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BORON EPOXY ROCKET MOTOR CASE PROGRAM

FINAL REPORT

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ABSTRACT

Three 28 inch diameter solid rocket motor cases were fabricated using 1/8 inch wide boron/epoxy tape, Rigidite 5505. The cases had unequal end closures (4-1/8 inch diameter forward flanges and 13 inch diameter aft flanges), and metal attachment skirts. The flanges and skirts were titanium 6Aℓ-4V alloy. The original design for the first case was patterned after the requirements of the Applications Technology Satellite (ATS) apogee kick motor. The second and third cases were designed and fabricated to approximate the requirements of a Small Applications Technology Satellite apogee kick motor. All case designs were generated by JPL. Martin Marietta Corporation conducted a critique of the first design only. The program demonstrated the feasibility of designing and fabricating large-scale filament-wound solid-propellant rocket motor cases with boron/epoxy tape.

TABLE OF CONTENTS

Section		Page
I	INTRODUCTION	1
II	TECHNICAL DISCUSSION (DESIGN AND FABRICATION)	2
	A. Case Design	2
	1. First Case Design	2
	2. Second Case Design	3
	3. Third Case Design	3
	B. Fabrication	4
	1. Mandrel Fabrication	4
	2. Winding	4
	a. Rocket Motor Case #1 (RMC-1)	5
	b. Rocket Motor Case #2 (RMC-2)	6
	c. Rocket Motor Case #3 (RMC-3)	7
III.	DISCUSSION AND CONCLUSIONS	8
	A. Boron Tape Placement	8
	B. Boron/Epoxy to Titanium Bond	11
IV.	RECOMMENDATIONS	12
V.	NEW TECHNOLOGY	13
References		14
Appendix A		15
Appendix B		21
Appendix C		30

LIST OF FIGURES AND TABLES

Figure		Page
1	Partially Completed Mandrel	35
2	Completed Rocket Motor Case #1 (RMC-1)	35
3	Completed Rocket Motor Case #2 (RMC-2)	36
4	Completed Rocket Motor Case #3 (RMC-3)	36
5	Tape Migration - Shingling During Winding of Rocket Motor Case #2 (RMC-2)	37
6	Tape Shingling on the Forward Dome of Rocket Motor Case #2 (RMC-2)	37
7	Tape Shingling on the Aft Dome of Rocket Motor Case #2 (RMC-2)	38
8	Shrink-Tape Wrap of Rocket Motor Case #3 (RMC-3)	38
9	The Forward Dome of Rocket Motor Case #3(RMC-3)	38
10	Partitioning of Vessel for Stress Analysis Showing Boundary Conditions	39
11	Ribbon Path Over Forward Dome	40
12	Ribbon Path Over Aft Dome	41
13	Thickness of Composite in the Forward Dome	42
14	Thickness of Composite in the Aft Dome	43
15	Stress Resultants in Vessel Wall	44
16	Bending Moments in Vessel Wall	45
17	Stress in the Forward Dome	46
18	Stress in the Cylinder	47
19	Stress in the Aft Dome	48
20	Mandrel-JPL Rocket Motor Case	49
Tables		
1	Rocket Motor Case Parameters	31
2	Shell Model for Stress Analysis	32
3	Maximum Stress in Metal Parts	34

I. INTRODUCTION

Continuous fiber-reinforced composites fabricated by filament winding are particularly attractive for making pressure vessels and rocket motor cases. The strength-to-density properties of typical fibers are high, and the filament winding technique generally permits orienting the fibers exactly as needed to resist imposed stresses.

Filament-wound solid-fueled missile cases have already been successfully used in the Polaris, Minuteman and Scout programs. Fiberglass is used as the filament because of its very high specific strength. However, fiberglass has a relatively high elongation at effective operating stresses (1½ to 2% strain). Where stiffness is a requirement, the use of higher modulus fibers such as boron is indicated. Some data are available on filament winding with boron (Ref. 1), but the information is restricted to small-scale pressure vessels.

The desirability of using boron for large-scale vessels (such as the 28-inch diameter cases described in this report) indicates the need for development work in filament-winding large vessels with boron/epoxy tape. This program has provided both the experience of winding large-scale vessels with boron/epoxy tape and the test articles needed to determine the efficiency and effectiveness of filament-wound motor cases of this material.

This program covered an evaluation of the original design and fabrication of three boron/epoxy rocket motor cases. The design and testing of the cases were performed by JPL.

II. TECHNICAL DISCUSSION (DESIGN AND FABRICATION)

The technical effort by Martin Marietta Corporation in this program consisted of an analysis of the original boron/epoxy rocket motor case design and the fabrication of 3 boron/epoxy rocket motor cases. Two additional designs were generated by JPL during the course of the program and were used for the actual case fabrication. A brief description of these designs and a comprehensive description of the fabrication of the rocket motor cases and their mandrels are given herein:

A. Case Design

Three boron/epoxy rocket motor case designs were generated during the course of this study and are described and discussed in the following paragraphs:

1. First Design (JPL Dwg. 10033186, Rev. A)

The first design was 29.27 inches long, 28.000 inches inside diameter, with a 14.40 inch long cylindrical section. Both fore and aft domes were oblate spheroids with rise/radius ratios of 0.50, (coordinates derived from a 14.000 by 28.000 ellipse). The wrap sequence consisted of 3 inner hoop layers on the cylinder section, 6 planar wrap layers (3 layer pairs) over the entire case, and 3 outer hoop layers on the cylinder section.

A critique of this design was performed as part of the contract effort (Appendix A).

The critique analysis indicated that the design did not use the strength of the boron/epoxy wrap efficiently. In several areas, the stresses produced by internal pressure far exceeded the capability of the material. It was determined that these highly stressed regions could not be efficiently relieved by redistributing the boron/epoxy wrap and/or increasing the number of wraps.

An analysis of this case design at JPL substantiated the findings of the critique described herein. The case was subsequently redesigned at JPL.

2. Second Design (JPL Dwg. 4211267, Rev. A)

The second design was also 29.27 inches long, but was 27.980 inches inside diameter, and had a cylinder length of 12.10 inches. The domes were computer-generated rather than oblate spheroids. The forward dome had a rise/radius ratio of about 0.61 and the aft dome had a rise/radius ratio of about 0.48 (both ratios taken at the dome/flange junction).

The new wrap sequence consisted of 3 inner hoop layers on the cylinder section, 8 planar layers (4 layer pairs) over the entire case, and 4 outer hoop layers on the cylinder section. The fabrication of the first rocket motor case (RMC-1) was based on this design.

3. Third Design (JPL Dwg. 10038934, Rev. A & B)

The third design was for a smaller propellant load and was 22.68 inches long, 27.980 inches inside diameter, and had a cylinder length of 3.45 inches. The domes were also computer-generated. The forward dome had a rise/radius ratio of about 0.62 and the aft dome had a rise/radius ratio of 0.60 (again, both ratios were taken at the dome/flange junction). The wrap sequence consisted of 3 inner hoop layers on the cylinder section, 8 planar layers over the entire case, and 3 outer hoop layers on the cylinder section. The fabrication of RMC-2 and RMC-3 was based on this design.

B. Fabrication

The fabrication of the rocket motor cases and the mandrels on which they were wound are described in the following paragraphs.

1. Mandrel Fabrication

The mandrels for the RMCs for this program were made in accordance with the Fabrication and Process Plan developed for this program (Appendix B). The drawing for the mandrels (referred to in the Fabrication and Process Plan) is included in this report as Appendix G.

The mandrels were made using plywood and cardboard skeletons bolted to the mandrel shafts with aluminum collars, covered with aluminum screen wire (Fig. 1), and swept with "Brak-Away" plaster. The outside contours and dimensions were controlled through the use of accurate sweep templates. The mandrels were swept about 0.030 inch oversize on the diameter to allow for plaster shrinkage during drying and to allow final sanding to size. The mandrel surfaces were then sealed with polyvinyl alcohol. Assembly detail -009 was used for the first RMC mandrel. Assembly detail -019 was used for the second and third RMC mandrels. The difference between -009 and -019 was due to the change between the RMC designs No. 2 and 3.

2. Winding

Winding of the RMCs was done in accordance with the Fabrication and Process Plan (FPP) (Appendix B). Pertinent parameters of these three cases are given in Table I. General fabrication notes and modifications for each case are given in the following paragraphs:

a. RMC-1

The applicable JPL drawings for RMC-1 were:

1) 4211267, Rev. A, Vessel, Filament Wound (JPL SR-28 MOTOR)
2) 4211265, Rev. A, Aft Flange, Filament Wound Vessel (JPL SR-28 MOTOR)
3) 4211266, Rev. A, Forward Flange, Filament Wound Vessel (JPL SR-28-MOTOR)
4) 10031046, Rev. C, Cylindrical Skirt, Filament Wound Vessel (JPL SR-28-MOTOR)

The mandrel for RMC-1 was mounted in the lathe winder and three layers of 1/8 inch wide boron/epoxy tape, Rigidite 5505, were hoop-wound on the cylindrical section and faired into the dome ends per FPP, para. 6.2.2.1. The wrap tension was 9 to 10 pounds.

The mandrel was then mounted on the polar winder. Prior to polar winding, the forward and aft flanges were cleaned and adhesive applied. The flanges were fitted to the mandrel, and four polar layer pairs were wound on the mandrel (each layer pair consisting of two layers of 88, 1-inch-wide ribbons). The winding tension on the boron/epoxy tape was 8½ pounds at the beginning of this wrap. The wrap tension was reduced to 6 pounds at ribbon 8 of the first layer pair and remained at that level for the rest of the polar wrap. This change in wrap tension is discussed in Section III of this report.

The mandrel was then returned to the lathe winder. The skirt was cleaned and adhesive applied. The skirt was then secured to the case and four outer hoop layers were applied.

The cylindrical section was covered with a 5-mil thick TFE teflon film and overwrapped with a layer of 20-end clean glass roving at 16 threads/inch and 6 lb. tension. RMC-1 was then cured per the FPP. Figure 2 shows the completed RMC-1.

b. RMC-2

The applicable JPL drawings for the second rocket motor case were:

1) 10038934, Rev. A, Chamber, Boron/Epoxy Tape Wrap (JPL SR-28-MOTOR)
2) 4211265, Rev. B, Aft Flange, Filament Wound Vessel (JPL SR-28-MOTOR)
3) 4211266, Rev. A, Forward Flange, Filament Wound Vessel (JPL SR-28-MOTOR)
4) 10031046, Rev. C, Cylindrical Skirt, Filament Wound Vessel (JPL SR-28-MOTOR)

The mandrel for RMC-2 was mounted in the lathe winder and three layers of boron/epoxy tape were hoop-wound on the cylindrical section and faired into the dome ends per FPP, para. 6.2.2.2. The wrap tension was 9 pounds.

The mandrel was then mounted on the polar winder. Prior to polar winding, the forward and aft flanges were cleaned and adhesive applied.

The flanges were fitted to the mandrel, and four layer pairs were wound on the mandrel at 6 pounds tension. The boron/epoxy tape used in these polar wraps was aged at room temperature for 12 to 15 days prior to winding. The reason for this tape aging is discussed in Section III of this report.

The mandrel was then remounted on the lathe winder. The skirt was cleaned and adhesive applied. The skirt was then secured to the case and 3 outer hoop wraps of boron/epoxy tape were applied. The cure was the same as for RMC-1. Figure 3 shows the completed case.

c. RMC-3

The applicable JPL drawings for RMC-3 were the same as for RMC-2 except that Rev. B of the chamber drawing was used which changed the tolerance notation and changed the design burst pressure from 300 to 340 psi.

The fabrication of RMC-3 was the same as for RMC-2 with the following three exceptions:

1) An elastomer was used between the aft flange surfaces and the wrapped boron/epoxy material. After the normal cleaning procedure, the flange was brushed with Chemlock 205 primer, air dried for 10 minutes, and oven dried for 20 minutes at 160°F. After mounting the aft flange on the mandrel, and before polar winding, a sheet of uncured ethylene-propylene (Hilgard 4010) rubber was fitted to the flange surface over which the boron tape was to be wrapped.
2) 10 pounds winding tension was used for all wraps.
3) Each polar layer pair was partially cured in the oven while constrained with a shrink tape wrap.

The final cure was modified from that of the first two cases by slowing the heat-up rate. Figure 4 shows the completed RMC-3. The reasons for the three exceptions noted above are discussed in Section III of this report.

III. DISCUSSION AND CONCLUSIONS

Although the last rocket motor case (RMC-3) has not been tested as of this writing, it can be said, generally, that the program was successful and demonstrated the feasibility of designing and fabricating filament-wound boron/epoxy rocket motor cases.

Several problems arose in the course of the program, however, and are discussed in the following paragraphs:

A. Boron Tape Placement

The degree of resin advancement (or polymerization) in the tape was found to be critical. Too little advancement resulted in roping of the tape when under tension, and migration of the tape on the case being wound when the winding path specified deviated markedly from the preferred geodesic path. The term roping describes the bunching of the boron filaments into a cylindrical cross section rather than the original tape form where the filaments lie side by side. Too much advancement, on the other hand, reduced the chances of obtaining good compaction during winding.

The first RMC was wrapped soon after receiving the boron/epoxy tape from JPL. The resin in the tape was very "green" and easily distorted from its tape configuration. This tape distortion (or roping) became a problem during the first part of the polar wrap of RMC-1 and caused gaps as much as 0.040 inch between tapes. The roping was eliminated by reducing the winding tension from 8½ pounds to 6 pounds at ribbon 8 of the first layer pair. The trace and laydown of the tape was subsequently good with zero to 0.015 inch maximum gaps between tapes. However, the tape would slip, or migrate approximately two turns (or ribbons) subsequent to its initial laydown on the mandrel. The 1/8 inch wide tape would then lift to about 60^{o} (shingle) while the tension side of the tape remained tight to the case. The second layer pair had less shingling, but some shingling persisted throughout the remaining layers.

The second case (RMC-2) was designed for a smaller propellant load. The overall diameter remained the same as did the forward and aft flange openings. The reduced propellant load capability was obtained by shortening the case about 6½ inches. The new configuration increased the polar wrap angle from 19^{o} to 24^{o}.

The boron/epoxy tape used in the polar wraps of RMC-2 was aged at room temperature for 12 to 15 days to change its tack characteristics to reduce the tendency to migrate and shingle subsequent to laydown. However, the shingling was worse than in RMC-1. The increase in wrap angle from 19^{o} to 24^{o}, made necessary by the decreased length of the new design, required the tape to lay at a much different path than the stable geodesic. This was especially true of the forward dome where the stable geodesic wrap would be obtained with a wrap angle of about $8\frac{1}{2}^{o}$ (Ref. 2, page 227). As in RMC-1, the trace and laydown was good initially and shingling began to appear about two ribbons subsequent to its initial laydown (Fig. 5). While the migration and shingling was a much slower phenomenon, it continued in each layer until stabilized by subsequent overwraps. As might be expected, the forward dome had more severe shingling than the aft dome (Figs. 6 and 7). The winding tension for the polar wraps, kept at 6 pounds as in RMC-1, appeared to be somewhat low and did not provide adequate compaction during winding of the room-temperature-aged material. The subsequent application of the outer hoop wraps at 10 pounds tension, using unaged material, produced some buckling and marcelling of the underlying hoop and polar wraps. Buckling and marcelling describes the wavyness caused by compression of the wrap in the direction of the fibers.

Several changes were made to try to improve the polar wrap on RMC-3. As with RMC-2, the boron/epoxy tape was aged at room temperature. The material for the first layer pair was aged 13 to 15 days; for the second and third layer pairs, 11 to 13 days; and 10 to 11 days for the last layer pair. The polar wrap tension was increased to 10 pounds to achieve better compaction while winding. The aged tape did not rope as it did for RMC-1.

After the first layer pair was wrapped, it was covered with a polar and hoop layer of shrink tape (Fig. 8) and partially cured (staged) in the oven for 1/2 hour at 200°F.

