DEVELOPMENT OF MANUFACTURING TECHNIQUES FOR A METAL FABRIC REINFORCED RE-ENTRY PARAGLIDER

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Early in 1963 a contract for the development, fabrication, and test of re-entry paraglider components was awarded to Space-General Corporation by the Manufacturing Technology Division of the Air Force Materials Laboratory. The first phase of the project included optimization of the vehicle configuration, selection of the proper trajectory with emphasis on the aero-thermodynamic aspects of the re-entry regime, materials evaluation and selection to meet the environmental and inherent structural objectives, and design of the actual critical components of the vehicle. The results of this work during the first year were presented at the First Aerospace Expandable Structures Conference in October 1963.

In order to summarize the program objectives and the earlier work, reference is made to Figure 1 showing a photograph of a model of the proposed paraglider with a cutaway showing the position of the man and life support system. This completely flexible, inflated vehicle would be capable of returning a human being from orbit by re-entering the earth's atmosphere at hypersonic velocity and decelerating to effect a subsonic controlled landing on earth. The vehicle consists of an inflated body made up of three tapered booms attached to a common toroidal apex. Attached between the center boom or keel and each leading edge boom is a thin flexible wing membrane which assumes an approximately semi-conical shape during flight. The booms taper from 32 inches in diameter at the forward end to 13 inches at the aft tip with an overall vehicle length of approximately 23 feet. The jets at the boom tips are used for attitude control in space while the aft edge of the flexible wing can be gathered and pulled downward or let out by use of a trailing edge cable for aerodynamic flight control.

An artist's concept of the deployment of the paraglider is shown in Figure 2. The vehicle is packaged similar to a life raft and attached to the space station such that a man can enter the crew compartment section of the paraglider from within the space station; the vehicle is then ejected away and subsequently inflated. Having been aligned at the proper attitude, the vehicle is retro-fired from orbit and re-enters sensible atmosphere at about Mach 30. It is expected that the vehicle can be controlled remotely from the space station or the ground, by self contained auto pilot, or manually by the man on board. Since this is to be used as an escape vehicle it must be assumed that the occupant may be incapacited due to injury or illness and the vehicle must return him to the ground without manual control in as short a time as possible.

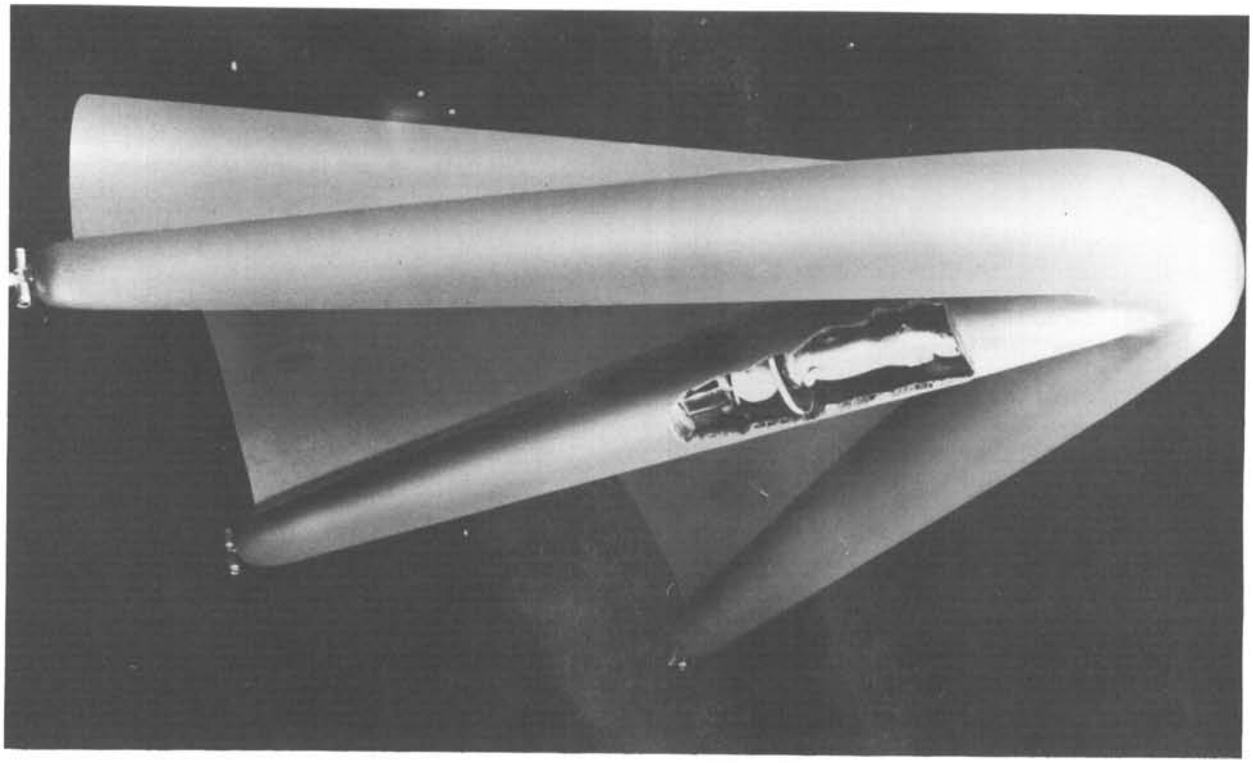

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FIGURE 1. RE-ENTRY PARAGLIDER

