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GRAPHITE COMPOSITE AIRCRAFT LANDING GEAR WHEEL.(U)
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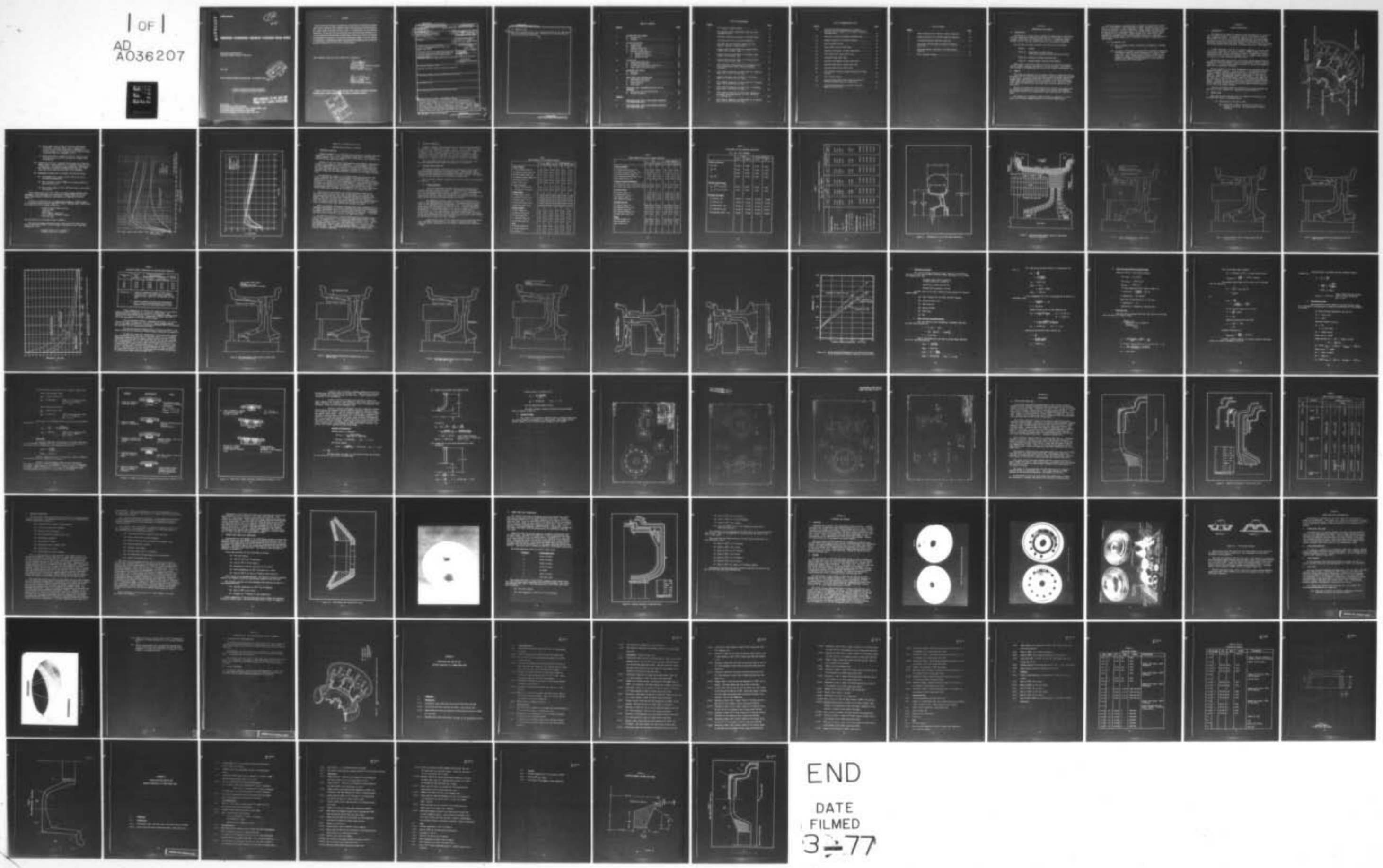

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GRAPHITE COMPOSITE AIRCRAFT LANDING GEAR WHEEL

HERCULES INCORPORATED
BACCHUS WORKS, MAGNA, UTAH 84044

MAY 1976

FINAL REPORT PERIOD 18 MARCH 1974 - 30 OCTOBER 1975

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Prepared for
DEPARTMENT OF THE AIR FORCE
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES (AFSC)
AIR FORCE FLIGHT DYNAMICS LABORATORY
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

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The effort during Phase I of the contract included detailed design of a composite wheel assembly to function structurally and mechanically in a manner identical to the existing metal braked main landing gear wheel for the T-39 aircraft. The design and analysis of the graphite composite landing gear wheel was based on demonstrated material properties. A thermal analysis of the composite structure showed the maximum wheel temperature to be 406° F. adjacent to the steel brake keys (inner wheel half) and 223° F on the outer

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20. ABSTRACT (Cont)

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wheel half. Hercules 4397/AS resin system was selected for the inner wheel half and 3501/AS for the outer half. During Phase II, one inner and two outer wheel halves were fabricated.

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SECTION I

INTRODUCTION AND SUMMARY

A. INTRODUCTION

The objective of this contract (F33615-74-C-3040) was to demonstrate that the braked main landing gear wheel for the T-39 aircraft could be designed, fabricated, and successfully tested at a significant weight savings over the existing aluminum wheel by using graphite composite.

The contract was phase oriented, consisting of the following.

Phase I - Design

Phase II - Fabrication of Three Wheels
(Only after go-ahead approval by the Air Force)

Phase III - Testing at Wright-Patterson AFB

Phase IV - Modify Design, Fabricate Three Wheels

This report is the final report and covers the design and analysis, thermal studies, drawings, fabrication, tooling concepts, and problems that resulted in accomplishing only half of the original fabrication plan.

B. SUMMARY

The design and analysis of the graphite composite braked main landing gear wheel for the T-39 aircraft was based on material properties discussed in Section II. A thermal analysis of the composite structure showed the maximum wheel temperature to be 406° F adjacent to the steel brake keys (inner wheel half) and 223° F on the outer wheel half. Hercules 4397/AS resin system was selected for the inner wheel half and 3501/AS for the outer half.

The most critical area of the design was located at the flange under an ultimate tire pressure of 735 psi and a side load of 20,000 pounds. The critical stress in the flange under these conditions was 7000 psi in shear.

The weight of the graphite composite wheel was computed to be 18.6 pounds, 28.5 percent lighter than the 25.97-pound aluminum wheel.

From this program, it appears that, although the technology is available for using addition type polyimides in single, relatively thin structures, the extension of this technology to thick, complex structures requires further development. Further, lower cost, simpler design and fabrication procedures must be investigated before the potential cost savings offered by composites can be realized. Simpler designs can evolve only if composites are considered in early wheel design efforts; i.e., material substitution designs appear overly restrictive in braked, high-temperature applications.

It is recommended that:

(1) Future composite wheels and brakes be designed as a package approach.

(2) A program be initiated to extend 450° F capability composites technology to enable low-cost fabrication of thick, complex structures. This should include studies to determine the effects of reduced bleed/compaction cycles on the physical properties of laminate and optimization of cure cycles to minimize potential delaminations.

SECTION II

DESIGN AND ANALYSIS

A. INTRODUCTION

The design of the graphite composite wheel was based on the criterion that the wheel function as a substitute for the T-39 aircraft metallic main landing gear wheel. The graphite composite wheel is to be fitted with a 26 x 6.6 type VII tire and T-39 production hub and brake assembly and must function structurally and mechanically identically to the T-39 production metallic wheel and brake assembly. Also, the design must readily facilitate assembly and disassembly of the wheel and tire. (See Figure 1.)

A major advantage in the use of graphite composite in aircraft wheel fabrication, other than the obvious potential weight savings, is a non-catastrophic wheel failure and pressure blowout. Fragmentation damage is minimized to both personnel and aircraft, and, in general, wheel failure is expected to cause a gradual depressurization.

Mechanical design and analysis of the wheel was performed using the strength-of-materials approach utilizing experimentally verified laminate properties. A finite-element computer analysis of the axially symmetric wheel was not considered necessary.

Thermal analysis of the wheel configuration was performed using the HETRAN II computer program. In this analysis, a two-dimensional (2-D) axially symmetric grid was modeled which closely approximated the 3-D geometry. Using experimentally measured temperatures on the aluminum production wheel, time-dependent heat load was defined. This heat load was then used to predict the thermal effects in the graphite composite wheel by varying the heat flux linearly as a function of applied kinetic energy. Analyses were performed for a normal braking condition (2.35×10^6 ft-lb kinetic energy) and an overload (ultimate) braking condition (2.94×10^6 ft-lb kinetic energy).

Hercules AS graphite fiber was selected for its high strength properties, low cost, availability, and handling characteristics.

B. DESIGN LOADS

The loads to which the wheel will be subjected as defined by the Air Force Test Plan are summarized below:

(1) Pressurization and Static Load:

(a) Pressurize to 200 psi and allow to stand for a minimum of 24 hours. Air loss should not exceed 5 percent.

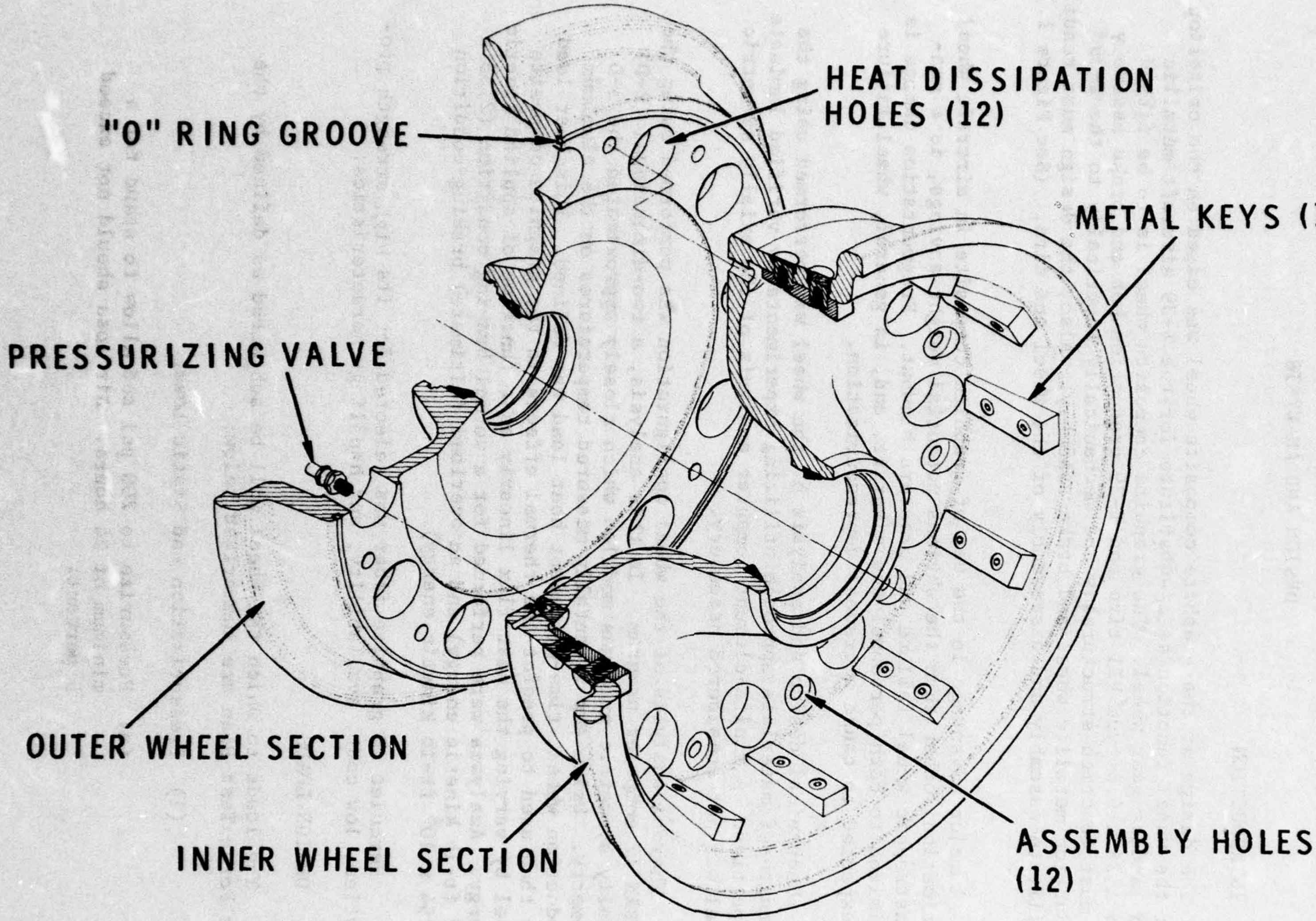


Figure 1. T-39 Graphite Composite Wheel

(b) Apply radial load of 8200 lb with tire pressurized at 200 psi. Increase radial load to design yield value of 39,700 lb per MIL-W-5013 H, Paragraph 4.5.5.1. Increase radial load to design ultimate value of 59,600 lb per MIL-W-5013 H, Paragraph 4.5.5.2.

(c) Apply side load at a radius of 10.2 in. from the axle to yield load of 13,320 lb followed by ultimate load of 20,000 lb.

(2) Dynamometer Slow Roll - Maintain wheel speed of 4-6 mph and apply a radial load of 8200 lb for a minimum rolling distance of 1500 miles. The wheel will be periodically disassembled and inspected for structural damage during the test. Continue test until wheel failure occurs or is imminent.

(3) Dynamometer Braking Tests for Normal and Overload Stops:

(a) One-hundred brake stops of 2.35×10^6 ft-lb K.E. at 10 ft/sec^2 deceleration.

(b) Apply tangential load of 9800 lb at rolling radius of the tire (11.2 in.).

(c) Three brake stops of 2.94×10^6 ft-lb K.E. at 10 ft/sec^2 deceleration.

Brake temperatures for 2.94×10^6 ft-lb kinetic energy obtained from dynamometer tests performed on the production aluminum wheel by the Air Force Flight Dynamics Laboratory are plotted as a function of time in Figure 2.

Theoretical prediction of the temperature response at critical areas in the metallic wheel was also supplied by AFFDL. Maximum wheel temperatures were predicted for the design conditions,

18,000 lb gross weight aircraft
1/2 worn brake
5 mph wind
100° F ambient temperature
4.329×10^6 ft-lb kinetic energy
8.1% tire drag

and are plotted as a function of time in Figure 3.

The critical design mechanical static loads on the T-39 wheel specified in USAF Drawing 59F15, entitled "Wheel and Brake, 26 x 6.6 Type III, Assembly Of", are:

Ultimate radial load = 59,600 lb
Ultimate side load = 20,000 lb

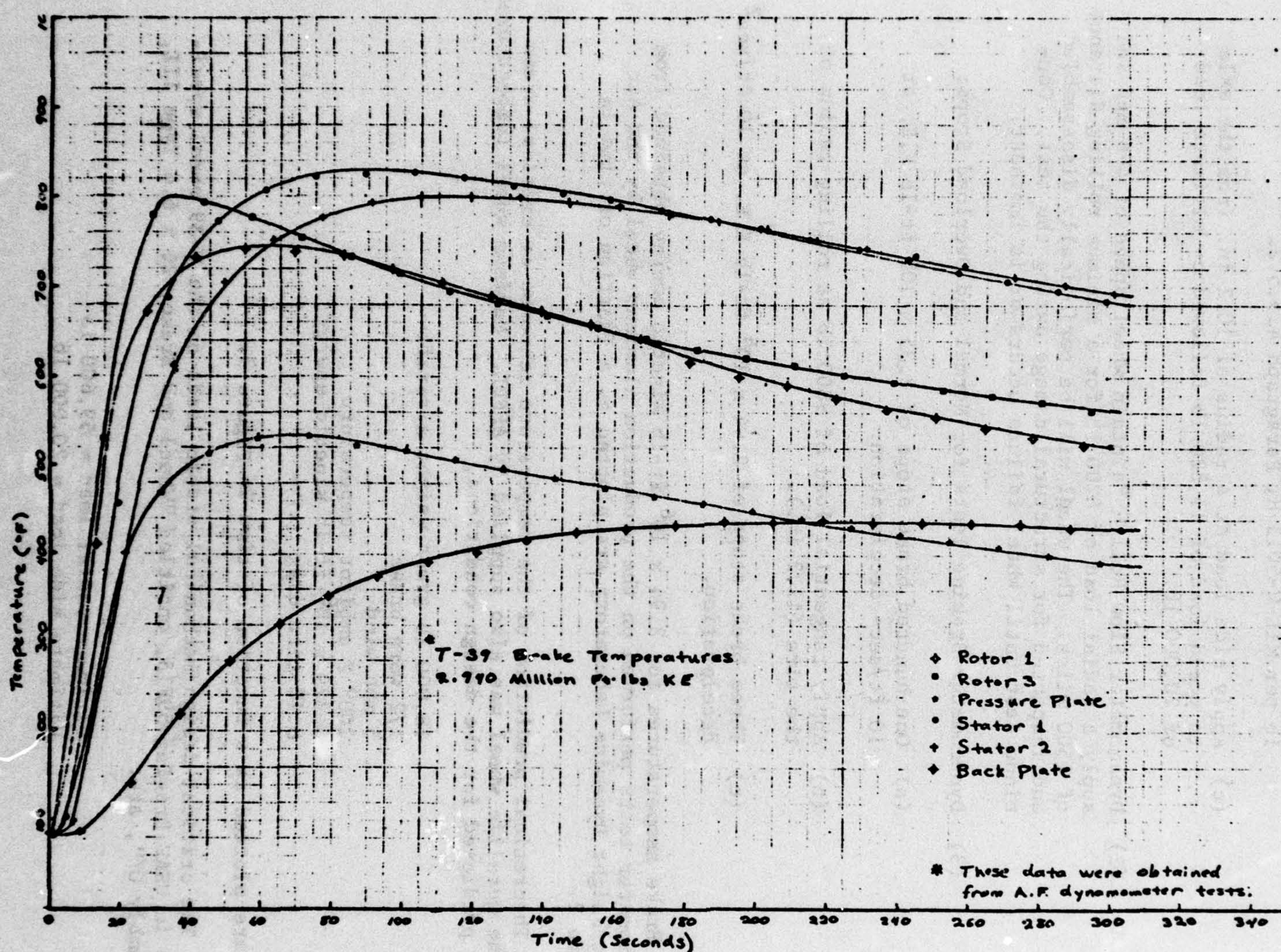


Figure 2. T-39 Measured Brake Temperatures from Air Force Dynamometer Tests

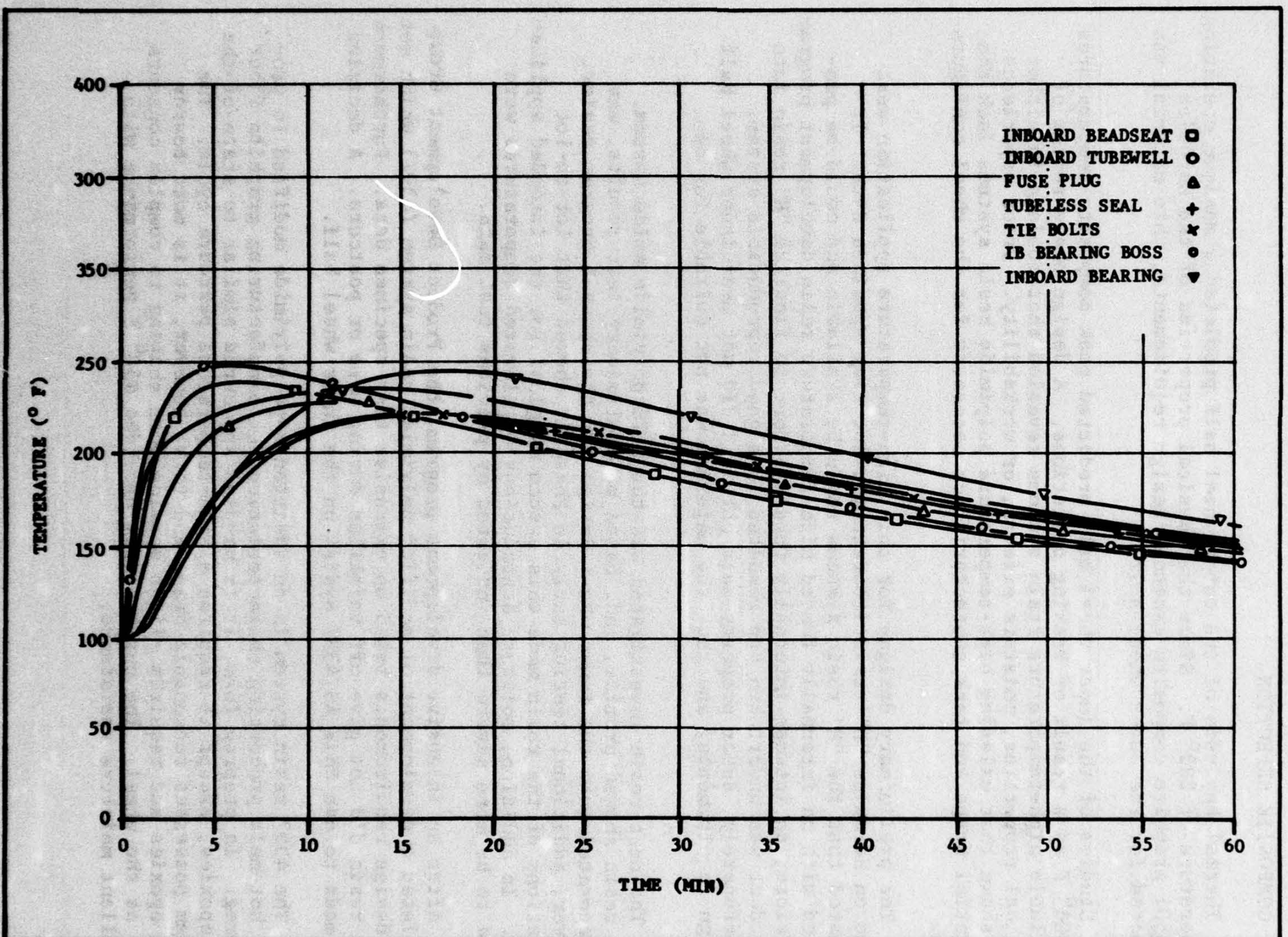


Figure 3. Predicted Temperature Response in Metallic Wheel

Applied at a radius of 10.2 in.

