

- ϕ 0 – Extension of square sail design and/or manufacturing studies through September 30 (Government FY 77);
- ϕ I – Preliminary designs and specifications – sail manufacturing equipment, facilities and methods;
- ϕ II – Final, detail machinery and equipment designs; fabrication of machinery, equipment, tooling and fixtures; metalizing and fabrication process and QC specs; perforate, metalize, fabricate and delivery prototype, PTM and flight sails.

3.3.2 Reel-to-Reel

The phasing of activity under a Reel-to-Reel manufacturing method would be virtually the same except for longer lead times associated with the definition of requirements, design, fabrication and checkout of the specialized reel-to-reel seaming and folding equipment.

Project start would be approximately six months earlier. In effect, Phase I activity would have to include letting of contracts for, and commitment to, the long lead fabrication equipment.

FOLDOUT FRAME 1

ORIGINAL PAGE IS OF POOR QUALITY

SOLAR SAIL SHEET (SQUARE SAIL)

PROGRAM PLAN - HALF SAIL MANUFACTURING METHOD

FOLDOUT FRAME 2 ORIGINAL PAGE IS OF POOR QUALITY

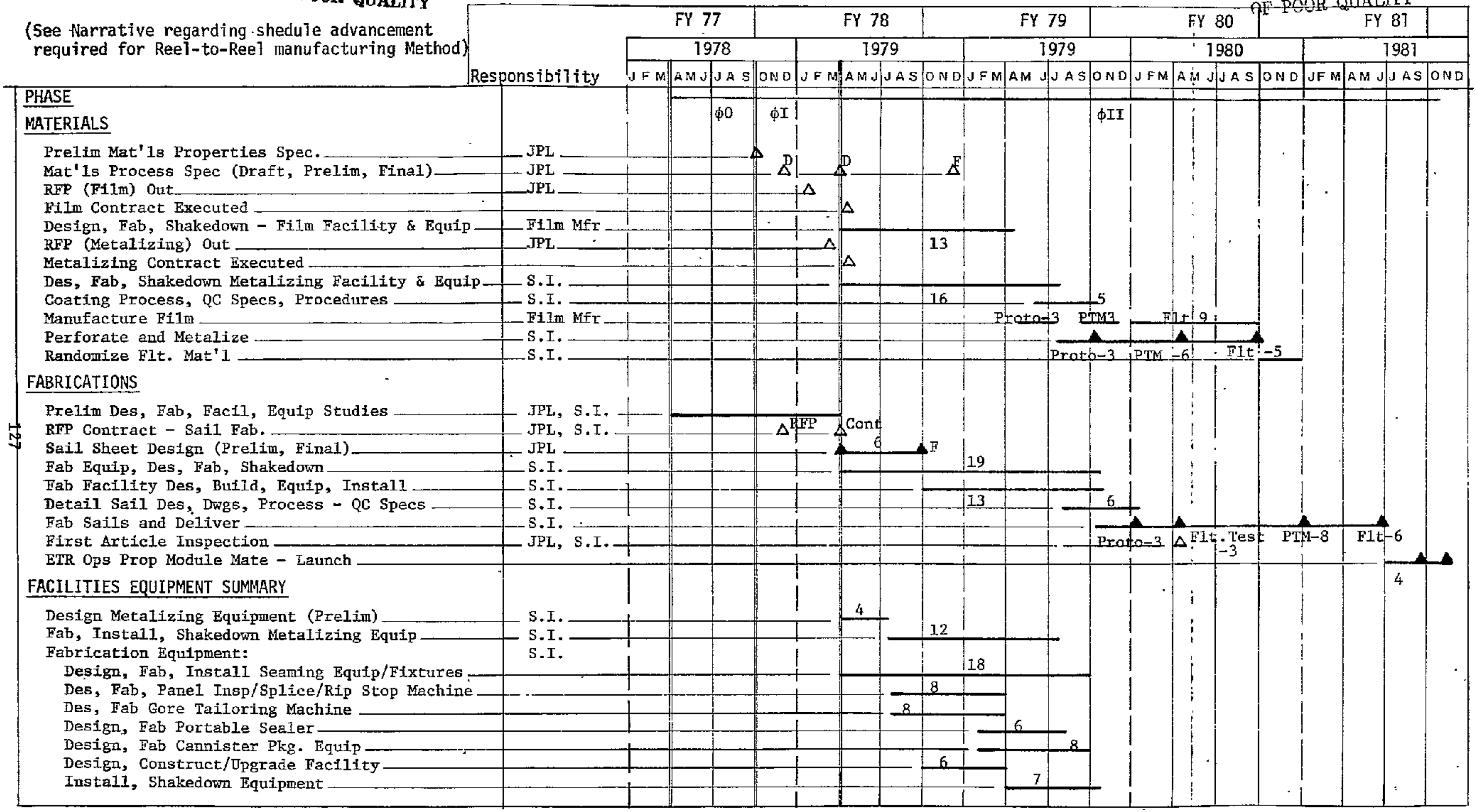


Figure II-33

3.4 ROM Cost Estimates

Table II-3 presents a preliminary ROM estimate of costs for both the Reel-to-Reel and preferred Half Sail (Long Table) methods of manufacture.

While totals are not significantly different, a cost advantage is indicated for the Half Sail approach.

Within the various cost segments, however, there is clear indication of a significant cost advantage associated with the less complex manufacturing methods and equipment of the Half Sail which is in part offset by the higher cost resulting from larger space and facilities requirements of this method.

Costs shown encompass Phases I and II activity only, excluding any extension of pre-project studies or experimental work, and also assume Government-furnished raw film material.

The allocation of facility costs between Materials and Fabrications is arbitrary. A single facility is planned, and allocated costs indicated do not stand alone.