FIGURE 2. DEPLOYMENT OF ESCAPE VEHICLE

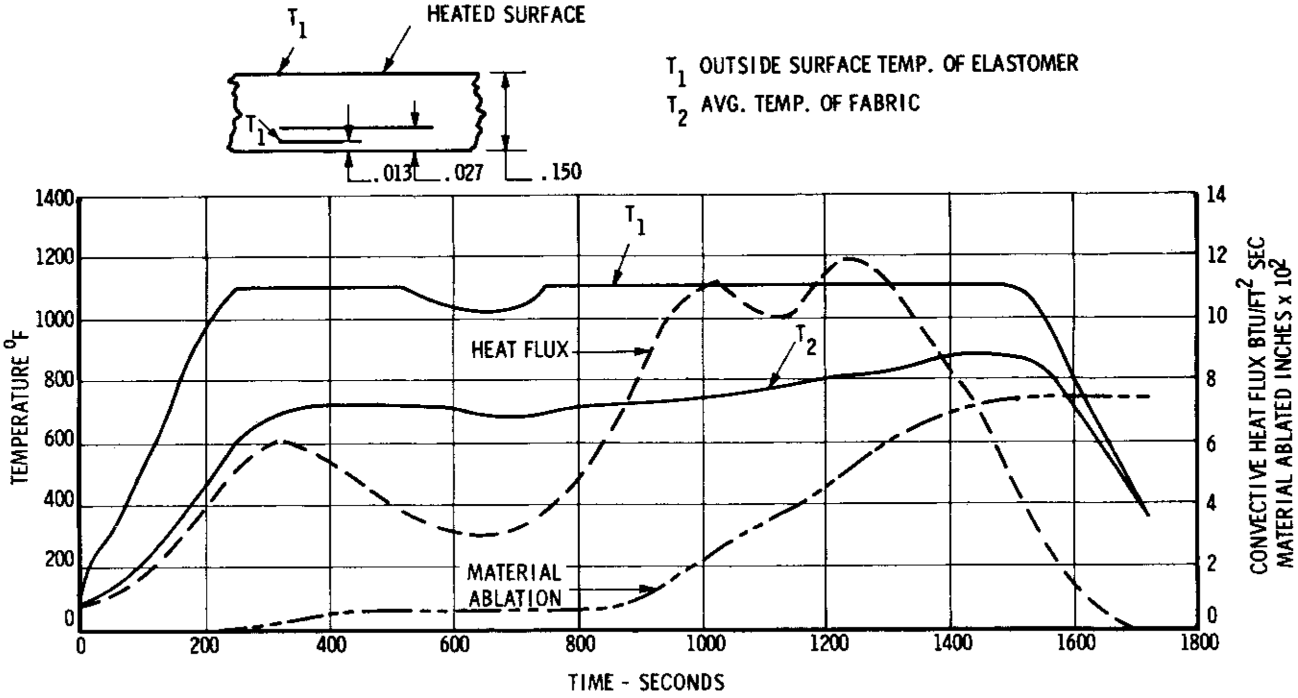

FIGURE 4. PARAGLIDER HEATING EFFECTS AT TIP OF BOOM

flux reaches a maximum of about 12 BTU/ft^2 sec. Consistent with our desire for the use of flexible materials, the dynamic pressure, deceleration forces, and heat flux are relatively low for a re-entry body because of the utilization of a vehicle configuration and corresponding flight attitude to maximize the lift coefficient. The amount of material ablated is predicted to be 75 mils, leaving a residual coating of about 50 mils of high temperature silicone rubber as a heat barrier contingency to assure that the ablation will not reach the metal fabric reinforcement even in the most critical areas.

The reinforcing fabric was manufactured from metal yarns consisting of 49 one mil filaments, plied and cabled by textile twisting methods. The fabric was woven of 58 yarns per inch in each direction using a 2x2 basket weave. An enlarged photograph of this fabric is shown in Figure 5. Each of the apparent strands consists of two yarns. Due to the low textile twist in these yarns, they tend to flatten, giving the fabric a rather smooth surface and also preventing large transverse openings. The 2x2 basket weave was selected after evaluation of numerous weaves because it allows close grouping of yarns (i.e. high pick and end count) with nominal crimping of yarns while retaining reasonable in-plane sturdiness (i.e. it is not "sleazy"). The one mil wire is actually a potentiometer type resistance wire consisting of 73% nickel and 20% chromium which displays approximately 20% greater tensile strength for a given weight and weave than the more common 80-20 alloy. More flexibility for the desired strength could have been obtained using a smaller diameter wire, but the selection was one of economics, the cost of 0.5 mil wire being about 6 times that of the 1.0 mil wire at the time of procurement. Future work should employ the finest possible diameter of filament consistent with the

The total flight time from a position 200 miles above the earth to a controlled landing location would be under 2 hours. The trajectory characteristics during the re-entry heating regime are depicted in Figure 3. It may be seen that the vehicle encounters the first significant dynamic pressure below 400,000 feet altitude. Its velocity begins to rapidly decay below 300,000 feet altitude while the dynamic pressure increases to a maximum of about 5.3 psi, then rapidly falls off as subsonic velocities are approached.