Minimum burst pressure = 735 psi

C. COMPOSITE SELECTION

Thermal analysis of the outer wheel half predicted a maximum operating temperature of 223° F. Since the physical properties of the Hercules AS/3501 graphite composite exceeded design requirements, this material was selected for the outer wheel half.

Studies of the inner wheel half predicted peak composite temperatures of 406° F as a result of braking operations. A design phase review of available high-temperature resin systems revealed shortcomings in either physical properties, moisture effects, or workability. Prior experience has shown that existing high-temperature polyimide resin systems lack the essential drape and tack characteristics necessary for the wheel configuration.

The preliminary designs for this high-temperature application were based on Hercules "H" resin laboratory/pilot line specimen data. It appeared that the "H" resin systems would be available and could be processed with an internally funded high-temperature resin development program. Therefore, an intense internally funded effort to finalize "H" resin into a product was undertaken and resulted in a good reproducible system. Unfortunately, shear property data obtained did not meet inner wheel half design requirements, and thus the material was not suitable for use.

The next resin investigated was the F178 polyimide amide system. This resin showed promise, and, based on preliminary test results, was incorporated into the inner wheel design for the Phase I program review. However, additional testing early in Phase II showed that lot-to-lot variations of the resin made this system marginal for the intended application. In addition, moisture degradations at elevated temperatures were found to be more severe than indicated by previous test data.

After an intensive development program, the Product Development Group completed a development of modified polyimide resin system (4397) which met all design requirements based on extensive test specimen data. Furthermore, this resin did not give off volatiles during cure or postcure. A decision was made to use this AS/4397 system on the inner wheel half.

The 4397 resin system is an addition-type polyimide modified to provide hot-melt processing characteristics for manufacturing graphite fiber prepreg. In prepreg form, it is handled and cured similar to state-of-the-art epoxies, except it requires a high-temperature postcure cycle. The system possesses reasonable drape and tack; however, it is more boardy than epoxies and requires slight warming when shaping to complex contours such as the wheel. The cured system provides 450° F performance with excellent moisture resistance.

D. MATERIAL PROPERTIES

Graphite composite lamina properties used in the design and analysis of the wheel are summarized in Tables 1 and 2. For the composite layup of ($0_2 \pm 45$, 90), the "A" allowables, laminate properties are summarized in Tables 3 and 4. Thermal properties are defined in Table 5. The brake keys are machined from 4130 steel and heat treated to a Rockwell hardness of 39 to 41 C, resulting in a tensile strength of 182,000 to 190,000 psi. Properties for this strength were taken from MIL-HDBK-5.

The valve adapter and brake key screws are also 4130 steel alloy, and their properties were based on values given in MIL-HDBK-5.

E. DETAILED DESIGN ANALYSIS

The proposed graphite composite wheel configuration design does not vary significantly from that of the metal wheel. Sharp corners were removed, smooth transitions for graphite fibers were provided, and wall thicknesses were increased to accommodate high shear stresses. The design envelope was not exceeded for the composite configuration.

Basic tire/wheel assembly dimensions for the metal wheel are specified in Figure 4.

1. Thermal Analysis

The basic wheel/brake assembly configuration was modeled for computer analysis as shown in Figure 5. Using measured thermocouple data for the aluminum wheel defined in Paragraph B, above, time-dependent heat load was defined. Heat flux was applied to the brake with heat entering the wheel by conduction through the brake keys and bearings on the wheel and by convection and radiation from the brake.

The HETRAN II computer program utilized a 2-D symmetric grid which closely approximated a 3-D geometry. Time-dependent heat flux was varied in the analysis of the aluminum wheel until the computed temperatures agreed with experimentally measured values. Computed temperature distributions in the aluminum wheel at 5, 10, and 15 minutes are shown in Figures 6, 7, and 8, respectively, for kinetic energy load of 4.329×10^6 ft-lb. The heat flux for the normal condition of 2.35×10^6 ft-lb kinetic energy and the overload condition of 2.94×10^6 ft-lb kinetic energy are proportioned directly to the heat flux for 4.329×10^6 ft-lb and are plotted as a function of time in Figure 9.

Using the heat flux for the normal condition and overload condition, temperature distributions in the graphite composite wheel were computed. Thermal properties for the graphite composite were specified in Table 5.

TABLE 1

LAMINA PROPERTIES FOR 4397/AS GRAPHITE COMPOSITE

	Dry			Severe Moisture		
	77° F	400° F	450° F	77° F	400° F	450° F
Elastic Constants						
0° Tensile Modulus (E_{11_T}), msi	19.8	19.8	19.8	19.7	19.7	19.5
0° Compressive Modulus (E_{11_C}), msi	16.0	16.0	15.5	15.8	15.8	15.0
90° Tensile Modulus (E_{22_T}), msi	1.3	1.0	0.9	1.3	1.0	0.9
90° Compressive Modulus (E_{22_C}), msi	1.6	1.4	1.3	1.5	1.2	1.0
Shear Modulus (G_{12}), msi	0.65	0.58	0.55	0.65	0.58	0.55
Poisson's Ratio (ν_{12})	0.25	0.25	0.25	0.25	0.25	0.25
Thermal Coefficients						
0° (α_{11}), 10^{-6} in./in./°F	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2
90° (α_{22}), 10^{-6} in./in./°F	13.0	13.0	13.0	13.0	13.0	13.0
Ultimate Strains						
0° Tensile (ϵ_{11_T}), in./in.	0.0115	0.0115	0.0109	0.0110	0.0107	0.0103
0° Compressive (ϵ_{11_T}), in./in.	-0.0100	-0.0091	-0.0087	-0.0098	-0.0079	-0.0077
90° Tensile (ϵ_{22_T}), in./in.	0.00369	0.0040	0.0042	0.0035	0.0038	0.0042
90° Compressive (ϵ_{22_T}), in./in.	-0.0100	-0.0100	-0.0100	-0.0100	-0.0100	-0.0100
In-plane Shear (γ_{12}), in./in.	±0.0100	±0.0100	±0.0100	±0.0100	±0.0100	±0.0100
Ultimate Strengths						
0° Tensile (σ_{11_T}), ksi	227	227	215	216	210	200
0° Compressive (σ_{11_T}), ksi	160	145	135	155	125	115
90° Tensile (σ_{22_T}), ksi	4.8	4.0	3.8	4.6	3.8	3.6
90° Compressive (σ_{22_T}), ksi	30.0	25.0	22.0	28.0	22.0	19.0
In-plane Shear (τ_{12}), ksi	14.7	9.4	7.4	12.9	7.8	6.3
Other						
0° Flexural Strength, ksi	259	188	161	258	162	119
0° Flexural Modulus, msi	17.6	17.7	17.9	17.4	17.7	16.7
SBS Strength, ksi	14.7	9.4	7.4	12.9	7.8	6.3

TABLE 2

LAMINA PROPERTIES FOR 3501/AS GRAPHITE COMPOSITE

	Dry			Severe Moisture		
	77° F	175° F	200° F	77° F	175° F	200° F
Elastic Constants						
0° Tensile Modulus (E_{11_T}), msi	20.4	20.4	20.4	20.4	20.4	20.4
0° Compression Modulus (E_{11C}), msi	16.0	16.8	17.0	15.2	15.7	15.9
90° Tensile Modulus (E_{22T}), msi	1.46	1.28	1.2	1.38	1.20	1.12
90° Compression Modulus (E_{22C}), msi	1.5	1.40	1.35	1.43	1.31	1.28
Shear Modulus (μ_{12}), msi	0.65	0.61	0.60	0.65	0.58	0.55
Thermal Expansion Coefficients						
0° Coefficient (α_{11}), in./in./$^\circ$F x 10^{-6}	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2
90° Coefficient (α_{22}), in./in./$^\circ$F x 10^{-6}	13.0	13.0	13.0	13.0	13.0	13.0
Ultimate Strains						
0° Tensile (ϵ_{11_T}), %	1.15	1.13	1.13	1.13	1.13	1.13
0° Compression (ϵ_{11C}), %	1.44	0.85	0.81	0.92	0.75	0.72
90° Tensile (ϵ_{22_T}), %	0.64	0.57	0.56	0.60	0.50	0.50
90° Compression (ϵ_{22C}), %	2.33	2.14	2.00	2.22	1.88	1.74
Ultimate Strength						
0° Tensile (σ_{11_T}), ksi	230.5	230.5	230.5	230.5	230.5	230.5
0° Compression (σ_{11C}), ksi	154.0	143.0	138.0	140.0	117.0	114.0
90° Tensile (σ_{22_T}), ksi	9.2	7.3	6.7	8.4	6.0	5.5
90° Compression (σ_{22C}), ksi	35.0	30.0	27.0	31.8	24.6	22.3
In-Plant Shear (σ_{12}), ksi	16.1	12.5	11.6	14.1	9.6	8.9
Other						
0° Flex Strength, ksi	261.8	239.5	225	238.2	196.3	185.8
0° Flex Modulus, msi	18.1	18.0	17.9	17.2	16.9	16.8
SBS Strength, ksi	16.1	12.5	11.6	14.1	9.6	8.9

TABLE 3

CALCULATED 4397/AS LAMINATED PROPERTIES

$[0_2, \pm 45, 90]$ GEOMETRY

	Dry		Severe Moisture	
	77° F	400° F	77° F	400° F
Elastic Constants				
E_x, msi	10.010	9.888	9.964	9.841
E_y, msi	6.521	6.341	6.493	6.313
ν	0.305	0.305	0.305	0.305
G_{xy}, msi	2.443	2.384	2.433	2.374
Thermal Coefficients				
α_x, 10^{-6} in./in./°F	0.379	0.251	0.382	0.253
α_y, 10^{-6} in./in./°F	1.361	1.037	1.367	1.043
Ultimate Strengths				
S_x Tensile, psi	36,875	39,550	34,870	37,400
S_y Tensile, psi	24,017	25,360	22,720	23,990
S_x Compressive, psi	-76,694	-75,780	-76,340	-75,430
S_y Compressive, psi	-57,603	-53,040	-54,160	-49,870
Interlaminar Shear, psi	18,002	19,080	17,030	18,050

TABLE 4

CALCULATED 3501/AS GRAPHITE COMPOSITE LAMINATE PROPERTIES

$[0_2, \pm45, 90]$ GEOMETRY

	Dry			Severe Moisture		
	RT	175° F	200° F	RT	175° F	200° F
Elastic Constants						
E_x, msi	10.33	10.26	10.23	10.31	10.22	10.18
E_y, msi	6.76	6.66	6.61	6.73	6.60	6.55
ν	0.309	0.309	0.308	0.308	0.309	0.310
G_{xy}, msi	2.51	2.48	2.47	2.51	2.46	2.43
Thermal Coefficients						
α_x, 10^{-6} in./in./°F	0.425	0.352	0.320	0.394	0.319	0.285
α_y, 10^{-6} in./in./°F	1.485	1.303	1.220	1.404	1.221	1.137
Ultimate Strenghts						
σ_x Tensile, psi	66,110	58,470	57,300	61,860	51,090	50,890
σ_y Tensile, psi	43,280	37,940	37,040	40,360	33,010	32,740
σ_x Compressive, psi	-78,920	-78,390	-78,230	-78,850	-76,630	-73,280
σ_y Compressive, psi	-56,250	-55,460	-53,570	-56,020	-49,510	-47,140
Interlaminar Shear, psi	25,120	24,780	24,680	25,080	24,560	24,330

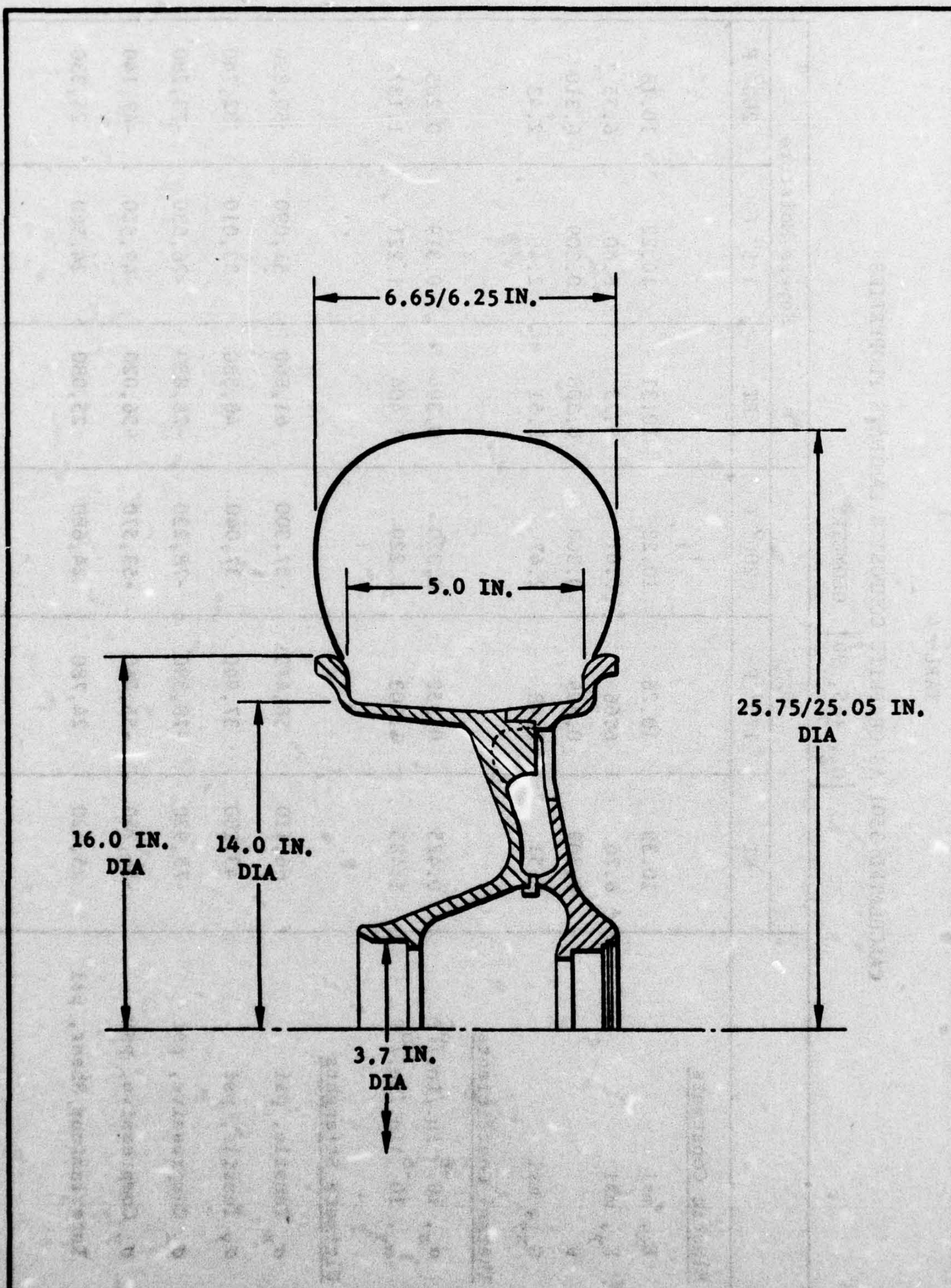


Figure 4. Configuration of the T39 Metal Wheel/Tire

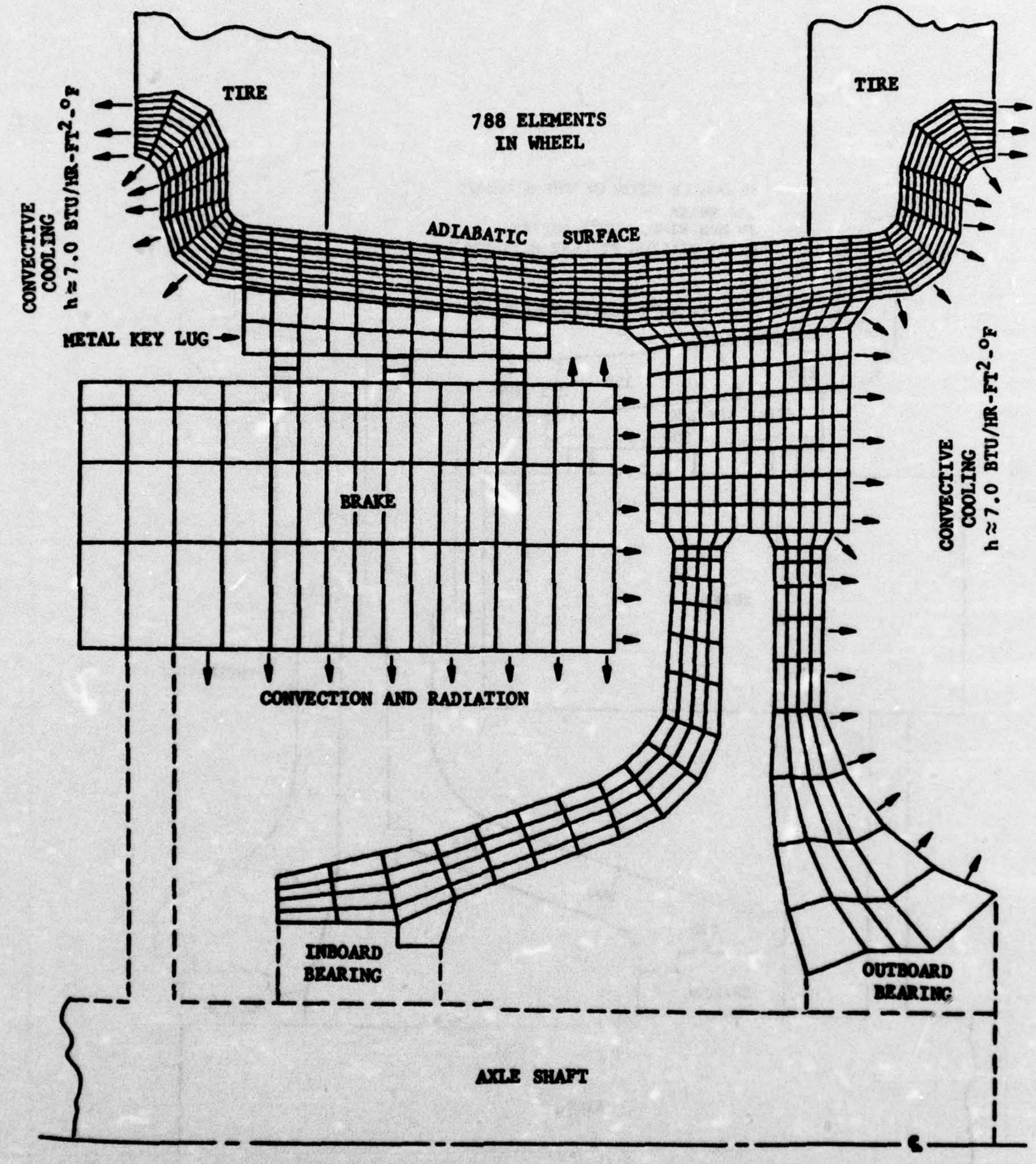


Figure 5. Grid Used for Heat-Transfer Analysis of T39 Graphite Composite Airplane Wheel

