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FABRICATION REPORT

FILAMENT-WOUND GRAPHITE/EPOXY ROCKET MOTOR CASE

by

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ABSTRACT

This report describes the fabrication procedures for a filament-wound rocket motor case, approximately 56 cm long x 71 cm diameter, utilizing high tensile strength graphite fibers. The process utilized Fiberite Hy-E-1330B prepreg tape which consists of Courtaulds HTS fibers in a temperature-sensitive epoxy matrix. This fabrication effort, with resultant design, material and process recommendations, substantiates the manufacturing feasibility of graphite/epoxy rocket motor cases in the 56 cm x 71 cm size range.

GLOSSARY

FEP - Flourinated Ehtylene Propylene

MEK - Methyl Ethyl Ketone

M & IR - Manufacturing & Inspection Record. A "traveller" type of process document used by the Brunswick Corporation to describe and record all manufacturing and inspection operations.

SUMMARY

The object of this program was to fabricate a filament-wound rocket motor case using graphite/epoxy pre-impregnated tapes. Design of the motor case was initiated by JPL and critiqued by the Brunswick Corporation. This report covers the fabrication of the agreed design, the problems encountered during fabrication, and the resolution of the problems. A revised stress analysis is presented to represent the as-built conditions, although detailed design and stress considerations are not included within the scope of this report.

The motor case was polar-wound over a sand mandrel with machined contours described by netting analysis. Following the cure of the motor case, a titanium skirt was bonded on a conical ramp section joining the forward dome and the cylinder section. The sand mandrel was washed out from the interior of the motor case. The rocket motor case was shipped to JPL for proof test, installation of insulation, static firing and subsequent hydro-burst. The motor case is currently being insulated following a successful proof-test cycle.

The quality of the completed motor case was far from optimum. Severe gapping in the early polar layers allowed extrusion of the final polar layer into the gaps caused by the external curing pressures required to compact the laminate. The adverse gapping was caused by three fabrication problems, all of which verify that techniques successful for S-glass filament-winding are not necessarily transferable to fabrication with graphite tape.

1. Slippage or Shingling: An extreme mismatch of desired winding angles related to the small size of the forward boss, the cylinder diameter and the length of the motor case resulted in an unstabilized condition for winding. The tapes migrated until the winding tension reached equilibrium, thus slippage caused gapping, loss of tension, and local buckling of fibers.

2. Tape Widths: Graphite tape widths cannot be transferred from the winding package to the wound part without realizing a reduction in tape width and subsequent gapping.

3. Wind Tension: The winding tensions selected for the polar layers were too high and adversely contributed to gapping and tape width control.

Other problems experienced during fabrication were; an adverse polar build-up at the forward boss, unstable prepreg characteristics (tack and width control), and seating-out of the titanium skirt caused by a diametrical mismatch.

Conclusions from the program verify that it is possible to successfully fabricate a graphite/epoxy rocket motor case in this size range (56 cm [22 inches] length x 71 cm [28 inches] diameter)† with commercially-supplied pre-preg tapes. However, quality of the unit may be appreciably improved by adopting the following recommendations:

1. Minimize the critical slip angle from 0.24 rad (13.5°) to approximately 0.14 rad (8°).
2. Combine the three polar layers at net band width of 5.08 mm (.200 inch) into two polar layers with a net band width of 3.38 mm (.133 inches).
3. Lower winding tension by approximately 50%.
4. Eliminate post-bonded skirts and fabricate the skirt in place using graphite tapes and graphite fabric.
5. Utilize temporary tooling over polar boss attach areas to protect threads.
6. Define an alternate resin system which will be more compatible with tape width control.
7. Define tackiness of pre-preg and develop a technique of measurement and verification of candidate graphite tapes.

NEW TECHNOLOGY

No reportable items of new technology have been identified as a result of this program.

†Measurements within the body of this report are presented in SI units, followed by U.S. customary units in parentheses. U.S. customary units were used in the measurements and calculations, and calculations presented in the text of this report are in U.S. customary units with SI units presented in parentheses for all final answers.

INTRODUCTION

In the past, production rocket motor cases have been fabricated from high-strength metals or fiberglass/epoxy composites. With the advent of advanced composites, specifically those utilizing boron, graphite, or PRD-49 fibers in an epoxy matrix, it was recognized that these high specific modulus composites could be combined with the efficiency of filament winding to yield motor case structures with significantly-improved performance characteristics.

The Brunswick Corporation was contracted by JPL to evaluate and fabricate one filament-wound graphite/epoxy rocket motor case (Figure 1) in accordance with JPL Drawing No. 10039486. The program consisted of the following objectives: (i) Evaluation of the adhesive and its placement, (ii) evaluation of current fabrication processes with respect to the graphite/epoxy composite, (iii) a critique of the rocket motor case design with respect to design reliability, (iv) recommendations of changes to optimize producibility or weight of the rocket motor case, and (v) fabrication and delivery of one graphite/epoxy rocket motor case.

To support the structural analysis of the graphite/epoxy rocket motor case, the Brunswick Corporation conducted a company-funded, in-house program in which six sub-scale (1640 cm^3 [100 $inch^3$]) graphite/epoxy pressure vessels were fabricated, tested and evaluated. The findings from the sub-scale program were applied to the finalized design to which the graphite/epoxy motor case was fabricated.

This Fabrication Report presents; (i) the fabrication procedures employed by Brunswick in building the graphite/epoxy rocket motor case, (ii) problems encountered and their corrective actions, (iii) recommended changes to design, fabrication procedures, and material specifications, and (iv) a revised stress analysis. A summary of the Brunswick-funded pressure vessel program (Appendix A) is included with this report for ready reference.

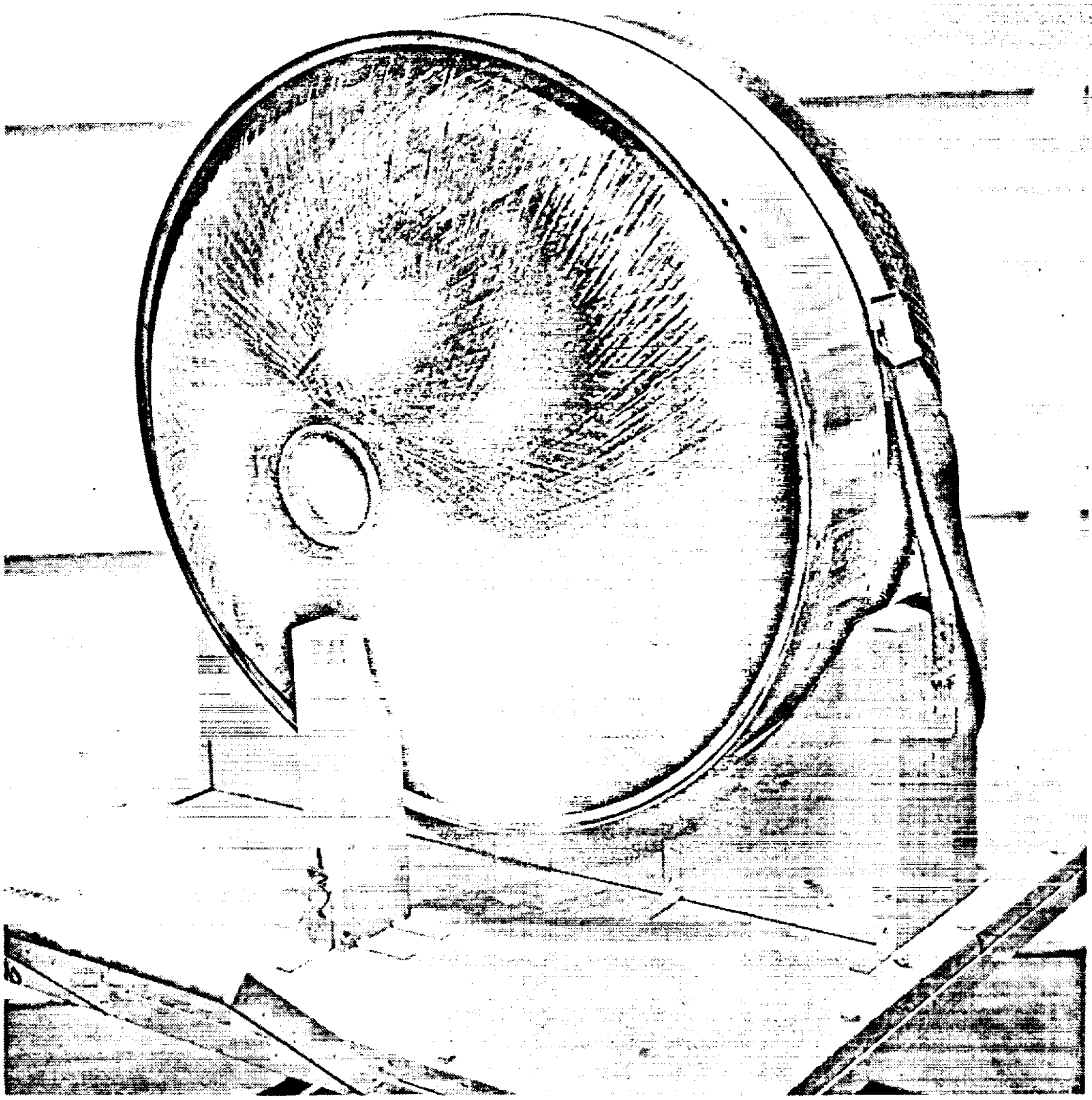

Figure 1

Graphite/Epoxy Rocket Motor Case

TECHNICAL DISCUSSION

Fabrication

Prior to the start of fabrication, the initial case design (JPL Drawing No. 10039486) was updated and finalized as a joint effort between Brunswick and Jet Propulsion Laboratory (JPL). Design finalization was based upon inputs from JPL and the results of Brunswick's fabrication process study and design optimization and producibility recommendations.

Following the design finalization and JPL's approval of Brunswick's fabrication plan, the Brunswick Corporation commenced fabrication of the graphite/epoxy rocket motor case in accordance with the manufacturing sequence depicted in Figure 2.

Each task in the manufacturing sequence is described in an abridged summary of the processes and techniques employed by Brunswick in manufacturing the motor case. Brunswick's M & IR's provided detailed step-by-step directions for all manufacturing and inspection operations and, in addition, provide a permanent record of the "as-built" configuration. The following paragraphs describe the manufacturing sequence:

Bond Rubber Spacers

Temporary rubber spacers, 0.38 mm (0.015 inch) thick, were bonded to the recessed faces of both polar fittings to provide gage-point reference surfaces for machining the dome contours. Refer to Figure 3.

Tooling Assembly

The wind axis, polar boss fittings, and adapter were assembled and inspected to verify the dimensional locations of the fittings as specified on JPL drawing 10039486. These dimensions were verified and recorded on the M & IR.