Although not fully explored, among alternatives that may be considered for providing factory space is an existing government-owned facility. In addition, lease of facilities of the type needed, if available when required under suitable terms and satisfactorily located, could be investigated. A further option, preferred by Sheldahl, would be the construction of a facility to our specifications in reasonable proximity to Northfield. This option contemplates financing by the contractor or other agencies and lease to Sheldahl for the period and under other terms compatible with needs.

Financial trade-off of costs to the government of construction of a new facility versus lease of existing or new facilities over an extended period have not been performed.

Table II-3

ROM Costing - Solar Square Sail

(Phase I-II Combined)

Haley's Mission

(1977 Dollars - 000's)

	Reel-to-Reel Method	Half Sail Method
I. MATERIALS		
A. Machinery and Equipment		
1. Conceptual Designs	90	90
2. Detail Design, Fab, Install, C/O	1,600	1,600
	1,690	1,690
B. Metalizing		
1. Non recurring	15	15
2. Coatings (GFE Film)	2,075	2,075
	2,090	2,090
*C. Dedicated Facility	50	50
SUBTOTAL MATERIALS	3,830	3,830
II. FABRICATIONS		
A. Program Management	640	535
B. Machinery and Equipment - Sail Fab		
1. Sail Fabrication Machine	1,350	200
2. Gore Tailoring Machine	150	150
3. Panel Inspection, Splicing, Rip stop, etc.	150	150
4. Special Sealer - Repair, etc.	25	25
5. Canister Packing Equipment	200	200
6. Final Seam Sealer	-	75
	1,875	800
C. Fabrications		
1. Non recurring	25	1,025
2. Fabrications	4,740	4,740
	4,765	4,765
*D. Dedicated Facility	175	25
SUBTOTAL FABRICATIONS	7,455	7,125
TOTAL PROGRAM	11,285	10,955

*Approximate allocation by space utilization. A single dedicated facility planned. Materials, Fabrication facility prices do not stand alone.

4.0 AREAS REQUIRING FURTHER ATTENTION

This section contains a topical list of candidate fields for further study of feasibility, requirements, definition, preliminary designs, etc.

The original intent was to enlarge on the importance or reasons for extended study and/or the nature and scope of further efforts suggested. I view of the determination to redirect activity and the focus of attention to the spinning sail, no further effort was made here.

To the extent applicable, some or similar items will have also been discussed in Section I of this report.