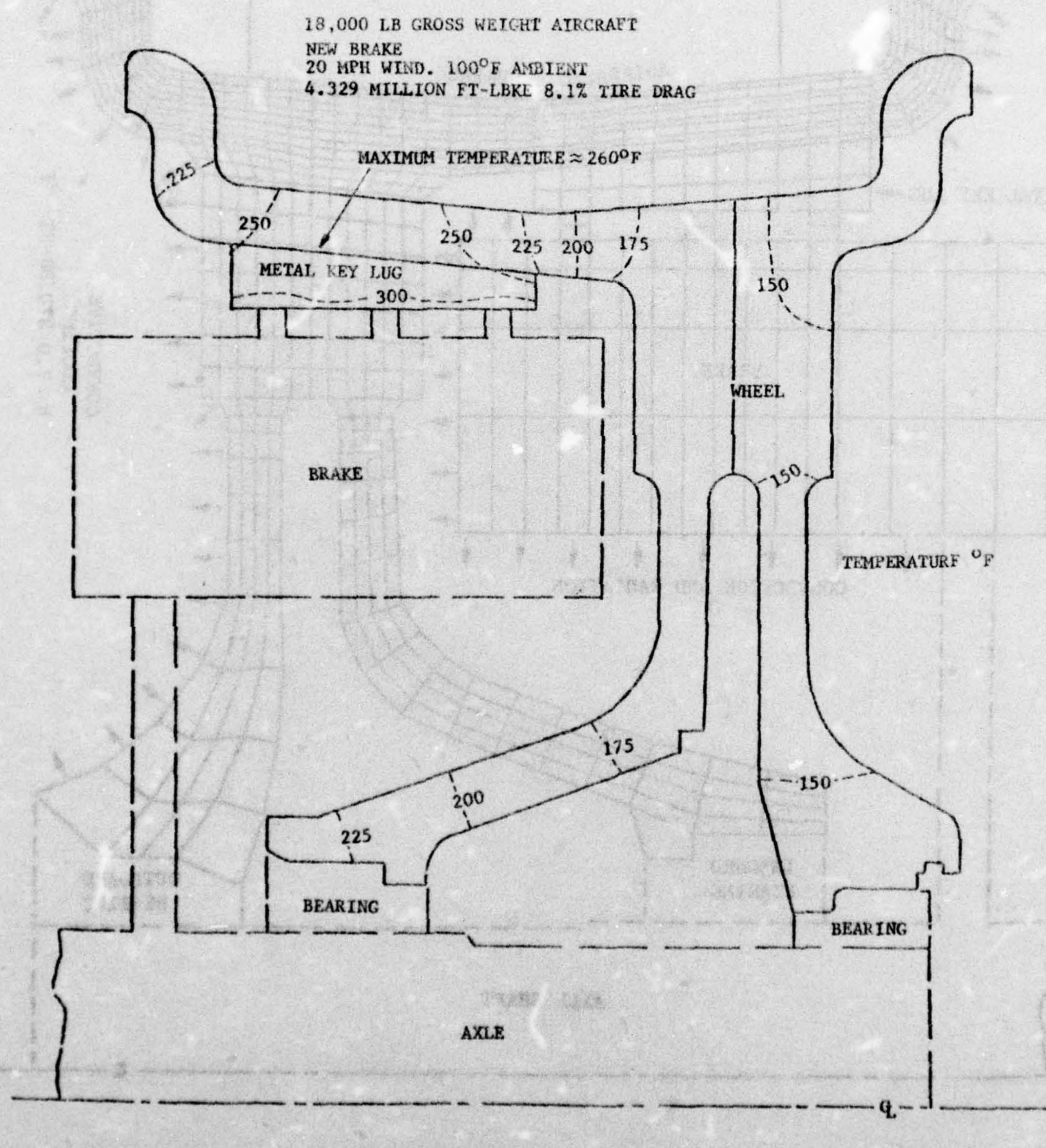


Figure 6. Aluminum T39 Airplane Wheel at 5 Minutes Under 4.329 x 10^6 ft-lb K.E. Load

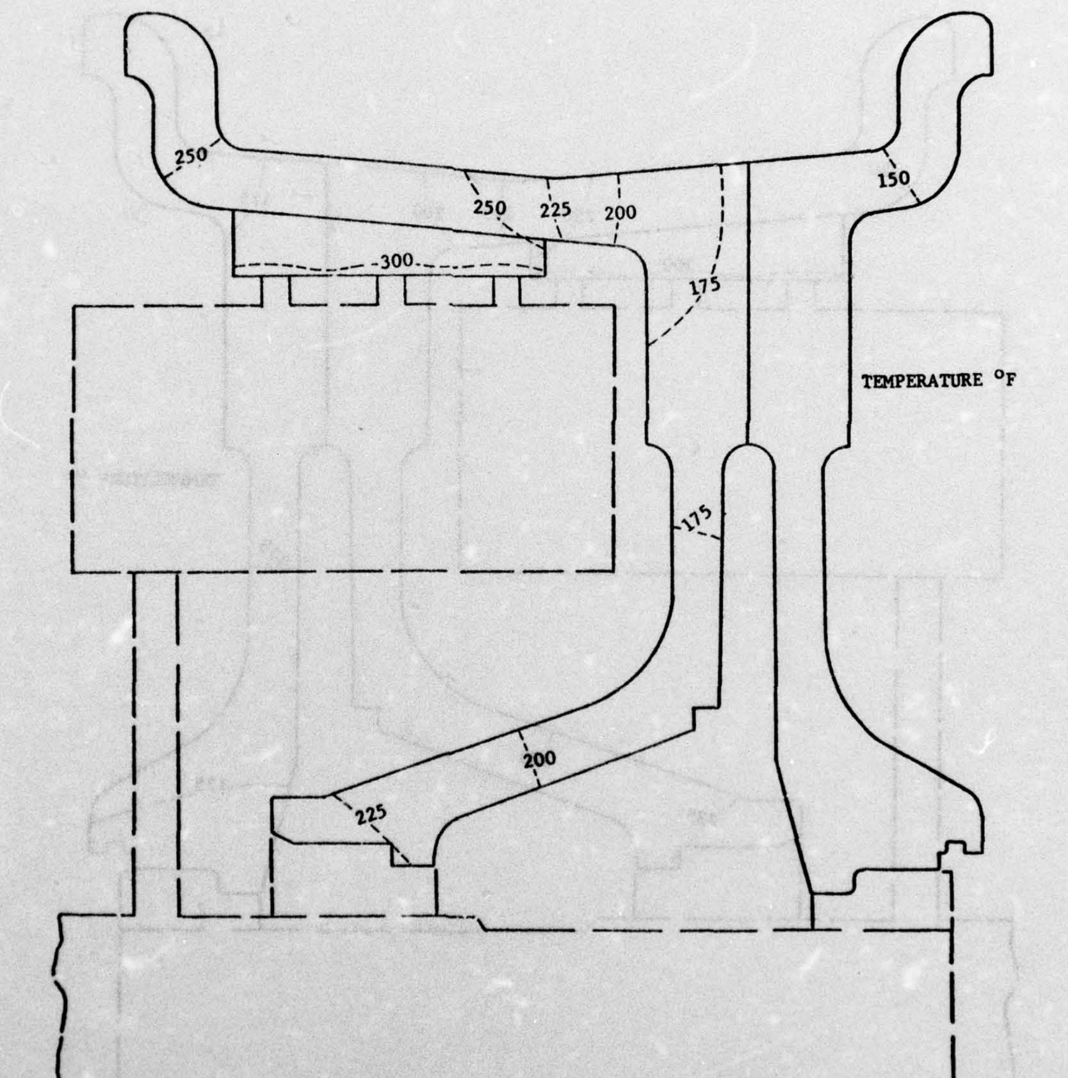


Figure 7. Aluminum T39 Airplane Wheel at 10 Minutes Under 4.329×10^6 FT-LB K.E. Load

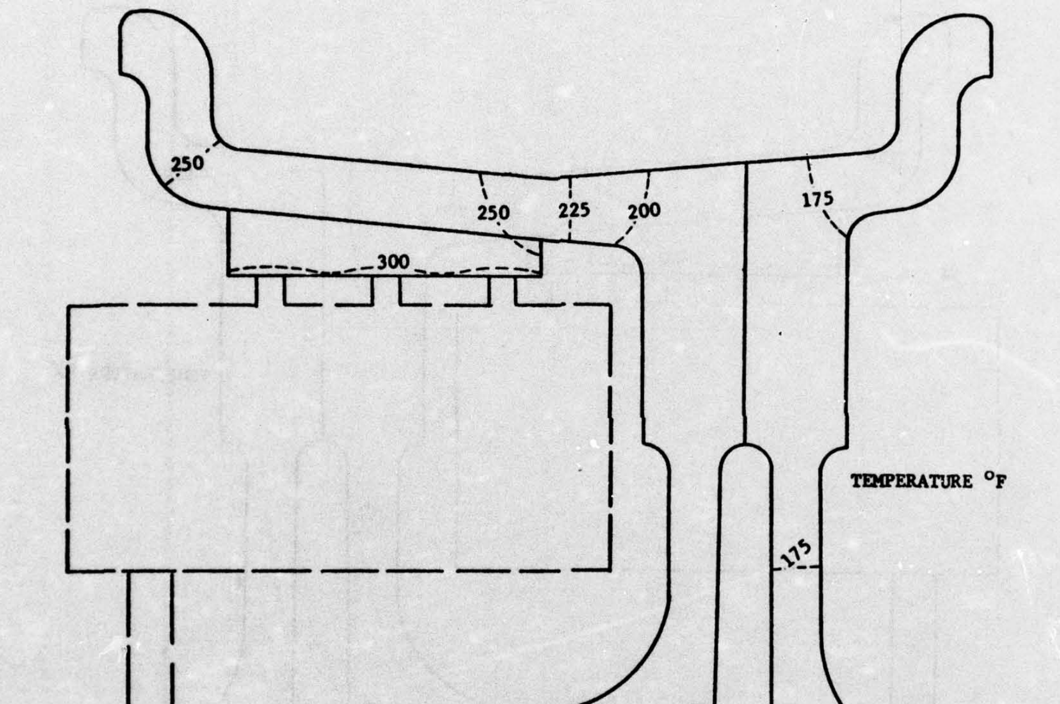


Figure 8. Aluminum T39 Airplane Wheel at 15 Minutes Under 4.329 x 10^6 FT-LB K.E. Load

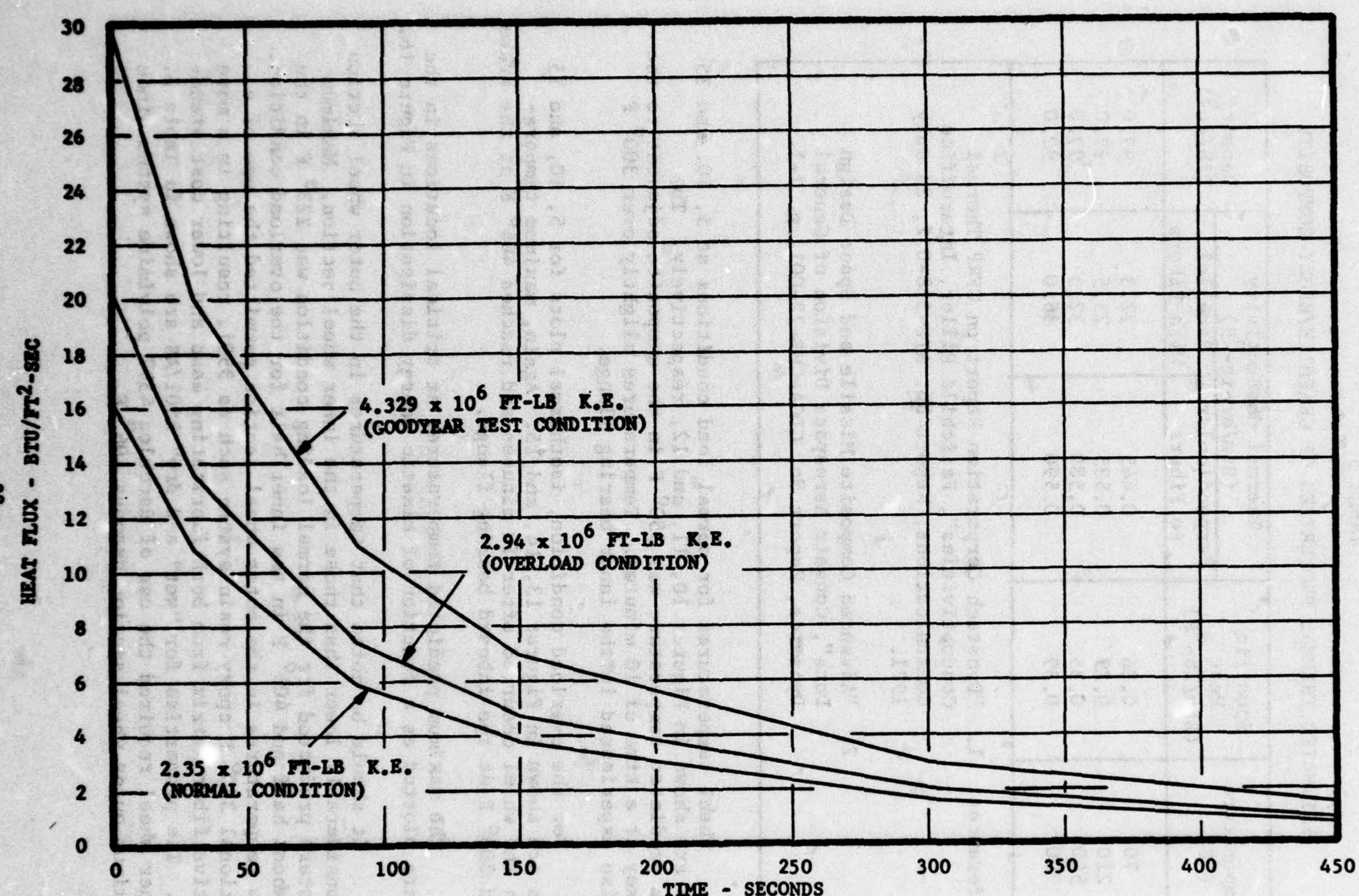


Figure 9. Calculated Heat Fluxes Applied to the Brake of the T39 Airplane Wheel Under Simulated Braking Conditions

TABLE 5

ESTIMATED THERMAL PROPERTIES OF GRAPHITE/EPOXY COMPOSITE

Temperature (°F)	Specific Heat (Btu/lb-°F)	Thermal Conductivity (Btu/hr-ft-°F)		Density (lb/ft³)
		Perpendicular to Fibers	Parallel With Fibers	
70	0.26	0.445	22.3	97.0
210	0.29	0.535	25.5	97.0
500	0.35	0.580	32.3	97.0
700	0.39	0.590	36.0	92.0

References:
1. "Dynatech Corporation Report on GFRP Thermal Conductivities", Fairchild Hiller, Interoffice Communications, Report No. ATS-318-072, 23 July 1971.
2. "Advanced Composite Missile and Space Design Data", Convair Aerospace Division of General Dynamics, Report No. GDCA-CHB-72-001, p. 7-1.

Wheel temperatures for normal load conditions at 5, 10, and 15 minutes are shown in Figures 10, 11, and 12, respectively. The maximum predicted temperature was 350° F in the composite adjacent to the brake key at a time of 10 minutes. Temperatures slightly over 300° F were also experienced in the inner bearing flange.

For the overload condition, isothermal plots for 5, 10, and 15 minutes are shown in Figures 13, 14, and 15. Again, maximum temperature in the wheel occurred after 10 minutes and reached 406° F at the brake key and 305° F at the inboard bearing flange.

The maximum predicted temperatures at critical locations in the wheel are plotted as a function of kinetic energy dissipation in Figure 16.

It should be noted that temperatures in the outer wheel section were considerably lower than those in the inner wheel section. Maximum temperature predicted for the normal loading condition was 223° F in the outer wheel half and 406° F in the inner half for the overload condition. The low temperatures in the outer wheel section permitted the use of a conventional 350° F epoxy resin system such as 3501, resulting in a more attractive fiber matrix from both fabricating ease and lower cost standpoints. The properties for "wet" and dry" 3501/AS are shown in Table 2. The inner wheel required the use of Hercules 4397 polyimide system since the maximum outer wheel section reaches 406° F.