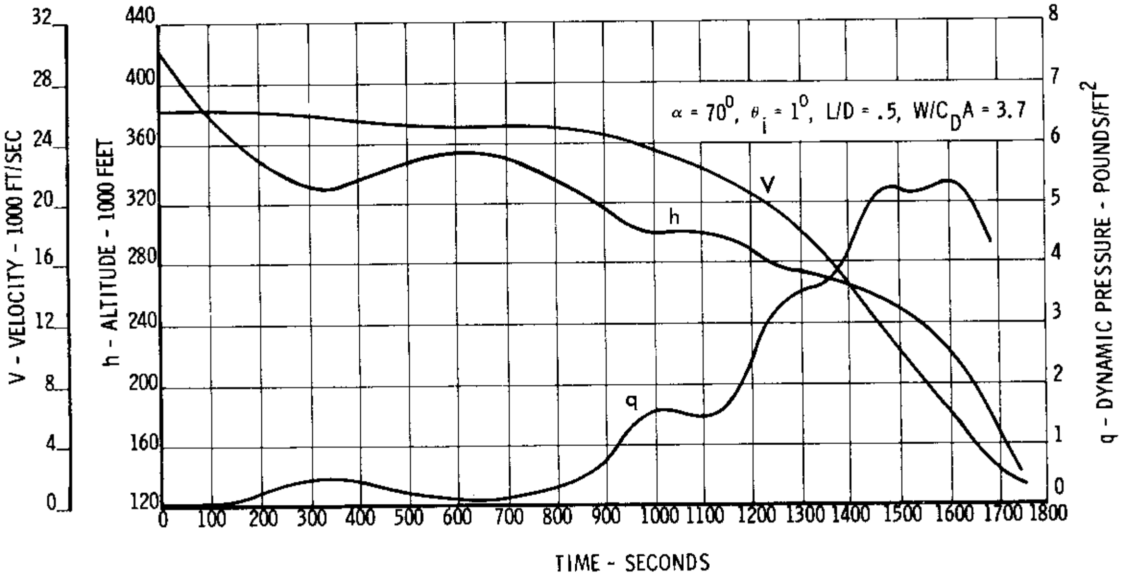

FIGURE 3. TRAJECTORY CHARACTERISTICS

The thermodynamic data presented at the previous meeting has been refined by further computer studies based on more recent air-arc plasma-jet evaluation of the silicone rubber coating that was selected, and the final temperature, heat-flux history during the re-entry period is shown in Figure 4. The vehicle re-enters at an angle of attack of 70 degrees and the data is for the aft tip of the boom which is the hottest point created by re-entry heating due to its reduced diameter.

The materials selected after considerable research are a nickel-chromium metal fabric woven from fine filaments in the form of a textile resembling a lightweight canvas, and two kinds of silicone rubber, one for impregnating or saturating the two plies of metal fabric, and the other for exterior coating as an ablative and heat resisting material. The two plies of metal fabric made up in bias relationship total approximately 27 mils thickness with a maximum silicone rubber coating of an additional 123 mils, making a total maximum thickness in the hottest areas of 150 mils.

Although the exterior char surface of the ablative silicone rubber reaches about 2000°F, the surface of the underlying interface between parent elastomer and char does not exceed approximately 1100°F. as shown by curve T_1 in Figure 4. There is only a small variation between the inside metal fabric surface and the outer surface of the outer metal fabric ply. Curve T_2 shows the average temperature of the metal fabric as predicted by computer analysis. The heat