4.1 Metalizing chambers and equipment - requirements, characteristics, conceptual designs

4.2 Sail fabrications equipment - requirements, characteristics and preliminary designs

4.3 Thermal control coating degradation - test and evaluation

4.4 Tear Propagation - analysis, test and evaluation

4.5 Facilities - requirements, availability, alternatives, trade-offs

4.6 Loads and stress analysis - corner and center design

4.7 Seam quality/integrity, monitoring equipment and techniques

4.8 Continued materials test and evaluation

- Adhesive systems, seaming techniques
- Blocking tests - coated surfaces and tape/adhesives squeeze-out
- Heat/aging tests

4.9 Sail shape

- Gore tailoring
- Edge straightening (wrinkle reduction)

4.10 Test equipment requirements - special designs, etc.

- Inspection/rejection/removal procedure (measurement speed)
- Continuous monitoring of bond integrity
- Measurement of butt joint gap
- Correlation of measured data with footage, each roll

4.11 Alternate canister design employing venting techniques to avoid canister structural design problems

5.0 VERIFICATION OF CONCEPTS AND FABRICATION TECHNIQUES

This task was contemplated as one in the statement of work that would be undertaken under JPL technical direction on a change in scope basis.

Verbal instructions to proceed with a project to fabricate a 2000 sq. ft. segment of sail using .1 mil Mylar coated with 1000 Å aluminum were received in the course of the May 10 - 11 coordination meeting. The purpose was to demonstrate seaming, folding and packing methods with a film having characteristics reasonably similar to the baseline Kapton and to document results in a movie film.

Materials were ordered and preliminary work to design, secure and modify tooling and fixtures was started before notice was received of program redirection to pursue the spinning sail configuration.

The following film "script" was developed and intended as the scene sequence. The "script" is included in this report for later reference in the event a filmed demonstration project is deemed feasible and useful in conjunction with the spinning sail blade. Those sequences dealing with the metalizing portion of the task would remain essentially the same.

Square Sail Fabrication Demonstration Film "Script"

1. Raw film - received and ready to insert in vacuum deposition chamber.
2. Overall view of vacuum deposition Chamber #5 - open position.
3. Vacuum deposition Chamber #5 with film loaded and being closed.
4. Metalizing process inside chamber (if possible to film).
5. Chamber #5 being opened - remove metalized film.
6. Samples being measured (tested) for A and E characteristics.
7. Inspection -- roll-to-roll-- in Thin Films area or doctor machine.
8. Repair/splicing/rip-stop operations simulation with Vertrod Sealer-adjacent to inspection machine.
9. Overall shot -- Reel-to-Reel fabrication machine.

10. Closeup - edge guiding - sealing operation.

11. Transition.

12. Closeup - folding and stacking.

13. Above two steps repeated from opposite sides of machine.

14. Final overall shot - zoom back away.

15. Final shot - girls holding sealed and folded stack sufficient to show approximately 10 seals and folds.

Appendix

APPENDIX

SOLAR SAIL ADHESIVE AND BONDING STUDY

1.0 Test Plan

1.1 Materials

The materials study was begun using .3-mil, Type H Kapton as the base film for preliminary screening of adhesive candidates. After initial screening, .3-mil, Type H Kapton with 1000Å of aluminum on one side and 120Å of chrome on the other side was used to more accurately simulate actual bonding conditions to be used in the sail. This metalized film was used in all "advanced study" of adhesive candidates.

Adhesives studied in preliminary testing included:

Adhesive	Type
duPont 1-mil Pyralux WA/A	Acrylic
Lord Chemlok 7005 & 7250	Polyisocyanate
UpJohn Polyimide 2080 D	Polyimide
Ironsides DP9-65	Phenolic Resin
Rohm & Haas Rhoplex HA-12	Acrylic Polymer
duPont NR-150 B2G	Polyimide
Sheldahl 3P	Polyimide - Polyamide- Polyester
B. F. Goodrich 2679X6	Acrylic

1.2 Seaming Equipment

Seaming equipment included the following:

- High temperature oven
- Sheldahl impulse sealer
- Vertrod impulse sealer
- Sheldahl wheel sealer
- Doboy band sealer
- Platen press

1.3 Sealing Methods

The following is a brief description of sealing methods and conditions used for each adhesive. In the case of some adhesives two or more methods were tried.