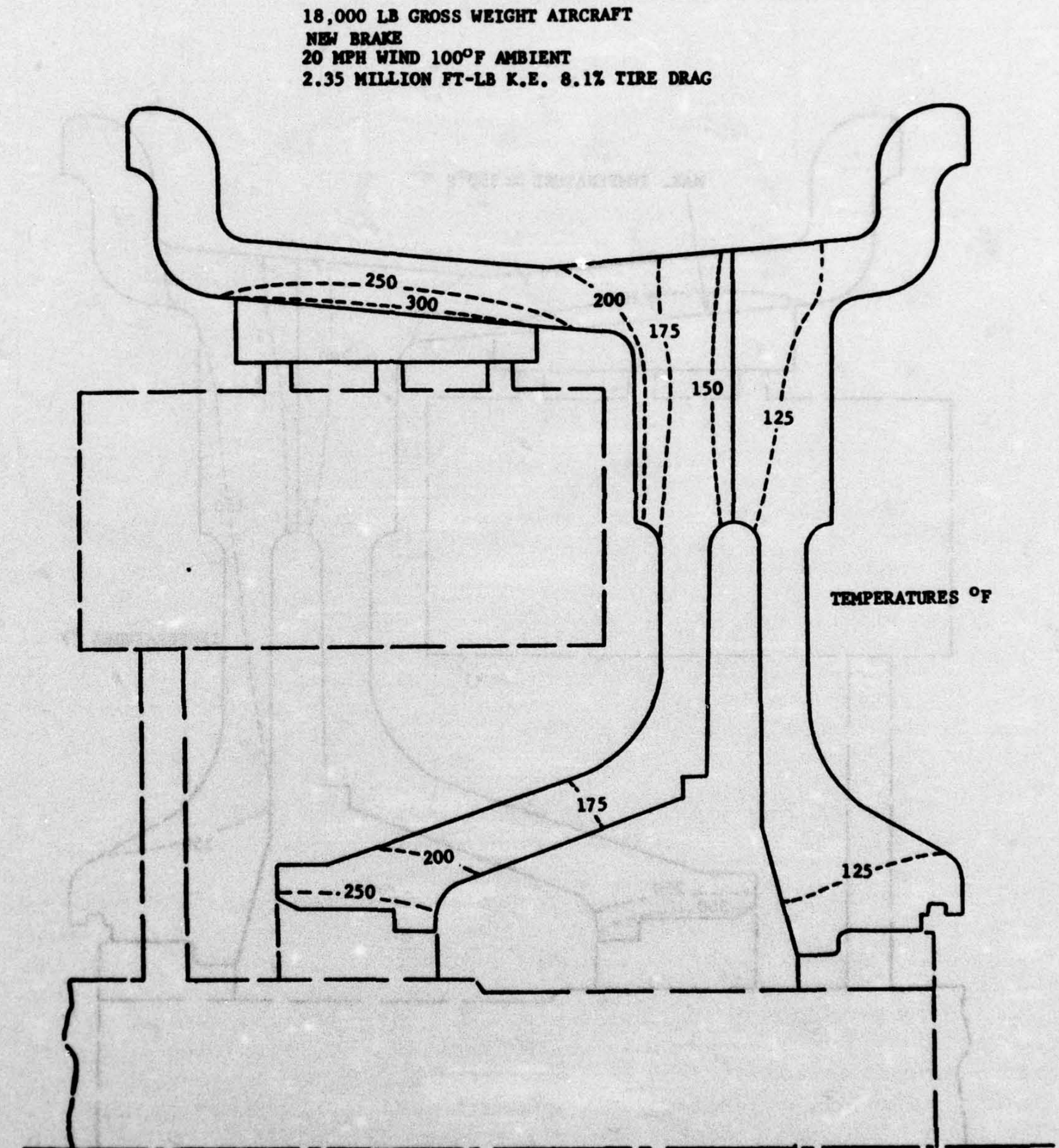


Figure 10. T39 Graphite Composite Airplane Wheel at 5 Minutes Under 2.35 x 10^6 FT-LB K.E. Load

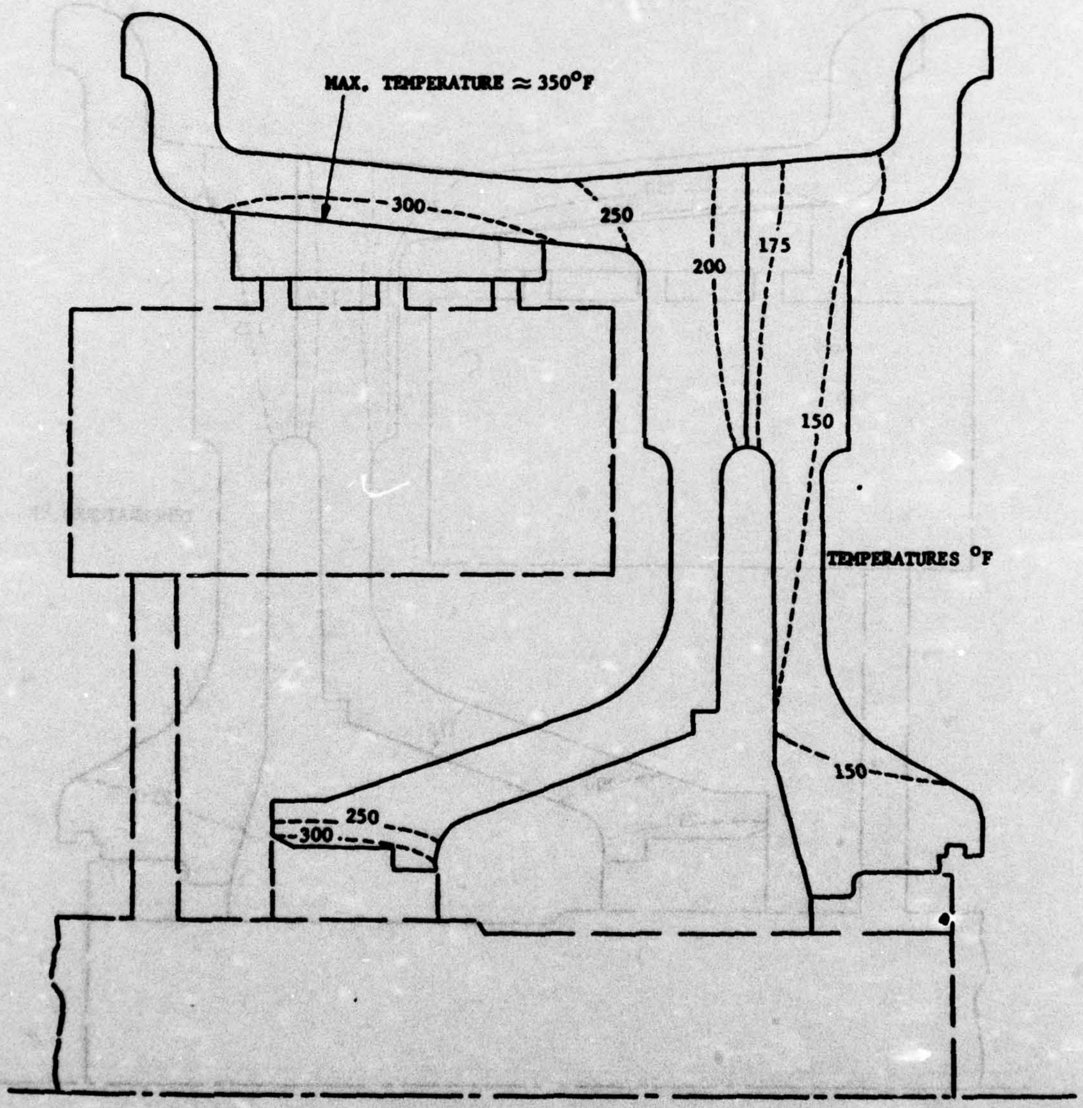


Figure 11. Graphite Composite Airplane Wheel at 10 Minutes Under 2.33 x 10^6 FT-LB K.E. Load

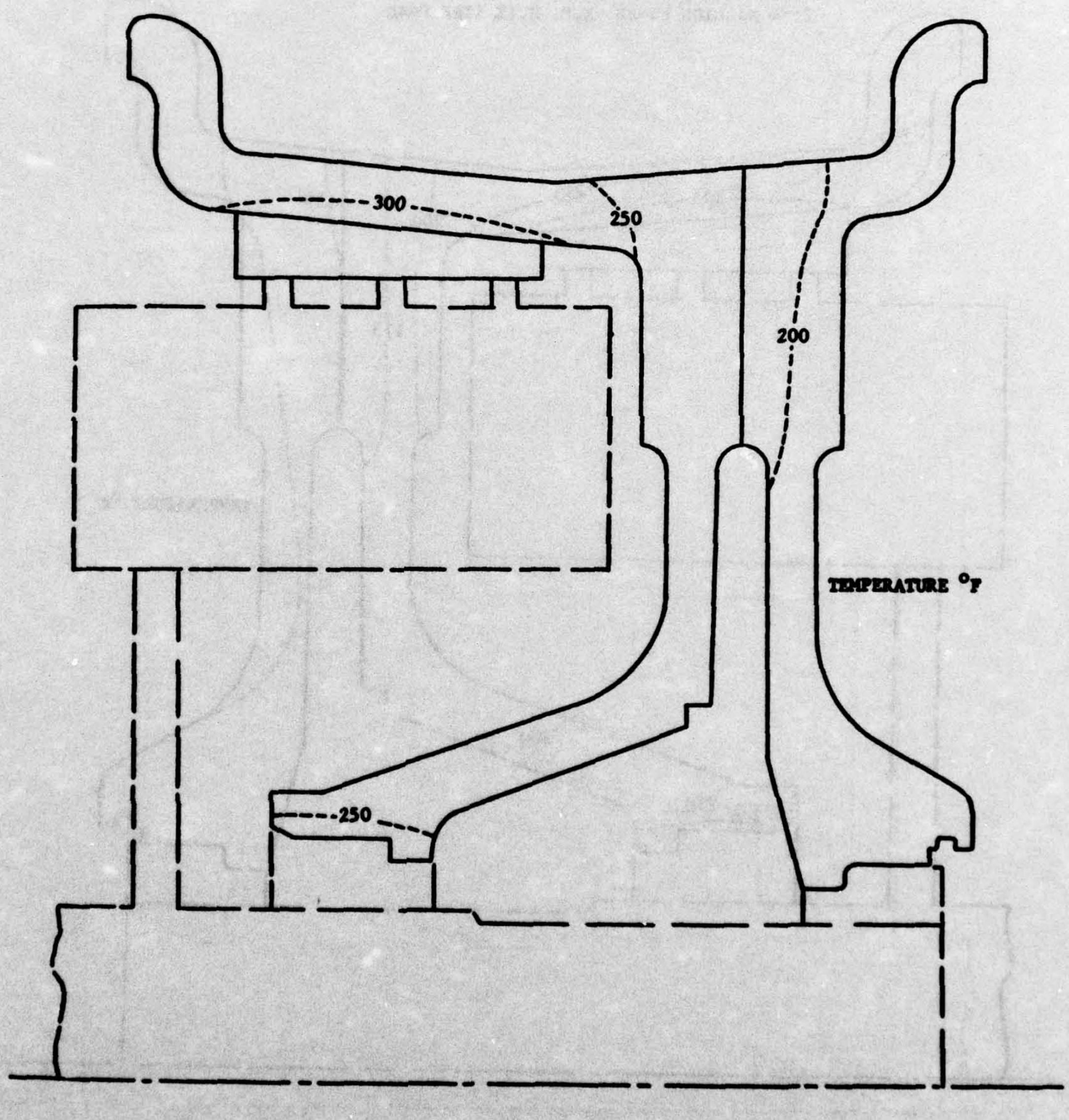


Figure 12. T39 Graphite Composite Airplane Wheel at 15 Minutes Under 2.35×10^6 FT-LB K.E. Load

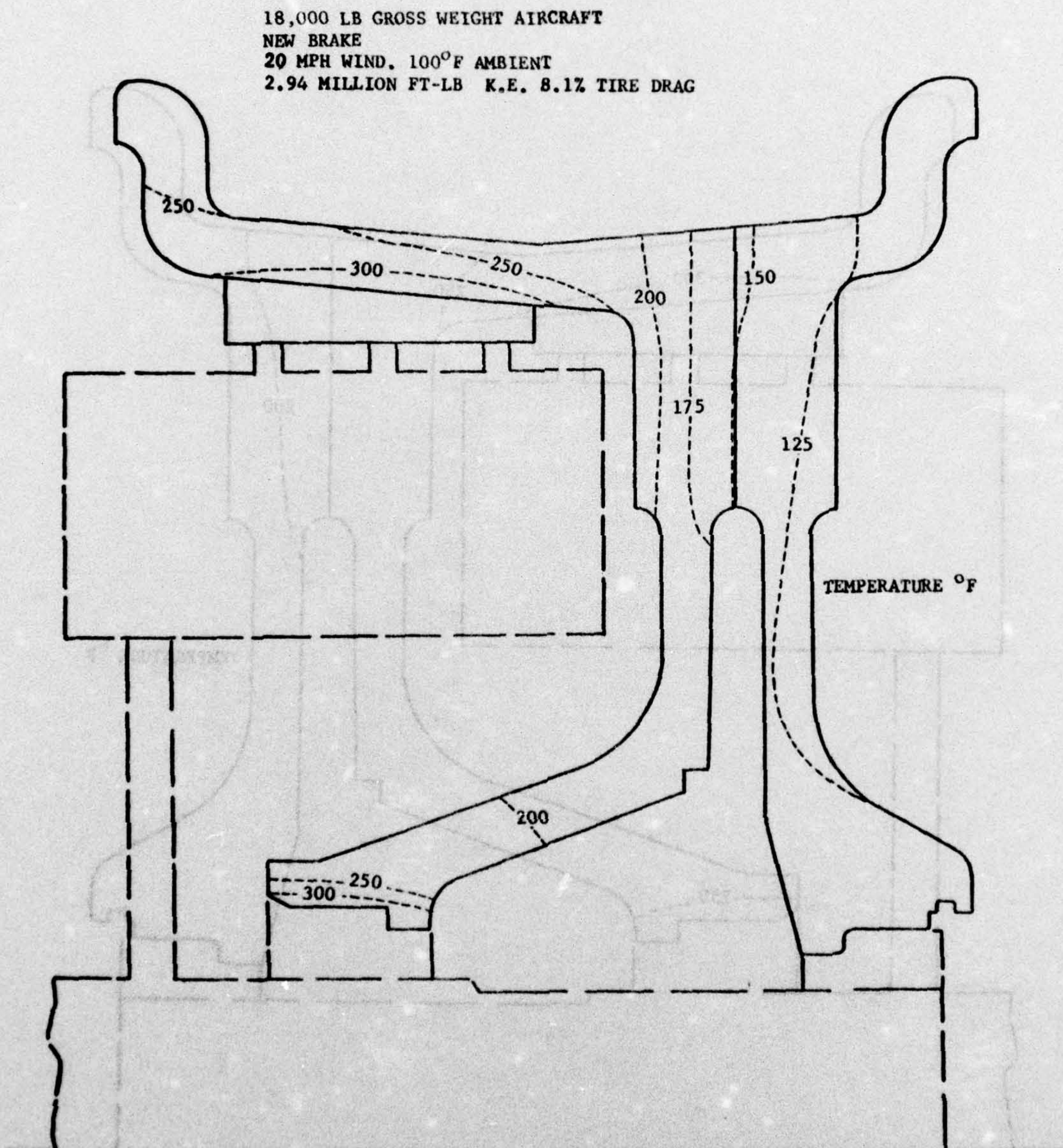


Figure 13. T39 Graphite Composite Airplane Wheel at 5 Minutes Under 2.94×10^6 FT-LB K.E. Load

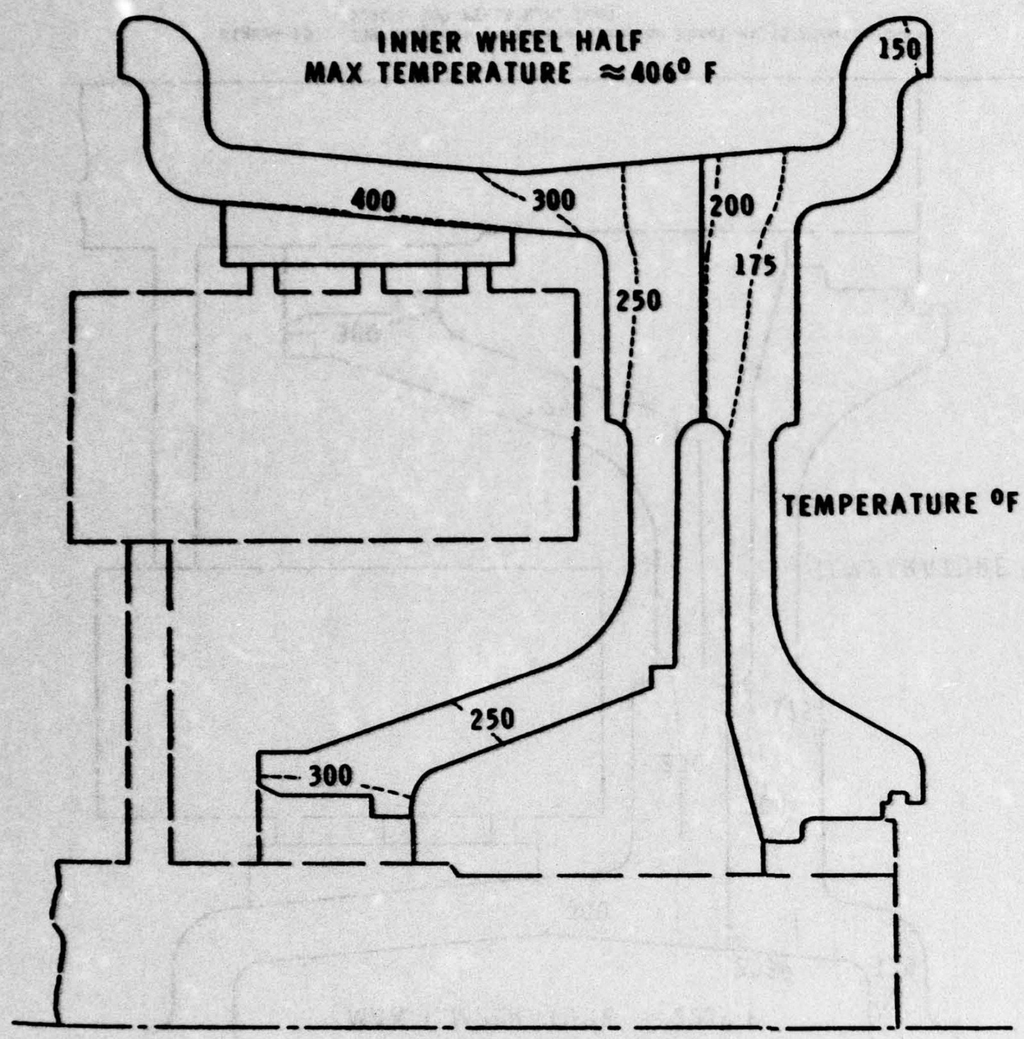


Figure 14. T-39 Graphite Composite Aircraft Wheel Temperature 10 Minutes After Application of 2.94 x 10^6 ft-lb K. E. Braking Load

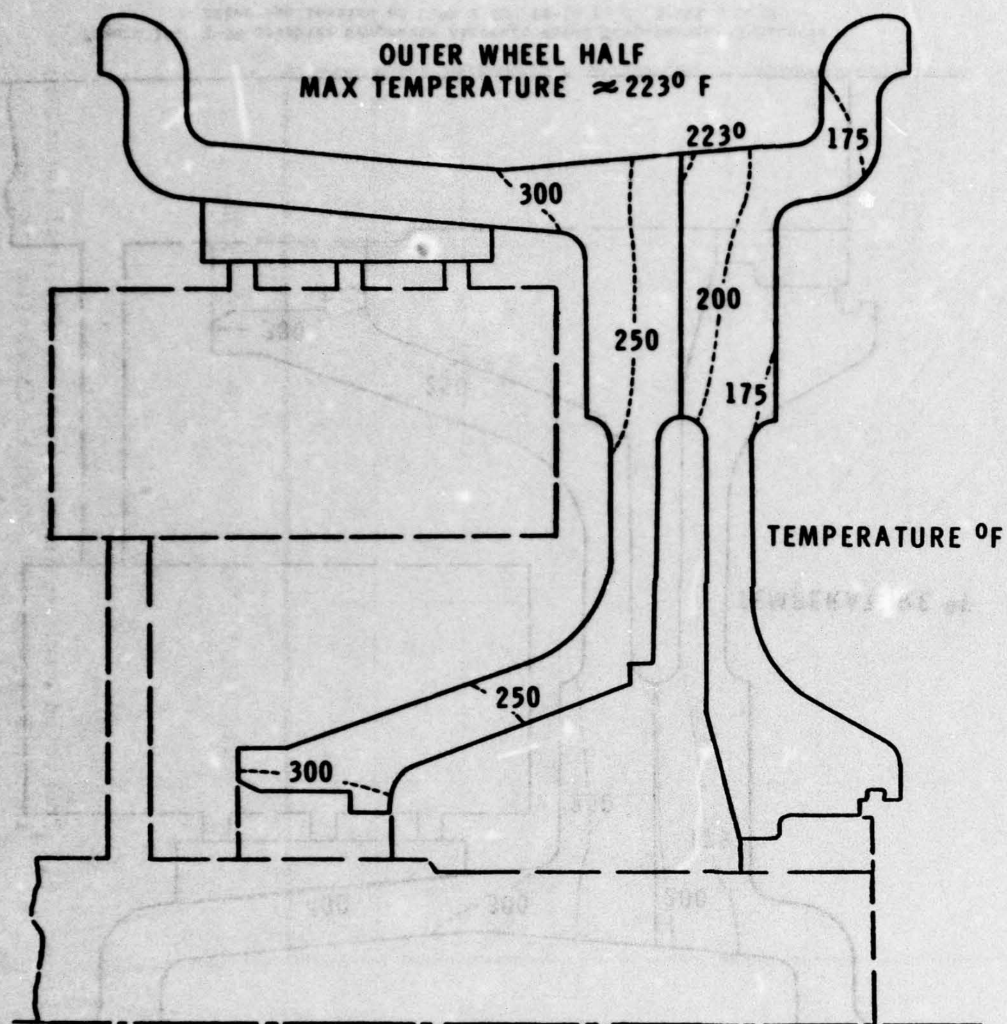


Figure 15. T39 Graphite Composite Airplane Wheel at 15 Minutes Under 2.94×10^6 FT-LB K.E. Load