A small amount of migration and shingling of this first layer pair was noticed after removal of the shrink tape and during winding of the second layer pair. Consequently, the second layer pair was staged for one hour at 200°F (again, with shrink tape). This second layer pair showed no apparent migration or shingling after removal of its shrink tape or during subsequent winding of the third layer pair. The third layer pair was staged the same as the second layer pair. The last layer pair was also shrink-tape wrapped and was staged one hour at 200°F and an additional 1/2 hour at 250°F. This extended aging of the last layer was done to keep the boron/epoxy tape from migrating during the cure cycle which was done without the constraint of a polar shrink tape wrap. The tendency for the tape to migrate during cure was further reduced by changing the rate of heating from 75° per hour to 25°F per hour between the 200° and 350°F portions of the cure.

The procedure described above almost eliminated the apparent shingling in this last RMC (Fig. 9).

B. Boron/Epoxy to Titanium Bond

Successful utilization of the rocket motor cases described herein requires complete bonding between the boron/epoxy wrap and the titanium 6Aℓ-4V alloy fittings (forward and aft flange, and skirt).

The titanium surface preparation, adhesive, and adhesive application described in the FPP were used for all titanium fittings except for the aft flange in RMC-3. The bond between the boron/epoxy wrap and the forward flange and cylindrical skirt proved to be good in RMC-1, RMC-2 and RMC-3. However, the bond between the boron/epoxy wrap and the aft flange on RMC-1 and RMC-2 was poor, showing less than half the required area bonded. It was suspected that the large diameter of this aft flange coupled with the difference in thermal expansion coefficient between the titanium and the boron/epoxy overwrap resulted in stresses which exceeded the bond strength of the adhesive. It was, therefore, decided to sandwich a layer of elastomeric material between the boron/epoxy wrap and the aft flange in RMC-3 to relieve the stress concentration in this area. The Chemlok materials were applied to the titanium appropriate for adhesion with this elastomer rather than the adhesive called out in the FPP. A visual inspection of the completed RMC-3 indicated a good bond had been achieved in this area.

IV. RECOMMENDATIONS

Based on the successful fabrication of the 28 inch diameter boron/epoxy rocket motor cases for this program, the consideration of boron/epoxy tape for fabricating similar structures is strongly recommended.

If possible, consideration should be given to designing future cases with more nearly equal diameter end closures. In order to wind a stable pattern over both ends of a case with unequal openings, it is necessary for the tape to enter each end at different helix angles. This requires the helix angle to vary along the length of the cylinder. If a single angle is used (as in planar winding), the proper helix angle may not be met in one or both ends. In either case, the tendency to slip will be built into the design. This slippage (depending on its severity) cannot help but degrade the structural performance.

Where tape migration (or slippage) is a problem for whatever reason, aging (or "B" staging) of layers while constrained with shrink tape, as was done during the fabrication of RMC-3, is required.

V. NEW TECHNOLOGY

There was no new technology generated in the performance of this program.

REFERENCES

1. E. E. Morris and R. J. Alfring: Cryogenic Boron Filament-Wound Containment Vessels. NASA CR-72330, Aerojet-General Corporation, November, 1967.

2. D. V. Rosato and C. S. Grove, Jr.: Filament Winding, Chapter 7. Interscience Publishers, New York, 1964.

APPENDIX A

VESSEL DESIGN

A. STRESS ANALYSIS

The shell configuration was subjected to a linear stress analysis using a computer program developed by A. Kalnins of Lehigh University and given in "Static, Free Vibration, and Stability Analysis of Thin Elastic Shells of Revolution", AFFDL-TR-68-144, March, 1969. The method is a numerical initial value integration of the actual equations of thin shell theory which develops continuous variations of all fundamental variables in the problem.

For analysis, the shell was sectioned in nine parts as shown in Figure 10. Each part was modeled into a number of isotropic and/or orthotropic layers as necessary to describe the physical characteristics of the shell. See Table 2.

With Hooke's Law given as

$$\begin{bmatrix} \epsilon_1 \\ \epsilon_2 \\ \epsilon_3 \end{bmatrix} = \begin{bmatrix} 1/E_1 & -\nu_{12}/E_1 & -\nu_{31}/E_1 \\ & 1/E_2 & -\nu_{23}/E_2 \\ \text{(Symmetric)} & & 1/E_3 \end{bmatrix} \bullet \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \end{bmatrix}$$

and

$$\gamma_{12} = \tau_{12}/G_{12}$$
$$\gamma_{23} = \tau_{23}/G_{23}$$
$$\gamma_{31} = \tau_{31}/G_{31}$$

The physical constants with respect to the principal axes of the filaments were taken as

$$E_1 = 29.9 \times 10^6 \text{ psi}$$

$$E_2 = E_3 = 2.71 \times 10^6 \text{ psi}$$

$$\nu_{12} = \nu_{31} = 0.21$$

$$\nu_{23} = 0.25$$

$$G_{12} = G_{31} = 1.00 \times 10^6 \text{ psi}$$

$$G_{23} = 1.08 \times 10^6 \text{ psi}$$

The values were taken from "Structural Design Guide for Advanced Composite Applications", August, 1969, prepared under Contract No. F33615-69-C-1368 by the Los Angeles Division of North American Rockwell Corp. for the Air Force Materials Laboratory. (See p. 2.3.2.1.A.4). All composite strength properties were also taken from this source. Titanium properties were taken from "Materials Engineering, Materials Selector Issue" mid-October, 1969, p. 148. The composite properties at different winding angles (angle between ribbon and meridian) were obtained using a separate computer program which does the necessary orthogonal transformation. Winding layers at plus and minus a given winding angle were grouped together so that the transformed properties remained orthotropic. The winding angles were obtained by physical measurement on a full scale mock-up of the mandrel with one ribbon wound on. (See Figures 11 and 12.)

The variable thickness in the domes was obtained by multiplying the average number of layers piled up at a given location by the layer thickness (0.005 in.). Average number of layers piled up at a given radius, r, per winding revolution was calculated as

$$n = 2(88)s/2\pi r$$

where 88 is the number of windings per revolution of the mandrel and is is the circumferential projection of one ribbon width at radius r. Values of s were physically measured on the mock-up. Results of the measurements are plotted in Figures 13 and 14. The variation of winding angle and of thickness in the domes was accounted for by a linear interpolation routine internal to Kalnins' program. Loading was internal pressure of 300 psi and the boundary conditions were chosen to represent a static pressure test (see Figure 10.)

A relatively coarse grid finite element analysis was made in the region of the forward boss using displacement values taken from the primary analysis to derive displacement boundary conditions. The program used was written by E. L. Wilson and R. Jones at the University of California, Berkeley, in 1967.* The purpose of this analysis was to provide a measure of the shear stress existing between the overwrap and the boss flange. When the results were examined the shear stresses were found to be so far beyond the capability of any adhesive, as explained in Section B, that it was decided not to make an analysis of the aft boss area, as the inadequacy of the vessel shape was already demonstrated.

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* Air Force Report No. BSD-TR-67-228.

B. RESULTS OF ANALYSIS AND EVALUATION

1. Material Distribution

The results of the stress analysis described in Section A are presented in Figures 15 through 19. One of the advantages of using composite filament wound construction for a pressure vessel is that with the proper vessel shape material can be located to achieve a generally uniform stress state. It is immediately apparent from the large variations in stress in Figures 17 and 19 that this advantage is being wasted. Certain maximum stress levels are of particular interest. In Figure 17, the maximum hoop compressive stress in the forward dome is approximately 100 ksi, and it occurs at a point about 2 inches up the head from the dome-cylinder junction. The boron material in this area is oriented at an angle of about 85° with respect to this stress, meaning that the stress would have to be carried primarily by the resin. The compressive strength of this resin is 23.52 ksi (p.2.2.3.1.1.4)** and the transverse compressive strength of the composite is 46.8 ksi (p.2.3.2.1.A.4)**. Regardless of which of these values one wishes to consider as the strength of the material in this region, the stresses are far beyond the capability of the material. A similar condition exists in the aft dome about 1-3/4 inches up from the junction where the maximum compressive hoop stress is about 125 ksi.

** Structural Design Guide.

Another location of concern is the edge of the flange of the forward boss. The maximum meridional tensile stress is 110 ksi at this point. Yet, the average angle of orientation of the fibers with respect to the meridian is about 37^{o}. Though this material has a tensile strength of about 190 ksi unixially, the strength at 37^{o} to the fibers is, of course, considerably less than that value, and consequently, the location under discussion is a potential premature failure location. The highly stressed regions discussed above cannot be efficiently relieved by redistributing the composite material in the vessel and/or putting more material in the domes. What is required is a new shape which more effectively utilizes the material.

2. Stresses in the Metal Parts

Figures 17, 18 and 19 do not contain information on the metal parts. The maximum stresses determined in the metal parts using the primary analysis are listed in Table 3. All of these values are well within the yield strength of 6Aℓ-4V titanium, the room temperature value being 128 ksi.* Therefore, the metal parts appear to be quite adequate from the point of view of the stress analysis.

3. Shear Stress in Adhesive

As stated in Section A, a coarse grid finite element analysis was made of the area comprising the forward boss flange and the associated overwrap. The maximum shear stress determined between the overwrap and the flange was approximately 17 ksi, and the maximum tensile stress approximately 5 ksi, in the same vicinity. No adhesive can take these stresses simultaneously. The fault lies not with the design of the boss

* Materials Selector.

flange or the overwrap in that region, but with the shape of the vessel. In order to make the finite element analysis, displacements from the primary analysis were used as boundary conditions. These displacements result, of course, from the assumed loading applied to the particular vessel shape under consideration. A beneficial change in that shape would result then, in different displacements and less shear and tensile stress in the flange/composite bond line.

APPENDIX B

FABRICATION AND PROCESS PLAN

1. SCOPE

This document describes the fabrication and processes for the manufacture of rocket motor cases per JPL contract number 952841.

2. FUNCTIONAL FLOW DIAGRAM

(See page 22)

3. APPLICABLE DRAWINGS AND DOCUMENTS

3.1 JPL drawings and documents

JPL contract number 952841

Vessel, Filament Wound (JPL SR-28 Motor), drawing number 4211267, Rev. A, for the first rocket motor case (RMC-1), 10038934, Rev. A (for RMC-2), and 10038934, Rev. B (for RMC-3).

Aft Flange, Filament Wound Vessel, drawing number 4211265, Rev. A (for RMC-1), and 4211265, Rev. B (for RMC-2 and RMC-3)

Forward Flange, Filament Wound Vessel, drawing number 4211266A

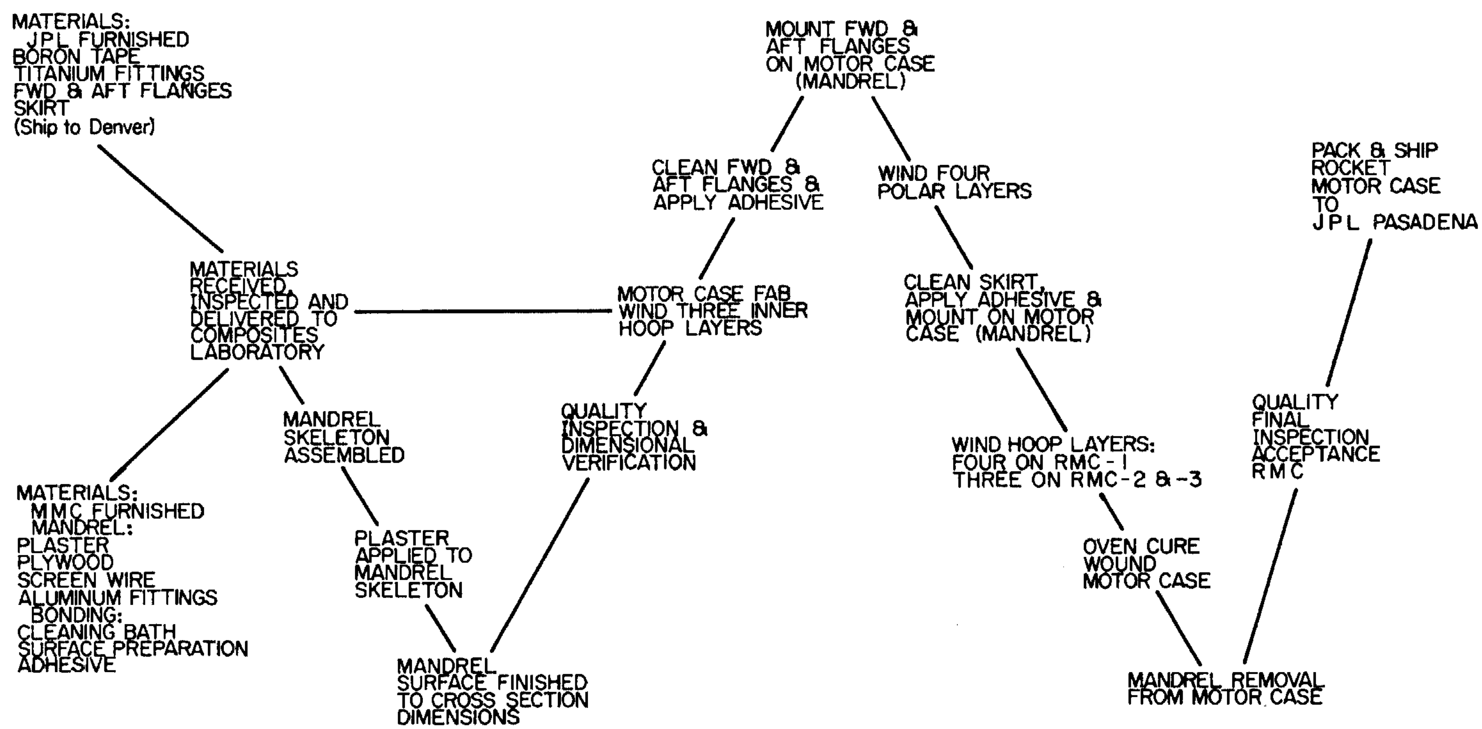
Cylindrical Skirt, Filament Wound Vessel, drawing number 10031046, Rev. C.

3.2 Martin Marietta drawing and documents

Design Critique Section II (Adhesive Evaluation) and Section III (Fabricability) dated May 4, 1970

Process Specification EPS 50063 (Cleaning Titanium and Titanium Alloys includes EPS 50046 and EPS 50036).

Mandrel, JPL Rocket Motor Case, drawing number FWL 70002.



Rev 7/27/71

Boron/Epoxy Rocket Motor Cases Functional Flow - Fabrication Process Specification

4. MATERIALS

4.1 JPL Furnished Material

Boron/epoxy tape, Rigidite 5505 - 1/8 inch wide

Titanium fittings (forward flange, aft flange, and skirt).

4.2 Martin Furnished Materials

4.2.1 Mandrel materials

Plaster, "Brak-away" manufactured by U. S. Gypsum or equivalent

Plywood, 1/4 inch thick, fir, A-D or better

Screen wire, aluminum mesh, 16 mesh

Cardboard, 1/4 inch thick, double flute

Aluminum fittings, 6061-T6 or equivalent

Polyvinyl alcohol sanding sealer, "Reso-part" from Plasticrafts or equivalent

4.2.2 Bonding materials

4.2.2.1 Titanium surface preparation materials per Martin Process Specification EPS 50063 - Method I, (also EPS 50046 and EPS 50036).

Trichloroethylene, MIL-T-27602 (per EPS 50046)

Hot alkaline solution, Spec. MMS K810 (per EPS 50036)

Nitric acid, technical, Spec. O-N-350

Hydrofluoric acid, technical, Spec. O-H-795

Surface activator, Pasa-Jell 107 (from Semco)

4.2.2.2 Adhesive, Narmco 3180 (from Whittaker Corporation).

5. MANDREL FABRICATION (per Drawing No. FWL 70002)

5.1 Mandrel Skeleton: The mandrel skeleton is assembled per drawing FWL 70002 using detail -009 for RMC-1, and detail -019 for RMC-2 and RMC-3, as follows:

5.1.1 Slide skeleton discs onto mandrel shaft. Align edge slots with each other and tighten set screws on the two skeleton collars.