DuPont 1-mil Pyralux WA/A was placed between two sheets of .3-mil, Type H Kapton film and platen pressed for 30 minutes at 190°C, 100 psi. A second sample was pressed for 30 minutes at 205°C.

Lord Chemlok adhesive system was sprayed on Kapton using an air brush and then placed in an oven for 3 minutes at 80°C to dry off solvents. Per the manufacturers instructions, coated film samples were assembled and pressed between wear plates for 2.5 hours using a 10.15 kg weight.

UpJohn 2080 D was applied using an air brush and dried in an oven for 3 minutes at 80°C to dry off solvents. Samples were platen pressed for 15 minutes at 170°C, 50 psi. (No good samples were obtained because the adhesive tended to curl the film beyond handling ability.)

Ironsides DP 9-65 was applied by air brush and dried for 15 minutes at 100°C in an oven. Per the manufacturers instructions samples were then pressed between wear plates for 2 hours using a 10.15 kg weight.

Rohn & Haas Rhoplex HA-12 was applied by air brush, dried 2 minutes at 150°C and pressed between wear plates for 1 hour using a 10.5 kg weight per the manufacturers instructions.

DuPont NR-150 B2G was applied using an air brush. Several sealing methods were tried. First, samples were dried 2-4 minutes at 100°C and wheel sealed at 290°C, 8.04 ft/min. (No bond was made). Secondly, samples were dried 2-4 minutes at 100°C and then sealed at 165°C on an impulse sealer using a 25-second heating cycle followed by a 25 second cooling cycle (resulted in some bond, but not good). Thirdly, samples were dried for 5 minutes at 65°C and sealed at 315°C on a Sheldahl impulse sealer using a 15-second heating cycle followed by a 15 second cooling cycle. Satisfactory results were obtained using the third method.

Sheldahl 3P adhesive was likewise sealed in several manners. All samples were applied using a 10% solids solution in a 1.0-mil draw bar coater and dried for 5 minutes at 40°C. First, samples were wheel sealed at 180°, 205°, and 250°C at 8.04 ft/minute, none of which produced a bond. Second, samples were sealed using a Vertrod impulse sealer at 160°C and cooled under pressure. Third, samples were impulse sealed at 160°C using a 25-second heating/cooling cycle on a Sheldahl impulse sealer. Both Vertrod and impulse sealing methods resulted in good bonds, but the impulse method was more controllable and and was used for the majority of sealing.

B. F. Goodrich 2679X6 was applied to .3-mil metalized Kapton (the only adhesive not tested on plain .3-mil Kapton) with a 1.0-mil draw bar coater. Samples were dried for 5 minutes at 70°C and impulse sealed at 160°C using a 25-second heating/cooling cycle.

1.4 Test Equipment and Procedures

Testing equipment used to evaluate adhesive samples included ovens, Instron test equipment, Instron heat/cold chamber, and a dead weight fixture. Tests were performed as follows:

Test	Temperature	Method
Peel	-100°F (-73°C)	ASTM-D-1876
	+550°F (+288°C)	
Shear	-100°F (-73°C)	FTM-5102
	+550°F (+288°C)	

2.0 Test Results

Test results are recorded in two parts, preliminary screening study, using plain .3-mil, Type H Kapton, (Tables 1 and 2) and advanced study using .3-mil metalized Kapton (Tables 3 and 4).

A dead load +290°C test replaces the +290°C shear (per FTM-5102) in the preliminary section because equipment was not available at the time of testing to do the shear test per the FTM standard. The dead load test was performed using an aluminum fixture which permitted one end of the shear sample to be held tightly between jaws and the other end to hang freely. A two (2) pound weight was clamped to this free end and the entire fixture was placed in an oven at +290°C. The time required for bonds to break was recorded.