A wire mesh cage was constructed around the assembly at approximately 6.35 cm (2.5 inches) below the final contours. A flexible heating element 12.7 m (50 feet) long, was coiled around and attached to the wire mesh. The wire mesh reinforced the sand

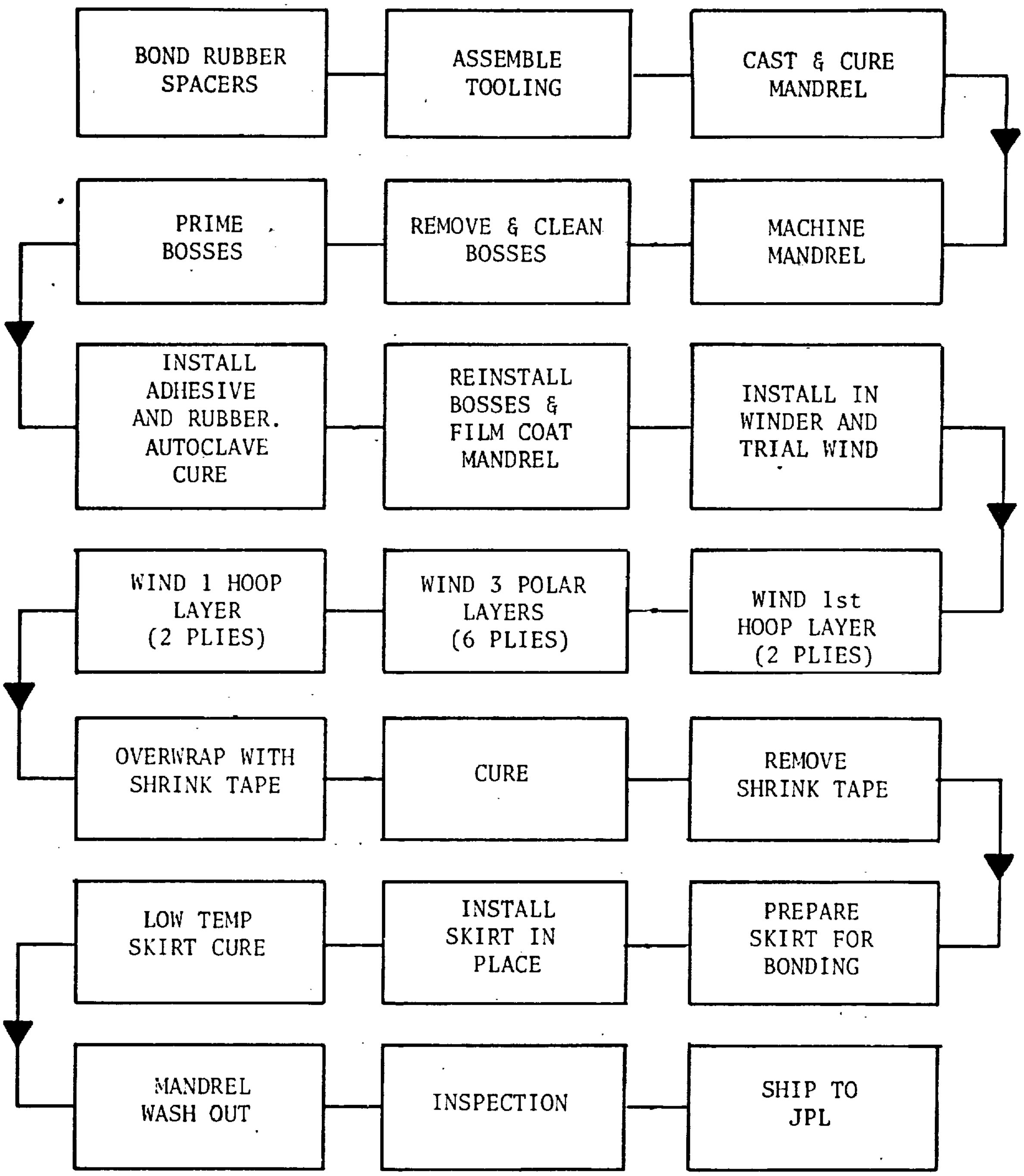

Figure 2
Manufacturing Flow Diagram

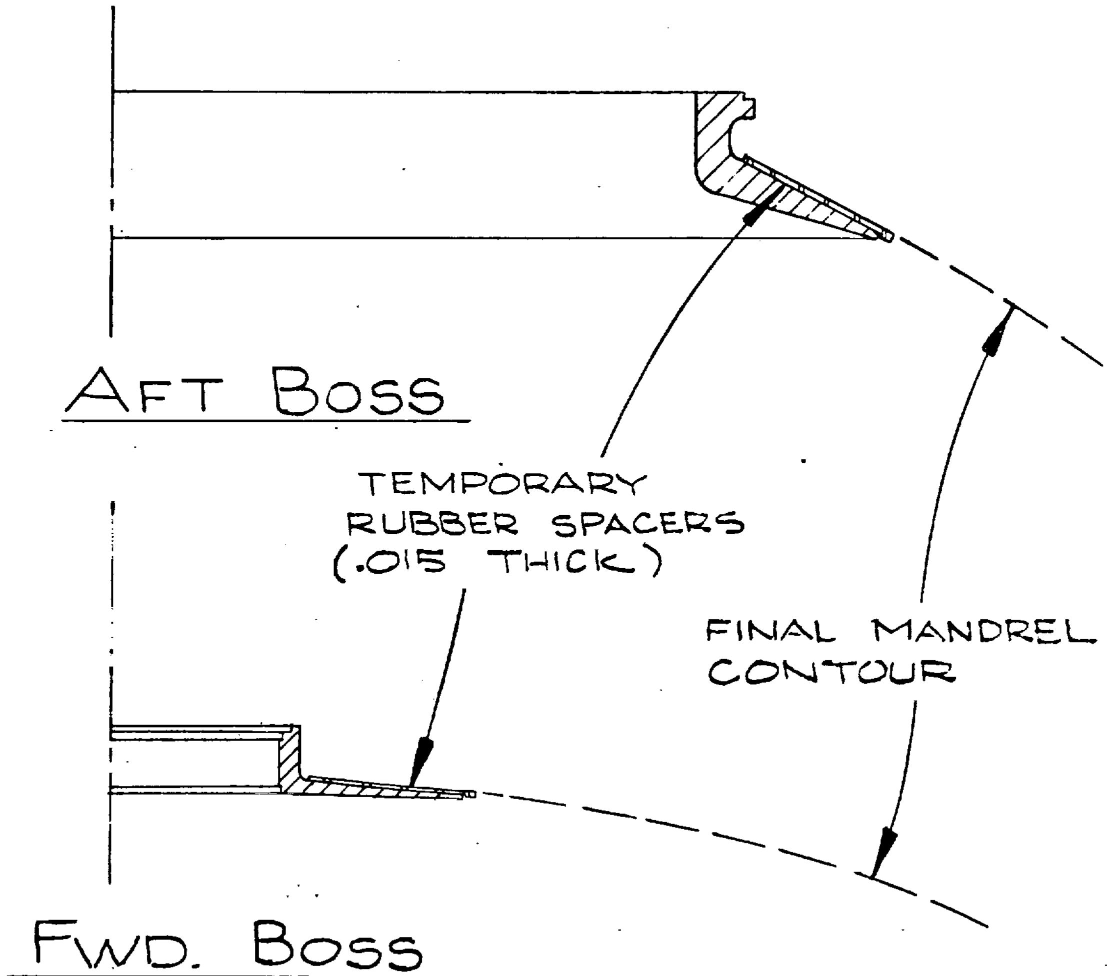

Figure 3
Bonded Rubber Spacers

and provided a firm attachment and location for the flexible heating element. The flexible heating element is used to heat the mandrel to 333-339 K (140-150°F.) during polar winding and prior to hoop winding. See Figure 4.

The entire wind axis assembly and heating elements were then assembled into a vertical sheet metal sleeve and aligned with wooden spiders. A pipe, 74.295 cm (29.25 inches) diameter, was then installed over the sheet metal sleeve assembly and vertical spacing rods were inserted between the pipe and sleeve (Figure 4).

Mandrel Casting & Cure

A sand mixture with a water-soluble binder matrix was prepared for casting. The cylindrical mold was filled with the sand mixture, moisture probes were installed, and a vacuum bag was installed over the open end of the mandrel to enhance moisture removal during sand curing. The sand mandrel was cured at 436 K (325°F.) for 12 hours. Moisture probes were cast into the sand to monitor the duration of cure required. These probes were calibrated to measure a change in electrical resistance which indicated the required moisture content compatible with maximum mandrel properties.

Mandrel Machining

The tooling was removed and the cylinder machined to size. The dome ends were machined to the proper contours with tracer attachments using the polar bosses and the cylinder section for reference. (Figure 5). These dimensions were then verified and recorded in the M & IR.

Boss Cleaning

Both polar bosses were removed from the cast mandrel and the temporary rubber spacers were removed. The bosses were then cleaned for priming in accordance with the sequence described in Table I.

Boss Priming

The priming and adhesive system consisted of Chemlok 205 (primer) and 220 (adhesive). Both were diluted with toluene (33%), then brush-coated on the bonding surfaces of both bosses. Both bosses were air-dried for 30 minutes prior to oven bake of 20 minutes at 344 K (160°F.).