5.1.2 Insert skeleton stringers into skeleton discs.

5.1.3 Cover entire skeleton with screen wire, holding it in place with staples.

5.2 Plaster sweep:

5.2.1 Mount mandrel skeleton and shaft in lathe.

5.2.2 Attach sweep platform to lathe.

5.2.3 Secure sweep template to platform to provide the smallest diameter sweep possible without scraping the skeleton.

5.2.4 Make batch of plaster (5 Kg water and 5 Kg plaster).

5.2.5 When plaster has become sufficiently firm to stick to skeleton without falling off when mandrel is rotated, rotate mandrel and apply plaster.

5.2.6 Slide template away from mandrel 1/8 inch, measure mandrel diameter, and repeat steps 5.2.4 and 5.2.5 until proper diameter is obtained (drawing number FWL 70002).

5.2.7 Place mandrel in oven 48 hours at $150^{\circ} \pm 20^{\circ}F$ to dry.

5.3 Mandrel finishing:

5.3.1 When mandrel has been dried, return it to the lathe and sand surface until proper dimensions are attained.

5.3.2 Cut lands for end bosses on each end of mandrel.

5.3.3 Seal plaster surface with polyvinyl alcohol solution.

5.3.4 Apply teflon spray release on mandrel surface just prior to winding.

6. CASE FABRICATION (per Contract No. 952841, JPL Drawing Nos:
4211267, Rev. A
10038934, Rev. A
10038934, Rev. B).

6.1 End boss and skirt preparation:

6.1.1 Clean end bosses and skirt per EPS 50063, Method I.

6.1.2 Apply Pasa-Jell 107 as follows:

Place the details to be treated on a clean polyethylene film.

Paint the Pasa-Jell 107 onto the areas of each detail that will be covered with adhesive immediately following Step 6.1.1 above.

NOTE: The painting should be done with a polyethylene or polypropylene brush. Remaining areas need not be painted. Pasa-Jell 107 is a corrosive acid containing a combination of chromic, nitric and hydrofluoric acids.

Allow Pasa-Jell 107 to remain for 10 to 15 minutes. Do not allow any areas to dry up.

Rinse with clean cold reagent water.

Dry parts with clean room temperature air.

6.1.3 Apply Narmco 3180 adhesive to the inner flange surface (as a primer) and outer flange surfaces of end bosses and inner and outer flange of skirt just prior to incorporation into case, but within 3 hours after cleaning of details.

6.2 Inner Hoop Layers:

6.2.1 Mount mandrel assembly in lathe winder.

6.2.2.1 RMC-1 - Wind 3 hoop layers of boron tape on cylinder portion of mandrel. The first layer is to extend 0.42 inch beyond the forward dome/cylinder junction (FDC), and 0.25 inch beyond the aft dome/cylinder junction (ADC). The second layer is to extend 0.67 inch beyond FDC, and 0.50 inch beyond ADC. The third layer is to extend 0.92 inch beyond FDC and 0.75 inch beyond ADC.

6.2.2.2 RMC-2 and RMC-3 - Wind 3 hoop layers of boron tape on cylinder portion of mandrel. The first layer is to extend 0.50 inch beyond the forward and aft dome/cylinder junction. The second layer is to extend 0.25 inch beyond the forward and aft dome/cylinder junction. The third layer is to coincide with the forward and aft dome/cylinder junctions.

6.2.3 Winding spacing between tapes will be 1/8 inch.

6.2.4 Winding tension will be 10 ± 2 pounds on the 1/8 inch wide tape.

6.3 Planar wrap:

6.3.1 Mount the mandrel assembly in the polar winder.

6.3.2 Mount forward and aft flanges on mandrel and secure in place with holding fixtures (Drawings FWL 70002), after preparation per 6.1.

6.3.3 Wind four sets of polar layers on the case (eight layers total).

6.3.4 Winding spacing between tapes will be 1/8 inch.

6.3.5 Winding tension will be 6 $\pm$ 2 pounds for RMC No. 1 and RMC-2, and 10 $\pm$ 2 pounds for RMC No. 3 on the 1/8 inch wide tape.

6.3.6 Winding pattern will be 88 one inch wide ribbons per set.

6.3.7 Winding angle will be $19^{o} \pm 1^{o}$ for RMC No. 1 and $24^{o} \pm 1^{o}$ for RMC No. 2 and RMC-3.

6.3.8 The boron/epoxy tape for the planar wraps for RMC-2 and RMC-3 will be aged at room temperature as follows:

a) 13 to 15 days for first layer material

b) 11 to 13 days for second and third layers

c) 10 to 11 days for fourth (last) layer

6.3.9 RMC-3 only, shrink tape shall be wrapped over each planar layer pair and the wrap shall be aged in the oven as follows:

a) age first planar wrap 1/2 hour at $200^{o}F$

b) age second and third planar wrap 1 hour at $200^{o}F$

c) age fourth planar wrap 1 hour at $200^{o}F$ and 1/2 hour at $250^{o}F$

6.4 Skirt attachment:

6.4.1 Prepare skirt per 6.1.

6.4.2 Slide skirt over forward dome and secure with holding fixture (drawing No. FWL 70002).

6.5 Outer hoop wrap:

6.5.1 Mount mandrel assembly in lathe winder.

6.5.2.1 RMC-1 - Wind 4 hoop layers of boron tape on cylinder portion of case. Wrap is to be wound over the skirt flange and extend to the cylinder-dome tangency points.

6.5.2.2 RMC-2 and RMC-3 - Wind 3 hoop layers of boron tape on cylinder portion of case. Wrap is to be wound over the skirt flange 1.5 inches and extend over the aft dome/cylinder tangency points as follows:

a) Extend 0.5 inches beyond aft dome to cylinder tangency point.

b) Extend 0.25 inches beyond aft dome to cylinder tangency point.

c) Extend to length of barrel only

6.5.3 Winding spacing between tapes will be 1/8 inch.

6.5.4 Winding tension will be 10 $\pm$ 2 pounds on the 1/8 inch wide tape.

7. CURE

7.1 The finished case will be cured 90 $\pm$ 5 minutes at 200 $\pm$ 5^{o}F, plus 60 to 90 minutes from 200 to 350^{o}F, plus 90 $\pm$ 5 minutes at 350 $\pm$ 10^{o}F.

8. MANDREL REMOVAL

8.1 After the case is cured, remove from oven and remove end boss and skirt holding fixtures.

8.2 Cut and remove plaster to expose inside aft closure.

8.3 Cut and remove plywood skeleton and screen wire.

8.4 Partially fill case with warm water and let soak to soften plaster.

8.5 Remove plaster (do not use a sharp-edged tool).

8.6 Thoroughly rinse with tap water and dry case in the oven (not to exceed 150^{o}F).

8.7 Inspect inside case for completeness of mandrel removal.

8.8 If inspection indicates case is not clean, repeat 8.5, 8.6 and 8.7.

9. QUALITY CONTROL

9.1 Receiving Inspection - Raw materials will be inspected upon receipt at MMC. Certification of physical and chemical property tests will be required to preclude redundant raw materials testing at MMC.

9.2 Process Inspection - Inspection measurements will be documented for all program hardware. Typical inspection/verification checks anticipated in the fabrication process plan include but are not limited to:

a) finish dimensions on winding mandrel;
b) finish dimensions on insert fittings;
c) angle of planar wraps;
d) ends per inch settings of the winding machine and number of plies;
e) winding tension;
f) cleaning preparation;
g) in-process fabrication and dimensional checks including the critical junction area (skirt/wrap);
h) assurance that the gap between tapes is less than 0.020 inch, and that splices are no closer than 12 inches in adjacent tapes and have sufficient overlap for structural integrity;
i) cure process variables (time and temperature);
j) finish dimensions on the deliverable article;
k) bond integrity of inserts to the structure (bond verification to be by the tap method);
l) cleanliness of inside surface.

Results of the inspection shall be documented in the fabrication log for the deliverable article.

APPENDIX C

Drawing FWL-70002

Mandrel, JPL Rocket Motor Case

TABLE I

ROCKET MOTOR CASE PARAMETERS

Parameter	RMC #1	RMC #2	RMC #3
Inner Hoop Layers			
No. of Layers	3	3	3
Tension (lb)	9-10	9	10
Weight (lb)	1.31	0.37	0.41
Polar Layers			
No. of Layer Pairs	4	4	4
Wrap Angle (degrees)	19	24	24
Tension (lb)	6-8	6	10
Weight (lb)	12.11	9.75	9.69
Outer Hoop Layers			
No. of Layers	4	3	3
Tension (lb)	8½	9	10
Weight (lb)	1.60	.37	.38
Case Length (in)	29.29	22.70	22.70
Boron/Epoxy Weight (lb)	15.0	10.5	10.5
Total Case Weight (lb)	28.0	22.5	22.6

TABLE 2 SHELL MODEL FOR STRESS ANALYSIS

Part No.	Description	Radius in.	Length in Terms of Meridional Coordinate in.	Thickness in.	Layers	Material	Cone Angle	Number of Points Used to Establish Properties and Thickness Variation by Linear Interpolation
1	Cylindrical part of aft boss	6.175	1.30	0.350	1	Titanium $E=16.5x10^6$ psi $\nu = 0.36$	-	-
2	Conical part of aft boss with composite overwrap	-	1.838	0.175 0.225	1 2	Titanium Composite, winding angle = 70^o	70	-
3	Aft Dome	-	From ϕ = 0.335 to $\pi/2$ radians	Variable (Fig. 4)	1	Composite winding angle variable, see Fig. 2.	-	7, at equal intervals of radius
4	Cylinder	14.0	12.9	0.015 0.030 0.015	1 2 3	Composite, Angle = 18^o Angle = 90^o Angle = 18^o	-	-
5	Cylinder with Skirt end	14.0	1.5	0.015 0.030 0.036 0.015	1 2 3 4	Composite, Angle = 18^o Angle = 90^o Titanium Angle = 18^o	-	-
6	Extension of Skirt	14.0	3.618	0.120	1	Titanium	-	-
7	Forward Dome	-	From $\phi = \pi/2$ to 3.0084 radians	Variable (Fig. 3)	1	Composite, winding angle, variable, see Fig. 1	-	12, at equal intervals of radius

(continued)

TABLE 2 SHELL MODEL FOR STRESS ANALYSIS - Continued

Part No.	Description	Radius in.	Length in Terms of Meridional Coordinate in.	Thickness in.	Layers	Material	Cone Angle	Number of Points Used to Establish Properties and Thickness Variation by Linear Interpolation
8	Conical part of forward boss with overwrap	-	1.780	0.080	1	Titanium	174.25°	-
				0.375	2	Composite, angle = 37.5°		
9	Cylindrical portion of forward boss	1.852	0.682	0.206	1	Titanium	-	-

TABLE 3 MAXIMUM STRESS IN METAL PARTS

Part No.	Description	Hoop Tension ksi	Hoop Compression ksi	Meridional Tension ksi	Meridional Compression ksi
2	Aft boss flange	24.6	5.8	33.4	50.9
5	Embedded Skirt	70.0	12.5	35.6	25.0
6	Skirt Extension	10.8	17.8	39.8	39.8
8	Forward boss flange	77.4	-	42.4	-

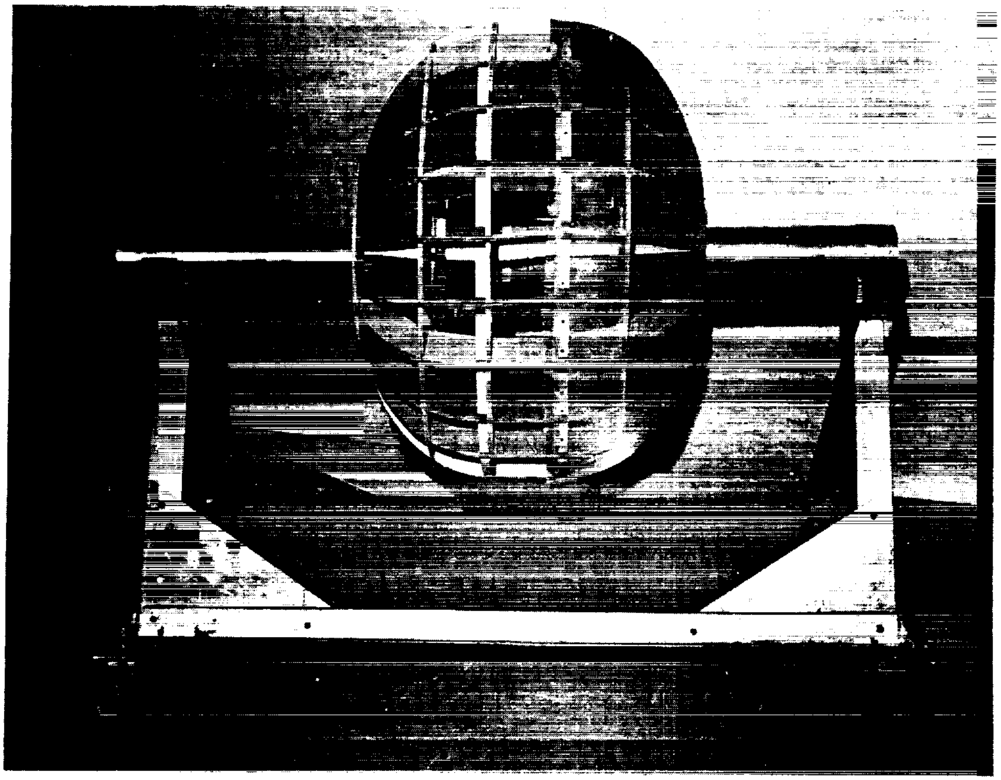


Fig. 1 Partially Completed Mandrel

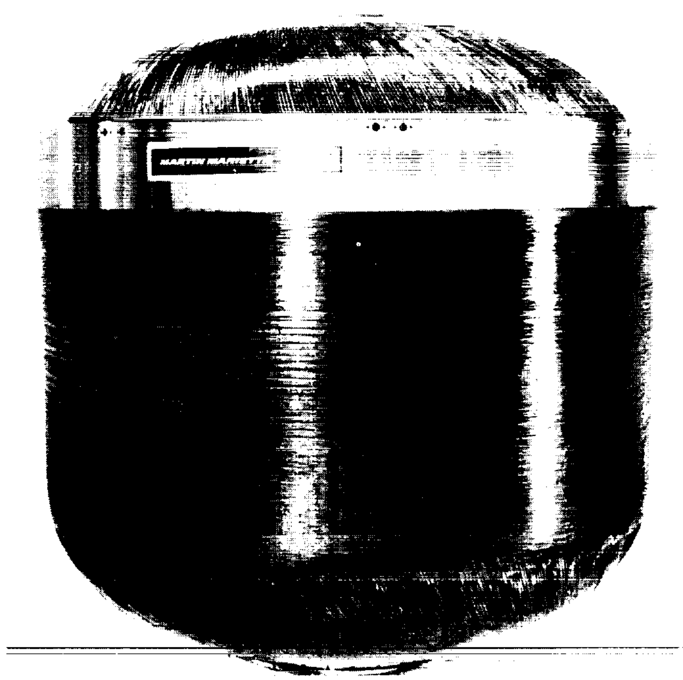


Fig. 2 Completed Rocket Motor Case #1 (RMC-1)