TABLE 1

PRELIMINARY SCREENING

+290°C Dead Load Test

ADHESIVE SAMPLE		RESULTS
1 mil Pyralux WA/A		
	#1A	Bond unbroken after 6 minutes
	#1B	Bond unbroken, but sample slipped from top jaw after 4 minutes
	#2D	Bond unbroken after 5 minutes
Chemlok 7005 & 7250		
	#4A	Bond broke upon affixing weight
	#4B	Bond broke upon affixing weight
	#4C	Bond broke upon affixing weight
	#4D	Bond broke upon affixing weight
Ironsides DP9-65		
	#2A	Bond broke upon affixing weight
	#2B	Bond broke upon affixing weight
Rhoplex HA-12		
	#7A	Bond broke upon affixing weight
	#7B	Bond broke upon affixing weight
	#7C	Bond broke upon affixing weight
	#7D	Bond broke upon affixing weight
NR-150 B2G		
	#1A	Bond unbroken after 6 minutes
	#1B	Bond unbroken after 6 minutes
Sheldahl 3P		
	#1A	Bond unbroken after 6 minutes
	#1B	Bond unbroken after 6 minutes
B.F. Goodrich 2679X6		
	#1E	Bond unbroken after 10 minutes
	#2E	Bond unbroken after 10 minutes
	#3E	Bond unbroken after 10 minutes

TABLE 2

PRELIMINARY SCREENING

-73^{o}C Cold Test (FTM-5102)

SAMPLE		TEAR STRENGTH	OBSERVATIONS
1 mil Pyralux WA/A			
	#2A	10.0#	Kapton tore, not adhesive bond
	#2B	4.8#	Kapton tore, not adhesive bond
Chemlok 7005 & 7250			
	#6B	4.25#	Kapton tore, not adhesive bond
	#6C	7.0#	Kapton tore, not adhesive bond
	#6D	7.6#	Kapton tore, not adhesive bond
Ironsides DP9-65			
	#2A	5.7#	Kapton tore, not adhesive bond
	#2B	4.9#	Kapton tore, not adhesive bond
Rhoplex HA-12			
	#7A	5.95#	Adhesive bond broke
	#9C	1.22#	Adhesive bond broke
	#8D	5.98#	Adhesive bond broke
NR-150 B2G			
	#2A	3.0#	Kapton tore, not adhesive bonds
	#2B	6.1#	Kapton tore, not adhesive bonds
	#2C	6.1#	Kapton tore, not adhesive bonds
	#3C	4.7#	Kapton tore, not adhesive bonds
Sheldahl 3P			
	#1A	10.0#	Kapton tore, not adhesive bonds
	#1B	3.9#	Kapton tore, not adhesive bonds
	#1C	6.6#	Kapton tore, not adhesive bonds
	#1C	9.7#	Kapton tore, not adhesive bonds

Note: Chart speed 5"/minutes
Cross head speed 2"/minutes

TABLE 3

"ADVANCED STUDY"

+290°C Heat Test

SAMPLE		TEAR VALUE	OBSERVATIONS
Sheldahl 3P			
Shear	A	3.4#	Bond tore
	B	2.2#	Bond tore
	C	2.6#	Bond tore
	D	2.2#	Bond tore
	E	3.0#	Bond tore
Peel	A	1.4#	Transfer of Aluminum to chrome side of Kapton
	B	1.2#	Transfer of Aluminum to chrome side of Kapton
	C	1.4#	Transfer of Aluminum to chrome side of Kapton
	D	0.4#	Transfer of Aluminum to chrome side of Kapton
	E	1.95#	Transfer of Aluminum to chrome side of Kapton
NR-150 B2G			
Shear	A	2.4#	Bond unbroken, Kapton tore
	B	4.2#	Bond unbroken, Kapton tore
	C	4.2#	Bond unbroken, Kapton tore
	D	4.2#	Bond unbroken, Kapton tore
	E	2.6#	Bond unbroken, Kapton tore
Peel	A	1.8#	Transfer of aluminum to chrome side, Kapton tore from bond after peel began
	B	1.8#	Transfer of aluminum to chrome side, Kapton tore from bond after peel began
	C	1.8#	Transfer of aluminum to chrome side, Kapton tore from bond after peel began
	D	1.8#	Transfer of aluminum to chrome side, Kapton tore from bond after peel began
	E	1.8#	Transfer of aluminum to chrome side, Kapton tore from bond after peel began