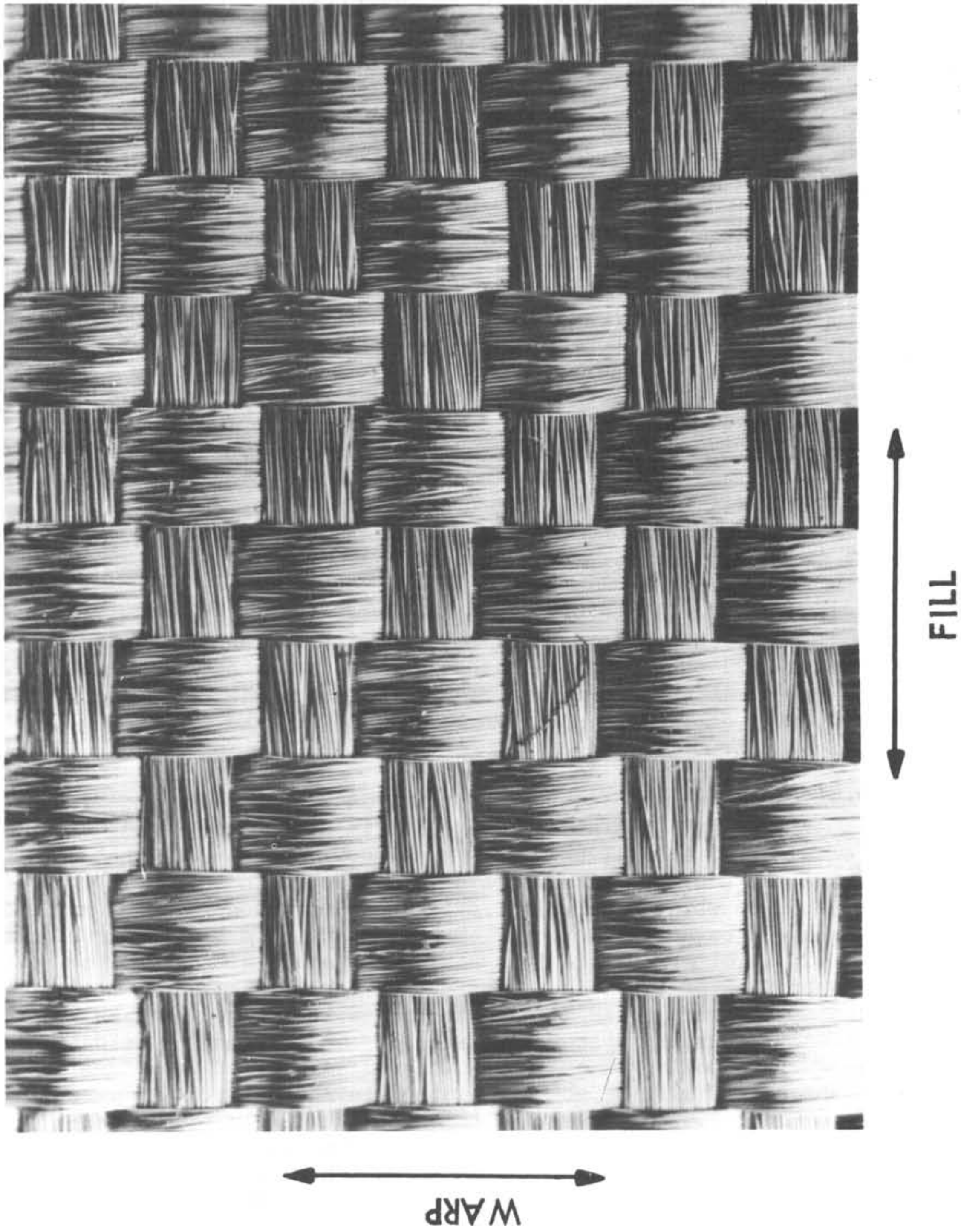

FIGURE 5. TWO BY TWO BASKET WEAVE (58 x 58), 1.0 MIL WIRE

budget considerations, type of fabric desired, and the filament strength required for the fabric manufacturing operations.

A pilot run of about 80 square feet of 26 inch wide fabric provided considerable background in the twisting of the yarn, warping and weaving on the loom and scouring or cleaning of the fabric. The final production run of the fabric was over 5 feet wide and nearly 80 yards long, being, perhaps, the largest quantity of such fabric produced as of that time. Over 400 yards of 1.6 inch wide metal fabric tape with 80 ends and 40 picks per inch were also woven using the same yarn. This tape is used in wrapping and strengthening the highly loaded areas of the apex, as will be shown later. One of the innovations resulting from the development work in the pilot run was the spooling of 7 filaments of wire on one spool to facilitate the twisting of a 7x7 or 49 filament balanced yarn. This resulted in a saving of about $6000 worth of wire which would otherwise have been wasted due to unequal runout of monofilament spools. The manufacture of the wire, the twisting into yarn, and the weaving were subcontracted separately so that each operation could be monitored directly from the Project Office. All work was done on the basis of formal specifications. The average direct cost of the fabric woven to date is $64 per square foot, not including administration and coordination expense. Most of this cost is due to the wire. Improvements in multiple fine wire drawing as well as in the twisting and weaving operations would bring today's cost of this fabric below the cost experienced last year.

Two plies of this fabric will be bonded together in 45° bias relationship to give maximum in-plane shear strength in torsion and shear loading. The combined matrix will exceed the required maximum design hoop strength of 176 pounds per inch at 1000°F provided a seam or minimum joint efficiency of 70% relative to parent fabric strength can be obtained in the numerous joints required in the construction.

Typical load elongation curves are shown in Figure 6 for the production run fabric. Approximately 5 weeks were spent in attempting to adjust the loom to obtain equal crimp in fill and warp yarns, however the best that could be obtained was about a 6 to 1 ratio. This is reflected in the two curves shown. It is desireable to obtain equivalent crimp or elongation in both warp and fill in order to have a balanced fabric which will distribute the loads uniformly and predictably. Better balance than this was obtained with some loom settings but at the sacrifice of fabric quality in that warp breakage occurred due to high loading of the warp in an attempt to reduce its crimp. A tabular summary of the physical properties is shown in Table I. The percent crimp was determined by measuring the length of a straightened segment of yarn from a known length of fabric. It will be noted that the yield elongation in warp and fill differ by only 2.8%, however, so that it is unlikely that gross distortion of the vehicle will occur due to this lack of crimp balance. The ultimate strength of the one mil wire was 184,000 psi which converted to a fabric strength of 339 to 375 pounds per inch, a calculated strength translation of 90-97%.