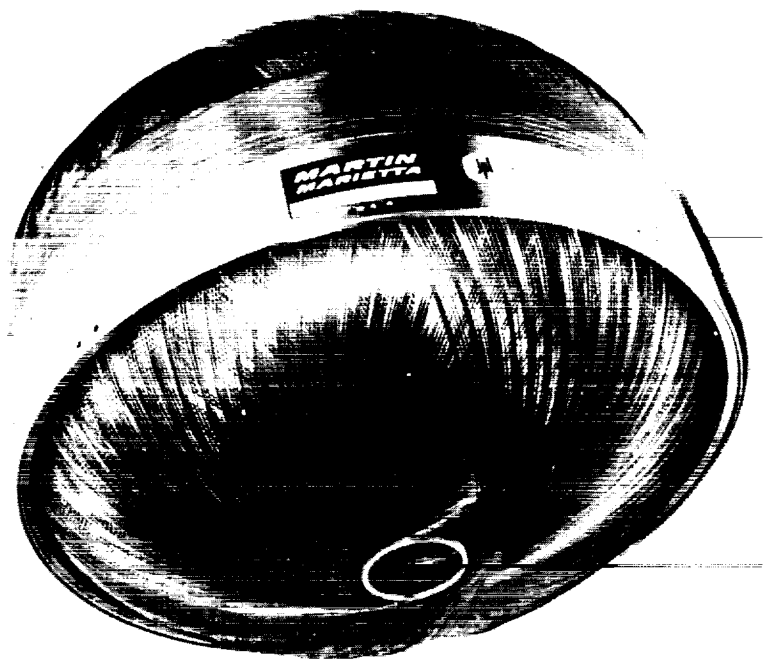


Fig. 3 Completed Rocket Motor Case #2 (RMC-2)

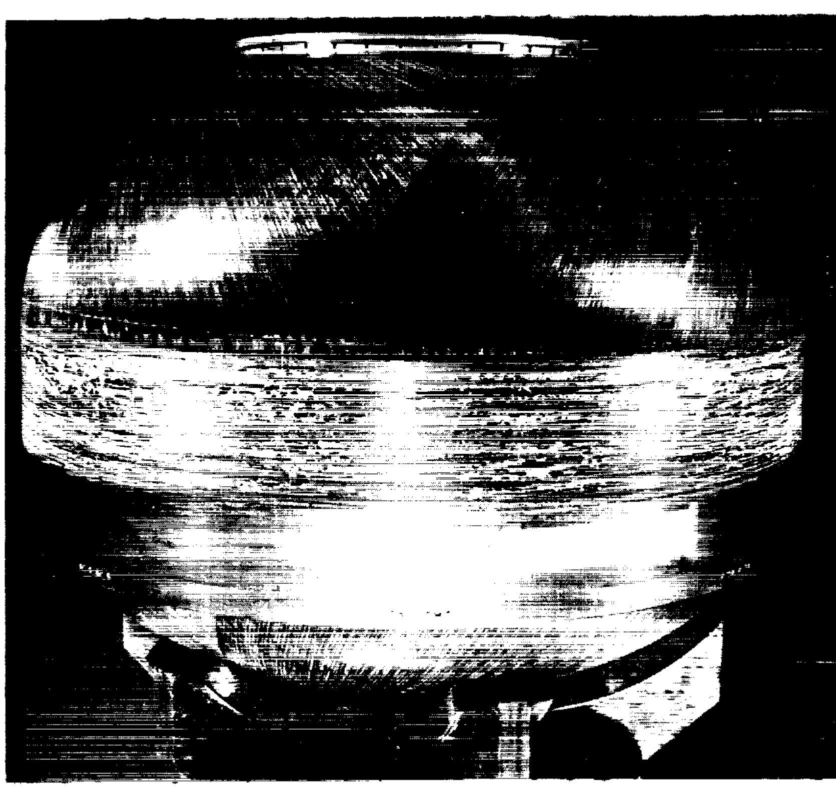


Fig. 4 Completed Rocket Motor Case #3 (RMC-3)

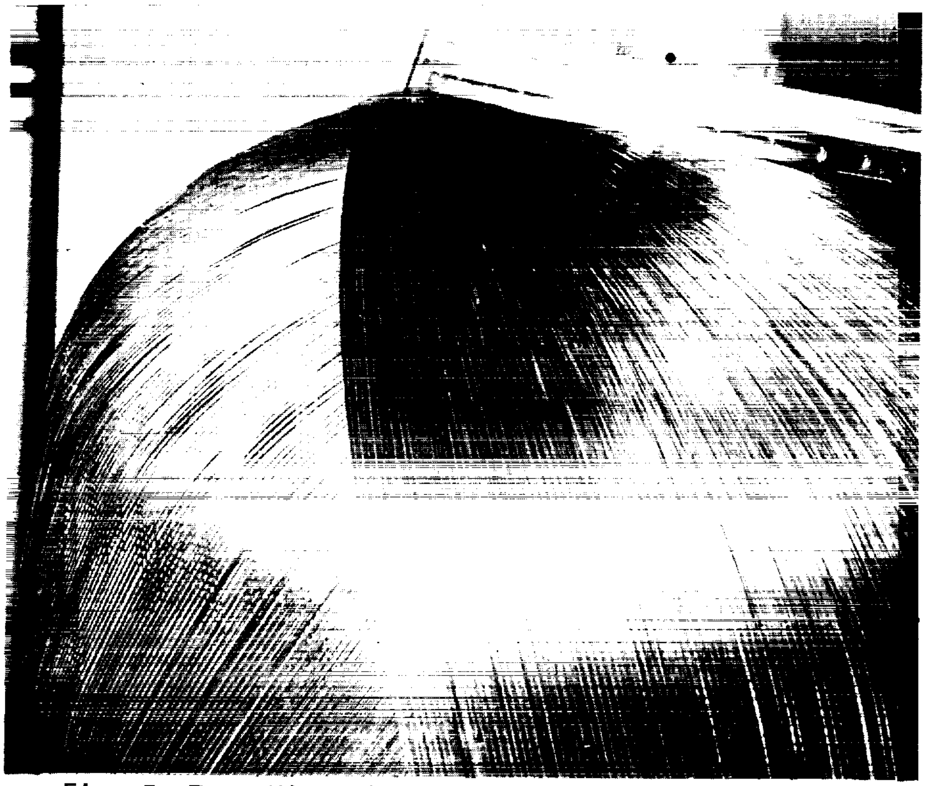


Fig. 5 Tape Migration - Shingling During Winding of Rocket Motor Case #2 (RMC-2)

Fig. 6 Tape Shingling on the Forward Dome of Rocket Motor Case #2 (RMC-2)

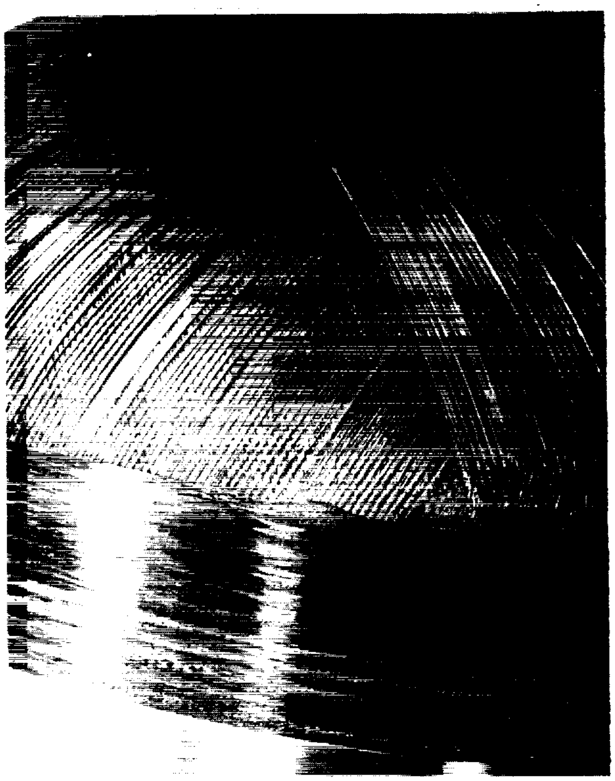


Fig. 7 Tape Shingling on the Aft Dome of Rocket Motor Case #2 (RMC-2)

Fig. 8 Shrink-Tape Wrap of Rocket Motor Case #3 (RMC-3)

Fig. 9 The Forward Dome of Rocket Motor Case #3 (RMC-3)