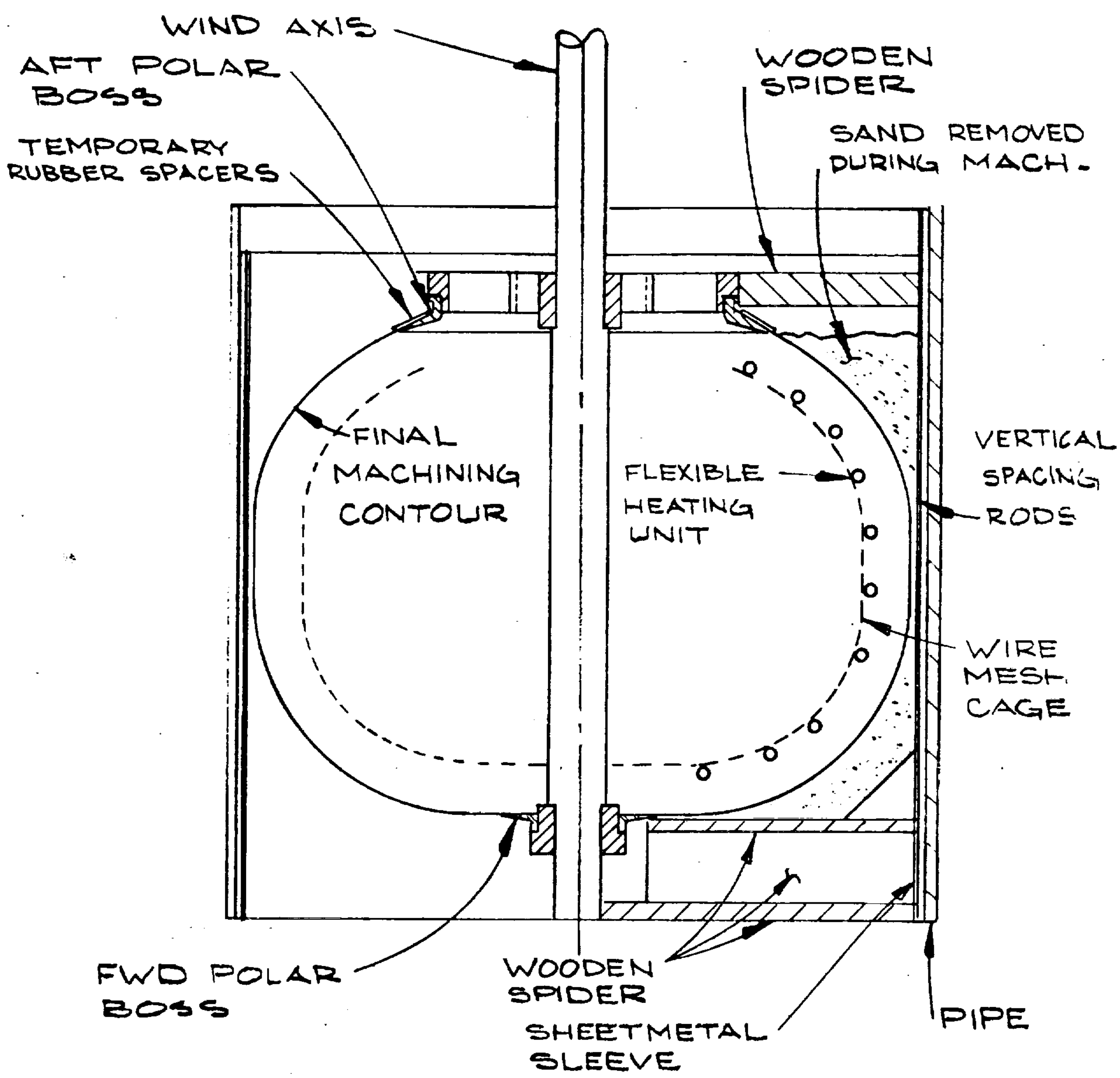

Figure 4
Mandrel Casting Assembly

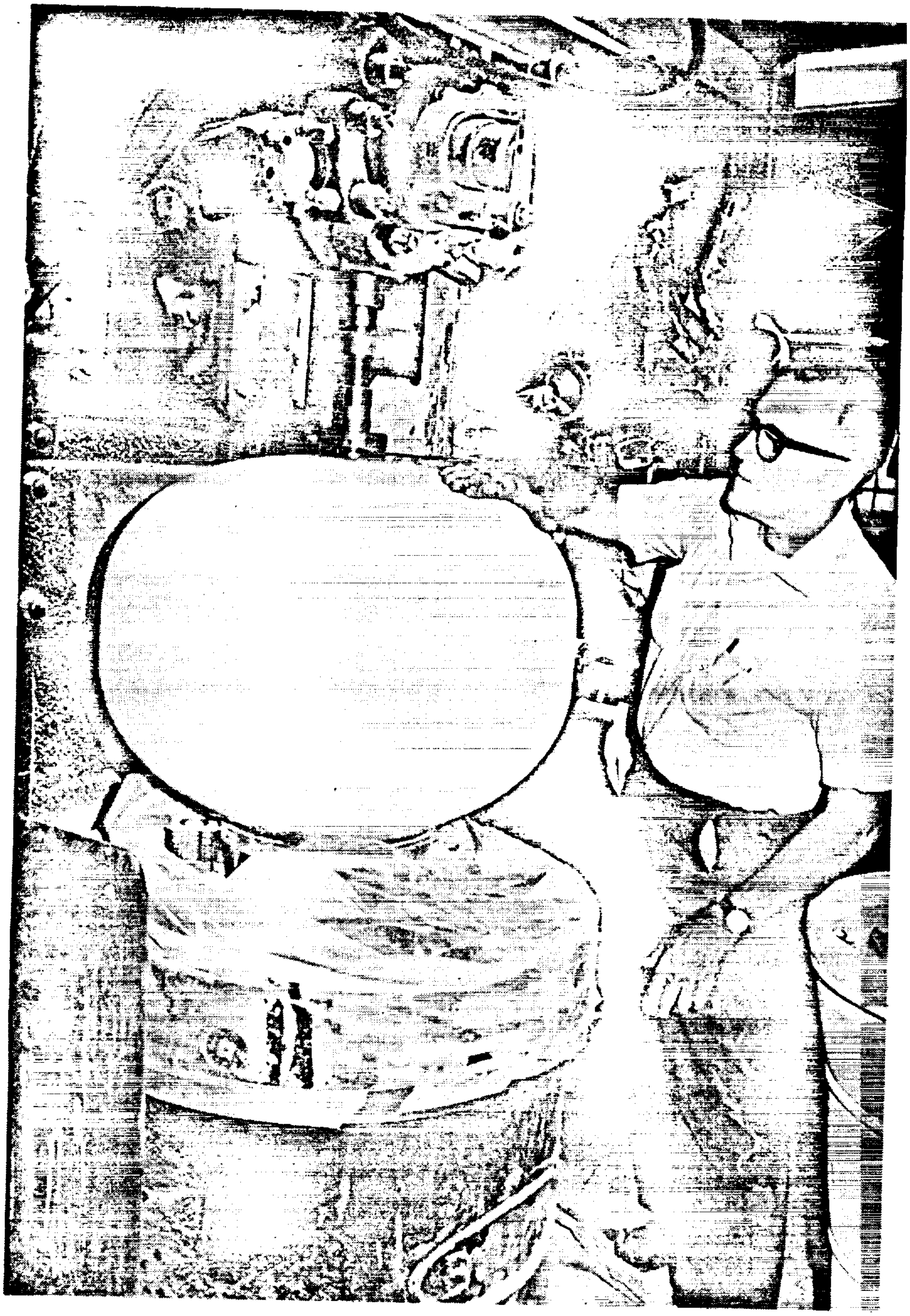

Figure 5

Mandrel Machining

TABLE I

BOSS CLEANING PROCEDURES

MEK Wipe With Clean Cloths

↓

Alkaline Soak Cleaner - Oakite 164 or Equivalent
Mixture: 4-8 oz/gal (27.8-55.6 cc/liter)
Temp: 356-373 K (180-212°F) — Time: 5-15 Minutes

↓

Hot Water Rinse — Temp: 333-345 K (140-160°F) — Time: 1-2 Minutes

↓

Cold Running Water Rinse — Time: 5 Minutes Minimum

↓

Nitric Acid (40° Bé) — 27-32% Volume
Hydrofluoric Acid 170% — 1.6-2.5% Volume
Water Remainder
Ratio HNO_3/HF = 15:1
Temp: 328-333 K (130-140°F.) — Immersion Time: 15-20 Seconds

↓

Cold Running Water Rinse — Time: 2 Minutes Minimum

↓

Nitric Acid (40° Bé) — 45-55% Volume
Water (Distilled) — Balance
Temp: 294-306 K (70-90°F)

↓

Hot Water (Deionized) Rinse, Over-Flowing
Temp: 333-345 K (140-160°F)

↓

Force Dry
Temp: 333-345 K (140-160°F) — Time: 15-30 Minutes

↓

Store in Plastic Bag

Rubber Shear Ply Installation

The rubber shear ply (V-45) was cured to the primed bosses at 41.37 N/cm^2 (60 psi) pressure at 400 K (250°F.) for 3.25 hours in an autoclave. Pressure, temperature, and time were recorded in the M & IR.

Preparation for Winding

The polar bosses were reinstalled on the sand mandrel. The locations were verified and recorded in the M & IR. The domes were covered with Teflon† tape and the cylinder was covered with two sheets of .0127 mm (.0005 inch) thick FEP. These parting agents provided an excellent barrier between the mandrel and the windings. The material was layed-up in an overlapping manner and, because of their thinness did not appreciably degrade the as-wound contours.

Winding Tensioners

The tensioning and delivery system is depicted in Figures 6 and 7. Figure 6 illustrates the 5-reel tensioning arrangement which was found to be inadequate during the first aborted winding. The 5-reel system was abandoned when it became evident that reels on a common spindle would not function independently due to friction effects. Since the path of any two tapes around the mandrel must always differ slightly, and the amount (diameter) of graphite on the reels were not identical, the reels rotated at different speeds which resulted in tension losses and breaks at the driven reel.

The 4-reel system (Figure 7) allowed each reel to be mounted on separate spindles free of common friction surfaces. This tensioning system was used to wind the graphite motor case. Tension was applied by using two magnetic tensioners for each graphite tape and allowing the reels to be free acting.

A portable tensioning system, consisting of a vertical plate on which two magnetically controlled tensioning pulleys were mounted, was used to apply the single graphite tape required for the circ winding.

Winding

Winding was performed in the Lincoln (planer) winder. Prior to winding, the heating element was connected to a rheostat and the temperature of the mandrel stabilized at 333-339 K (140-150°F.). Heat was applied only during the polar winding.

†TM - E. I. duPont

sequences. The winding sequence and winding details used for each sequence are shown in Table II.

Shrink Tape Application

Following the graphite winding, two layers of polyester shrink tape were over-wound on the chamber in the polar direction. For the shrink tape winding operation, the roll of shrink tape was mounted on the pay-off roller on the longo winding arm. A slight unmeasured tension in the tape was developed by tightening the mounting roll against a face plate on the end of the longo arm.

Cure and Cool Down

The graphite vessel was cured and cooled as directed in the following steps. These sequential steps were specified in the M & IR, monitored by production and quality control personnel and verified by quality control. All pertinent data was recorded in the M & IR.