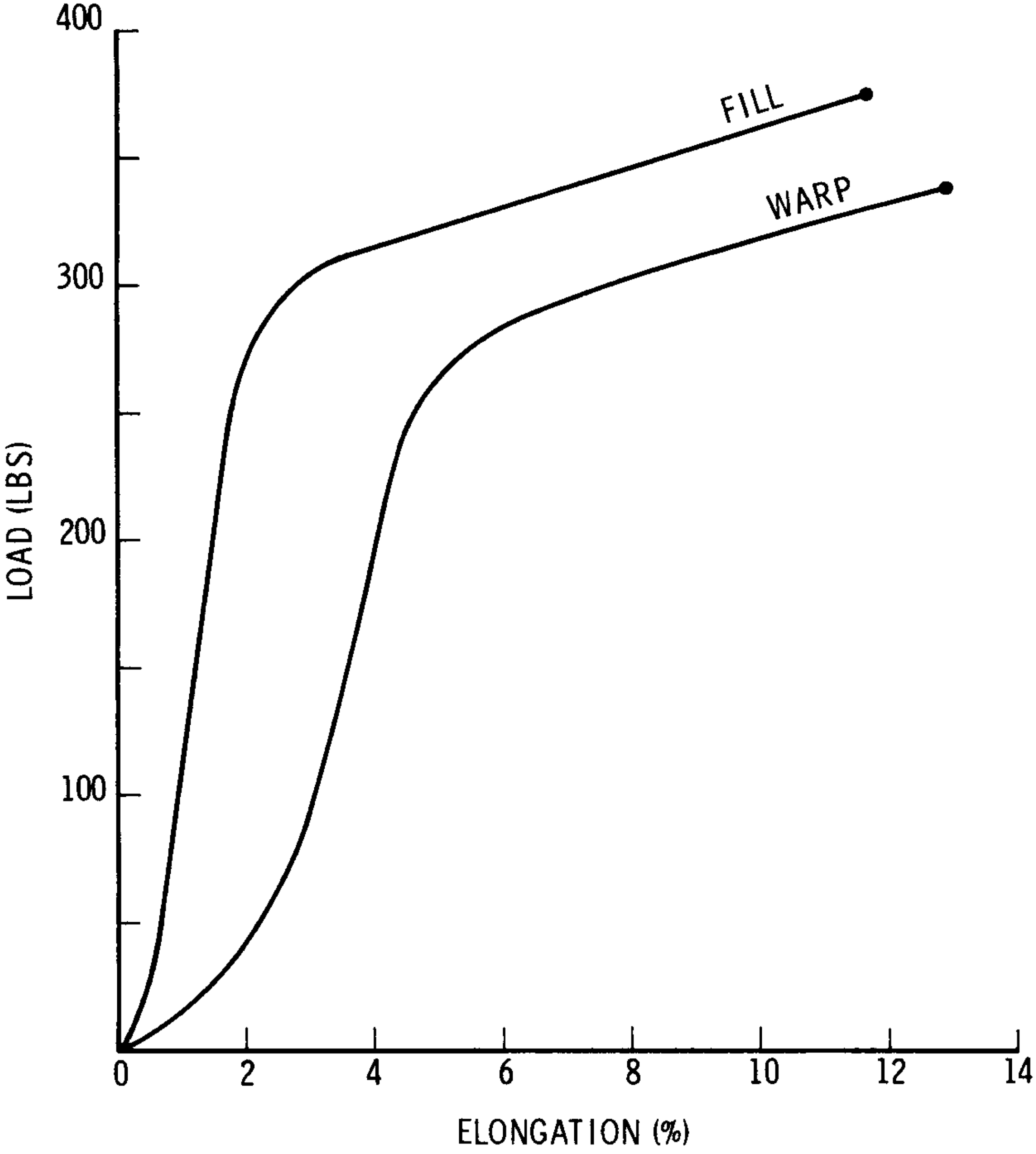

FIGURE 6. TYPICAL FABRIC LOAD VS ELONGATION AT 70°F

TABLE I

RESULTS OF TESTS ON MULTIFILAMENT METAL FABRIC AT 70°F

	Warp	Fill
Yield Elongation, %	4.83	2.05
Yield Load, lbs	278	300
Rupture Elongation, %	12.94	11.67
Rupture Load, lbs	339	375
Modulus of Elasticity, lbs x 10^{-2}	105	205
Crimp, %	1.84	0.29

The fabric was scoured or cleaned of the wax applied during the twisting and weaving operation by transferring it to a motor driven jig which passed the fabric through a spray of hot non-ionic detergent solution four times, followed by two rinses with hot clear water. The fabric was then dried with forced air and infrared lamps prior to final inspection.

Conclusions and recommendations based on experience in the manufacture of this unusual fabric include the following:

a. Yarns made from fine diameter wire filaments can be handled on normal textile handling equipment provided the guide surfaces and tensions are carefully prepared and monitored.

b. Because of the high modulus of elasticity of the wire yarn, standard weaving techniques to achieve certain fabric characteristics with textiles do not have the same effect in the weaving of metal fabrics.

c. The loom should have a small shed opening and positive let-off with maintenance of constant warp tension by hydraulic dash-pot or similar means. This may also help absorb beat-up shock and vibration and improve crimp balance.

d. Improved techniques of holding out the selvage rather than the usual selvage temples or "crow-pickers" should be studied to permit high warp tensions without breakage due to angulation of the yarns leaving the reed. High warp tensions would improve crimp balance.

e. The warp should be rolled on the beam with special caution to maintain uniform tension during weaving.

f. Jig scouring of wide metal fabrics requires more care and special handling than normal textile fabrics and special jig fixtures with crowned rolls should be provided to prevent wrinkling and skewing of the fabric during this operation.