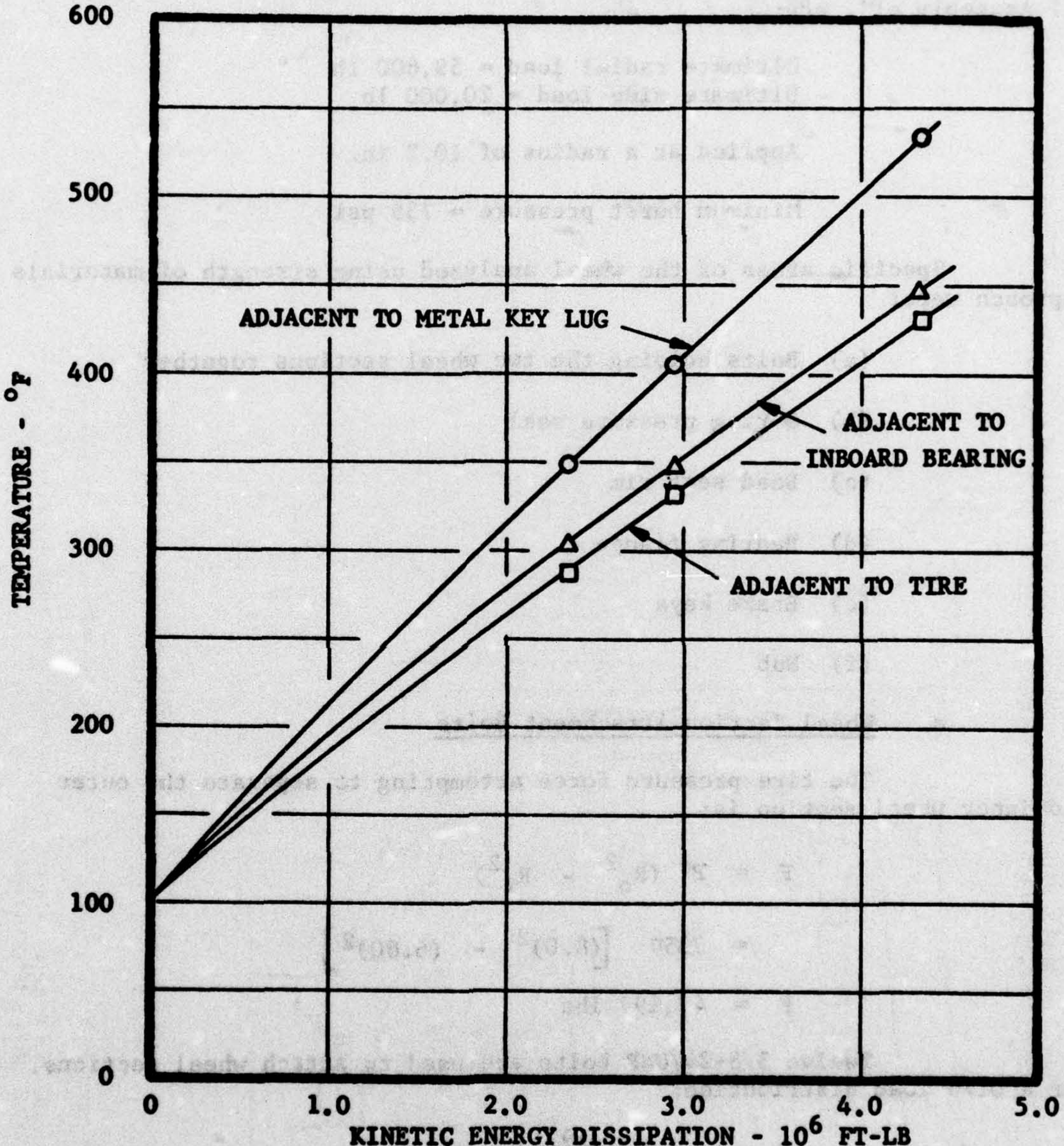


Figure 16. **Predicted Maximum Temperatures at Critical Locations in the Proposed T39 Graphite Composite Airplane Wheel**

2. Mechanical Analysis

The critical design mechanical static loads on the T-39 wheel specified in USAF Drawing 59F15, entitled "Wheel and Brake, 26 x 6.6 Type VII Assembly of", are:

Ultimate radial load = 59,600 lb
Ultimate side load = 20,000 lb

Applied at a radius of 10.2 in.

Minimum burst pressure = 735 psi

Specific areas of the wheel analyzed using strength of materials approach were:

(a) Bolts holding the two wheel sections together

(b) O-ring pressure seal

(c) Bead seat rim

(d) Bearing flange

(e) Brake keys

(f) Hub

a. Wheel Section Attachment Bolts

The tire pressure force attempting to separate the outer and inner wheel section is:

$$F = P\pi (R_o^2 - R_i^2)$$

$$= 735\pi \left[(8.0)^2 - (6.60)^2\right]$$

$$F = 47,197 \text{ lbs}$$

Twelve 3/8-24/UNF bolts are used to attach wheel sections. For a 0.75 load distribution:

$$F_{bolt} = \frac{47,197}{12 \times .75}$$

$$F_{bolt} = 5244 \text{ lbs}$$

$$\sigma_{bolt} = \frac{F}{A} = \frac{5244}{.0878}$$

$$\sigma_{bolt} = 59,728 \text{ psi} \qquad M.S. = +1.09$$

Bolt tightening preload of 300 in.-lb prestresses the bolt to:

$$f_{st} = \frac{16T}{\pi d3}$$

$$= \frac{16\ (300)}{\pi\ (.3344)^3}$$

$$f_{st} = 40{,}877 \text{ psi}$$

$$F_{bolt} = f_{st}\ A$$

$$= 40{,}877\ (.0878)$$

$$F_{bolt} = 3589 \text{ lbs}$$

It is recommended that bolt be preloaded to 90 percent of mechanical load.

$$T = \frac{.9\ (5244)}{3589} \times 300$$

$$T = 395 \text{ in-lb}$$

Washer bearing stress on the composite was:

$$\sigma_{br} = \frac{F}{\pi\ (R_o^2 - R_i^2)} \qquad R_o = 0.370 \text{ in.}$$

$$R_i = 0.190 \text{ in.}$$

$$= \frac{5244}{\pi\ [(.370)^2 - (.190)^2]}$$

$$\sigma_{br} = 16{,}500 \text{ psi} \qquad M.S. = +.81$$

Separation gap between wheel sections is:

$$\delta = \frac{\sigma}{E} \ell$$

$$= \frac{59{,}728\ (1.34)}{29.0 \times 10^6}$$

$$\delta = 0.0028 \text{ in.}$$

b. **Wheel Section Pressure Sealing O-Ring**

Using a 0.139 in. cross section O-ring:

$$A_{\text{"O" ring}} = \frac{\pi}{4}(.139)^2$$

$$A_{\text{"O" ring}} = .015175 \text{ in.}^2$$

$$A_{groove} = .01655 \text{ in.}^2$$

"O" ring compression after wheel assembly is:

$$\% \text{ compression} = \left[\frac{.01655}{.01518} - 1\right] 100$$

$$\% \text{ compression} = 9\% \text{ nominal}$$

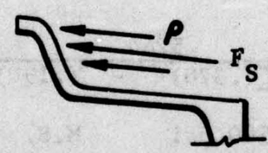
When tire is pressurized to p = 735 psi:

$$\% \text{ compression} = 8\%$$

Compression is adequate to maintain seal.

c. **Bead Seat Rim**

Combined internal pressure and side load forces on the bead seat rim result in a shear stress:



$$\tau t = \frac{3/2\, P\pi\, (R_o^2 - R_i^2)}{2\pi R} + \frac{Fs}{2r}$$

At ultimate design pressure, P = 735 psi (Fs = 0).

$$\tau t = \frac{735\pi\left[(9.95)^2 - (7.0)^2\right]}{2\pi\,(7.0)}$$

$$\tau t = 3937 \text{ lb/in.}$$

For an allowable shear strength,

$$Fs = 9800 \text{ psi @ } 175^{o} \text{ F in outer wheel section}$$

$$t_{required} = \frac{3937}{9800} = 0.40 \text{ in. minimum}$$

The maximum shear stress due to side load is developed from the expression,

$$F_s = 2\int_0^{\frac{\pi}{2}} rt\, \tau_{max} \cos\phi\, d\phi$$

$$= 2\tau_{max} rt$$

or,

$$\tau_{max} = \frac{F_s}{2rt}$$

$$= \frac{20000}{2\ (7.0)\ t} = \frac{1429}{t}$$

For an internal pressure of 210 psi:

$$\tau t = \frac{210}{735}\ (3937)$$

$$\tau t = 1125$$

Combining pressure and side load:

$$\tau t = 1429 + 1125$$

$$= 2554$$

Required thickness is:

$$t_{required} = \frac{2554}{9800} = 0.26 \text{ in.}$$

Ultimate internal pressure is critical condition requiring a wheel rim nominal thickness of 0.45 in.

Bending stress at the wheel rim for ultimate internal pressure is:

$$\sigma_b = \frac{F}{t} \pm \frac{6M}{t^2}$$

$$= \frac{3937}{.45} \pm \frac{6\ \frac{3937}{2}}{(.45)^2}$$

$$= 8748 \pm 58326$$

$$\max \sigma_b = 67{,}074 \text{ psi}$$

Under severe moisture environment F_b allow = 50,890 psi
M.S. = -.24

d. <u>Hub Bearing Flange</u>

The hoop thermal stress induced in the hub bearing flange due to expansion of bearing cup to achieve an interference fit was computed as follows:

At liquid nitrogen temperature for the cup:

ΔT = -320 to +75

ΔT = 395°F

Free hoop strain in cup is,

$$\epsilon_\theta = \alpha \Delta T$$

$$= 6 \times 10^{-6} (395)$$

$$\epsilon_\theta = .00237 \text{ in./in.}$$

Outer cup; R = 1.6732

Radial growth, $\Delta R = \epsilon_\theta R$ = .00237 (1.6732)

ΔR = .0040 in.

At - 320°F, R_{cup} = 1.669 in. R_{flange} = 1.665 in.

Inner cup; R = 1.8594

ΔR = .00237 (1.8594)

ΔR = .0044 in.

At - 320°F, R_{cup} = 1.855 in. R_{flange} = 1.850 in.

Induced thermal hoop stresses in the graphite flanges are:

Outer wheel section flange,

$$\sigma_\theta = .00474\ (6.66 \times 10^6)$$

σ_θ = 31,568 psi — Under severe moisture condition F_{tn} = 32,740 psi, M.S. = +.04

Inner wheel section flange,

$$\sigma_\theta = .0051\ (6.37 \times 10^6)$$

σ_θ = 32,487 psi — Under severe moisture condition F_{tu} = 23,990 psi, M.S. = -0.26

Shear stress on the outer bearing flange due to the 20,000-lb side load is,

$$\tau_{ave} = \frac{F}{dt} = \frac{20,000}{(3.33)\ (1.015)}$$

τ_{ave} = 1884 psi — Under severe moisture condition J_{allow} = 9800 psi, M.S. = +4.20

e. <u>Brake Keys</u>

The ultimate tangential load applied to the wheel brake keys is 17,515 pounds. Assuming this load is reacted by an effective area of 60 percent of the 12 brake keys, the design load per key is:

$$F/key = \frac{17515}{.6 \times 12}$$

$$F/key = 2433\ \text{lb}$$

Several configurations for the brake key to wheel attachment were considered and are summarized in Figure 17.

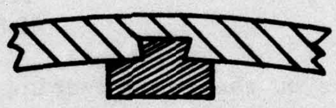
Concepts 1 and 2 utilized a steel key and required the machining of a groove in the wheel composite rim to react the braking load in bearing. High compressive stress due to rotation of key was considered a problem. Concept 3 was similar to 2 except key was lightened by substituting graphite for steel in the outer portion of the key.

CONCEPT | **CONFIGURATION** | **MERIT**

1. STEEL KEY BONDED IN COMPOSITE GROOVE

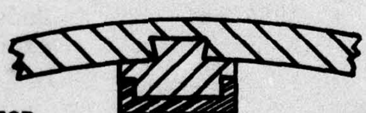
KEY EXPANDS AGAINST COMPOSITE AT ELEVATED TEMPERATURE
WT = 2.67 LB
σBR_{PAD} = 21,370 PSI
σBR_{COMP} = 5,380 PSI

2. SAME AS 1 EXCEPT GROOVE IS DOVETAILED



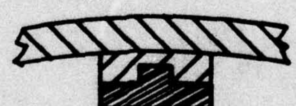
DOVETAIL PROVIDES RADIAL RESTRAINT
STRESSES SAME AS 1

3. SIMILAR TO 2 EXCEPT FOR COMBINED GRAPHITE/STEEL IN KEY



COMBINES CONCEPT 2 AND 3 TO MINIMIZE WEIGHT
WT = 1.25 LB

4. GRAPHITE BOSS WITH STEEL KEY BONDED TO WHEEL



BOND SHEAR STRESS = 1680 PSI
WT = 1.59 LB

5. SAME AS 3 EXCEPT FOR STEEL TO GRAPHITE INTERFACE

STEEL EXPANDS AGAINST COMPOSITE IN KEY AT ELEVATED TEMPERATURE
WT = 1.59 LB

Figure 17. Brake Key to Wheel Attachment Configurations (Sheet 1 of 2)

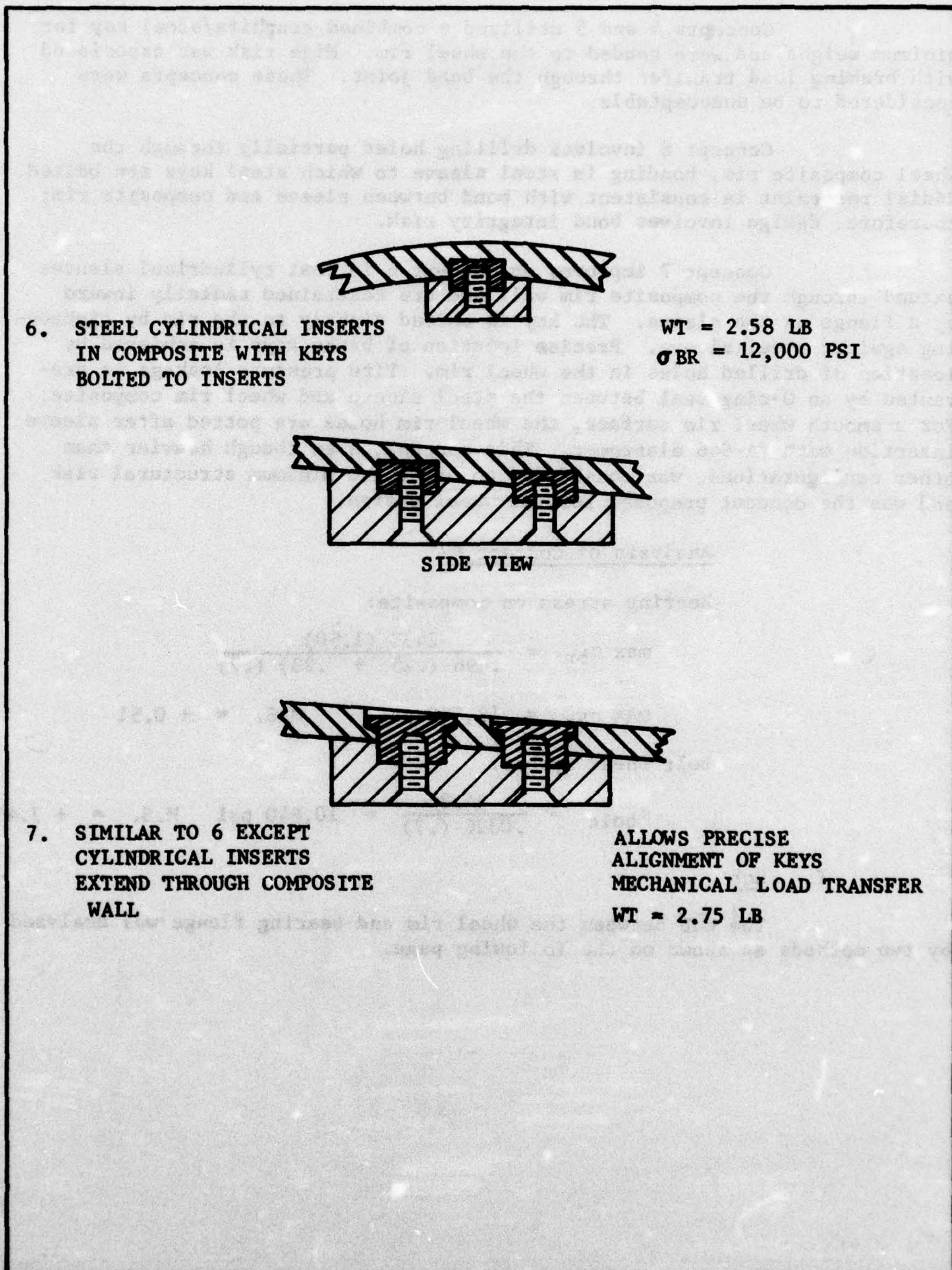


Figure 17. Brake Key to Wheel Attachment Configuration (Sheet 2 of 2)

Concepts 4 and 5 utilized a combined graphite/steel key for minimum weight and were bonded to the wheel rim. High risk was associated with braking load transfer through the bond joint. These concepts were considered to be unacceptable.

Concept 6 involves drilling holes partially through the wheel composite rim, bonding in steel sleeve to which steel keys are bolted. Radial restraint is consistent with bond between sleeve and composite rim; therefore, design involves bond integrity risk.

Concept 7 improves on Concept 6 in that cylindrical sleeves extend through the composite rim wall and are restrained radially inward by a flange on the sleeve. The key is bolted tightly to the rim by tightening against steel sleeve. Precise location of brake keys is achieved by location of drilled holes in the wheel rim. Tire pressure leakage is prevented by an O-ring seal between the steel sleeve and wheel rim composite. For a smooth wheel rim surface, the wheel rim holes are potted after sleeve insertion with EA-946 elastomer. This concept, even though heavier than other configurations, was considered to offer the minimum structural risk and was the concept proposed for the wheel design.

Analysis of Concept #7

Bearing stress on composite:

$$\max \sigma_{br} = \frac{2433\ (1.50)}{.496\ (.25 + .28)\ (.7)}$$

$$\max \sigma_{br} = 19{,}850 \text{ psi} \qquad M.S. = +\ 0.51$$

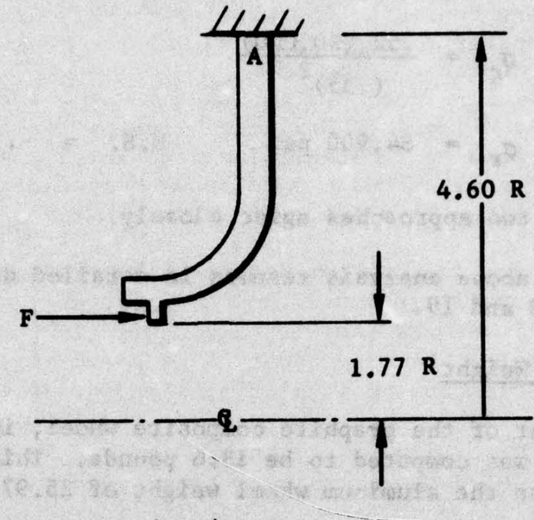
Bolt shear stress:

$$\tau_{bolt} = \frac{2433}{.0326\ (.7)} = 10{,}640 \text{ psi} \qquad M.S. = +\ 7.45$$

f. Hub

The hub between the wheel rim and bearing flange was analyzed by two methods as shown on the following page.