A. The oven was pre-heated to 339 K (150°F.).

B. The temperature was raised to 380 K (225°F.) in 30 minutes.

C. The temperature was held between 375-385 K (215-235°F) for 2 hours.

D. The temperature was raised to 436 K (325°F.) in 30 minutes.

E. The temperature was held at 436 K (325°F) for 4 hours.

F. The temperature was raised to 444 K (340°F.) in 30 minutes.

G. The temperature was held between 442-446 K (335-345°F.) for 4 hours.

H. The oven was set at 398 K (256°F.) for 90 minutes.

J. The oven was then set at 367 K (200°F.) for 90 minutes.

K. The oven was turned off and the doors remained closed for 9C minutes. The motor case was then removed from the over.

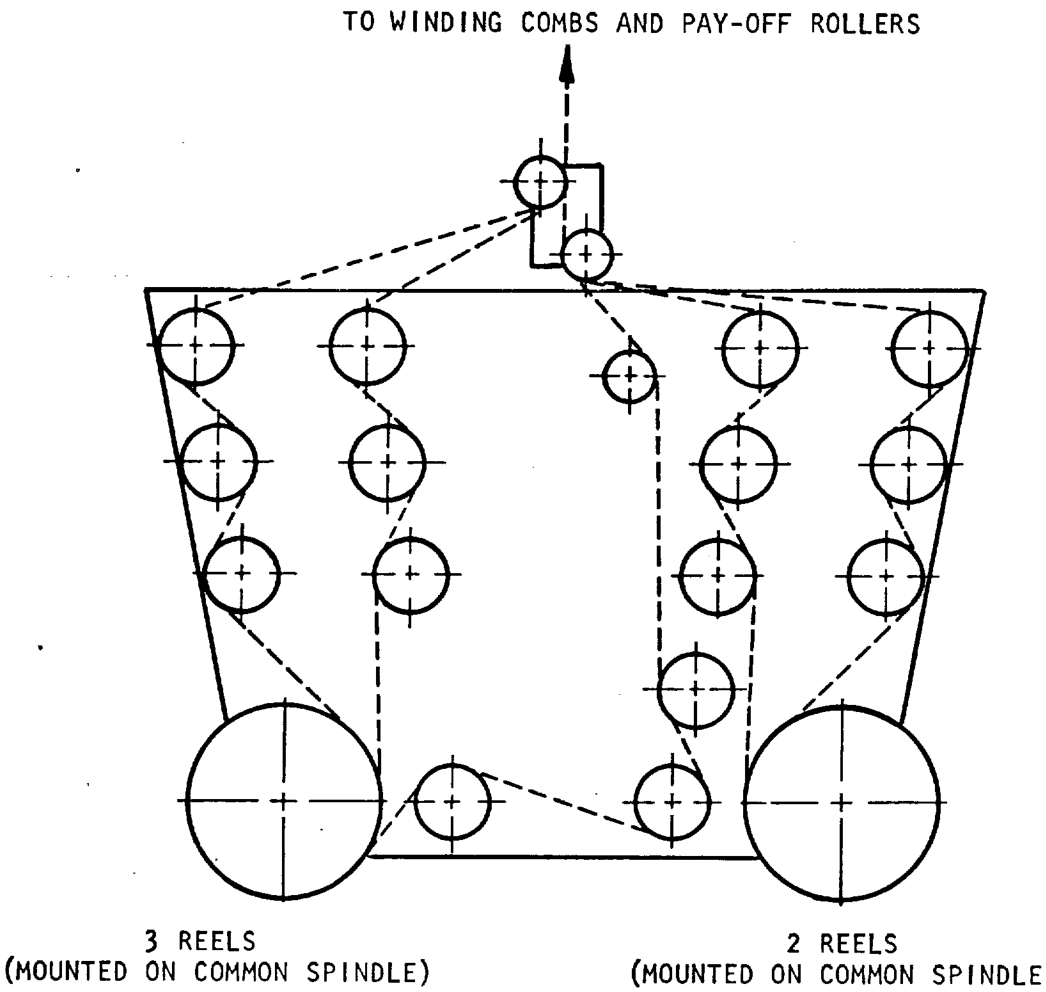

Figure 6. 5-Reel Tensioning and Delivery System

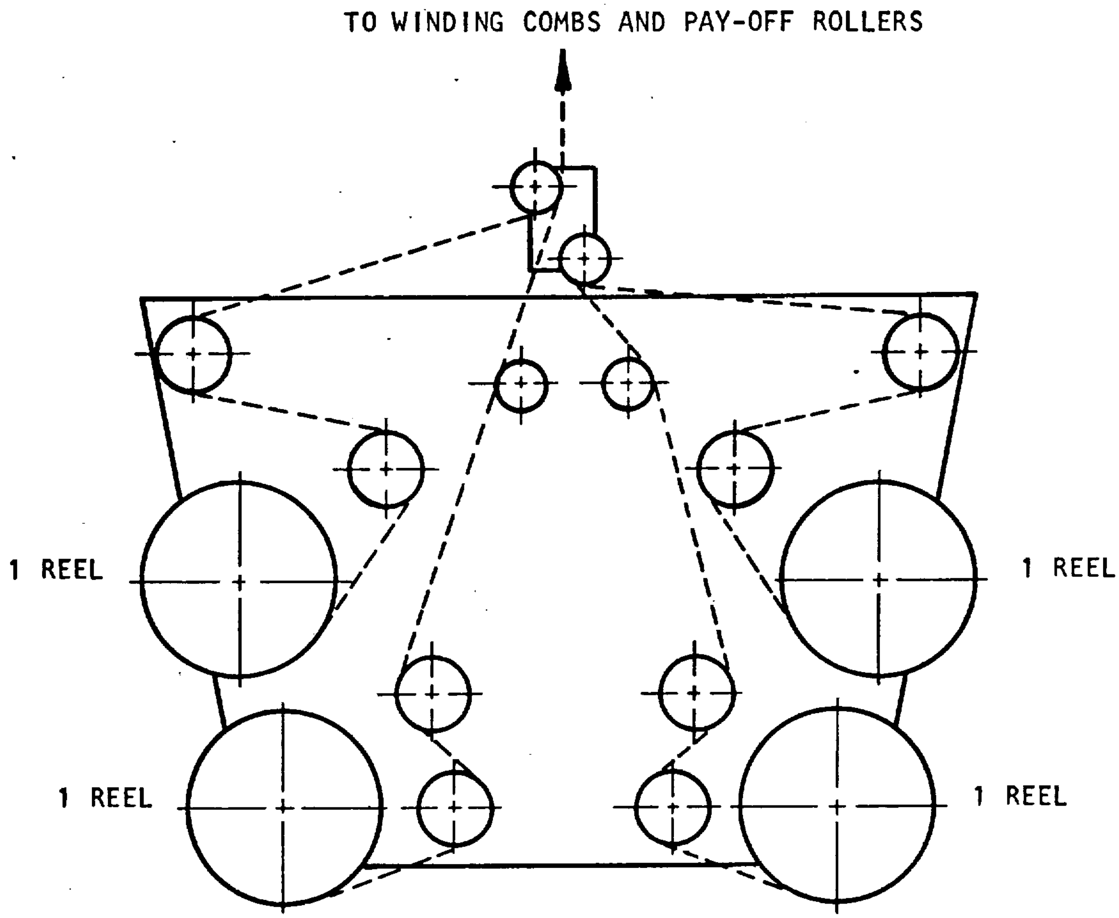

Figure 7. 4-Reel Tensioning and Delivery System

TABLE II WINDING DETAILS.

Sequence (Layers)	Graphite Tape Tension		Band Width		Polar Position at Aft Boss	Polar Position at Fwd Boss	Hoop Reversal	
	N	Lbf	mm	Inches			mm	Inches
1st Hoop	38.92	8.75	5.08	0.200	- - - -	- - - -	12.70	0.50
1st Polar	35.58	8.00	18.29	0.720	Adjacent	Adjacent	--	--
2nd Polar	35.58	8.00	18.29	0.720	Adjacent	Adjacent	--	--
3rd Polar	18.92	4.50	18.29	0.720	Adjacent	1/2 Band Width	--	--
2nd Hoop	40.03	9.00	5.08	0.200	- - - -	- - - -	6.35	0.25

Skirt Preparation (Titanium)

The metal was prepared for adhesive application using MEK and methyl alcohol washes followed by a light grit blasting operation using aluminum oxide. An MEK re-wash and water rinse were followed by a force drying operation of the titanium.

Chemlok 205 and 220 were again used and rubber layed-up on the bonding surface. The rubber was cured in an autoclave similar to the polar boss operations.

Skirt Bonding

The skirt was mounted on a locating spider (Figures 8 & 9) and both bonding surfaces cleaned and abraded prior to the application of adhesive. The adhesive (Versamide 140 and Epon 828 resin, 50/50 ratio) was applied to the masked bonding surface of the chamber and rubber surface on the skirt. The skirt was installed in place by torquing the locking nut at the prescribed torque value, 135.6 joules (100 ft-lbf).

The bond was oven-cured at 367 K (200°F.) for two hours.

Finishing Operations

The motor case and mandrel assembly was placed on a washout stand consisting of a table with a circular opening. The assembly rested on the skirt with the larger aft fitting up. Warm water, 333 K (140°F.) was directed into the exposed sand and the sand was allowed to soften sufficiently to permit removal of the wind axis and polar boss locating hardware. Warm water then circulated through the exposed sand mandrel until all sand was flushed and the wire mesh and heating element were removed. The motor case was then cleaned and submitted to quality control for a dimensional inspection.

Final Inspection

The Quality Control department performed a dimensional inspection of the finished rocket motor case. The findings of this inspection are presented in Table III.