Note: 3P samples sealed by impulse at 160°C, 25 second heat/cool cycle.
NR-150 B2G samples sealed by impulse at 315°C, 15 second heat/cool cycle.
Tested Per FTM-5102 & ASTM-D-1876

TABLE 4

" ADVANCED STUDY "

$-73^{o}C$ Cold Test

SAMPLE		TEAR VALUE	OBSERVATIONS
Sheldahl 3P			
Shear	A	10.0#	Bond unbroken, Kapton tore above bond
	B	8.3#	Bond unbroken, Kapton tore above bond
	C	6.2#	Bond unbroken, Kapton tore above bond
	D	9.9#	Bond unbroken, Kapton tore above bond
	E	8.8#	Bond unbroken, Kapton tore above bond
Peel	A	0.6#	Some transfer of aluminum to chrome side
	B	0.75#	Some transfer of aluminum to chrome side
	C	0.99#	Kapton tore at bond; adhesive stronger than film
	D	0.37#	Kapton tore at bond; adhesive stronger than film
	E	0.60#	Kapton tore at bond; adhesive stronger than film
NR-150 B2G			
Shear	A	5.4#	Bond unbroken, Kapton tore
	B	8.7#	Bond tore
	C	8.2#	Bond unbroken, Kapton tore
	D	9.7#	Bond tore
	E	9.9#	Bond tore.
Peel	A	0.80#	Transfer of aluminum to chrome side
	B	0.75#	Transfer of aluminum to chrome side
	C	0.55#	Transfer of aluminum to chrome side
	D	0.52#	Transfer of aluminum to chrome side
	E	0.65#	Transfer of aluminum to chrome side

Note: 3P samples sealed by impulse at $160^{o}C$, 25 second heat/cool cycle.
NR-150 B2G samples sealed by impulse at $315^{o}C$, 15 second heat/cool cycle.
Tested Per FTM-5102 & ASTM-D-1876

3.0 Quantitative Differential Thermal Analysis

Quantitative differential thermal anaylis tests were run on 0.3-mil Kapton, Type H, duPont NR-150-B2G polyimide adhesive and Sheldahl 3P polyimide-polyamide-polyester adhesive.

Fisher Scientific Thermalyzer Series 300 was used to measure thermal stability of these materials.

3.1 Kapton, 0.3-mil Type H

Figure 1 shows the results of the QDTA test. The test was performed in a vacuum atmosphere. There is no indication of a melt point, oxidative degradation or a glass transition. The large deflection after 214°C is probably a phase change in the Kapton structure causing a change in heat capacity of the polymer.

3.2 duPont NR-150-B2G

Figure 1 shows the results of the QDTA test. The test was performed in a vacuum atmosphere after a 30-minute bake, in vacuum, at 316°C. This trace is similar to the corresponding trace of Kapton in vacuum. Again, an apparent phase change at 191°C causes a baseline shift indicating a change in heat capacity of the material. No glass transition at 350°C is indicated as per duPont published literature on the product.