(1) **Assume rim is rigid with respect to hub**



at point A,

$$f_b = \frac{F}{A} \pm \frac{Mc}{I} = \frac{F}{2\pi Rt} \pm \frac{F\ell}{\pi Rt^2}$$

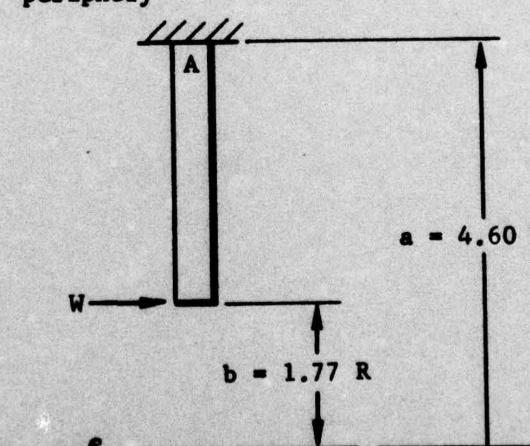
$$= \frac{20{,}000}{2\pi\ (1.77)\ (.35)} \pm \frac{20{,}000\ (2.83)}{\pi\ (1.77)\ (.35)^2}$$

$$= 5138 \pm 83{,}092$$

$$\max f_b = 88{,}230 \text{ psi}$$

Under severe moisture condition F_{bn} = 76,200 psi
M.S. = -.14

(2) **Assume hub is flat plate restrained at outer periphery**



$$a/b = \frac{4.60}{1.77} = 2.60$$

$$\max \sigma = \frac{\beta W}{t^2} \qquad \beta = .52 \text{ for } 2/b = 2.60$$

Radial stress is critical at A:

$$\sigma_r = \frac{.52\ (20,000)}{(.35)^2}$$

$$\sigma_r = 84,900 \text{ psi} \qquad \text{M.S.} = -.10$$

The two approaches agree closely.

The above analysis results in detailed design drawings shown in Figures 18 and 19.

3. <u>Computed Weight</u>

The weight of the graphite composite wheel, including brake keys and bearing cones, was computed to be 18.6 pounds. This weight is 28.5 percent lighter than the aluminum wheel weight of 25.97 pounds.

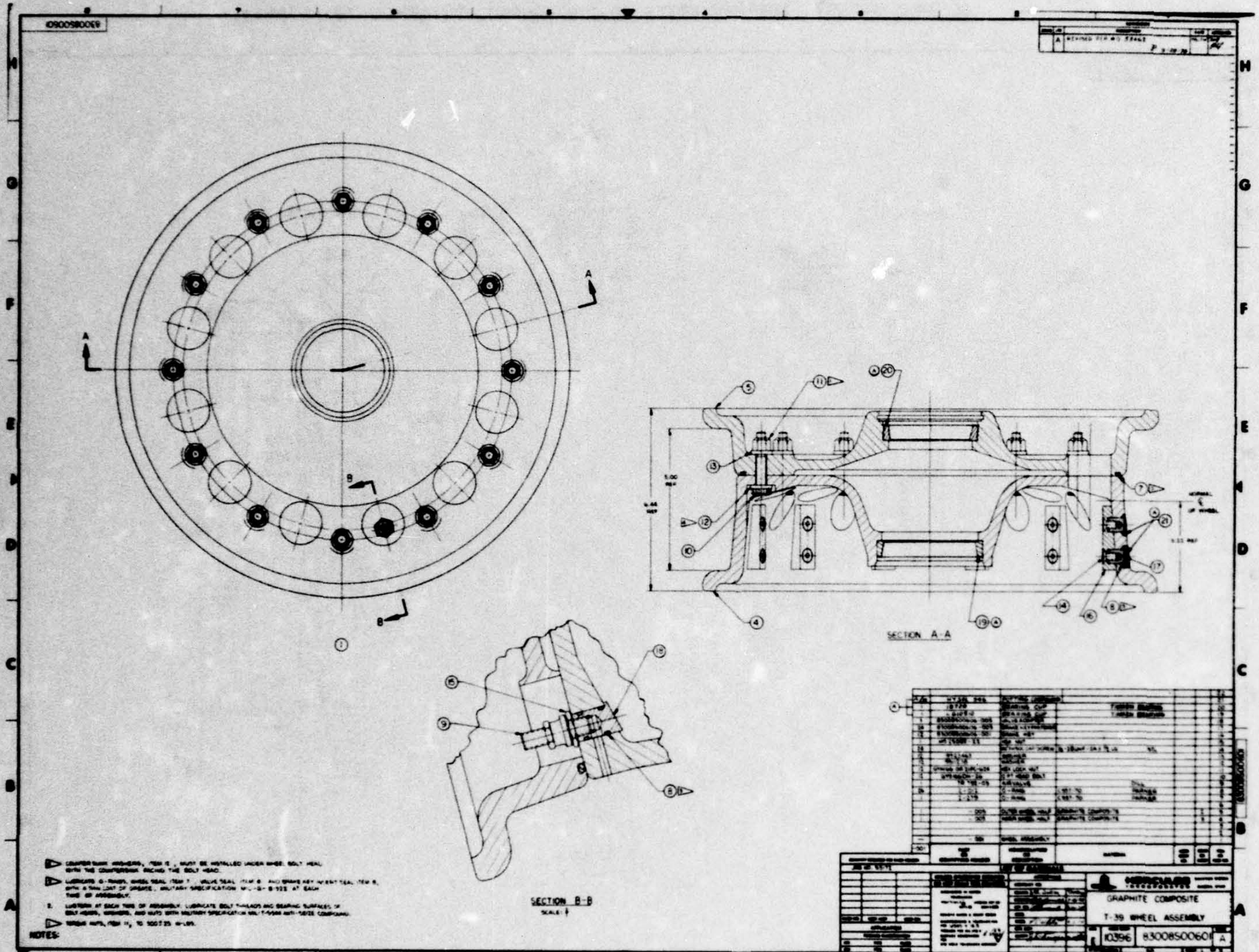


Figure 18. Graphite Composite T-39 Wheel Assembly (Sheet 1 of 3)

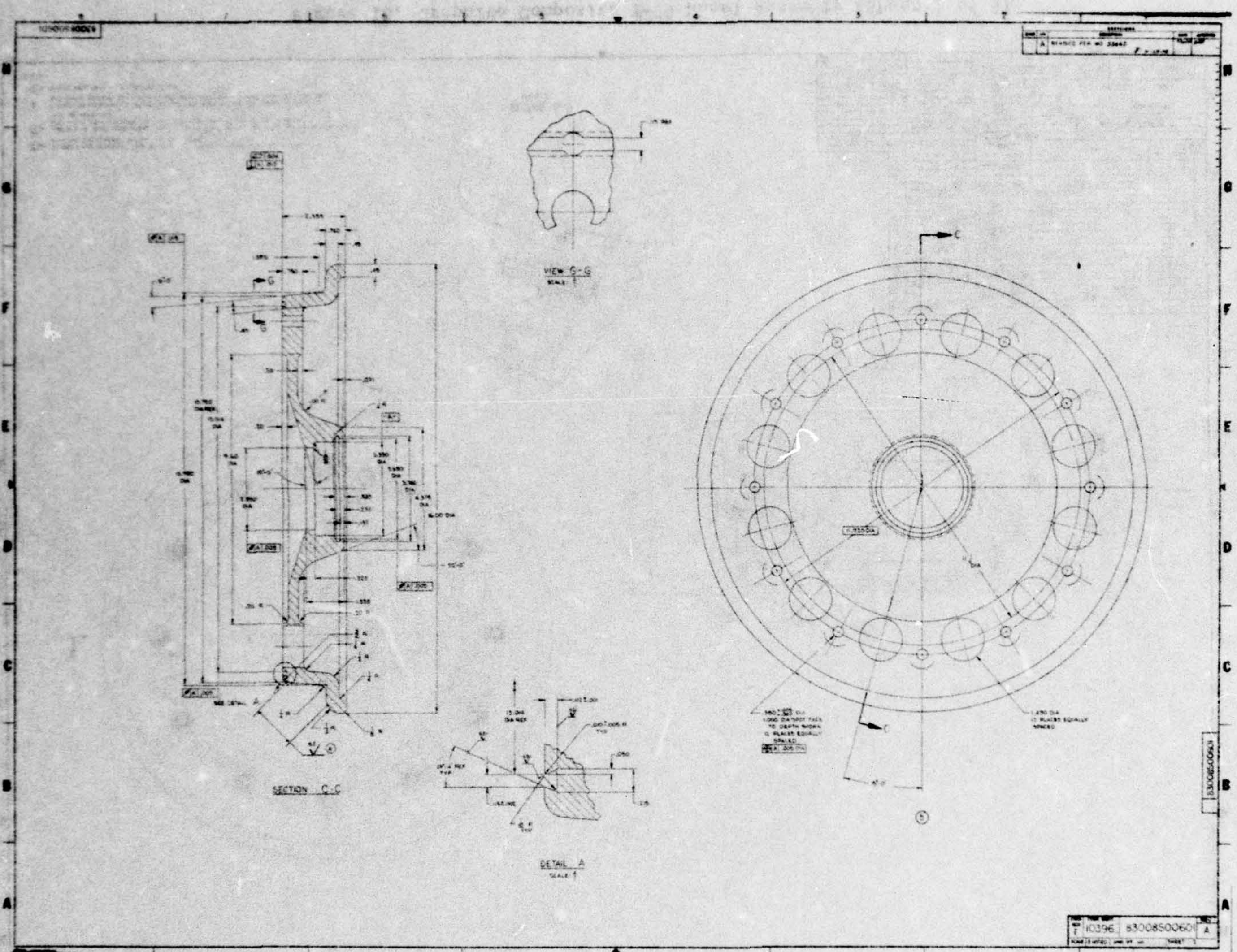


Figure 18. Graphite Composite T-39 Wheel Assembly (Sheet 2 of 3)

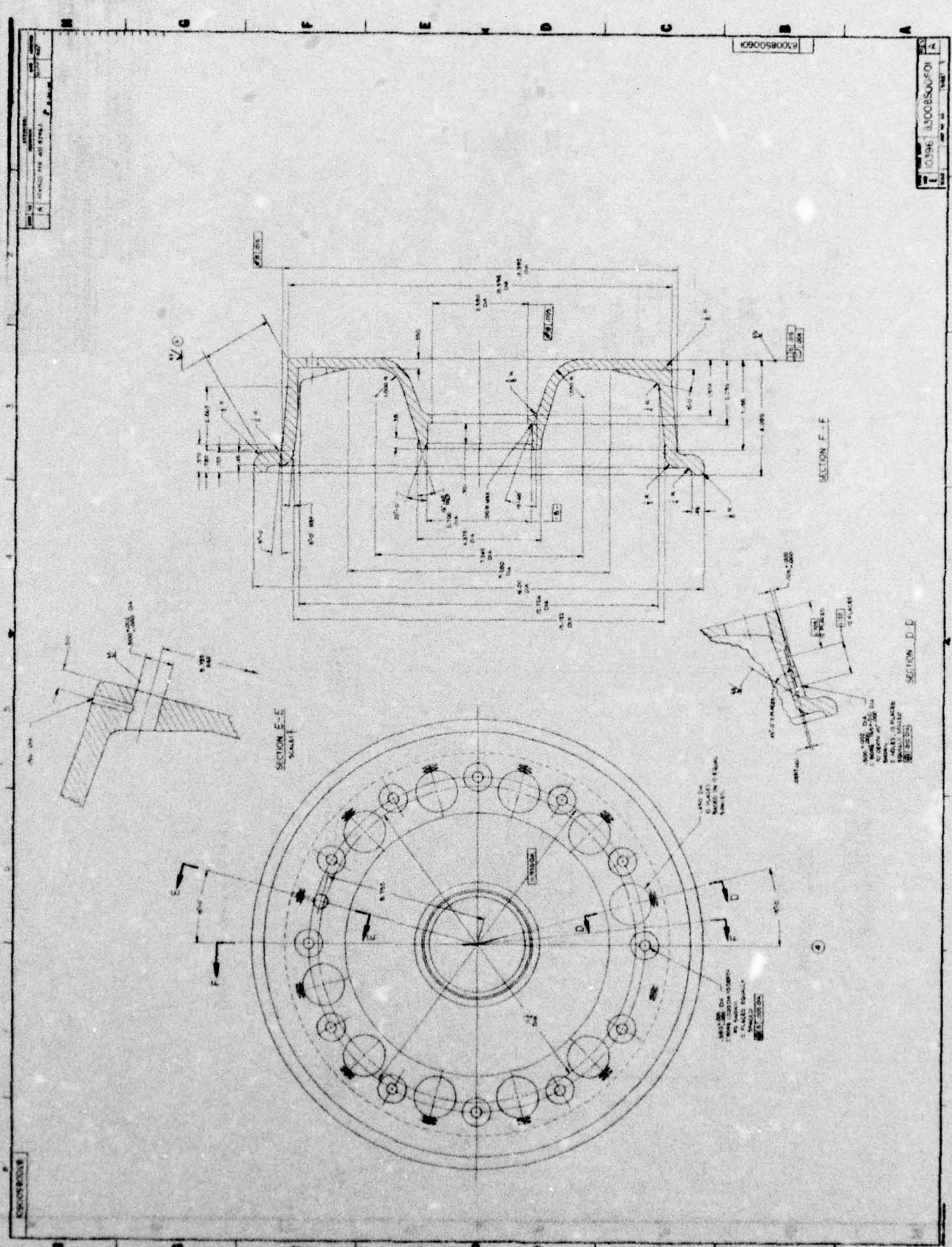


Figure 18. Graphite Composite T-39 Wheel Assembly (Sheet 3 of 3)

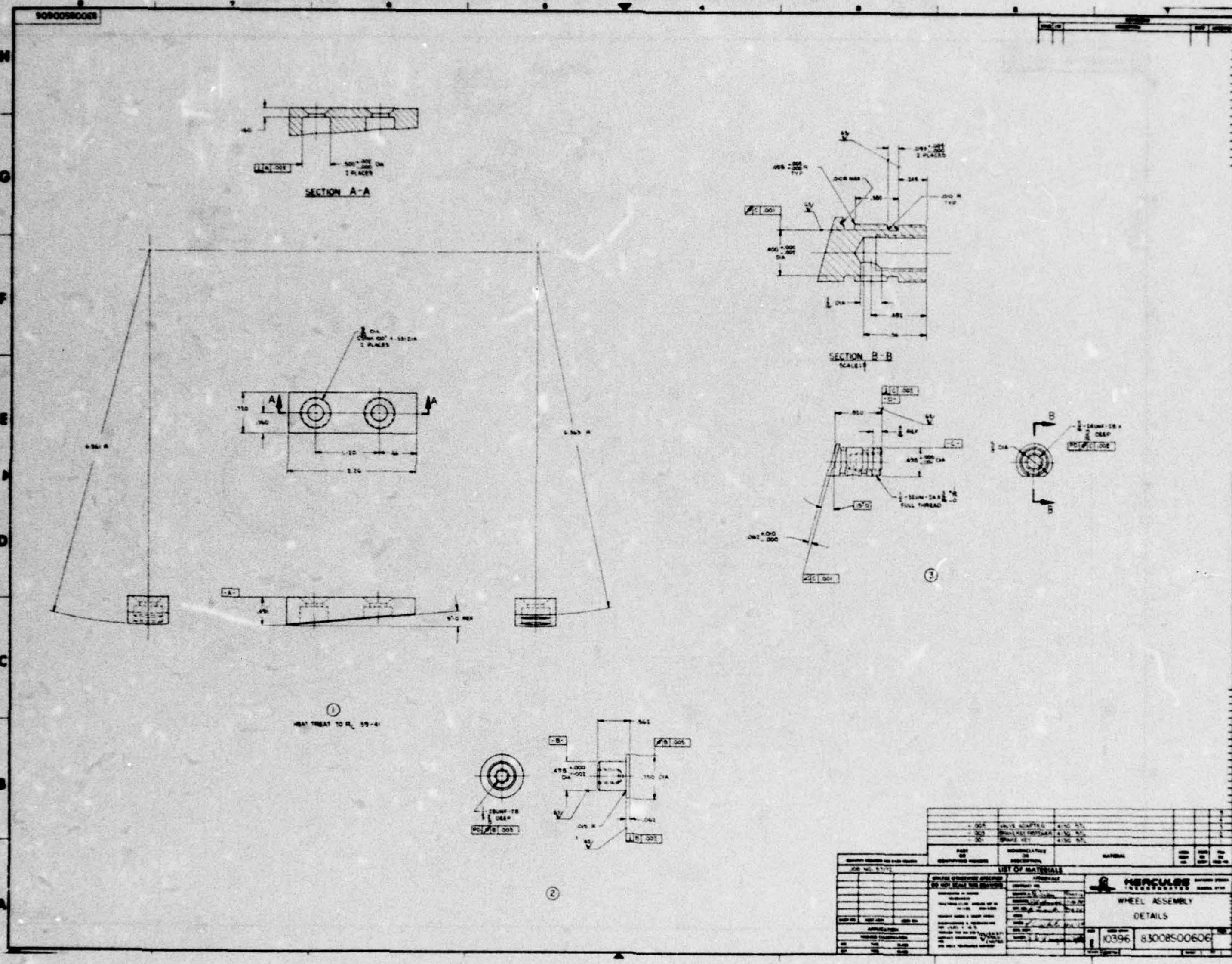


Figure 19. Wheel Assembly Details

SECTION III

FABRICATION

A. FIRST OUTER WHEEL HALF

It had been determined by design analysis that the most effective composite design required different prepreg orientations in the different contour areas of the wheel. Therefore, the wheel cross section was divided into Zones A through E (Figure 20) to facilitate design and layup. Since zones A and D required more hoop fiber, a $(0/\pm45/90_2)$ layup was used; and since Zones B, C, and E needed more radial plies, a $(0_2/\pm45/90)$ layup was used. (Radial fiber direction was the 0° orientation, and circumferential fiber direction was the 90° (hoop) orientation.)

The initial fabrication efforts were based on achieving the above idealistic design concept. Single-ply and two-ply prepreg segments covering a 45° arc, thin continuous hoop wafers in Zones B and C, and a "B" staged composite insert in the bearing seat area were used in the layup of the different zones. Figure 21 shows the composite increments used to fabricate this structure. A portion of the wheel stacking sequence is shown in Table 6. A ply which had the same fiber orientation in all zones was laid up with eight pie-shaped pieces of single prepreg which ran from the lip of the rim through the hub area. (Reference Ply No. 43.)

Where possible, two-ply segments of prepreg were laid up. (Reference Ply Nos. 41 and 42.) However, in some plies (see Ply 53) as many as 32 single-ply pieces of cut prepreg were laid up individually to install one full ply around the wheel cross section. Great care was taken in making the staggered butt joints. Gaps up to 0.05 inch were permitted, but no laps were allowed. Bleed and compaction steps were performed every six to eight plies.

The required 0.020-inch-thick prepregged wafers were made from twisted (one 360° twist per inch) 3,000 end AS tow. A development effort was required to successfully make and handle these thin hoop wafers. Prior to this program, 0.050-inch-thick wafers had been the thinnest fabricated.

The corner area of the wheel beneath the O-ring groove was built up with a shaped ring made of jelly-rolled pieces of 3501/181 style glass cloth. This was done to square the corner prior to layup of the final pieces of the graphite prepreg.

The insert in the bearing seat area was fabricated by B staging a stacked cylinder of $(0/\pm45/90)$ plies. This staged preform was then machined to the desired configuration and pressed into the hub.

At this point in the first outer wheel half fabrication, a review was undertaken to reassess the approach and techniques currently used.