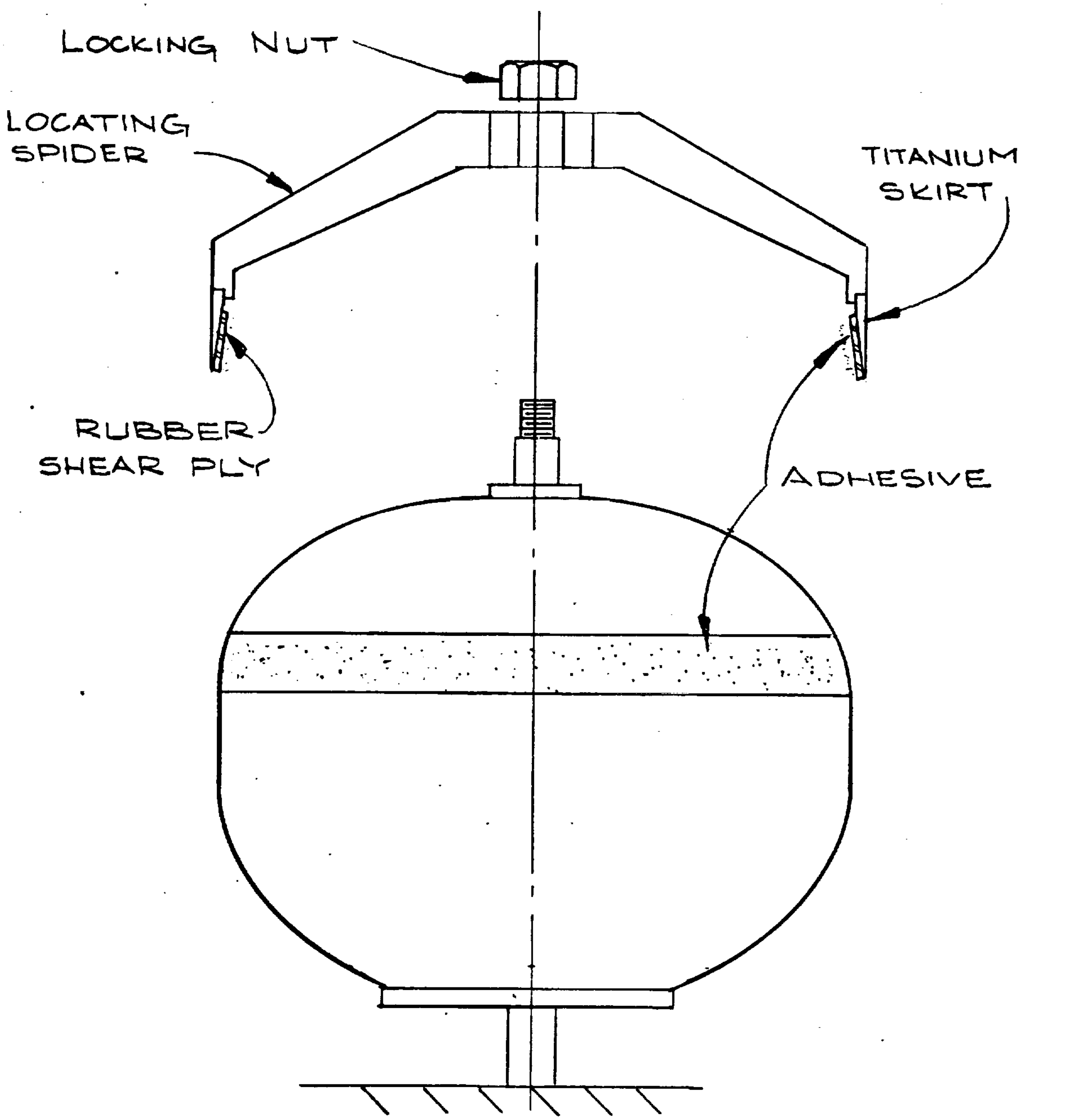

Figure 8
Skirt Bonding Fixture

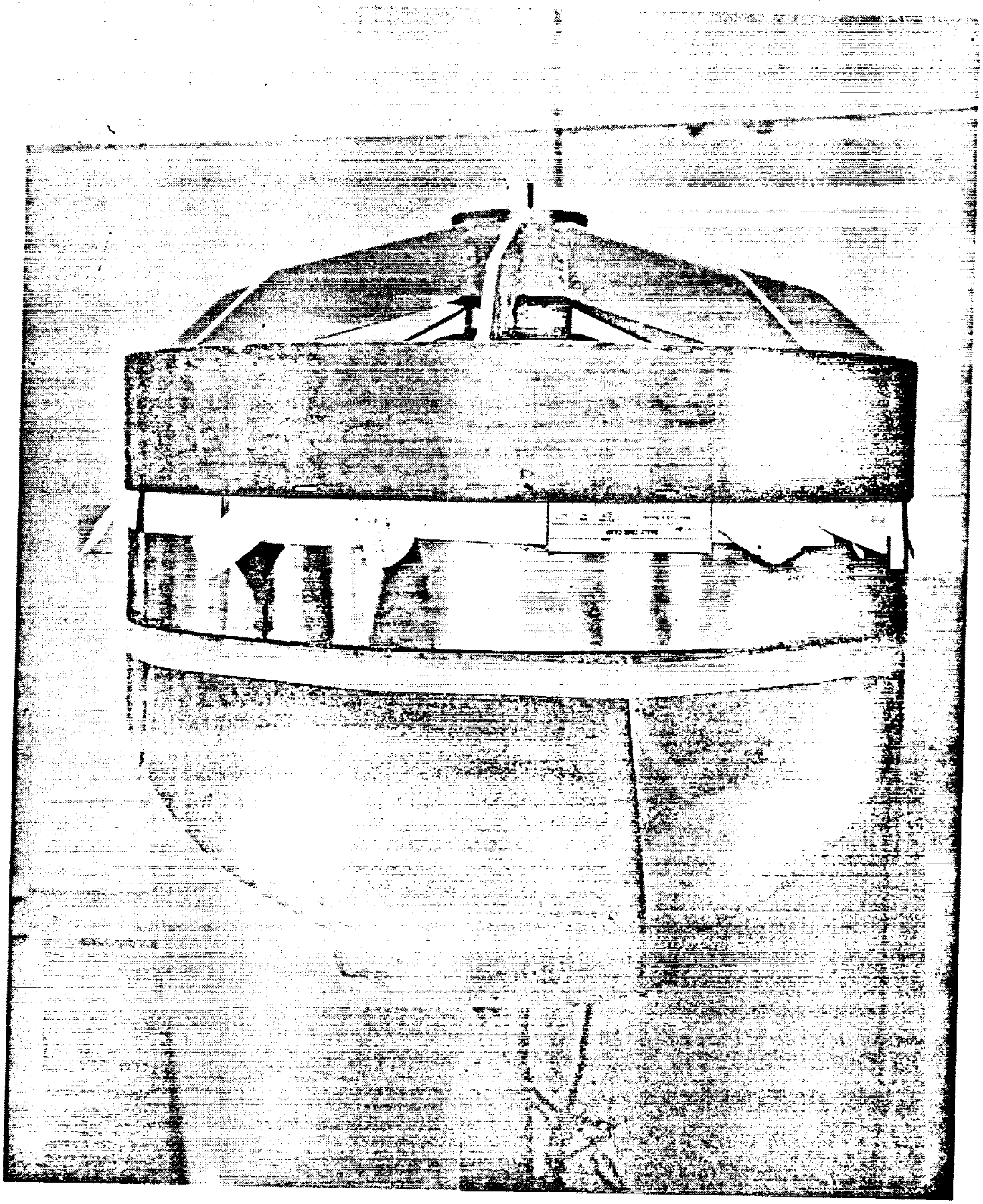

Figure 9

Skirt Bonding Assembly

TABLE III

DIMENSIONAL INSPECTION DATA

Measurement	As Engineered		Actual	
	cm	Inches	cm	Inches
Overall Length	57.506	22.64	57.866	22.782
Forward Boss to Skirt	14.580	5.74	14.051 13.894	5.532 Max. 5.470 Min.
Pi Tape 3 Radial Locations 24.9 cm (9.804 Inches) from Aft Boss (Inside Diameters)	71.780	28.260	71.112 71.110 71.105	27.997 27.996 27.994
Pi Tape 3 Radial Locations 27.4 cm (10.804 Inches) from Aft Boss (Inside Diameters)	71.831	28.280	71.206 71.209 71.211	28.034 28.035 28.036
Pi Tape 3 Radial Locations 30.0 cm (11.804 Inches) from Aft Boss (Inside Diameters)	71.742	28.245	71.145 71.145 71.143	28.010 28.010 28.009
Hoops from Aft Boss	24.267	9.554	23.317 23.165 23.241	9.180 Max. 9.120 Min. 9.150 Avg.

DATA EXTRACTED FROM BRUNSWICK QUALITY CONTROL REPORT OF 11 FEB. 72 (K. WILSON)

Problems and Corrective Actions

Several problems arose during fabrication of the graphite/epoxy rocket motor case which required departures from the planned processing. These changes were coordinated and mutually agreed upon by Brunswick and the JPL representative in the best interest of completing the fabrication within the cost and time frames of the contract.

PRE-PREG BAND WIDTH CONTROL

<u>Problem</u>

The first lot of the Fiberite Hy-E 1305B graphite tape was returned to the vendor following an aborted winding attempt during the last week in October, 1971. In the course of obtaining an acceptable winding pattern, it was discovered that the graphite tape did not meet the required 4.70-5.47 mm (.200 inch ± .015) width. In addition, the quality of the band width control deteriorated as the center of the package was approached.

Inspection of four reels of Hy-E 1305B graphite tape revealed the following band width inconsistencies:

Reel No.	Maximum Width		Minimum Width		Average Width	
	mm	Inches	mm	Inches	mm	Inches
5	4.57	.180	2.29	.090	3.28	.129
6	4.06	.160	2.29	.090	3.18	.125
2	4.57	.180	2.03	.080	3.53	.139
7	4.83	.190	2.54	.100	3.94	.155

Following the inspection of the above four trial winding tapes, an unopened reel of Hy-E 1305B graphite tape was opened and examined. The first 3.05 meters (10 feet) of the tape revealed the following band width inconsistencies.

Maximum Width		Minimum Width		Average Width	
mm	Inches	mm	Inches	mm	Inches
4.83	.190	3.302	.130	4.45	.175

In addition to the lack of band width control, the tack of the prepreg tape was insufficient to provide the required winding tensions with the existing delivery systems employed by Brunswick.

Corrective Action

All packages were returned to the vendor for replacement. Various impregnation techniques were attempted by the vendor prior to developing an acceptable product. The "hot melt" technique developed by Fiberite resulted in an acceptable tape that was free of the extreme variations in width. The "hot melt" system minimized the number of rollers contacting the tape prior to solvent flash-off. The pre-preg tape was packaged directly on the reels, using minimum directional control from rollers, and gathered immediately following solvent flash-off.

New material designated as Hy-E-1330B with the Fiberite X-505 resin system was shipped to Brunswick in January 1972. Brunswick performed trial winding with the new prepreg tape and found the tape width control to be much improved and acceptable for placing an order for the remaining material.

The tackiness of tape appeared to be compatable with Brunswick's tensioning system and no problems were anticipated. However, the acceptance trial winding was performed at an ambient temperature of 292 K (65°F.). Subsequent usage of the tape during the winding of the motor case at an ambient temperature of approximately 300 K (80°F.) showed that the resin system was quite sensitive to the change (15°F.) in ambient temperature, and resulted in a tape that was quite tacky and difficult to process.

From these trial windings it was deemed that the "hot melt" system of impregnation would provide a graphite tape with sufficient band width control and tackiness to implement their usage. Replacement material was ordered in accordance with revisions to the material properties listed in JPL Specification BS504230 A. These changes (Table IV) were negotiated between Brunswick, JPL and Fiberite representatives.

Fiberite supplied enough graphite to continue the program in accordance with the negotiated variations and agreed to certify the material in accordance with the test requirement of BS504230 A. Acceptance testing at Brunswick was not required in lieu of certification from the vendor.

TABLE IV

REVISIONS TO JPL SPECIFICATION BS504230

	Original	Revised
Resin Content	33% ± 3.0%	37% ± 3.0%
Voltile Content	4.0% Max. Avg. 6.0% Individual Max.	3.0% Max.
Tape Width	.470-.546 mm (.200 ± .015 inch)	.495-.572 mm (.210 ± .015 inch)
Flow	10-20%	5-20%
THE FLEXURAL STRENGTHS SHALL NOT EXCEED A 25% DETERIORATION AT 395 K (250°F.).		

BAND GAPPING AND SHINGLING

Problem

Probably the most serious short-coming of the delivered motor case were the gaps within the polar pattern (Figure 10 & 11). This phenomenon is caused by the following related effects, all of which contributed to the gapping: winding machine alignment, winding band splitting (returning to original roving width), tape tension, tape tack, and shingling. Refer to Appendix B for a definition of shingling.

The polar winding machine employed to wind the graphite motor case required the tape reels to be mounted on the rotating arm and that the graphite tapes make three right-angle turns prior to application on the mandrel. This necessitated several sets of pullies (as well as the magnetic tensionser themselves) to obtain precise alignment. If the tack of the graphite tape is too advanced, the band width can be influenced by the multiple arrangement of pullies and right-angle turns.

The original intent was to use five tapes to produce a winding band 25.4 mm (1.0 inch) wide (Figure 6). Because of the limited space on the rotating arm, this approach required 2 and 3 reels to be mounted on common spindles. It was determined during the attempted winding in October that the dual-mounting technique was not working since the reels mounted on common spindles would not operate independently because of the frictional contact between reels. Reels must be allowed to rotate at different speeds to maintain tension and prevent tape breakage.

The "shingling" effect proved to be extremely bad. The band slipped to reach an equilibrium position and thus negated any progress made in aligning and producing a quality band width.

The tape tension selected for the polar winding proved to be too high which caused splitting of the winding band between the pay-off head and mandrel surface. The high tension also was adverse in that the shingling effect was much worse at high tensions and that the band on the mandrel continued to lose winding tension and migrate inboard towards the forward polar boss until reaching equilibrium.

Refer to Appendix C for calculation techniques in setting tension levels.

Corrective Action

The tensioning and delivery system was redesigned to provide a 4-reel system (Figure 7) which allowed each reel to be