Joining techniques for metal fabric have been studied in depth. Much research has been conducted on methods of sewing and stitching, adhesive bonding, integral weaving, arc welding, exothermic brazing and welding, gold and silver alloy brazing using infrared heating sources, as well as electric heating, etc., spot brazing, and spot welding. The latter method was selected as being the most satisfactory due to its inherent flexibility without severely damaging the fabric and without the absolute need of an inert atmosphere. The joining technique which has been developed for the purpose of this project consists of 2 rows of spot welds with spots in each row being approximately 0.025 inches apart and the rows spaced approximately 1/8 inch apart with a 1/2 inch overlap of the fabric layers. As many as five layers of fabric have been successfully joined by this technique. A square pulse, capacitance discharge power supply is used with a deep throated welder producing "through" welds by virtue of small diameter electrodes being alternately reciprocated up and down. A schematic of this welder is shown in Figure 7. The expected induction losses with high rate of rise current discharge have been largely overcome through the use of wide, thin, flat conductors supported by the upper and lower arms of the welder frame. Several arm arrangements are being constructed to permit the welding of all of the intricately located seams, expecially those in the toroidal apex. The lower arms can be attached at two possible locations on the main frame.

A close-up schematic of the upper welder head is shown in Figure 8 showing the reciprocating probe electrodes and the silicone rubber tired driving wheel. The timing of the raising and lowering of the probes, intermittent action of the driving wheel (so that the fabric is not moving while a probe is in the down position performing the welding of one spot), and the signal to the power supply to pulse the weld current are synchronized by an adjustable timing device. The speed of welding will be variable from 0 to approximately 25 inches per minute. Welds typical of those shown in the photomicrograph, Figure 9, are produced.

Earlier attempts at welding with two electrode wheels in parallel on one side of the fabric joint with a backup conductive strip were found to be unsatisfactory for the purposes of this project because of the high wheel loading which was required. This would have resulted in heavy backup forms and strong but accurately aligned fixturing to move the welding head or/and part in relationship to one another, while proceeding down a seam of compound curvature.

The procedure planned for the welding machine shown in Figures 7 and 8 is to weld the material "soft" without backup forms using more conventional "through" welding with an electrode on each side of the fabric. This will prevent the serious difficulty previously encountered with the two electrodes on one side wherein a large proportion of the current shunted through the fabric layers without actually contributing to the weld fusion process. Thus, current consumption had to be increased with increase in number of fabric layers, and attendant burning of the fabric between the electrodes was encountered with the former method.