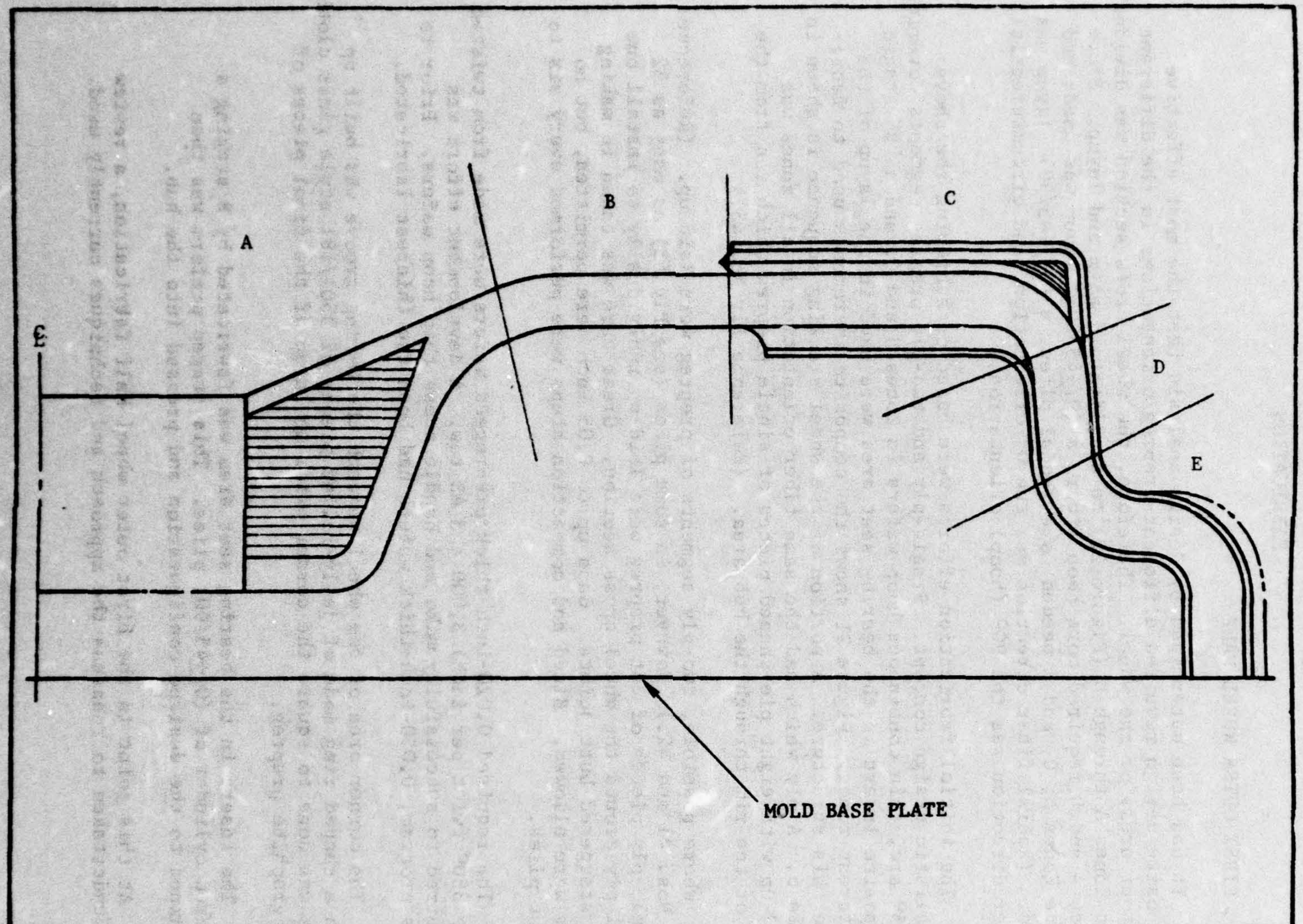
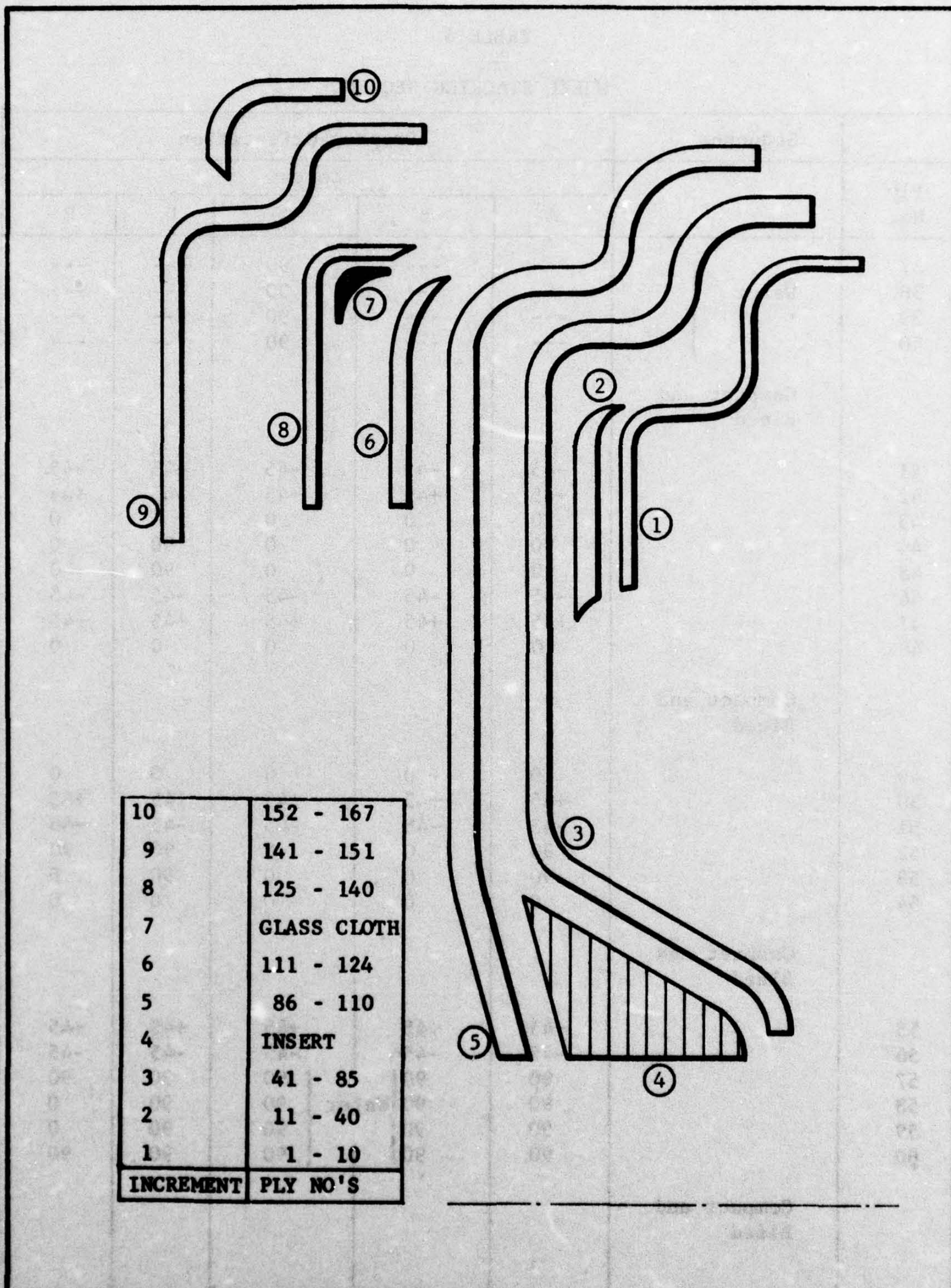


Figure 20. Outer Wheel Cross Section Zones



INCREMENT	PLY NO'S
10	152 - 167
9	141 - 151
8	125 - 140
7	GLASS CLOTH
6	111 - 124
5	86 - 110
4	INSERT
3	41 - 85
2	11 - 40
1	1 - 10

Figure 21. Composite Increments of Outer Wheel Half

TABLE 6

WHEEL STACKING SEQUENCE

Ply No.	Sequence	Prepreg Orientation – Zones A	B	C	D	E
37	Wafer	---	---	90	---	---
38		---	---	90	---	---
39		---	---	90	---	---
40		---	---	90	---	---
	Compact and Bleed					
41		-45	-45	-45	-45	-45
42		+45	+45	+45	+45	+45
43		0	0	0	0	0
44		90	0	0	90	0
45		90	0	0	90	0
46		-45	-45	-45	-45	-45
47		+45	+45	+45	+45	+45
48		0	0	0	0	0
	Compact and Bleed					
49		0	0	0	0	0
50		+45	+45	+45	+45	+45
51		-45	-45	-45	-45	-45
52		90	0	0	90	90
53		90	0	0	90	0
54		0	0	0	0	0
	Compact and Bleed					
55		+45	+45	+45	+45	+45
56		-45	-45	-45	-45	-45
57		90	90	90	90	90
58		90	90 Wafer	90	90	0
59		90	90	90	90	0
60		90	90	90	90	90
	Compact and Bleed					

B. PROBLEMS ENCOUNTERED

The wheel layup techniques originally utilized were requiring enormous amounts of man-hours. The following fabrication areas were identified as needing substantial improvement:

(1) Availability of segment cutting patterns

(2) Cutting of prepreg ply segments

(3) Layup of prepreg segments

(4) Fiber orientation changes within a ply

(5) Workmanship standards

(6) Fabricating of wafers

(7) Machining of the B staged insert

(8) Installation of insert

(9) Bleed/compaction step frequency

Prior to starting layup on the outer mold, the required steel rule cutters were obtained. It was found that the larger cutters (from tip to rim to hub) did not provide the contour fit needed. These patterns had all been designed to fit the wheel cross section contour based on theoretical thickness changes as the prepreg was installed. Consequently, new cutting patterns had to be developed as the layup progressed. The required prepreg segments were not cut out until they were needed in the layup sequence. These segments were initially cut by placing the one- or two-ply oriented prepreg tape over the cutter and tapping it with a plastic hammer until the desired pattern was cut. Great care was required in handling and draping the one- and two-ply prepreg segments since they were very fragile and tended to pull apart. Much trimming and filling was required to meet the limits of 0.050-inch gaps and no laps for the butt joints.

The fabrication and installation of hoop wafers was more time consuming than the equivalent prepreg plies. Machining of the B-staged insert proved to be very difficult. Freezing this preform prior to turning operations did not prove feasible since it tended to separate between plies. In addition, heat generated by the tool smeared the composite rather than removing the material. Prior to pressing the insert down into the hub area, the previously laid-up composite was heated to 180° F. However, as the insert settled in the hub, it forced some of the laid-up prepreg to flow upward and form a raised ridge around the inner face of the hub perimeter. To rework this discrepancy, the insert had to be removed and the ridged prepreg worked back down into its original location with heat and a tooling ring of the proper configuration. A second, completely cured insert was then installed. Heated, bleed/compaction cycles were performed every six to eight plies. Only about eight plies of the wheel layup could be installed and compacted per shift.

As a result of the above circumstances, a crash program was undertaken to reduce fabricating time and still produce an acceptable structure by using the remaining layup of this wheel half to develop more realistic layup techniques.

As a result of this reevaluation, a number of fabrication improvements were investigated. It was decided to implement the following changes in the remaining wheel half fabrication process.

(1) Cut multiple plies of prepreg at the same time

(2) Lay up multiple ply prepreg segments

(3) Maintain the same fiber orientation throughout a ply

(4) Widen workmanship standard

(5) Eliminate hoop wafers

(6) Cure the insert prior to machining

(7) Use additional tooling during insert installation

(8) Reduce bleed/compaction steps

The first area investigated was the use of multiple plies since it was felt that a large reduction in layup time could be made if more plies could be installed with each segment. A review of structural requirements disclosed that a ply orientation of $(0_2/\pm 45/90)$ throughout the laid-up areas would suffice. Thus, a set of prepreg plies with +45, 0, -45, 0, 90 orientation became the basis for fabrication. The steel rule cutters proved capable of cutting four sets (20 plies) of segments with one cycle of the press. (All of the prepreg was cut prior to start of layup of the second wheel half.) By permitting gaps up to 0.10 inch wide with no laps, a considerable amount of segment fitting time was eliminated. Deletion of the hoop wafers and using the 90° prepreg tape fibers was not considered detrimental to the design. Curing of the insert preform prior to machining saved a substantial number of man-hours. When the cured insert was installed with an additional tooling ring around its outside diameter, no problems were encountered. Further reduction of fabrication time was achieved by increasing the number of plies laid up between bleed/compaction cycles to two.

After installation of thermocouples and vacuum bagging, the layup was cured in an autoclave.

Examination of this wheel half after cure disclosed that one hairline circumferential crack was present in the insert bore surface. (See Figure 22.) Four axial, hairline cracks were also found in the outer lip area of the bearing seat. Since these ply surfaces had been butted against a steel center plug, it was felt that the cracks observed were in resin-rich areas and would clean up if machined. Of more concern, however, was the discovery that the as-cured composite thickness was too thin at the root of the rim lip. A review of the M&IR verified that the required prepreg plies had been laid up. However, measurements of the cured rim lip thickness were greater than anticipated. Apparently, excessive migration of resin occurred in the early stages of cure.

C. SECOND OUTER WHEEL HALF FABRICATION

Incorporation of the changes in the fabricating procedure as previously described worked very well during layup of the second outer wheel half. In addition, adjustments made in the bleed/compaction steps and the cure cycle to confine the composite in the rim and rim lip areas prevented any material migration. Fabrication time of this second wheel half was one-tenth of that required on the first outer wheel half. The complete layup procedure is presented in Appendix A.

Vacuum bag-autoclave cure was performed as follows:

(1) Pull full vacuum

(2) Heat to 275° F at 5° per minute

(3) Hold at 275° F for 30 minutes

(4) Pressurize to 100 psi and hold for 30 minutes

(5) Raise temperature to 350° F and hold for 2 hours

(6) Cool to 150° F or lower at 5°/minute under pressure

After removal of the bleeder material, the composite structure appeared sound in all respects except for the hairline cracks in the bore area.

The following postcure was then performed after placing the part in a room-temperature oven:

(1) Increase temperature to 400° F at 1° F/minute

(2) Hold at 400° F for 2 hours

(3) Cooldown at 1° F/minute to room temperature

Visual examination of the postcured part did not reveal any potential structural problem areas. This as-cured wheel half is shown in Figure 23.

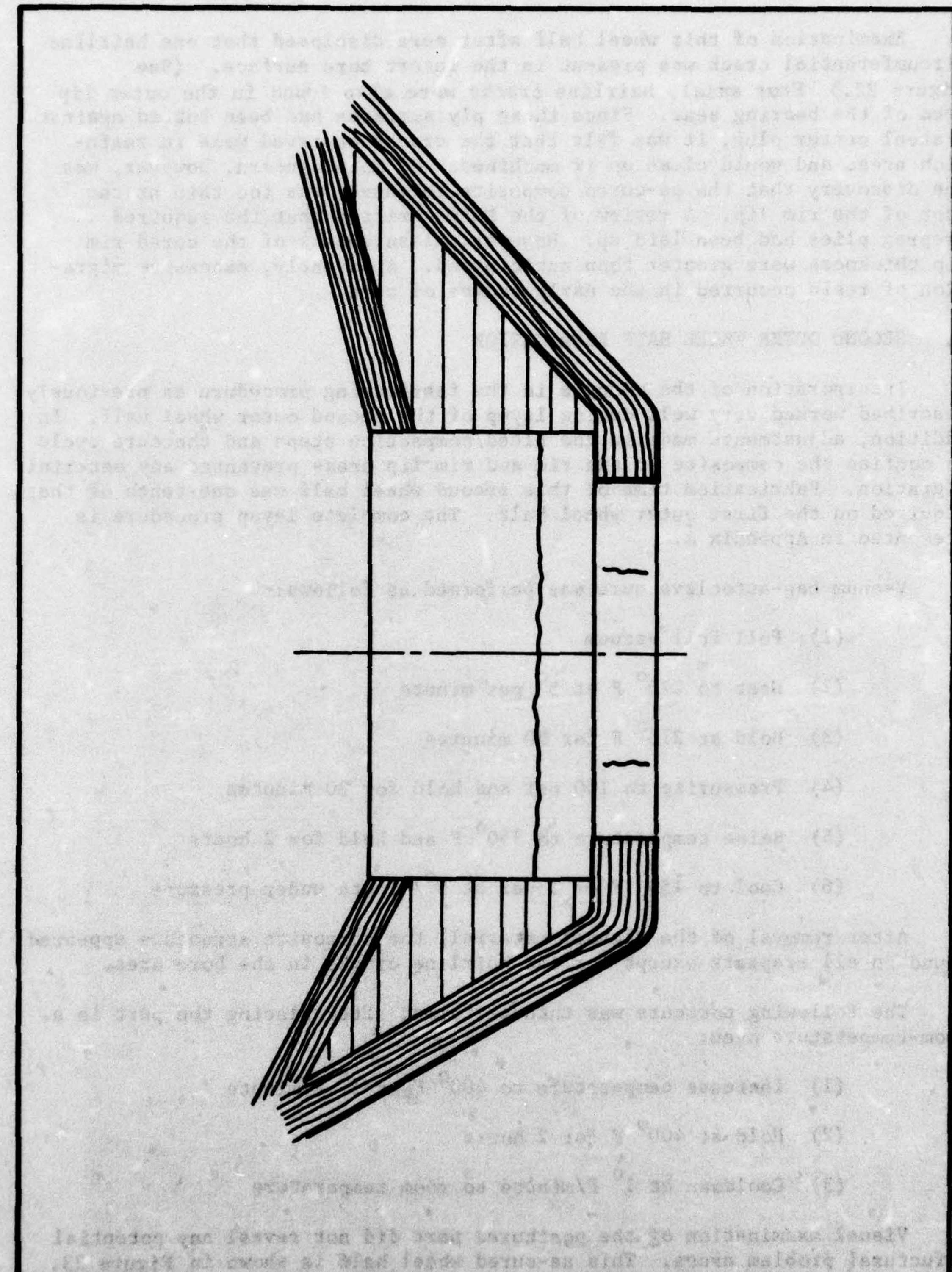


Figure 22. Outer Wheel Half Cracks After Cure

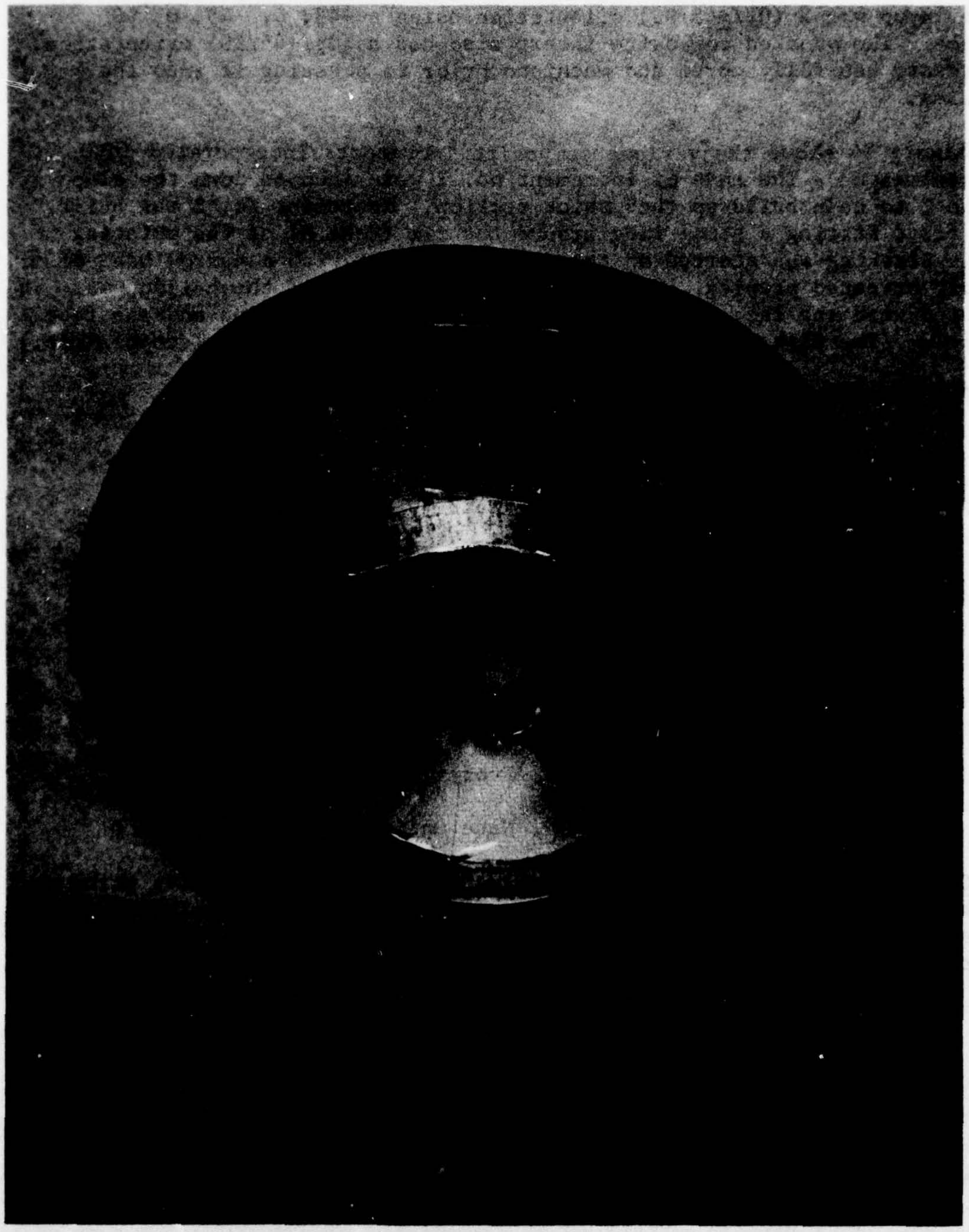


Figure 29. As-Molded Outer Wheel Half

D. INNER WHEEL HALF FABRICATION

The improved fabricating techniques used in the second outer wheel half were incorporated into the inner wheel half procedures. However, each prepreg segment had to be heated slightly with a heat gun to improve drape and tack. Layup was facilitated by dividing the wheel cross section into five zones similar to those used on the outer half. Again, the basis of the layup was a $(0_2/\pm45/90)$ orientation using a +45, 0, -45, 0, 90 sequence. The stacked composite insert also had a $(0_2/\pm45/90)$ orientation. This insert was fully cured and machined prior to pressing it into the bore area.