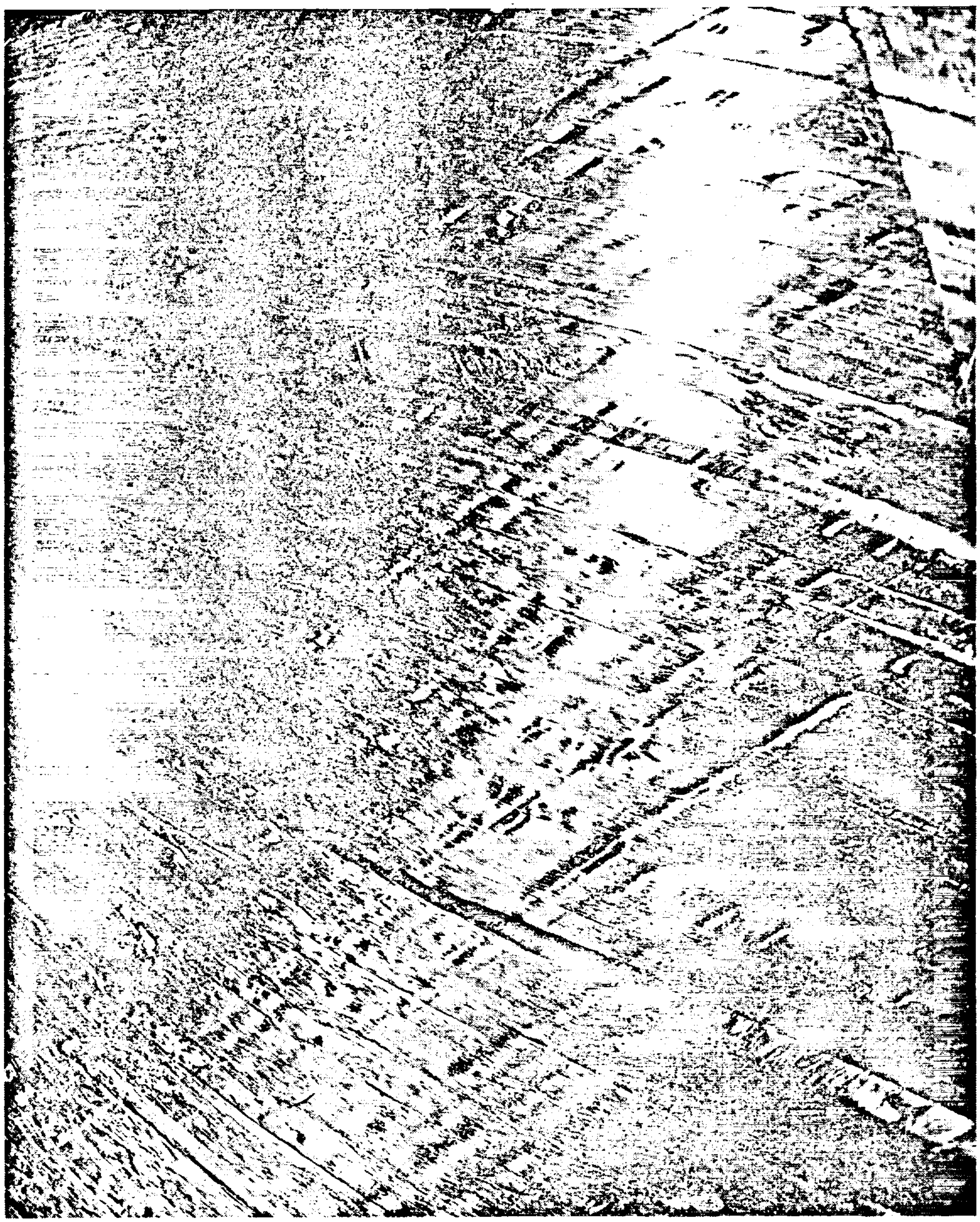

Figure 10

Gapping and Buckling of Polar Fibers

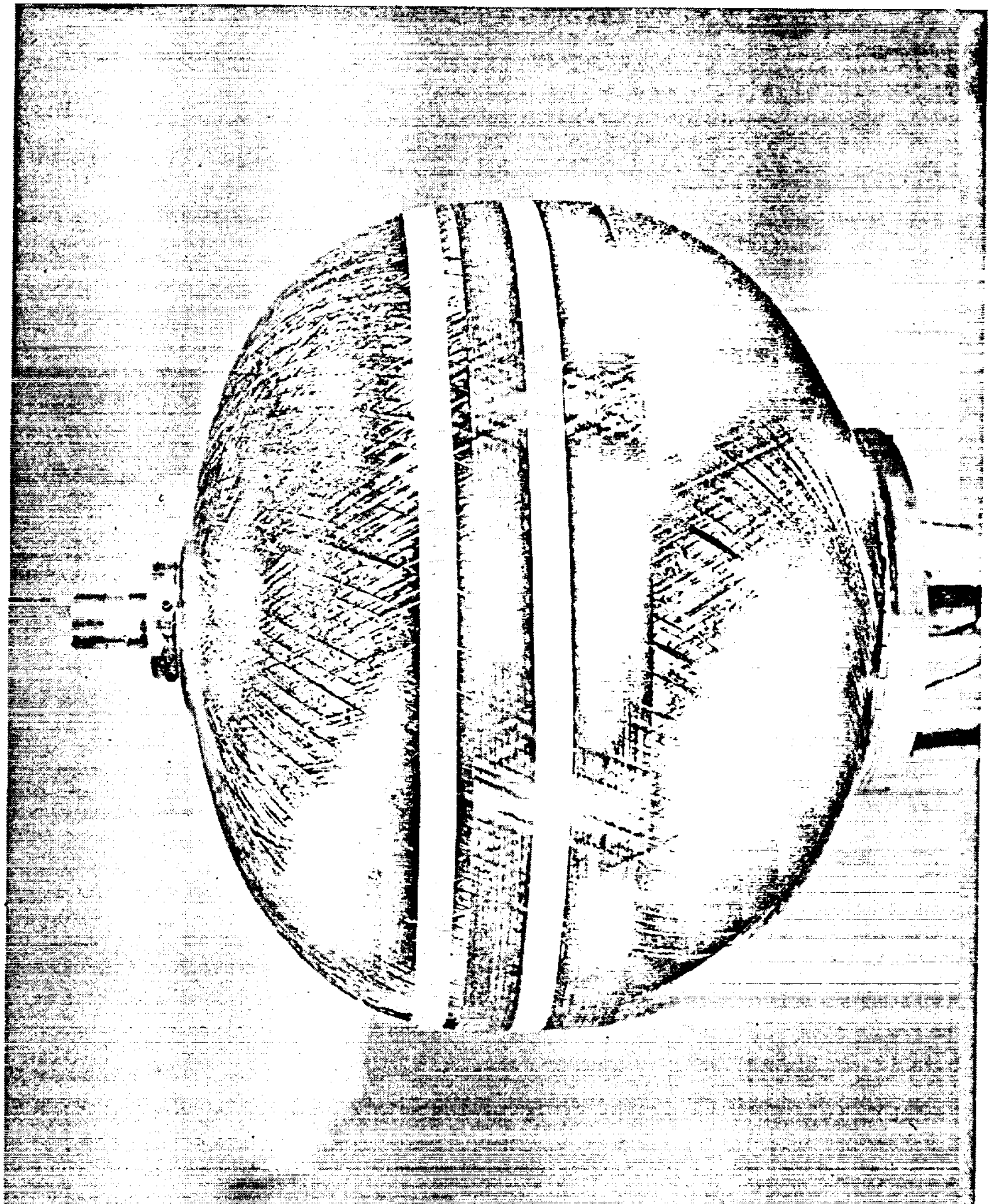

Figure 11. Rocket Motor Case Prior to Skirt Bonding

mounted independently. The band width was accordingly reduced from 25.4 mm (1.0 inch) to 20.32 mm (.800 inch) wide. A total of three days were used in attempting to align the tensioning system to meet the 5.08 mm (.200 inch) band width requirement. It was mutually agreed by Brunswick and JPL that the band width must be reduced to 4.57 mm (.180 inches) per tape, thus reducing the effective band width from 20.32 mm (.800 inch) to 18.29 mm (.720 inch) for the 4-tape winding band.

The problem was further complicated by excessively high tack on the pre-preg tape which caused the width to decrease further as the tape traversed the rollers. The new resin system was trial-wound by Brunswick at an ambient temperature of 292 K (65°F.). At this ambient temperature, the tack appeared to be excellent for the intended use. However, the actual winding of the motor case was performed at an ambient temperature of 296-298 K (72-77°F.).

As the first polar layer was wound, slippage occured as the windings layed over the FEP-covered cylinder and teflon tape-covered domes. The slippage resulted in gapping between bands occasionally as wide as 3.81 mm (.150 inch). The slippage continued until the remaining tension in the tape was very low. The fibers reached equilibrium with the inboard edge of the tape against the mandrel and outboard edge lifted free of the mandrel surface. This effect is described as "shingling".

JPL personnel agreed that, since all surplus graphite had been used for trial winding purposes, there was no alternative except to proceed with the fabrication because slippage of subsequent layers would be reduced when not winding over the FEP film. The gaps were hand-filled with segments of tape 46-61 cm (18-24 inches) and the winding continued.

A good pattern was wound on the mandrel for the second layer although the shingling effect was only delayed as a function of time. Each fiber slowly migrated toward the forward polar boss until all tension was lost; resulting again in the complete loss of tension in the fibers and, to a lesser extent, some gapping.

To finish the polar winding sequence, the winding tension was dropped from 35.58 N (8.0 lbf) per tape to 20.02 N (4.5 lbf) per tape. This change minimized slipping (shingling) since there was less tension loss in establishing equilibrium for the fibers.

This change was quite successful, and a good third layer was wound with minimal slippage. The decrease in tension also eliminated splitting and roping of individual winding bands into narrower widths.

The only adverse effect of the lower tension was that the compression (shrink energy) available in the shrink tape was higher than the tension in the polar fibers. This mismatch resulted in some buckling of fibers and extruded the last polar wraps into gaps of the preceding layers. This effect is visually evident on the exterior surface of the cured motor case.

EXCESSIVE BUILD-UP AT FORWARD POLAR BOSS

Problem

The build-up of tape at the forward polar boss is 100% greater than the original design depicted and is in interference with the threaded attachment area on the boss.

Corrective Action

Insufficient control was exercised during fabrication since the problem was neither anticipated nor recognized in time to implement the proper corrections.

The excessive build-up was caused by the narrower winding band, 17.83 mm (.72 inch) versus the original design of 25.40 mm (1.0 inch), and the slippage of all polar layers against the boss during shingling.

The problem was recognized following the application of the second polar layer. At this point Brunswick and the JPL representative jointly decided that the third polar layer should be setpped outboard of the existing build-up, but still on the boss.

The threads were covered with a thick layer of masking tape prior to installing the shrink tape. However, the tape was extruded off the threads and the graphite roving was pushed toward the boss by the shrink film during the curing operation. The intended fix was not successful.

SKIRT MISFIT

Problem

Following the cure of the body portion of the graphite rocket motor case, pi-tape dimensions indicated that the O.D. of the motor case was approximately 2.54 mm (0.100 inch) oversize. This condition would result in the skirt seating out at only one-half, 17.097 mm (0.75 inch), of the desired ramp length.

This larger diameter was caused by three contributing factors of near-equal magnitudes:

1. Thicker wall: It was necessary to wind with more polar tapes per unit-width (band density); hence the motor case wall thickness was greater than originally planned for the titanium skirt. This problem was further compounded by the slippage of the fibers, which made the polar laminate even thicker.

2. Thermal Growth: Following the cure, it was noted that the sand mandrel had shrunk away from the cured laminate. A tap test indicated that the mandrel was only contacting the domes at approximately 1/3 the distance from the tangent toward the bosses. This effect is predictable when noting that the mandrel and the graphite exhibit opposite thermal coefficients of expansion and that the graphite would tend to remain at its cured dimension.

3. Over-sized Mandrel: It is apparent that during the 4-month delay caused by the pre-preg problems previously identified, the diameter of the sand mandrel had grown approximately 0.76 mm (.030 inch). Subsequent investigations indicate that the sand mandrel is slightly hydroscopic and had absorbed moisture during this 4-month period causing the diametrical growth.

   Initial inspection of the sand mandrel following machining verified that the dimension was correct at the time of mandrel acceptance. The discrepancy in dimensions was not found until the M & IR records were researched for causes of the build-up.

Corrective Action

The clearance between the titanium skirt and cured graphite motor case was increased by: (i) machining the rubber shear on the skirt from 0.38 mm (.015 inch) thickness to 0.13 mm

(.005 inch) thickness and by, (ii) heating the titanium skirt and locating spider to 367 K (200°F.) which expanded the diameter approximately 0.43 mm (.017 inches).

The skirt and locating spider were installed and the seating operation was initiated. A maximum torque load of 135.6 joules (100 ft/lbf) was applied on the locking nut to push the skirt up the ramp. This torque value was calculated to limit the compressive stress in the laminate to 6894 N/cm^2 (10,000 psi) following cool down of the titanium skirt. By utilizing these corrective actions the skirt seated-out at 3.175 cm (1.25 inches) inboard of the tangent line, thereby locating at .635 cm (.25 inch) short of the intended position.

Revised Stress Analysis

Because of the necessary deviations of the original winding parameters, the polar composite thickness was increased. Previous stress analyses based on netting and composite theory have demonstrated the following margins of safety at a burst pressure of 248.18 N/cm^2 (360 psig):

Netting Analysis - Polar Band Width = 1.00 inch (25.4 mm)

M.S. (hoop) = +.24

M.S. (polar) = +.75

Composite Analysis - Polar Band Width = 1.00 inch (25.4 mm) in cylinder section

M.S. (hoop) = +.13

M.S. (polar) = +.19

Both analyses indicate that the critical mode of failure would be associated with the hoop fibers. The addition of hoop fibers could significantly add to the strength in the hoop direction for a very slight increase in total weight.

A netting analysis of the "as-wound" configuration follows.

Polar fiber thickness is:

$$t_{f\alpha} = \frac{\text{(no. of reels) (no. of layers) (area/reel) (2 plies/layer)}}{\text{(band width)}} \qquad (1)$$

$$= \frac{\text{(4 reels) (3 layers) } (.8078 \times 10^{-3} \text{ in}^2\text{/reel})}{\text{(.720 in.)}} \qquad (2)$$

$$t_{f\alpha} = .0269 \text{ inch } (0.683 \text{ mm}) \tag{3}$$

Hoop fiber thickness is:

$$t_{f\theta} = (\text{no. of reels})\ (\text{no. of plies})\ (\text{area/reel})\ (\text{turns/in.}) \tag{4}$$

$$= (1 \text{ reel})\ (4 \text{ plies})\ (.8078 \times 10^{-3} \text{ in}^2/\text{reel})\ (5.00 \text{ turns/in}) \tag{5}$$

$$= .0162 \text{ inch } (0.412 \text{ mm}) \tag{6}$$

Then fiber stresses at 360 psi (248.18 N/cm^2) contained pressure are:

$$\sigma_{\phi f} = \frac{PR}{2 \cos^2\alpha \ t_{f\alpha}} \tag{7}$$

where P is contained pressures, psi
R is mean radius to cylinder wall, in.
α is the polar wind angle
$t_{f\alpha}$ is the polar fiber thickness, in.

$$\sigma_{\phi f} = \frac{(360 \text{ psi})\ (14.025 \text{ in.})}{2\ (.835)\ \ (.0269 \text{ in})} = 112{,}000 \text{ psi } (77{,}213 \text{ N/cm}^2) \tag{8}$$

and

$$\sigma_{\theta f} = \frac{PR}{t_{f\theta} + t_{f\alpha} \sin^2\alpha} \tag{9}$$

where P, R, α, and $t_{f\alpha}$ are the same as above and

$t_{f\theta}$ is the hoop fiber thickness, in.

$$\sigma_{\theta f} = \frac{(360 \text{ psi})\ (14.025 \text{ in})}{.0162 \text{ in} + (.0269 \text{ in})\ (.166)} = 244{,}000 \text{ psi } (168{,}214 \text{ N/cm}^2) \tag{10}$$

As was done to determine the margins of safety for the netting analysis presented earlier in this section, a maximum stress theory of failure will be utilized. The allowable values for fiber stresses in the hoop and polar fibers are 310,000 psi (213,714 N/cm^2) are 220,000 psi (151,668 N/cm^2) respectively. These values are determined as the result of Brunswick testing of 100 in^3 (1639 cm^3) pressure vessels.

$$\text{M.S. (hoop)} = \frac{310,000}{244,000} - 1 = +.27$$

$$\text{M.S. (polar)} = \frac{220,000}{112,000} - 1 = +.97$$

It can be seen that the additional fibers should improve the burst strength only slightly since the contribution to the hoop strength is slight.