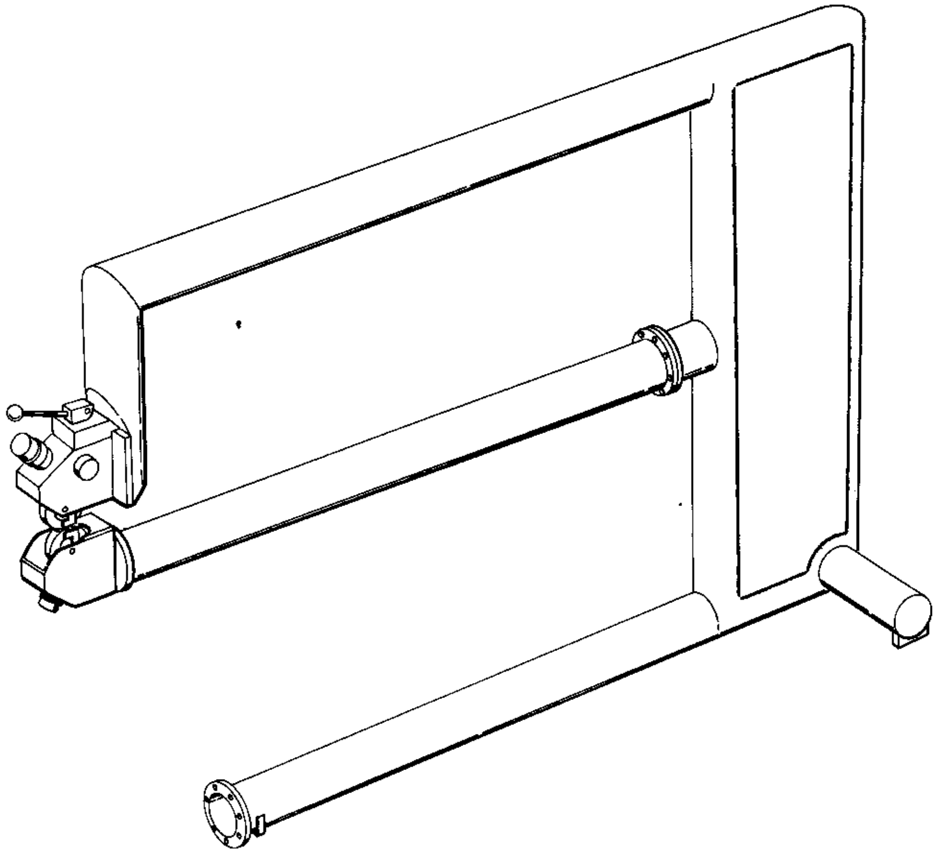

FIGURE 7. FABRIC WELDER

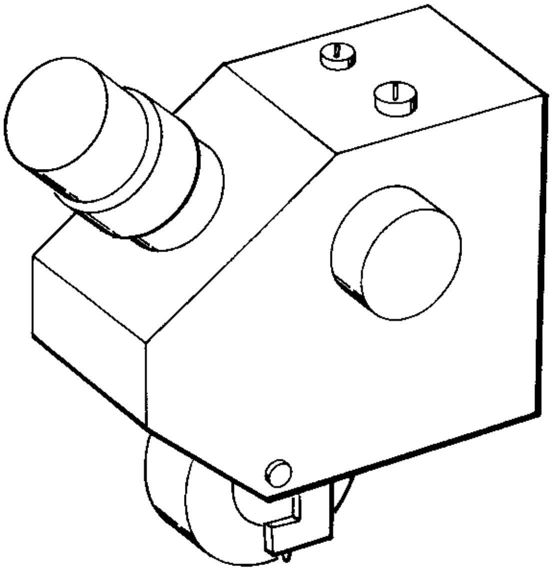

FIGURE 8. WELDER HEAD

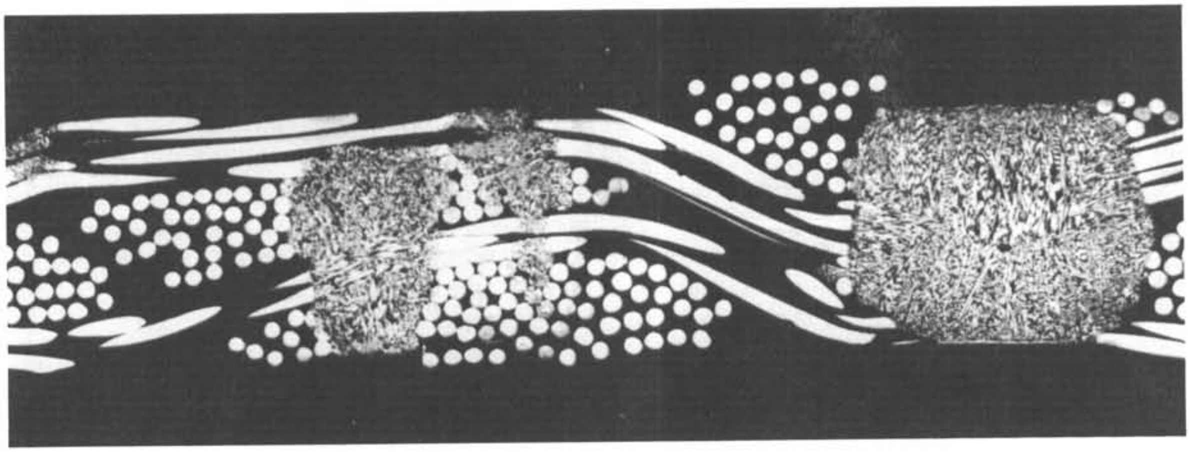

FIGURE 9. PHOTOMICROGRAPH OF SPOT WELDED JOINT

The objectives of this program include not only the development of the manufacturing techniques but the testing of a number of components of the paraglider using simulated re-entry loads and temperatures to prove out the design technology as well as the fabrication methods. Originally in the program, sub-scale components were to be built and tested, but scaling and similarity studies indicated that extrapolation of the results from sub-scale components to predict the performance of full scale components would require many assumptions difficult to firmly justify and result in unreliable design parameters for a full scale vehicle. This is true, in part, due to the fact that although the overall size of a component can be scaled, the fabric can not be scaled proportionately, and where high temperature testing is to be performed on a surface by heating in an intentional non-uniform manner, scale-up of test results becomes impossible.

The program has therefore been modified from that reported at the last Expandable Structures Meeting. Fifteen small 7 to 10 inch diameter, open ended frustums will be fabricated including impregnation and coating, and tested with end closures in place at internal pressures producing the proper reinforcing fabric loading while torsion, shear, and bending loads are applied both at room temperature and temperatures simulating those of the re-entry regime. Subsequently, a full scale boom tapering from 32 inches to 13 inches and 17 feet long will be built and tested throughout the full realm of loading and temperature environments that it would encounter in actual flight. After this experience has been gained, a full scale apex which will be nearly 12 feet wide and 7 feet long with a 32 inch diameter cross section will be similarly tested. These tests will be carried out in a relatively inert atmoshphere simulating the low oxygen content of the re-entry altitude. Quartz infrared heating lamps with gold plated, parabolic reflectors have been procured for the purpose of heating these components from one side to simulate the re-entry heating effect during the appropriate tests.

The complexity of construction of the apex is illustrated in Figure 10, which schematically indicates the layup of two plies of fabric with the individual pattern pieces cut small enough so that gross compound curvature can be avoided in any given piece. Finally the structure is "mummy" wrapped with two layers, at the outer periphery, of tape to carry the circumferential loads through the small crotch area. The load concentration in this area is obvious due to the interuption of the basic toroidal surface by the intersection of the keel boom. It has been elected not to use internal supporting drop yarns or fabrics in this area due to design, structural, and fabrication complexities which it is believed would be introduced.

Having reviewed the nature of the components to be built and the reinforcing fabric to be used, the fabrication process will be summarized so that a better understanding of the stepwise fabrication procedures including the impregnation and coating can be portrayed.