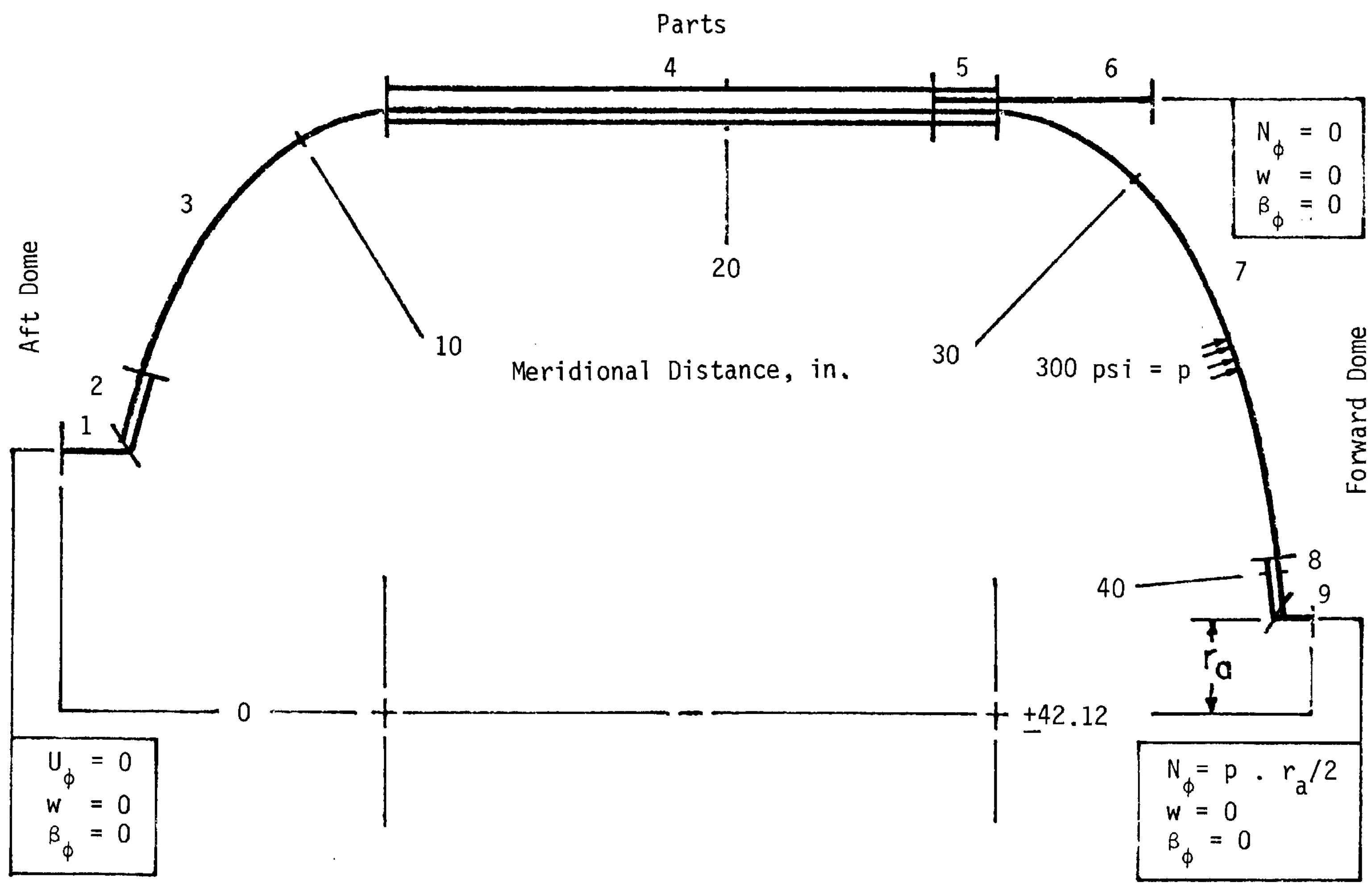


Fig. 10 Partitioning of Vessel for Stress Analysis Showing Boundary Conditions

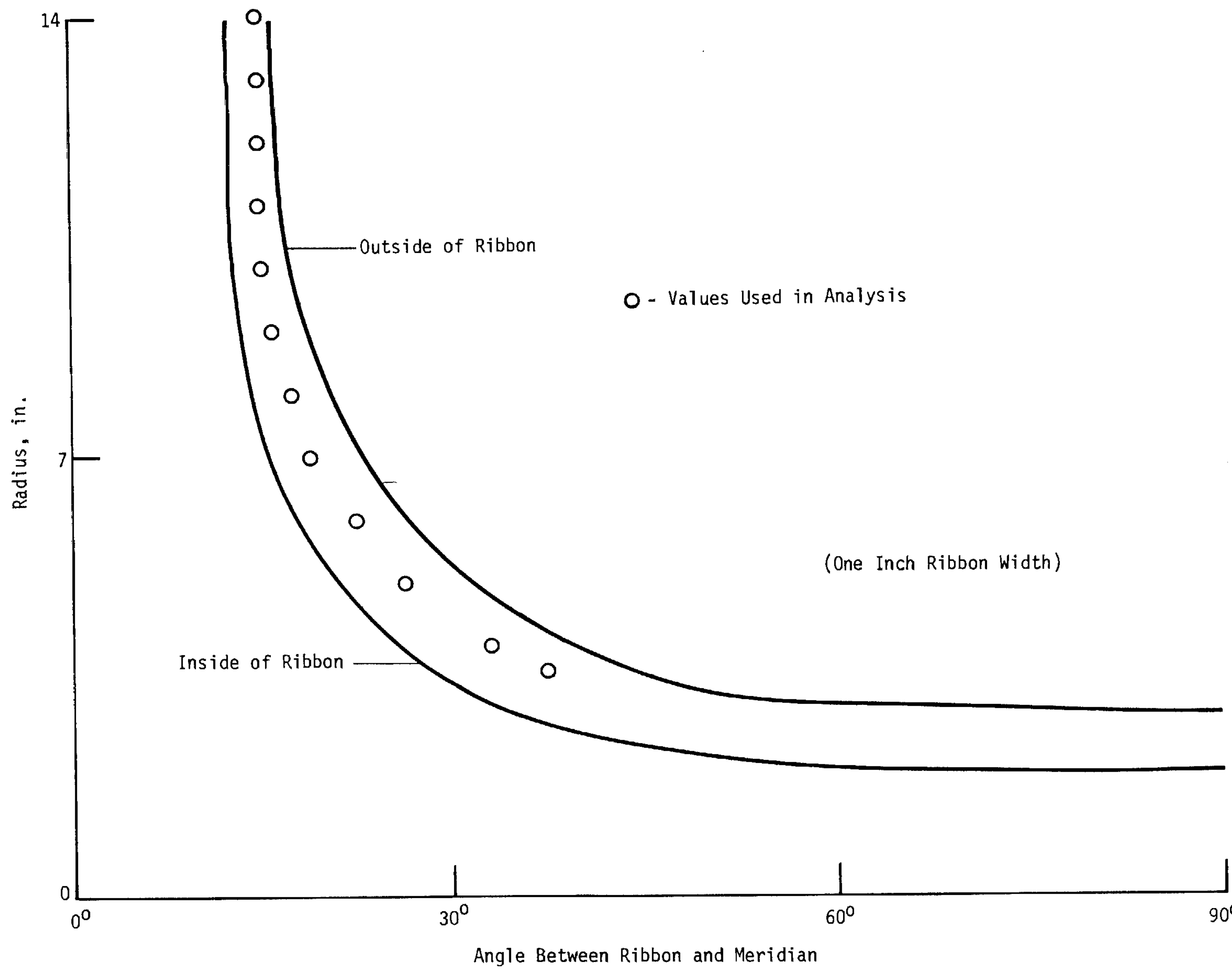


Fig. 11 Ribbon Path Over Forward Dome

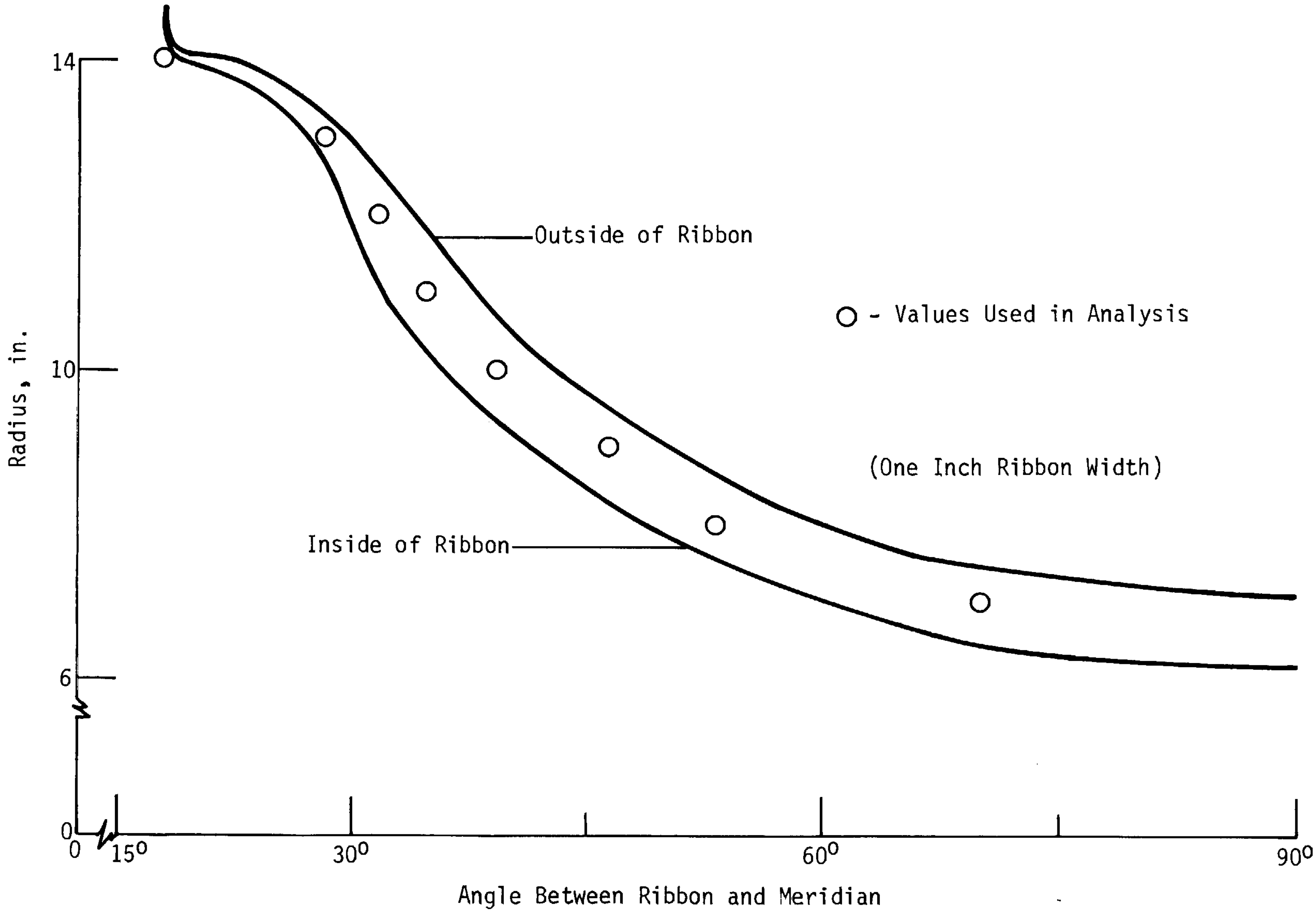


Figure 12 Ribbon Path Over Aft Dome

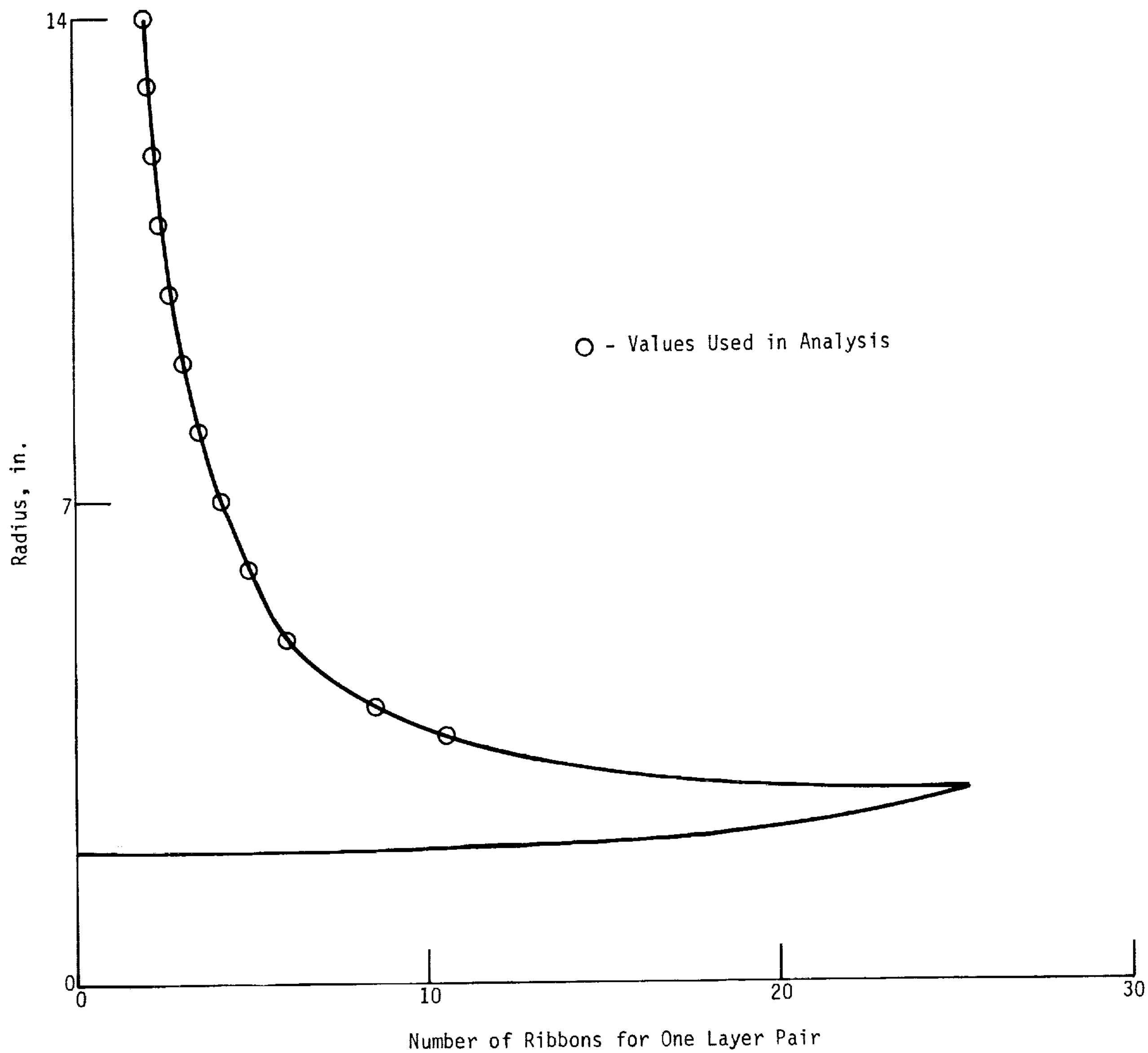


Figure 13 Thickness of Composite in the Forward Dome

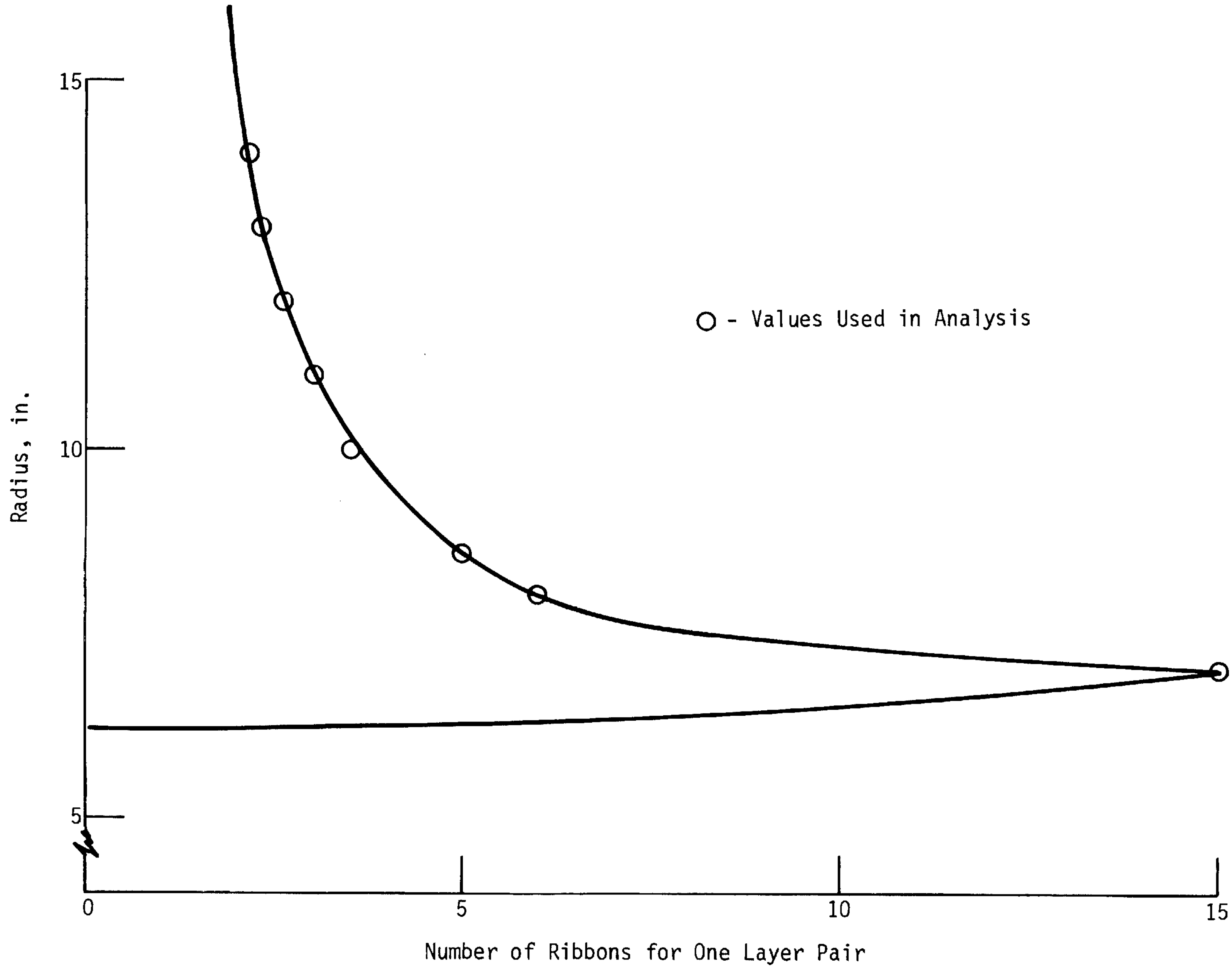


Fig. 14 Thickness of Composite in the Aft Dome

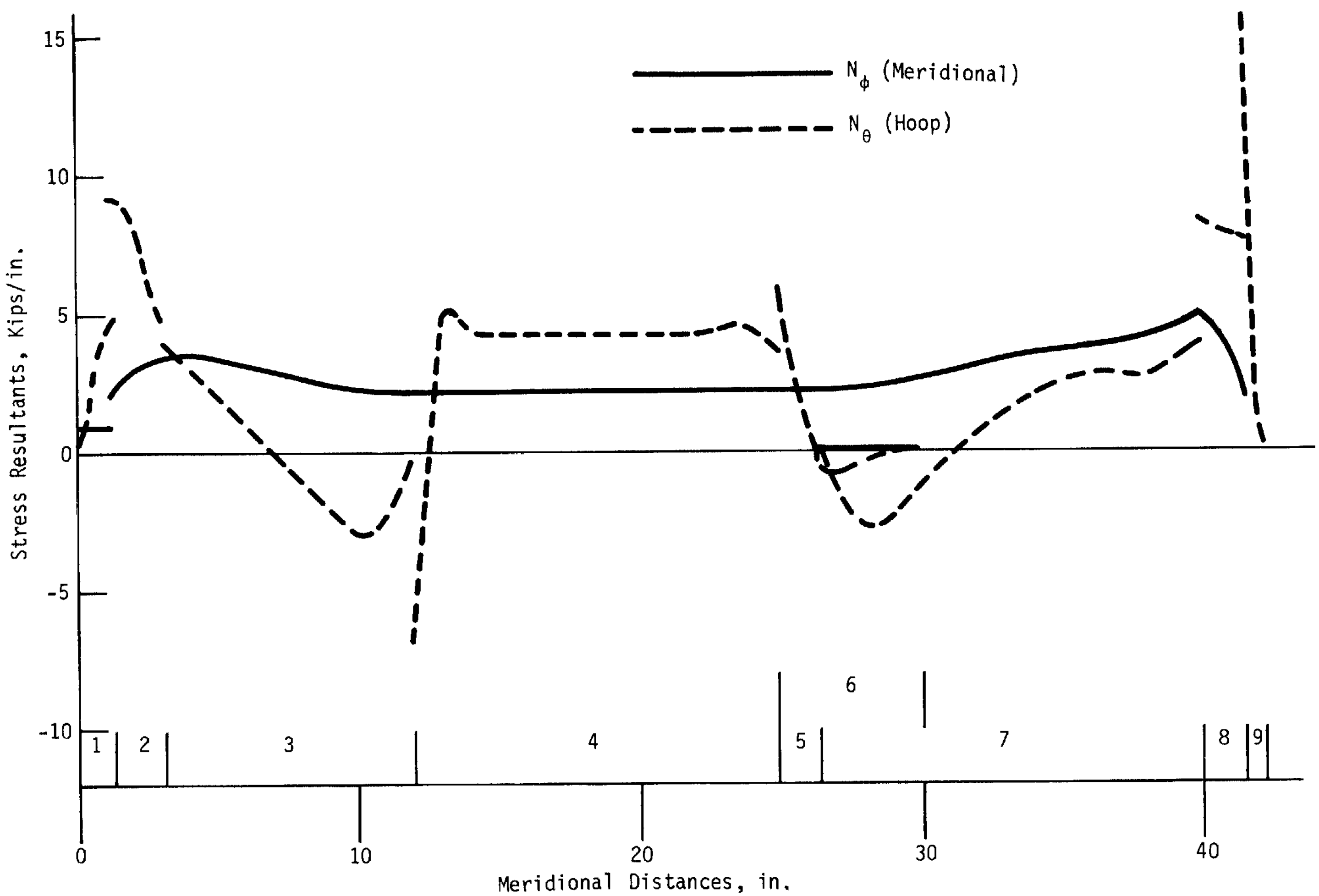


Figure 15 Stress Resultants in Vessel Wall

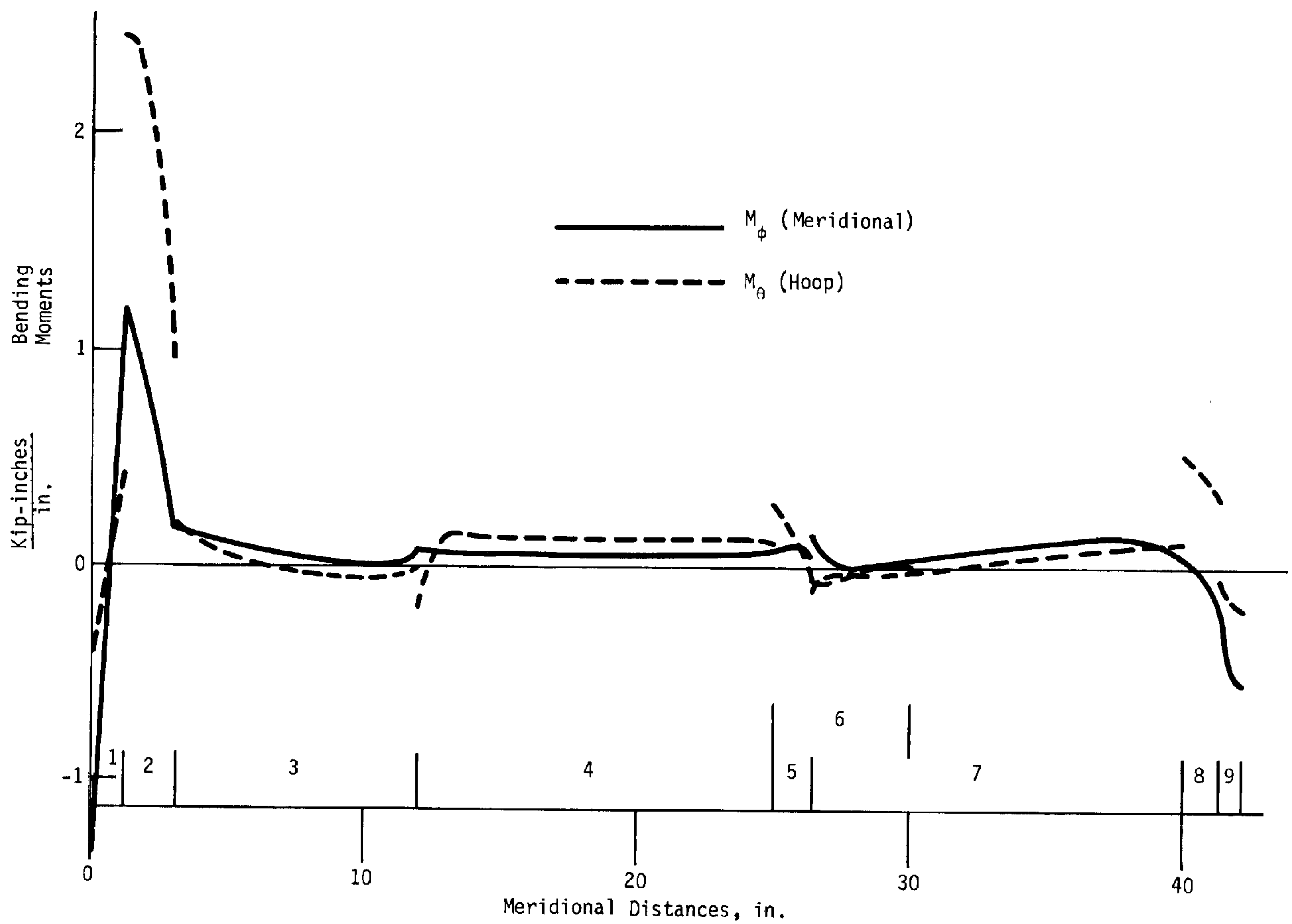


Figure 16 Bending Moments in Vessel Wall