CONCLUSIONS

As a result of this program, the following conclusions have been reached by the Brunswick Corporation:

1. Graphite/epoxy rocket motor cases in this size range (56 cm [22 inches] long x 71 cm [28 inches] diameter) can be fabricated using commercially-supplied pre-preg tapes.

2. JPL Specification BS504230 must be modified to allow usage of the "hot-melt" resin system necessary for the tape width control required to wind a motor case of this size.

3. Other modifications to JPL Specification BS504230 are required to define and measure "tack" of the pre-preg.

4. Established S-glass filament winding techniques are not necessarily applicable for filament winding graphite tapes for the following reasons:

   a. The mandrel shape for the graphite motor case was too adverse for slip-free winding, therefore, any tension applied to the graphite tapes would be lost during fiber migration. Regardless of the tensioning system utilized, a high quality, uniform-tensioned laminate would be impossible to wind with a slippage condition.

   b. The high winding tensions selected for the first two polar layers contributed to the above slippage and gapping conditions.

   c. It is not practical to polar-wind graphite tapes at the "net" width of the package. Some allowance must be made for decrease of band width through the delivery system.

   d. Gapping of polar fibers can be minimized through proper selection of geometry, wind tensions, and effective (on-mandrel) tape widths.

   e. The graphite tape build-up at the polar bosses exceeded theoretical analysis.

   f. Tape reels (graphite tape packages) must be free to operate independently.

5. The tapered ramp concept for externally installing skirts is a sound concept provided (i) the designer compensates for thickness variations in the laminate, (ii) that the sand mandrel is protected from long-term exposure to humid conditions, and (iii) allowances are provided for the "as-cured" diameter increase of the graphite laminate.

6. A wound-in-place graphite skirt would circumvent the above variables as well as decrease discontinuity loads during pressurization.

7. The internally heated mandrel has good potential as a fabrication aid but requires further coordination with the pre-preg supplier to match flow temperatures of the selected pre-preg material.

RECOMMENDATIONS

Based upon the knowledge gained from this program, the following recommendations are presented to optimize design, materials, and manufacturing processes for filament-wound graphite/epoxy rocket motor cases.

1. Modifications to JPL Specification BS504230, as defined in Table IV of this report, are recommended for future procurement. Further changes relative to mechanical properties at ambient and elevated temperatures should be coordinated with the vendor and JPL, and incorporated into the specification.

   In addition, a technical definition of "tack" must be authored and incorporated into the specification since the tack of the "hot-melt" system appears to be very sensitive to slight temperature changes between 292 and 298 K (65 to 75°F.). It is further recommended that the "hot-melt" system be changed to provide stability over a temperature range of 295 to 302 K (70 to 85°F.) to facilitate winding in normal shop ambients.

2. All future graphite chambers must be wound with much lower critical slip angles. It is recommended that the slip angle be decreased to 0.14 rad (8°) maximum to minimize the adverse effects caused by slippage.

   Machine alignment could be appreciably improved by winding in a different type of winding machine. The "tumble" winder, for instance, rotates the mandrel in a polar pattern while the winding band remains fixed in one plane. This type of equipment would require no right-angle turns of the winding band and would minimize the number of guide rollers necessary to describe the winding band. However, it should be noted that Brunswick's existing tumble winder is limited to a maximum mandrel weight of 90.72 kg (200 lbm) and a maximum envelope of 60.96 cm (24 in) diameter x 76.20 cm (30 in) length.

3. It is also recommended by Brunswick that the existing three-polar layer design be combined into two polar layers of equivalent total composite thickness. Thus, three layers of 5.08 mm (.200 in) wide bands could be wound far easier into two layers with a 3.38 mm (.133 in) wide band.

4. Winding tensions should be lowered by approximately 50% for both the hoop and polar layers. A decrease of this magnitude would result in smooth continuous bands without any separation of tapes within the band. This is well-documented and proven during the winding of the third polar layer sequence.

It is difficult to assess the combined effects of decreasing the net band width and also lowering the winding tensions. Both are corrections which would minimize gapping. It is possible that only one of the two techniques is required for a configuration in which the critical slip angle has been appreciably decreased.

Future fabrication should include sufficient graphite tape for trial winding and stripping of an entire motor case prior to final fabrication. Results of the trial winding should then be negotiated with JPL to finalize the extent of corrections that are absolutely necessary to fabricate an optimum chamber.

The drop in winding tension would require a change in the shrink tape fabrication sequence to minimize fiber buckling. It is suggested that the shrink tape be removed prior to maximum temperature cure (possibly following B-Stage curing). The technique of using the shrink tape during B-Stage only should be evaluated on 1638.7 cm^3 (100 in^3) pressure vessels prior to incorporation into a full-scale rocket motor case.

5. All future motor cases with a slip angle toward the boss should be wound with a winding plug in place. The plug should be threaded to fit over the boss and tapered on the outside for positive removal.

6. All sand mandrels should be stored in a sealed bag containing a desiccant to ensure dry storage conditions.

7. Future skirts should be fabricated and wound in place using graphite epoxy tapes and graphite broad goods over removable steel tooling. This modification has three advantages:

   a. Minimizes mismatch problems;

   b. Eliminates thermal mismatch during subsequent high temperature environments;

   c. Minimizes skirt discontinuity loads caused by the higher modulus titanium skirt.

APPENDIX A

SUB-SCALE TEST PROGRAM

Brunswick, under its internal R & D efforts, fabricated and tested six 1638.7 cm^3 (100 in^3) vessels in support of JPL's graphite/epoxy rocket motor case program. The purpose of the evaluation was threefold: (i) Obtain an evaluation of Ferro versus Fiberite graphite prepregs, (ii) evaluate the composite dome shape versus the netting analysis dome shape, and (iii) evaluate the effects of the symmetry of lamina within the cylindrical section.

DISCUSSION

All vessels were wound directly on FEP-covered sand mandrels; the rubber bladder was eliminated due to potential problems; and identical tensioning schemes were used on all vessels to eliminate this parameter as a variable. Refer to Table V. All vessels were overwrapped with shrink tape prior to cure and all vessels had identical cure cycles.

Four vessels were fabricated with two plies of hoops immediately over the sand mandrel followed by two layers of polars, then completed by winding two plies of hoops over the polars. This configuration is identified as a "split" or symmetrical hoop pattern.

Two vessels were fabricated with the two polar layers directly over the sand mandrel, followed by the hoop layers outboard of the polars. This configuration is identified as an "outside" or unbalanced hoop pattern.

The composite dome shape uses all equations of the standard theory, except that the ratio of hoop-to-meridonal loading is no longer set equal to the tangent squared of the local wind angle. Instead, a relation is used which takes into account the effect of the resin. It was believed that this expression for ratio of load in the two directions would be more applicable to the design of advanced composite structures since the strains are much lower and therefore, crazing is expected to be less severe in vessels fabricated using the advanced composites.

TEST RESULTS

Following cure and washout of the sand mandrels, the interior of the vessels were "slosh"-coated using TURCO†-5145. The vessels were then hydroburst without strain gage instrumentation. Results of the hydroburst are presented in Table VI.

†TM - TURCO Products, Purex Corporation

TABLE V DESIGN PARAMETERS

Unit Serial No.	Material	Dome Shape	Polar Tension		Hoop Tension		Hoop Pattern
			Newtons	lbf	Newtons	lbf	
210	Ferro E-293	Netting	35.58	8.0	40.03 & 44.8	9.0 & 10.0	Split
211	Ferro E-293	Composite	35.58	8.0	40.03 & 44.8	9.0 & 10.0	Split
212	Fiberite 1305	Netting	35.58	8.0	40.03 & 44.8	9.0 & 10.0	Split
213	Fiberite 1305	Netting	35.58	8.0	40.03 & 44.8	9.0 & 10.0	Outside
214	Fiberite 1305	Composite	35.58	8.0	40.03 & 44.8	9.0 & 10.0	Outside
215	Fiberite 1305	Composite	35.58	8.0	40.03 & 44.8	9.0 & 10.0	Split

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TABLE VI TEST RESULTS

Unit Serial No.	Material	Dome Shape	Hoop Pattern	Burst Pressure		Fiber Stresses			
						Polar		Hoop	
				N/cm^2	PSI	$10^3 N/cm^2$	KSI	$10^3 N/cm^2$	KSI
210	Ferro E-293	Netting	Split	1258.2	1825	79.28	115	110.99	161
211	Ferro E-293	Compos.	Split	1223.7	1775	77.21	112	107.55	156
212	Fiberite 1305	Netting	Split	1413.3	2050	88.93	129	124.09	180
213	Fiberite 1305	Netting	Outside	2426.7	3520	151.67	220	213.71	310
214	Fiberite 1305	Compos.	Outside	1999.3	2900	126.16	183	175.80	255
215	Fiberite 1305	Compos.	Split	1075.5	1560	67.56	98	94.45	137

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Failure Modes:

S/N-210. An apparent hoop failure initiating in the cylinder from boss-to-boss.

S/N-211. Adjacent to the blank boss flange edge to each tangent line.

S/N-212. An apparent hoop failure initiating in the cylinder from boss-to-boss.

S/N-213. Adjacent to the port boss flange edge to opposite dome. Stripped hoops off adjacent areas of cylinder.

S/N-214. Adjacent to the blank boss flange edge to opposite tangent line.

S/N-215. Adjacent to the port boss flange edge to each tangent line.

Both hoop failures initiated near the center of the cylindrical section and both had failure fractures across the polar layers. Although it is difficult to establish with complete confidence which mode of failure was initial and which was secondary, the majority of opinions agree that the initial failure was in the hoops.

CONCLUSIONS

Too few data points exist to statistically prove or disprove any variable; however, by averaging the variables at common data points and comparing against the opposite variable, significant trends can be derived as follows:

1. Material-Ferro vs Fiberite

Using vessels S/N 210 and 211 in comparison with S/N 212 and 215 (the vessels with all hoops outboard were not considered), it may be concluded that there is no significant difference between the two materials investigated.

S/N 210 & 211 (Ferro) average 1800 psi burst (1240.92 N/cm^2)

S/N 212 & 215 (Fiberite) average 1805 psi burst (1244.37 N/cm^2)

2. Netting versus Composite Domes

By averaging all three vessels with composite domes against all three vessels with netting domes, indications are that the netting dome is consistently and significantly superior to the composite dome.

Netting (3 vessels) average burst - 2465 psi (1699.37 N/cm^2)

Composite (3 vessels) average burst - 2078 psi (1432.57 N/cm^2)

3. Split versus All Hoops Outboard

Average values of split hoop layers (symmetrical) versus all hoops outboard show the outboard configuration to be vastly superior to the split configuration, as indicated by the following:

All Vessels

Split (4 vessels) average at burst - 1803 psi (1242.99 N/cm^2)

Outboard hoops (2 vessels) average - 3210 psi (2212.97 N/cm^2)

(Splitting decreases burst values by 44%)

Composite Domes

Split (2 vessels) average at burst - 1667 psi (1149.23 N/cm^2)

Outboard (1 vessel) average at burst - 2900 psi (1999.26 N/cm^2)

(Splitting decreases burst values by 42%)

Netting Domes

Split (2 vessels) average at burst - 1938 psi (1336.06 N/cm^2)

Outboard (1 vessel) average at burst - 3520 psi (2426.69 N/cm^2)

(Splitting decrease burst values by 45%)

4. Ranking of the Effect of Variables

A netting-type dome with the hoops all outboard resulted in the highest burst pressure of the six vessels tested.