The flat metal fabric is cut both in longitudinal patterns as well as bias patterns for the outer and inner plies respectively. The bias patterns are first laid up on a hard surface forming tool identical in shape to the desired part (e.g. frustum, boom or apex). The individual pieces of fabric are basted together using a stitching technique with the same metal yarn from which the fabric was manufactured. The stitching will be done by hand using a curved needle and will be the most time consuming step in the fabrication process. Tests of welded specimens with and without this metal yarn basting show no degradation due to the basting. The stitches are fairly long and can be put through slowly with a sharp needle causing negligible damage to the fabric. It should be noted that machine sewing of seams as a final method of joining the fabric (without welding) has been shown in previous Air Force contract efforts to be comparatively unsatisfactory, yielding seams in most cases not greater than 60% efficiency.

After basting of the first ply, the form is removed. In the case of the apex, the form will be separable by unclamping flanges from within and removing individual segments of the form. The basted part is then taken to the welding machine, properly supported by tubing racks or other devices to prevent wrinkling, and the seams are welded. The other outer ply is similarly fabricated. In the case of the apex the form is reinserted and the tapes basted in place followed by subsequent removal of the form and welding of these members in place. When all parts have been welded , the inner ply is placed inside of the outer ply and the forming tool again inserted. The forming tool is constructed such that it is vacuum tight. A plastic bleeder screen is placed over the fabric surface and the entire assembly is vacuumed bagged. A minimum vacuum of 28 inches of mercury has been found to be satisfactory for impregnation (although impregnation cannot be performed at atmospheric pressure) and degassed high temperature, phenyl base, liquid silicone rubber is introduced into the evacuated vacuum bagged assembly.

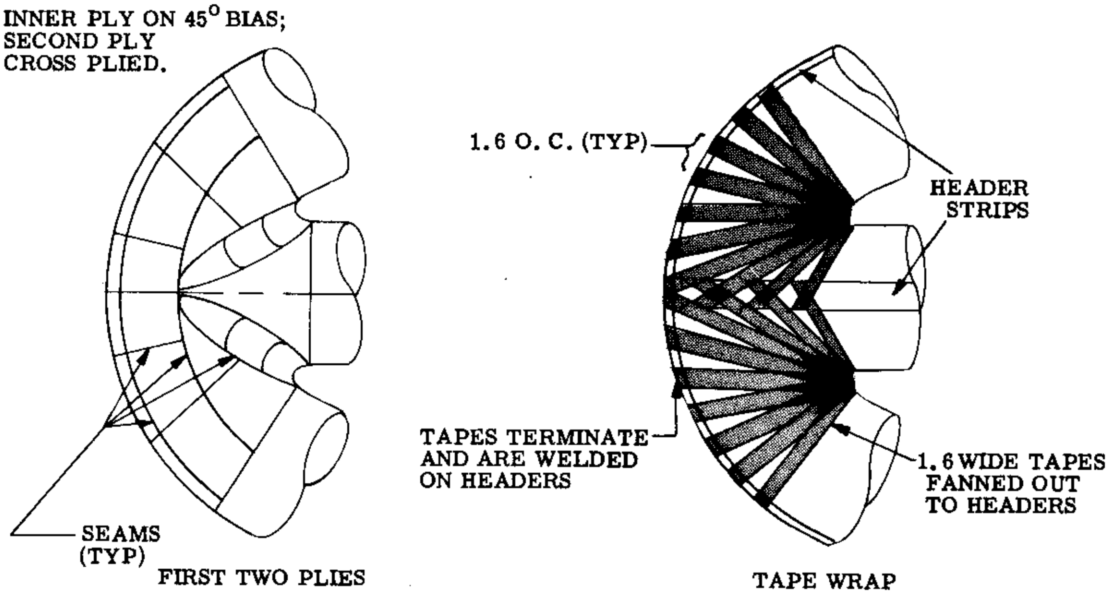

FIGURE 10. APEX CONSTRUCTION

After partial curing at room temperature, the vacuum bag and bleeder screen can be removed and the excess silicone rubber wiped off the surface of the metal fabric. The impregnated fabric is allowed to completely cure. An adhesive layer of the liquid RTV rubber is applied and the high temperature silicone rubber is overlayed using a calenered thickness of 0.025 inches. The adhesive is allowed to room temperature cure and subsequent layers of the high temperature silicone rubber are applied to build the contour to the maximum matrix thickness of 0.150 inches along the stagnation line at the bottom of the apex and boom tapering to a minimum of 0.025 inches at the top of these components where no ablation occurs. These calendered sheets are stitched in place so as to remove all entrapped air and the entire assembly vacuumed bagged to permit autoclave curing of the high temperature, ablative, silicone rubber coating. The forms and vacuum bags can be removed before the high temperature post-cure with the components supported on pipe racks or similar structures if necessary. The components are now complete and ready for environmental testing.

Considerable development effort has been applied to the technique of properly cleaning the cloth, and application of the impregnation primer in addition to the impregnation, coating and vacuum bagging techniques. These processes have been recently qualified to the point of issuance of final specifications. With the final qualification of the welding system the entire fabrication process will be released for manufacture of the major test components.

It is hoped that the techniques described will contribute measureably to the field of expandable structures particularly where metal fabrics may be employed.