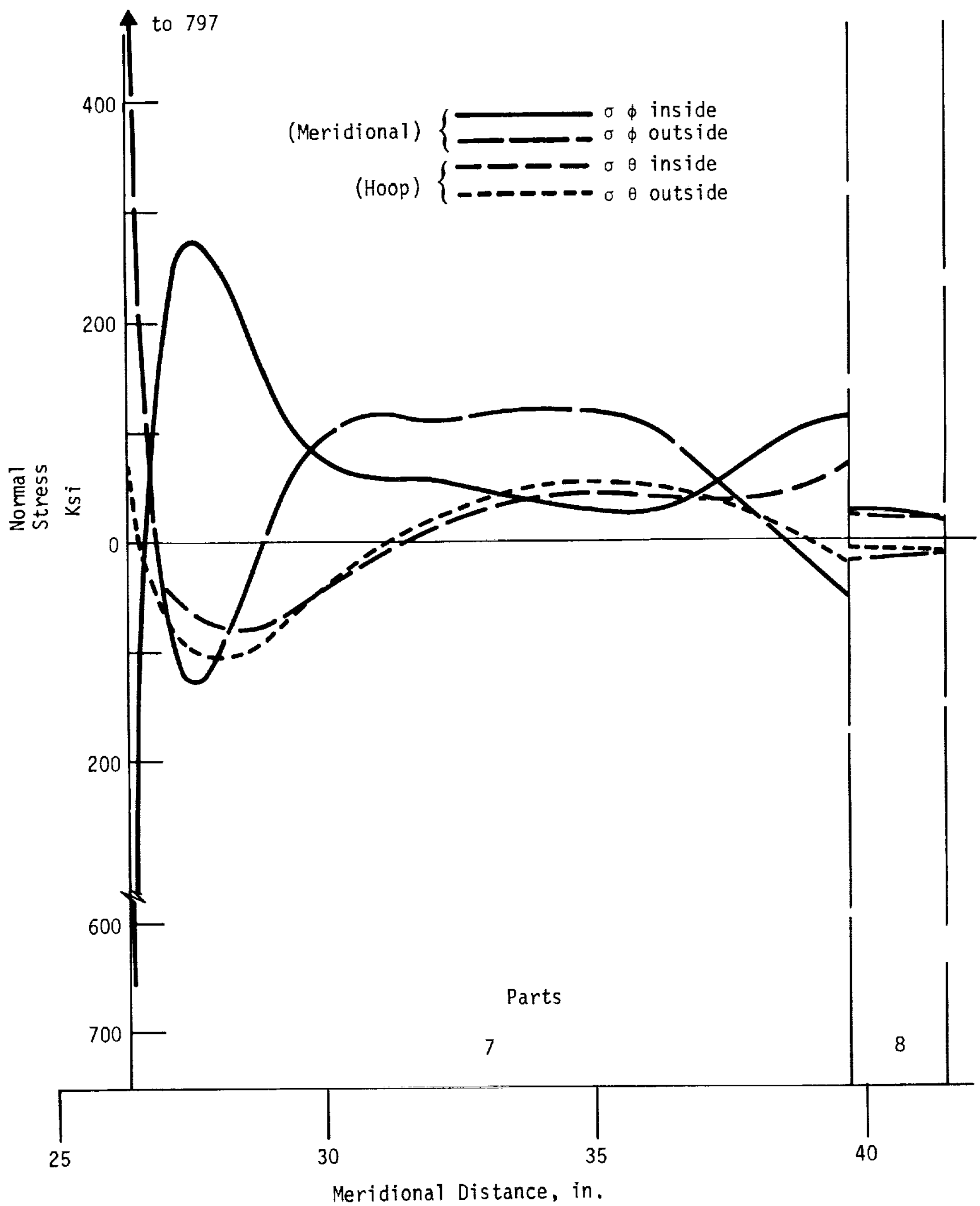


Figure 17 Stress in the Forward Dome

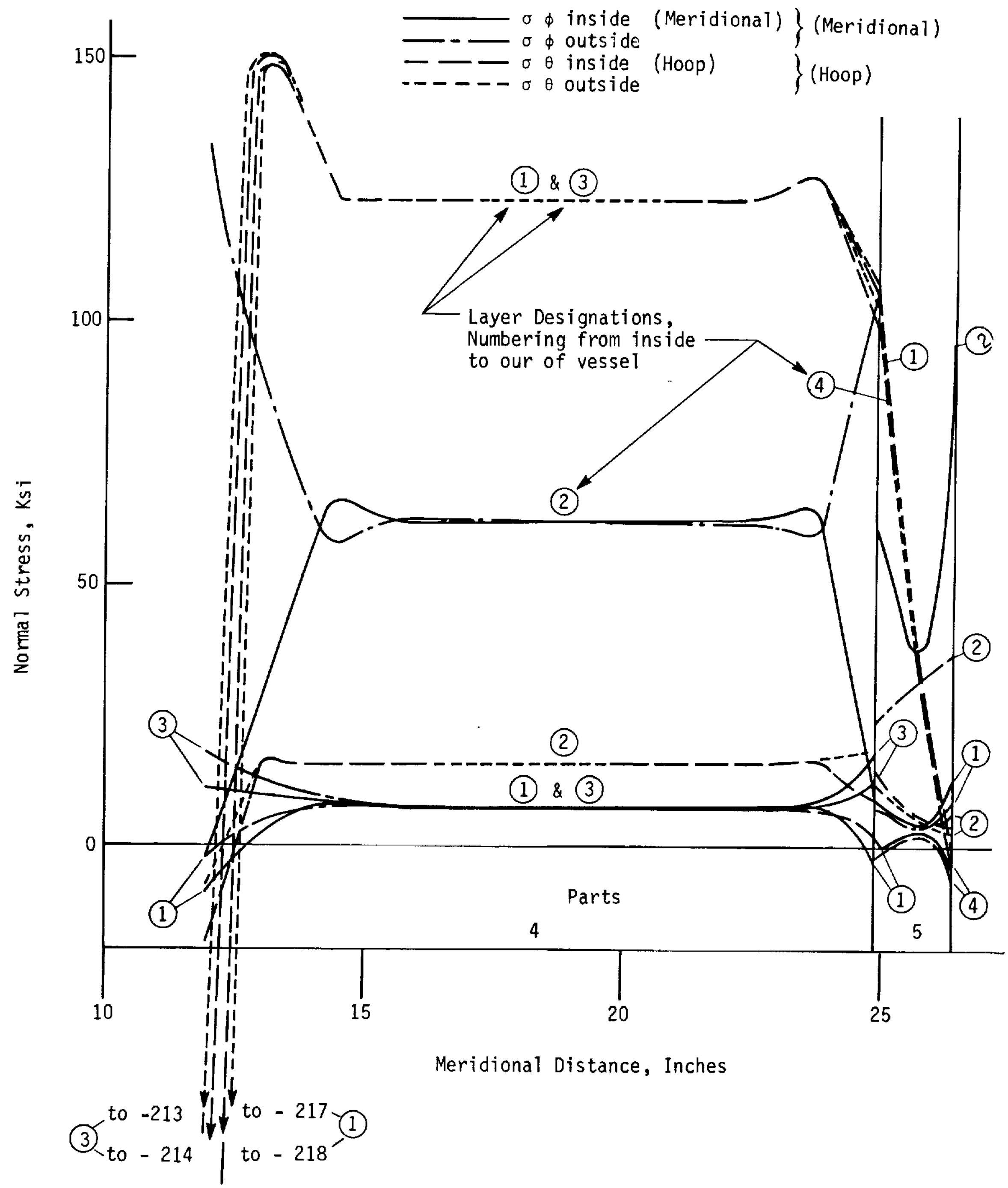


Figure 18 Stress in the Cylinder

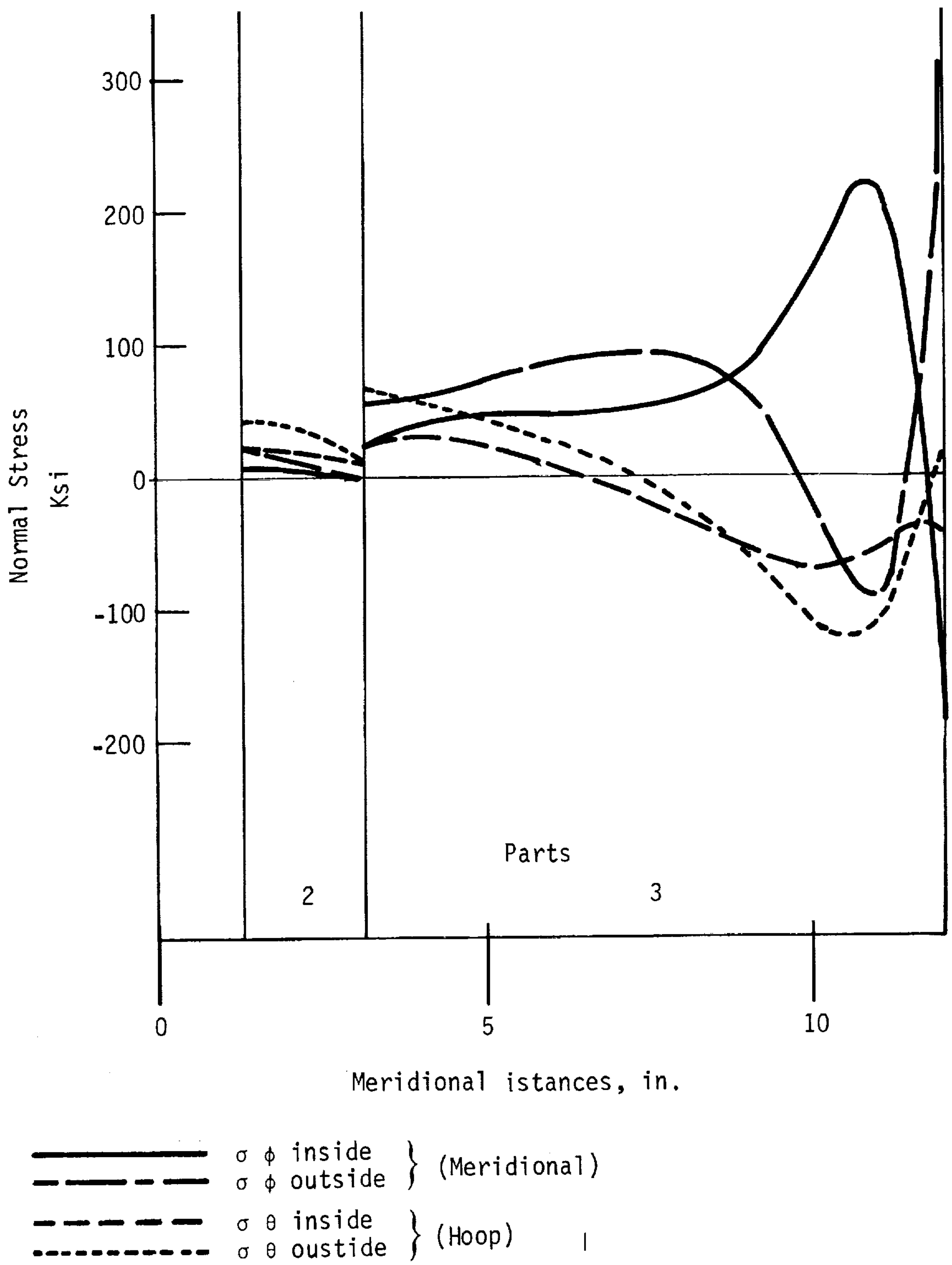


Figure 19 Stress in the Aft Dome

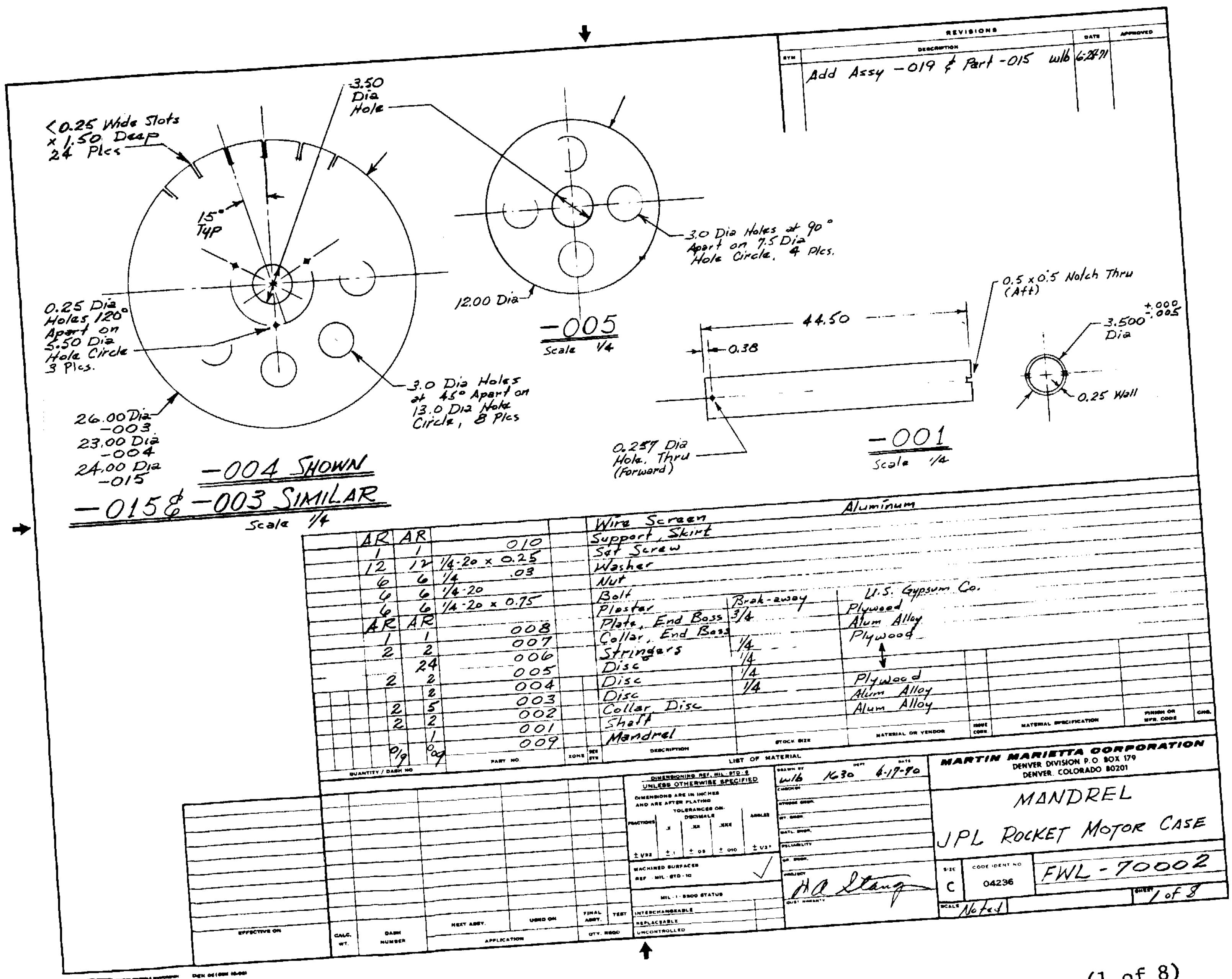
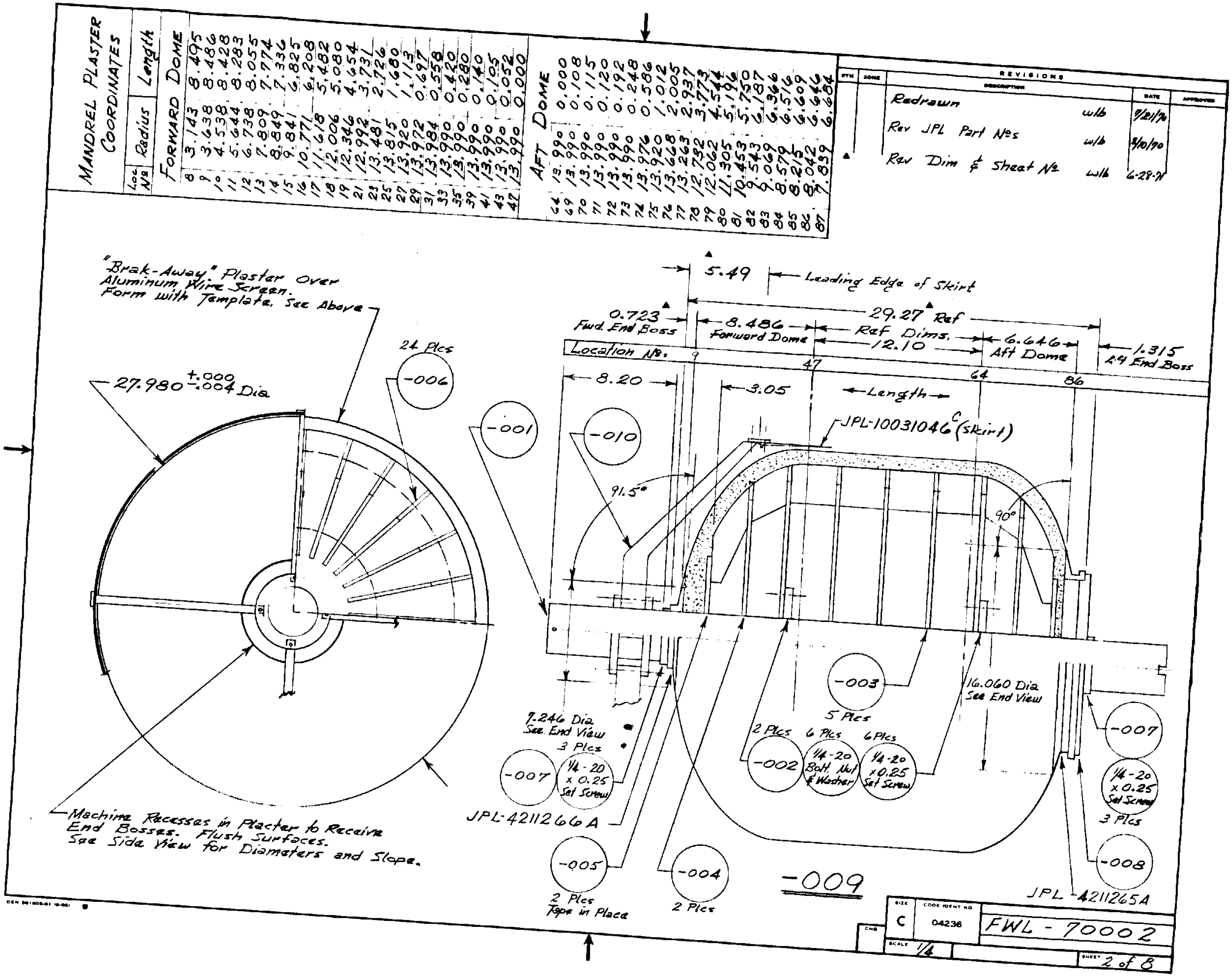


Fig. 20 Mandrel - JPL Rocket Motor Case

(1 of 8)



MANDREL PLASTER COORDINATES

Loc No	Radius	Length
FORWARD DOME		
8	3.143	8.495
9	3.638	8.486
10	4.538	8.428
11	5.644	8.283
12	6.738	8.055
13	7.809	7.774
14	8.849	7.336
15	9.841	6.825
16	10.771	6.208
17	11.618	5.482
18	12.006	5.080
19	12.346	4.654
21	12.992	3.731
23	13.481	2.726