The following table eliminates material as a variable and arranges the remaining variables (dome shape and hoop pattern) as a function of the highest burst pressures.

Variable	Rank	Burst Pressure	Number of Vessels & Mode of Failure
Netting/Outboard	Best	3520 psi (2426.69 N/cm^2)	Φ
Composite/Outboard		2900 psi (1999.26 N/cm^2)	Φ
Netting/Split		1938 psi (1336.06 N/cm^2)	ΘΘ
Composite/Split	Worst	1667 psi (1149.23 N/cm^2)	ΦΦ

RECOMMENDATIONS

1. Either material should be structurally acceptable; however, reconsideration might be advantageous as winding experience is developed during the fabrication of full size motor cases.

2. Brunswick recommends a netting-type dome (as in the current design) utilizing all hoop layers on the outside of the polars (contrary to the current design). Although the amount of data available from these tests is not sufficient to statistically prove or disprove either concept, the magnitude of differences is quite significant.

APPENDIX B

FIBER SLIPPAGE OR "SHINGLING"

The ideal path that a fiber would follow around the domes and across the polar boss would be a geodesic path allowing the fiber to be equally stressed along the entire length. The geodesic angle for each dome is a function of the cylinder diameter and the port boss opening. Specifically, this function is:

$$\sin \alpha_o = Re/R\alpha$$

Where:

Re = Radius to the center of winding band adjacent to the polar boss

Rα = Radius to center of the polar thickness at the cylinder/dome juncture

As depicted by JPL drawing 10039486, the geodesic angles for the forward and aft domes are 10° 32' and 29° 03' respectively. The large discrepancy, of course, reflects the difference in boss sizes for a common cylinder diameter.

In a polar-wound chamber, the filaments are oriented within a plane. The filament path over the dome is described as the intersection of the plane and the dome. Refer to Figure 12.

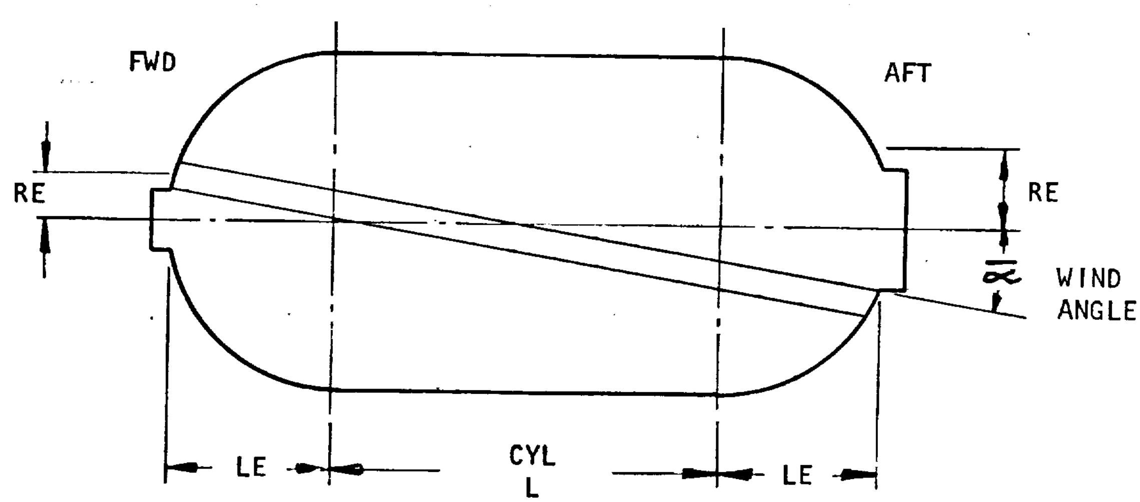

Figure 12

Polar Winding Geometry

Each successive band on the chamber is placed adjacent to the previous band in the cylinder section. The polar wind angle ($\bar{\alpha}$) is a function of the chamber length and RE, which is the distance from the longitudinal centerline to the middle of the band at the polar boss. It equals the angle whose tangent is:

RE (Fwd) + RE (Aft) / LE (Fwd) + LE (Aft) + L (Cyl.)

When designing a polar-wound chamber, it is necessary to look at both the polar angle and the theoretical geodesic angle. The difference between these two angles is referred to as the "slip angle". The larger the slip angle, the greater the tendency for the polar fibers to slip from their theoretical intended path. The resulting dis-orientation of fibers from the path for which the dome contour was calculated causes a lower performance.

The ideal situation is to have a zero slip angle although, small slip angles can be tolerated without any loss of strength. The maximum practical allowable slip angle is approximately 14°. At this angle, there can be a 5% to 10% loss in polar strength. A slip angle higher than 14° will usually dictate going to a helically-wound chamber.

The polar winding angle as shown on the graphite motor case drawing is calculated to be 24° 02'. Therefore, the slip angles for each dome are as follows:

<u>Aft</u>

$\Delta\bar{\alpha}$ = 29° 03' (geodesic) - 24° 02' (polar)

= +5° 01' (slippage outboard)

<u>Fwd</u>

$\Delta\bar{\alpha}$ = 10° 32' (geodesic) - 24° 02' (polar)

= (-) 13° 30' (slippage inboard)

The slip angle for the aft dome is neglectible; however, the fibers on the forward dome are very close to the critical slip angle and would tend to "walk" toward the polar fittings until reaching equilibrium.

The phenomenum could be described as "shingling" as the dome fibers work-up against the adjacent layer during winding and cure.

The polar boss would, of course, prevent any inward movement for fiber when adjacent to the fitting. There would, however, be a tendency for the fibers in the mid-area of the forward dome to shingle up against the previous winding band.

The tendancy to slip may be minimized upon initial design selection of geometry. In this case, the slippage angle could be more equally divided between the aft and forward domes by two geometrical changes.

1. Increase the geodesic angle of the forward dome by utilizing a larger polar boss or;

2. Decrease the polar winding angle by lengthening the cylindrical section of the chamber.

APPENDIX C

TENSIONING CALCULATIONS

The original technique used by Brunswick to select winding tension is first described, followed by the actual tensioning levels used and the resulting residual fiber loads.

ORIGINAL APPROACH

1. Sand mandrel--Thermal coefficient of 6×10^{-6} in/in/°F--assume no mandrel expansion. This is conservative since mandrel expansion will exert additional forces to curing laminate and enhance and increase fiber tension and promote resin flow.

2. Thermal coefficient of expansion of carbon = $.05 \times 10^{-6}$ or for all practical purposes, zero.

3. Winding tension at 8 lbf (35.58 N) per tape (max) outside polar and 9 lbf (40.03 N) per tape outside hoop layer.

4. Resin slump at 5%.

   Brunswick defines resin slump as that portion of the wall thickness which is lost during B-staging and curing operations. Brunswick's experience shows that 5 - 6% of wall thickness is a good value for resin slump in a graphite composite after overwrap of shrink tape and cure.

5. Theoretical Wall Thickness

   Last Hoop Layer

   10 plies at .008 inch/ply = .080 inch (2.03 mm) (1)

   Last Polar Layer

   8 plies at .008 inch/ply = .064 inch (1.62 mm) (2)

6. Graphite Fiber Modulus

   $E = 35 \times 10^6$ psi (24.13×10^6 N/cm^2)

7. Graphite Fiber Area Per Tape

   $A_t = .8078 \times 10^{-3}$ in^2/tape (.0052 cm^2/tape)

8. Design Wind Tensions

$$T_t = 8.0 \text{ lbf } (35.58 \text{ N}) \text{ per tape (polar)}$$

$$9.0 \text{ lbf } (40.03 \text{ N}) \text{ per tape (hoop)}$$

Then Resin Slump (δsr) in Outer Layers

$$\delta sr = 5\% \times .080 = .0040 \text{ inch } (0.102 \text{ mm}) \text{ (hoop)} \tag{3}$$

$$\delta sr = 5\% \times .064 = .0032 \text{ inch } (0.081 \text{ mm}) \text{ (polar)} \tag{4}$$

Preload in Outer fibers from Winding

$$\delta w = \frac{T}{A} \times \frac{R}{E} \tag{1}$$

$$\delta w = \frac{9 \times 14}{.808 \times 10^{-3} \times 35 \times 10^{-6}} = .0045 \text{ inch } (.114 \text{ mm}) \text{ (hoops)} \tag{2}$$

$$\delta w = \frac{8}{9}(.0045) = .0040 \text{ inch } (.102 \text{ mm}) \text{ (polars)} \tag{3}$$

Tension in fiber following cure

$$T = T(\text{Start}) \left(\frac{\delta \text{ final}}{\delta \text{ start}}\right) \tag{4}$$

$$T = 9.0\left(\frac{.0045 - .0040}{.0045}\right) = +1.0 \text{ lbf } (4.45 \text{ N})/\text{tape (hoop layer)} \tag{5}$$

$$T = 8.0\left(\frac{.0040 - .0032}{.0040}\right) = +1.6 \text{ lbf } (7.12 \text{ N})/\text{tape (polar layer)} \tag{6}$$

ACTUAL TENSIONS

The calculations for apparent residual winding tension (not including mandrel expansion) are based on the thicker polar build-up.

Increased polar thickness:

$$t_\phi = .008 \; \frac{.2 \text{ (planned band width)}}{.18 \text{ (actual band width)}}$$

$$= .0089 \text{ inches } (.226 \text{ mm})/\text{per ply (as wound)}$$

Actual Wall Thickness:

Last hoop layer

$$t\theta = 6 \times .0089 + 4\ (.008) = .0854 \text{ inch } (2.169 \text{ mm})$$

Last polar layer

$$t\phi = 6 \times .0089 + 2\ (.008) = .0694 \text{ inch } (1.763 \text{ mm})$$

Actual Winding Tensions:

Last hoop = 9.0 lbf (40.03 N)/tape

Last polar = 4.5 lbf (20.02 N)/tape

Resin Slump (Radial)

$$\delta sr = 5\% \times .0854 = .0043 \text{ inch } (0.109 \text{ mm}) \text{ (hoop)}$$

$$\delta sr = 5\% \times .0694 = .0035 \text{ inch } (0.088 \text{ mm}) \text{ (polar)}$$

Preload in Outer fibers from Winding

$$\delta w = \frac{9 \times 14}{.808 \times 10^{-3} \times 35 \times 10^{6}} = .0045 \text{ inch } (0.114 \text{ mm}) \text{ (hoop)}$$

$$\delta w = \frac{4.5}{9}\ (.00445) = .0022 \text{ inch } (0.055 \text{ mm}) \text{ (polar)}$$

Tension in fiber following cure:

$$T = 9 \left(\frac{.0045 - .0043}{.0045}\right) = +.4 \text{ lbf } (1.79 \text{ N})/\text{tape (hoop)}$$

$$T = 4.5 \left(\frac{.0022 - .0035}{.022}\right) = \text{negative tension (polar)}$$

The residual tension in hoop fibers would be further increased when considering mandrel expansion during cure. The polar layers would, however, still be negative even with mandrel expansion included. This is evident when examining the "pushed-in" appearance of the polar fibers when bridging gaps in the lower layers matrix.

It must be noted that due to effects of slippage (caused by the adverse mandrel shape), polar tapes had slipped to reach equilibrium and had very little residual winding tension remaining. In short, the mandrel shape for the graphite motor case was too adverse for slip-free winding, therefore, any tension applied to the graphite tapes would be lost during fiber migration. Regardless of the tensioning system utilized, a high quality, uniform tensioned laminate would be impossible to wind with a slippage condition.

If a motor case of a similar critical shape were to be wound again, low polar tensions would be recommended for all layers to negate gapping, particularly in the lower layer. A motor case wound in this manner would have a much more desirable appearance since the polar fibers would not be pushed into substructure gaps.