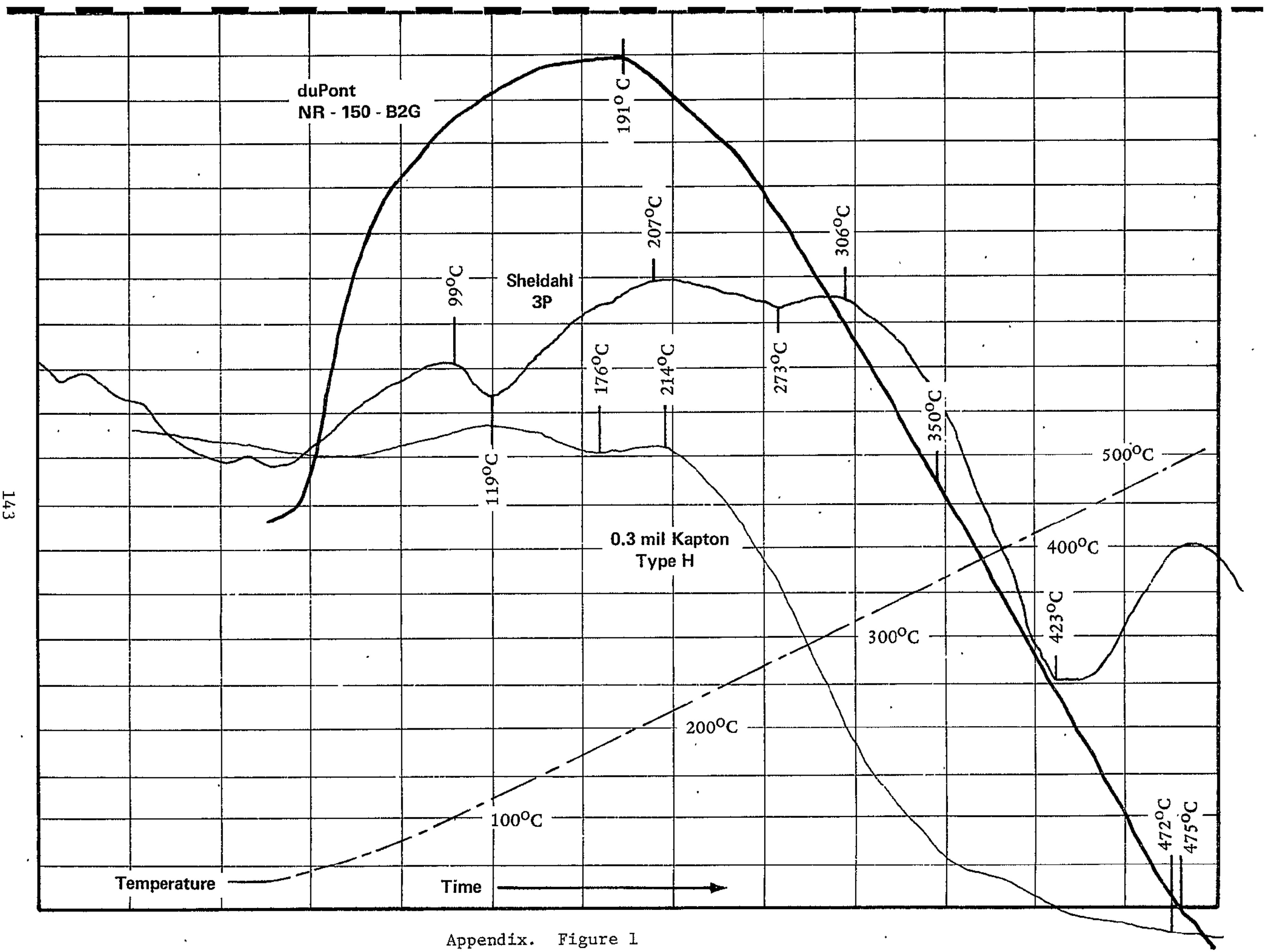
3.3 Sheldahl 3P

Figure 1 shows the results of the QDTA test. The test was performed in a vacuum atmosphere. This trace shows some initial baseline instability. Two phase changes appear at 119°C and 273°C. At 306°C a phase change occurs, similar to Kapton and NR-150, causing a baseline shift. Onset of thermal degradation occurs at 423°C (793°F) as witnessed by the flattened baseline followed by the broad exotherm peak.

4.0 SUMMARY

It is recommended that these adhesives and perphaps others be included in a program of further study, evaluation and development during the next interim phase of the Solar Sail Program.

The duPont NR-150-B2G and Sheldahl 3P seem to exhibit excellent bond strength and stability between -73°C and +290°C. Further studies should include long



Appendix. Figure 1

term aging and creep at +290°C.

Further work should also be done to refine the adhesive application method and control.

Work is also needed to refine the drying cycle used to flesh off the solvents after adhesive coating. In addition to the above items, the production sealing equipment and process should be developed.