25	13.815	1.680
27	13.920	1.113
29	13.972	0.697
31	13.984	0.558
33	13.990	0.420
35	13.990	0.280
39	13.990	0.140
41	13.990	0.105
43	13.990	0.052
47	13.990	0.000
AFT DOME		
64	13.990	0.000
69	13.990	0.108
70	13.990	0.115
71	13.990	0.120
72	13.990	0.192
73	13.990	0.248
74	13.976	0.586
75	13.920	1.012
76	13.668	2.005
77	13.263	2.937
78	12.732	3.773
79	12.062	4.544
80	11.305	5.196
81	10.453	5.750
82	9.543	6.187
83	9.069	6.366
84	8.579	6.516
85	8.215	6.609
86	8.042	6.646
87	7.839	6.684

Fig. 20 (Cont)

(2 of 8)

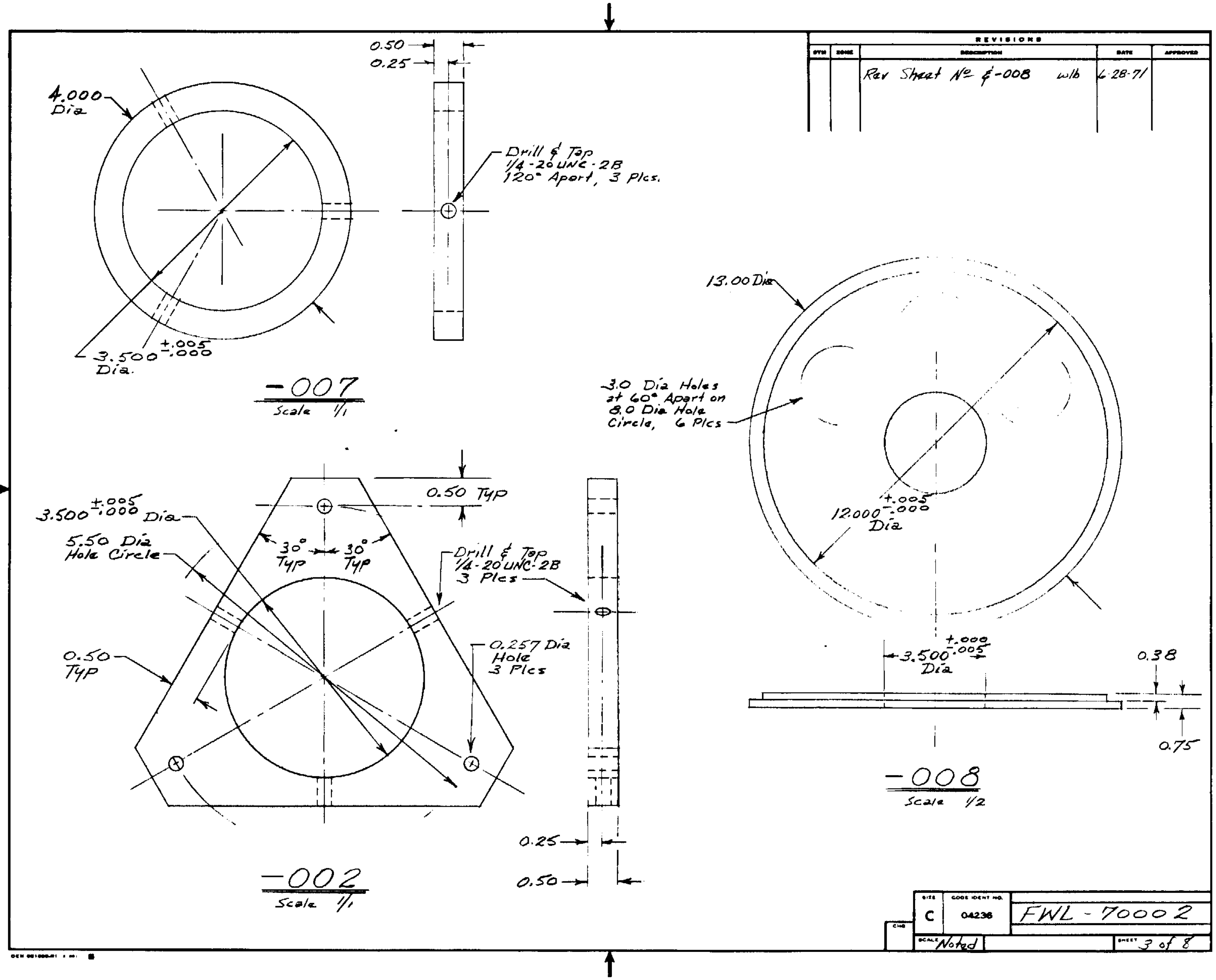


Fig. 20 (Cont)

(3 of 8)

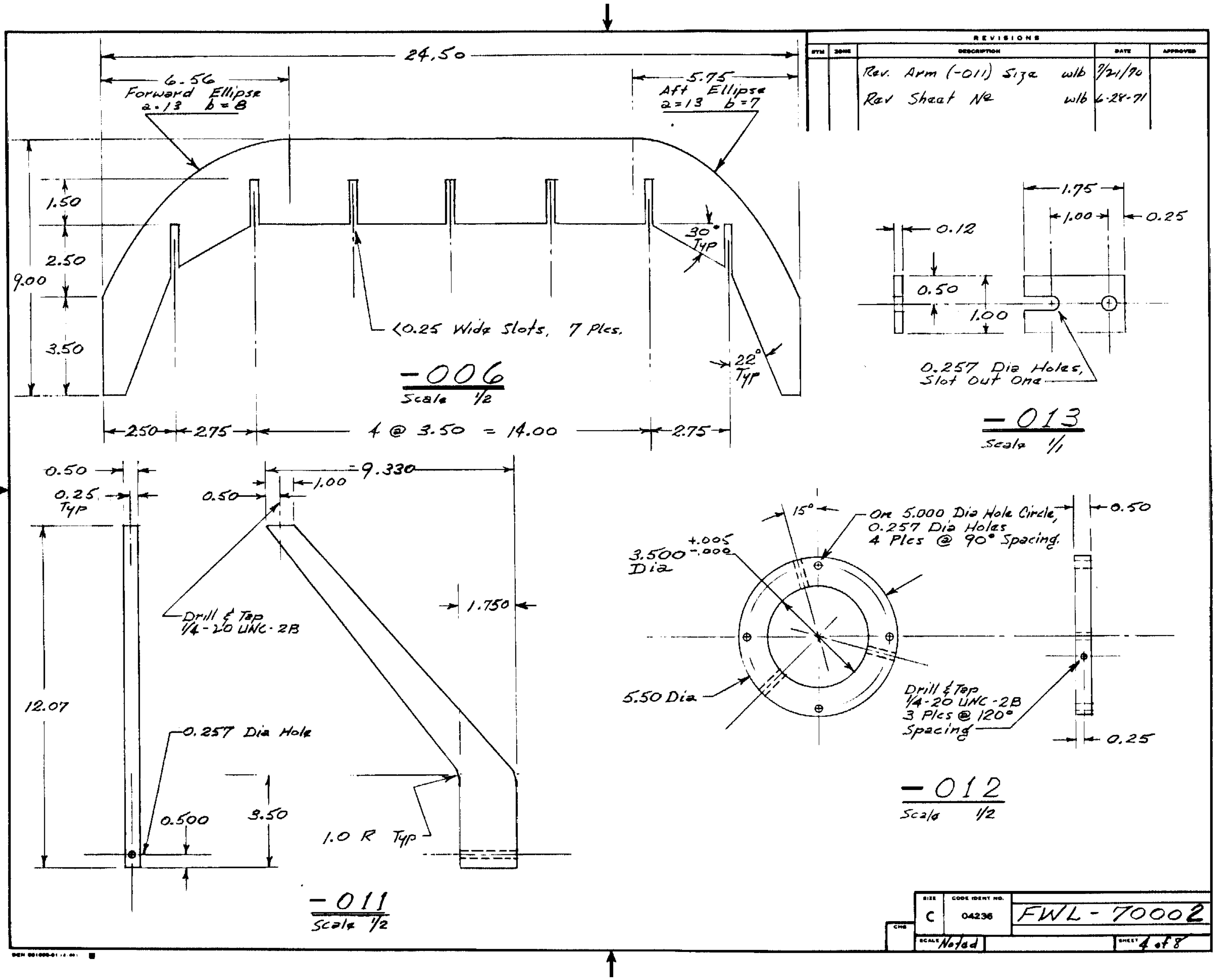


Fig. 20 (Cont) (4 of 8)

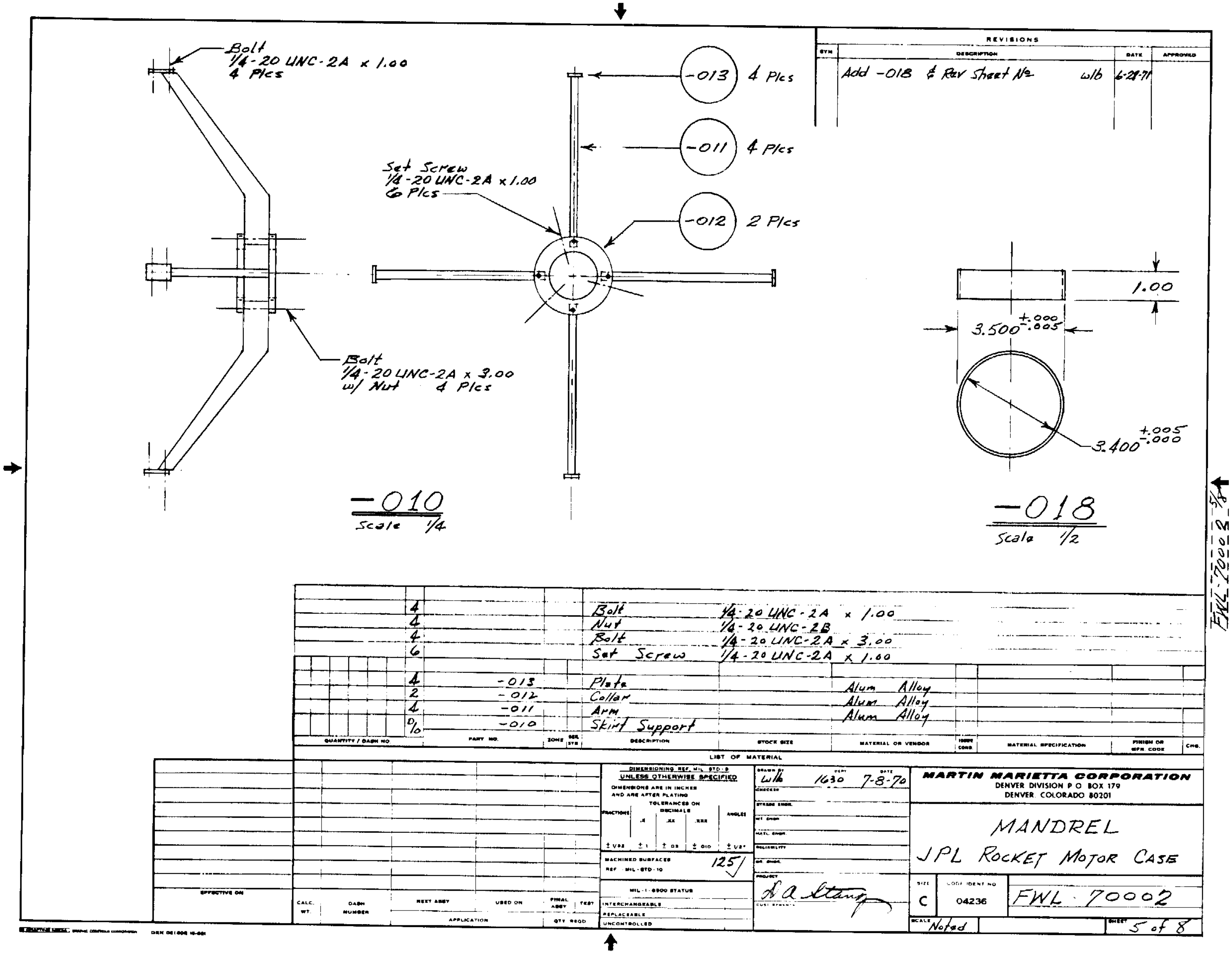


Fig. 20 (Cont) (5 of 8)

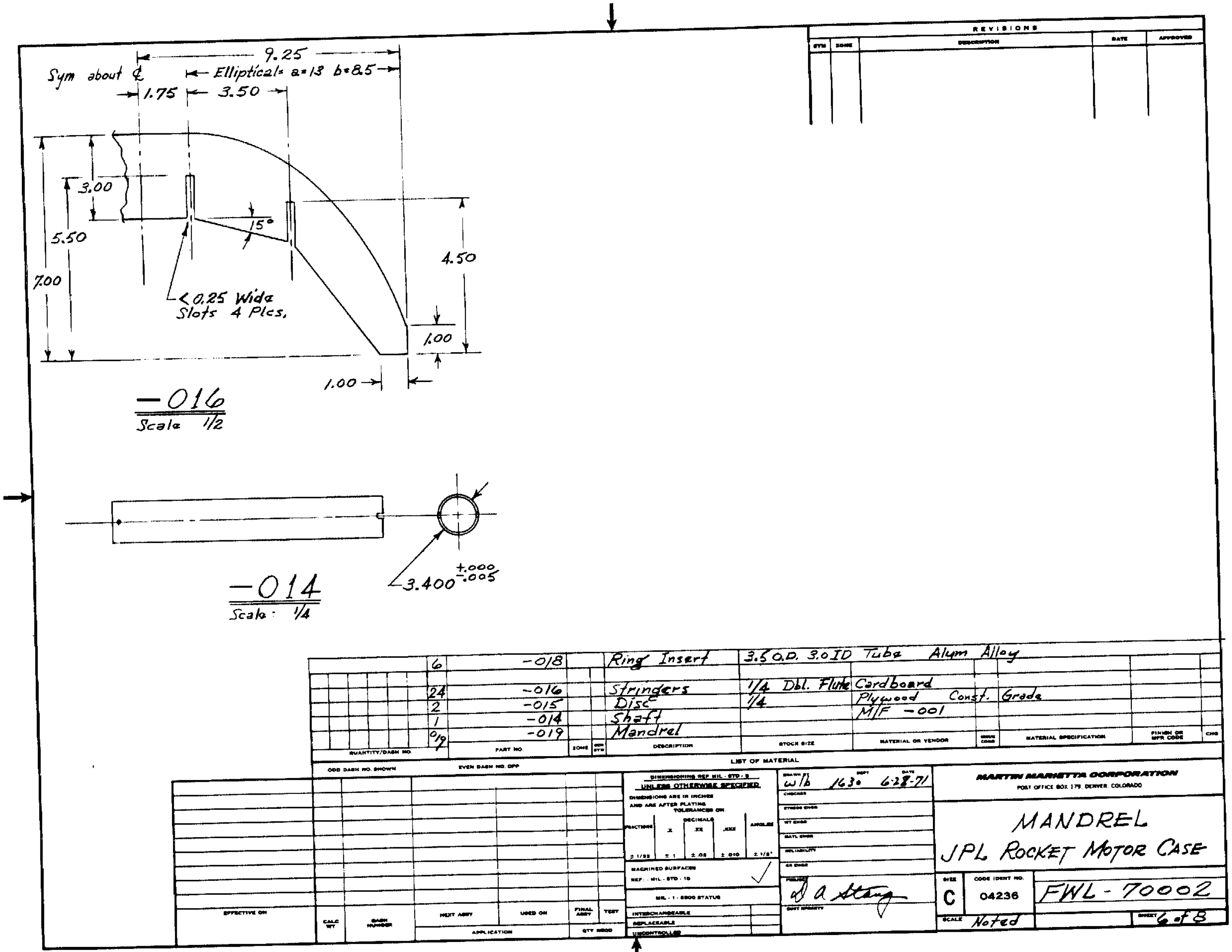


Fig. 20 (Cont)

(6 of 8)

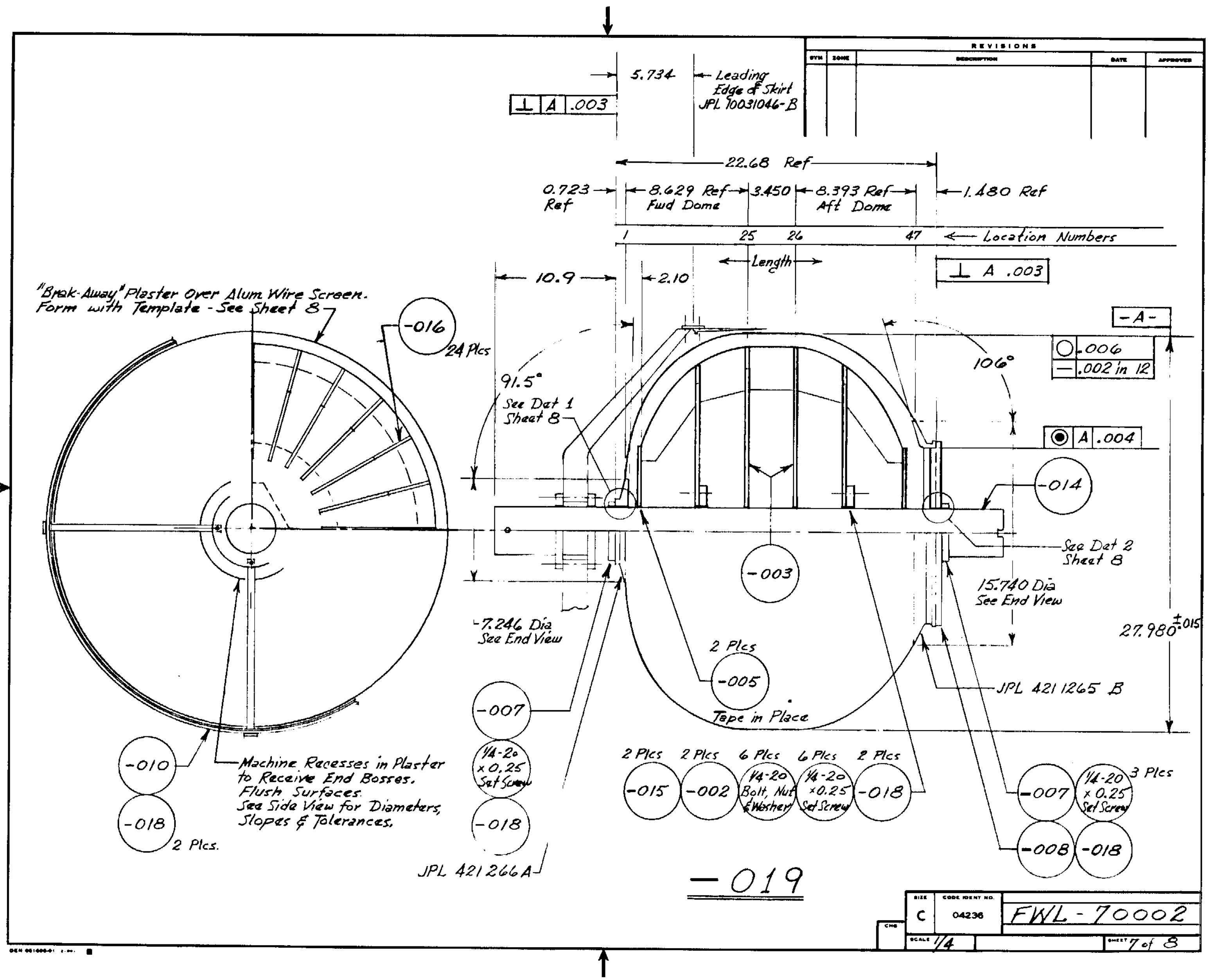


Fig. 20 (Cont) (7 of 8)

MANDREL PLASTER COORDINATES

	LOC. NO	RADIUS	LENGTH
FORWARD DOME	1	3.623	8.629
	2	4.081	8.606
	3	5.192	8.489
	4	6.291	8.289
	5	7.371	8.009
	6	8.424	7.636
	7	9.435	7.162
	8	9.921	6.888
	9	10.389	6.584
	10	10.839	6.254
	11	11.269	5.897
	12	11.677	5.514
	13	12.056	5.106
	14	12.409	4.672
	15	12.731	4.217
	16	13.021	3.739
	17	13.276	3.243
	18	13.495	2.730
	19	13.677	2.202
	20	13.820	1.661
	21	13.922	1.113
	22	13.984	0.558
	23	13.990	0.279
	24	13.990	0.105
	25	13.990	0.000
AFT DOME	26	13.990	0.000
	27	13.990	0.105
	28	13.990	0.279
	29	13.984	0.558
	30	13.922	1.113
	31	13.821	1.662
	32	13.682	2.203
	33	13.505	2.732
	34	13.293	3.249
	35	13.046	3.749
	36	12.766	4.234
	37	12.458	4.699
	38	12.121	5.144
	39	11.758	5.568
	40	11.372	5.972
	41	10.965	6.345
	42	10.537	6.713
	43	10.094	7.054
	44	9.402	7.525
	45	8.683	7.956
	46	8.069	8.289
	47	7.870	8.393

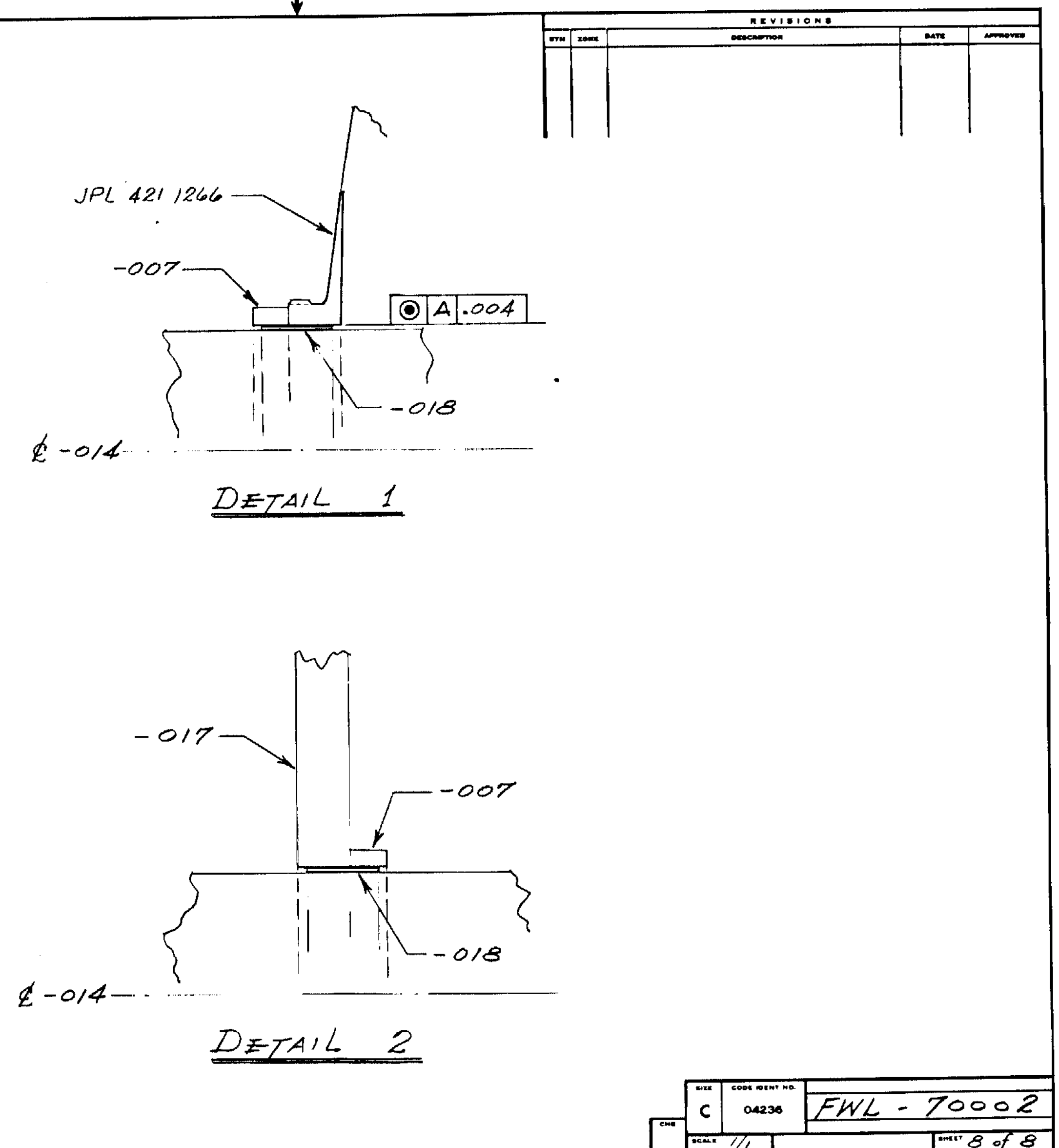


Fig. 20 (Concl) (8 of 8)