Figure 24 shows the various composite increments incorporated into the wheel layup. The ends of increment No. 2 were stepped down the slope in Zone C to help build up this thick section. Increment No. 3 was built up by first fitting a steel ring around the rim (Zone D) of the existing layup. Stacking was started on the outer perimeter with a narrow band of five-ply oriented prepreg. Wider bands were added until the buildup was completed with one face perpendicular to the wheel centerline and one face parallel. (The plies were in planes perpendicular to the wheel centerline.)

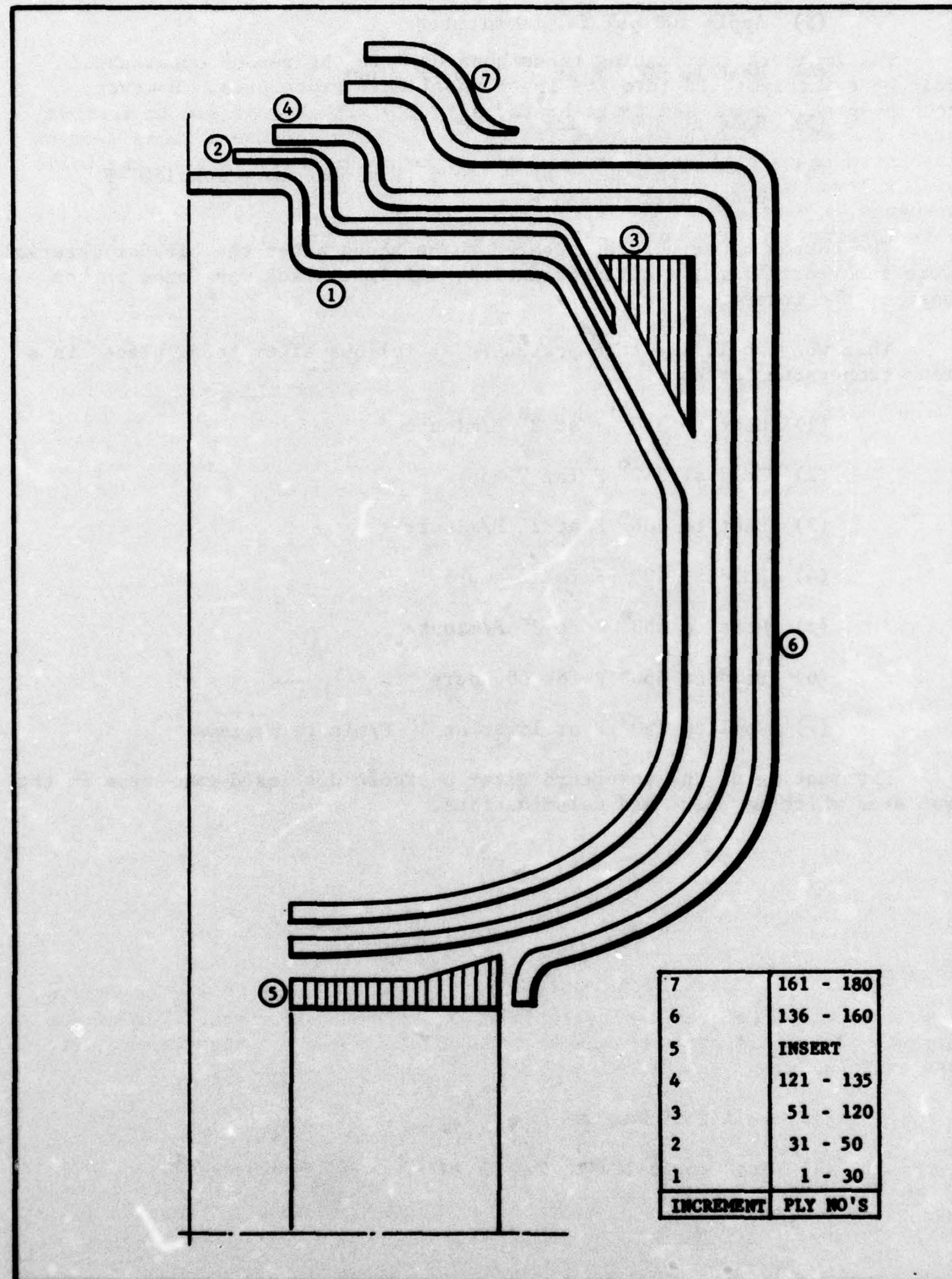
The bleed/compaction cycles occurred as shown below:

Increment	Bleed/Compactions
1	Every 10 plies
2	Every 20 plies
3	Every 70 plies
4	Every 15 plies
5	On insert
6	Every 15 plies
7	None until cure

Cure trials were made on thick 4397/AS composite right angles which were then sectioned until a suitable cure cycle was obtained. The vacuum bag-autoclave cure used on this high-temperature resin system wheel half was as follows:

(1) Pull full vacuum

(2) Heat composite to 275° F at 4° to 6° F/minute



INCREMENT	PLY NO'S
7	161 - 180
6	136 - 160
5	INSERT
4	121 - 135
3	51 - 120
2	31 - 50
1	1 - 30

Figure 24. Composite Increments of Inner Wheel Half

(3) Apply 100 psi for 60 minutes

(4) Heat to 400° F at 4° to 6° F/minute

(5) Hold at 400° F for 2 hours

(6) Cool from 400° F at 2° to 3° F/minute to below 150° F under full pressure

The composite structure appeared to be sound after the bleeder materials were removed. Again, a circumferential, hairline crack was found in the bore of the insert.

This wheel half was then postcured as follows after being placed in a room temperature oven:

(1) Heat to 350° F at 2° F/minute

(2) Hold at 350° F for 2 hours

(3) Heat to 400° F at 2° F/minute

(4) Hold at 400° F for 2 hours

(5) Heat to 450° F at 2° F/minute

(6) Hold at 450° F for 48 hours

(7) Cool to 150° F or lower at 1° F/minute maximum

Examination of the structure after postcure disclosed two areas in the web area which may have had delaminations.

SECTION IV

MACHINING AND TOOLING

A. MACHINING

Machining was performed with conventional lathes and mills. Turning operations were accomplished using diamond-tipped tool bits, and all holes were made with diamond core drills. Cutting tools and the surfaces of the composite being machined were flooded with water to keep temperatures low. Also, low feed rates of the tools into the wheel blanks were used to limit heat buildup. Holes were backed up during boring operations to limit delaminations of the composite as the core drill broke through. However, this proved difficult to accomplish on curved surfaces.

Where the quality of the composite was acceptable, as was the case for the 3501/AS outer wheel half, no surface finish problems were encountered. However, the high-temperature composite material in the inner wheel half tended to delaminate and finished poorly when material was removed parallel to the plane of the fiber. Those hairline cracks found after cure in the hub areas were not present after machining. Figures 25 and 26 show the machined configurations.

B. TOOLING

The tooling used to fabricate the wheel halves is shown in Figure 27. The two major tools were the two male molds upon which all the cut prepreg tape was laid up to make the inner and outer wheel halves. During tool design, two concepts were considered. (See Figure 28.) The first approach, which would require layups in the cavity offered two advantages: (1) most of the interface surfaces of the wheel half could be molded to dimension and would require little additional machining and (2) if an increase in composite cross section were required, it could be accomplished by simply adding more plies of prepreg without modifying the mold.

One shortcoming of this concept is that the rim area of the mold expands away from the composite during cure. A more serious drawback is the fact that it is much more difficult to lay up prepreg in a cavity of complex configuration and obtain sufficient compaction to assure structural integrity. It was anticipated that the high-temperature prepreg selected for the inner wheel half might be boardy.

The second concept, which would have the layup on the external mold surface, has several advantages, including: (1) The prepreg is easier to drape and compact, (2) installation of the composite insert in the bearing cup areas could be performed more readily, (3) heat during cure causes mold to expand and, thus, compaction is improved, (4) mold shrinks away from composite during cooldown, and (5) the outside surfaces of the wheel halves are easier to machine. Disadvantages of this concept are (1) all interfaces must be machined and (2) metal must be machined from the mold if composite cross section thicknesses need to be increased.

Figure 25. Machined Wheel Halves (Vacuum Bag Side)

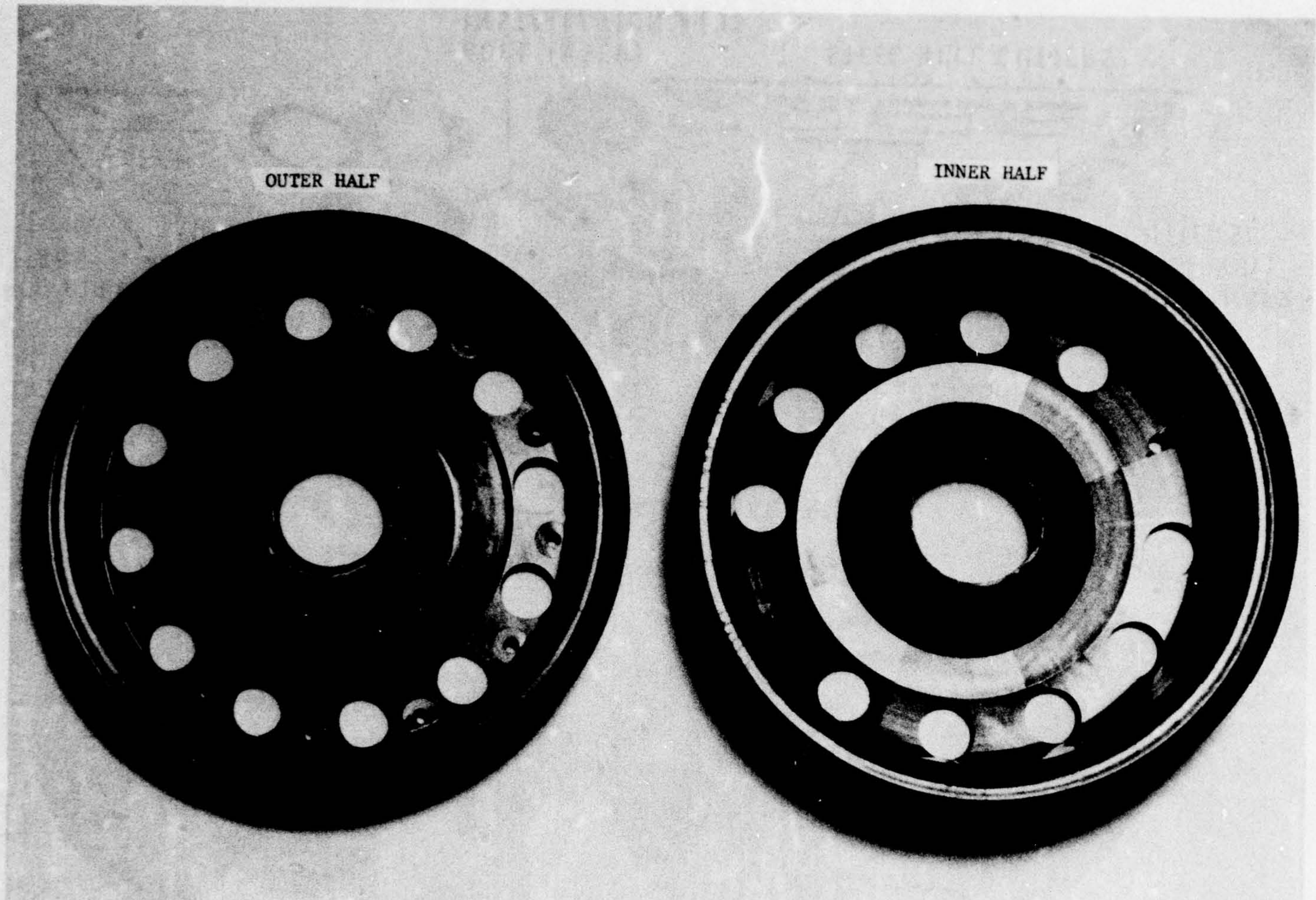


Figure 26. Machined Wheel Halves (Mold Side)

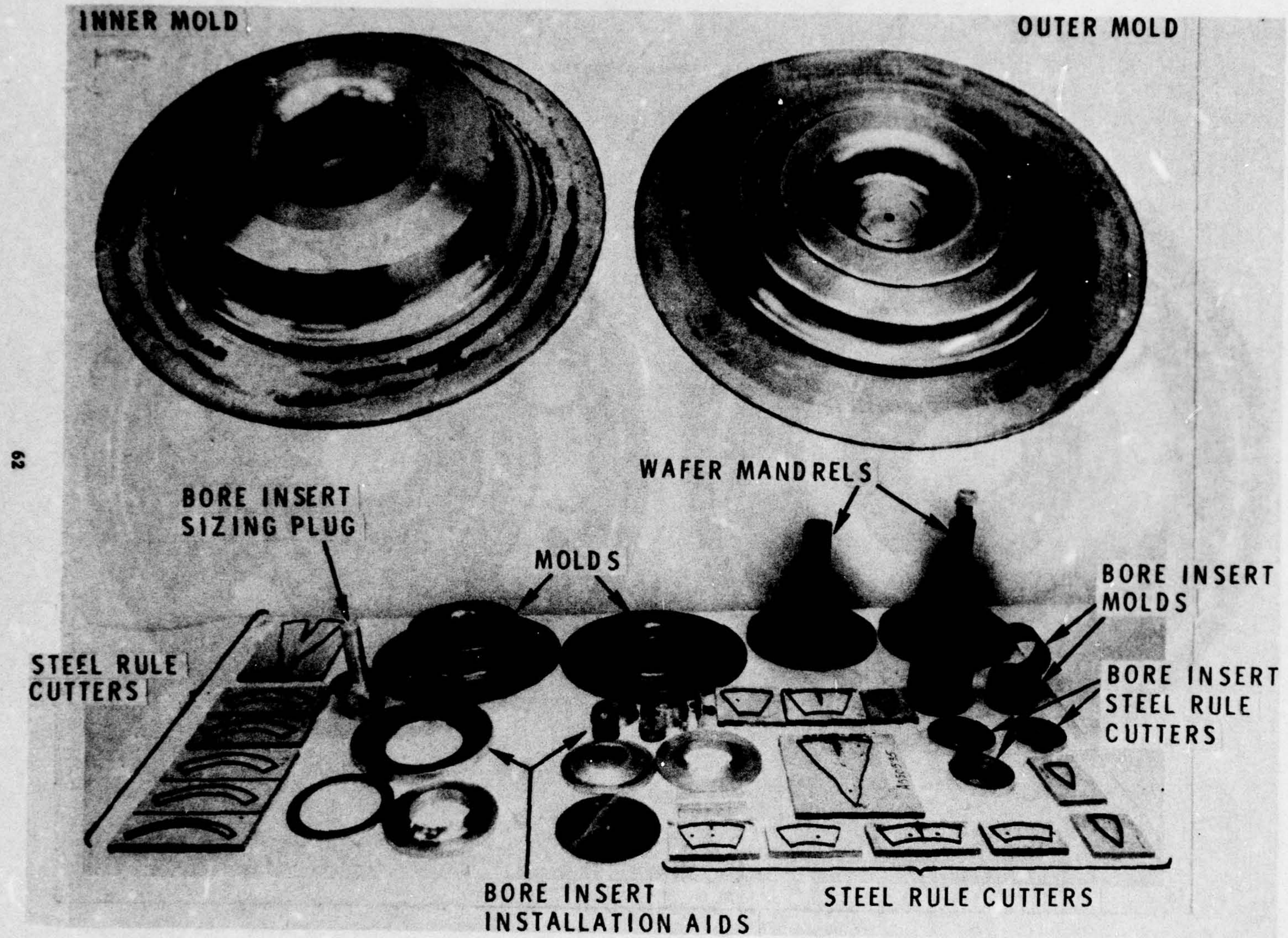


Figure 27. T-39 Graphite Composite Braked Landing Gear Wheel Tooling

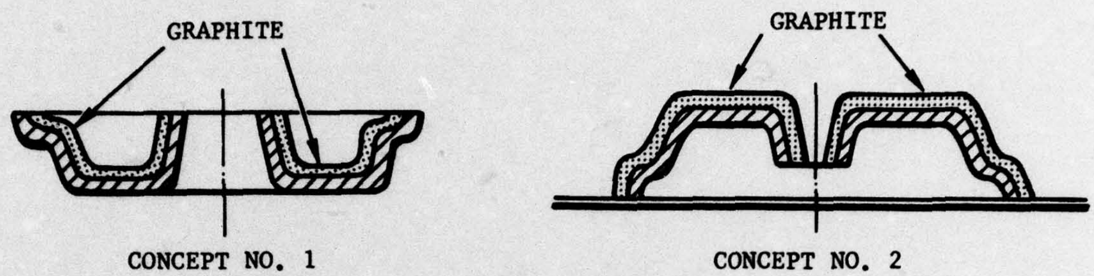


Figure 28. Tool Design Concepts

When overall costs and quality of the cured composite were considered in addition to the above, Concept No. 2 was considered to be the most desirable tooling approach.

Each mold was machined from P20 tool steel. This material is especially made for general-purpose plastic mold tooling of these cross sections because it is more nearly free of internal defects than other grades of tool steel and it is less costly. Steel was chosen over aluminum because it is more durable and has less dimensional changes during thermal cycles. Aluminum, however, would produce a lighter mold at a slightly lower cost.

Various fabrication aids, such as steel rule cutters, preform mandrels, compaction rings, wafer tooling, etc. were also procured to assist in the fabrication processes.

SECTION V

INNER WHEEL HALF DELAMINATIONS

Delaminations experienced in the inner wheel half are related to a number of circumstances. (See Figure 29.) These are individually discussed in the following paragraphs; however, the precise cause cannot be determined from one data point, and any or all may contribute to the delamination problem.

A. FABRICATION TIME LAPSE

This wheel half, for various reasons, was laid up over an extended period of time (approximately 6 weeks), with the wheel remaining at room temperature through most of this time. Several compaction cycles wherein the wheel was exposed to heat and vacuum for short periods of time were also performed during the layup. Resin advancement during this extended time and the compaction cycles may have been sufficient to reduce interlaminar strength, which could result in the delaminations found.

B. RESIN CHARACTERISTICS

The resin is a relatively low elongation system which exhibits somewhat greater shrinkage during cure than an epoxy system. This shrinkage and low elongation combine to increase internal stresses in the part during cooldown from the 450° F postcure temperature.

C. LAYUP GEOMETRY

The ply patterns, while necessary for wheel strength, may not be optimum for this particular resin system when the stresses are considered.

D. CURE CYCLE

The cure cycle was developed from flat panels (0°) and thick right-angle specimens (wheel layup). The 48-hour, 450° F postcure was found to be necessary for maximum mechanical properties and did not seem to degrade the angle specimens. Considering the larger mass of the wheel over the test specimens, it may be desirable to increase the temperature in smaller increments with longer hold times at the intermediate temperatures to provide a greater opportunity for stress relief. Also, a much slower cooldown, possibly incrementally, would aid stress relief.

If a second wheel half is built from the 4397 resin system, the following recommendations are suggested:

(1) Fabricate as rapidly as possible, limiting out time and compaction cycles to the absolute minimum.

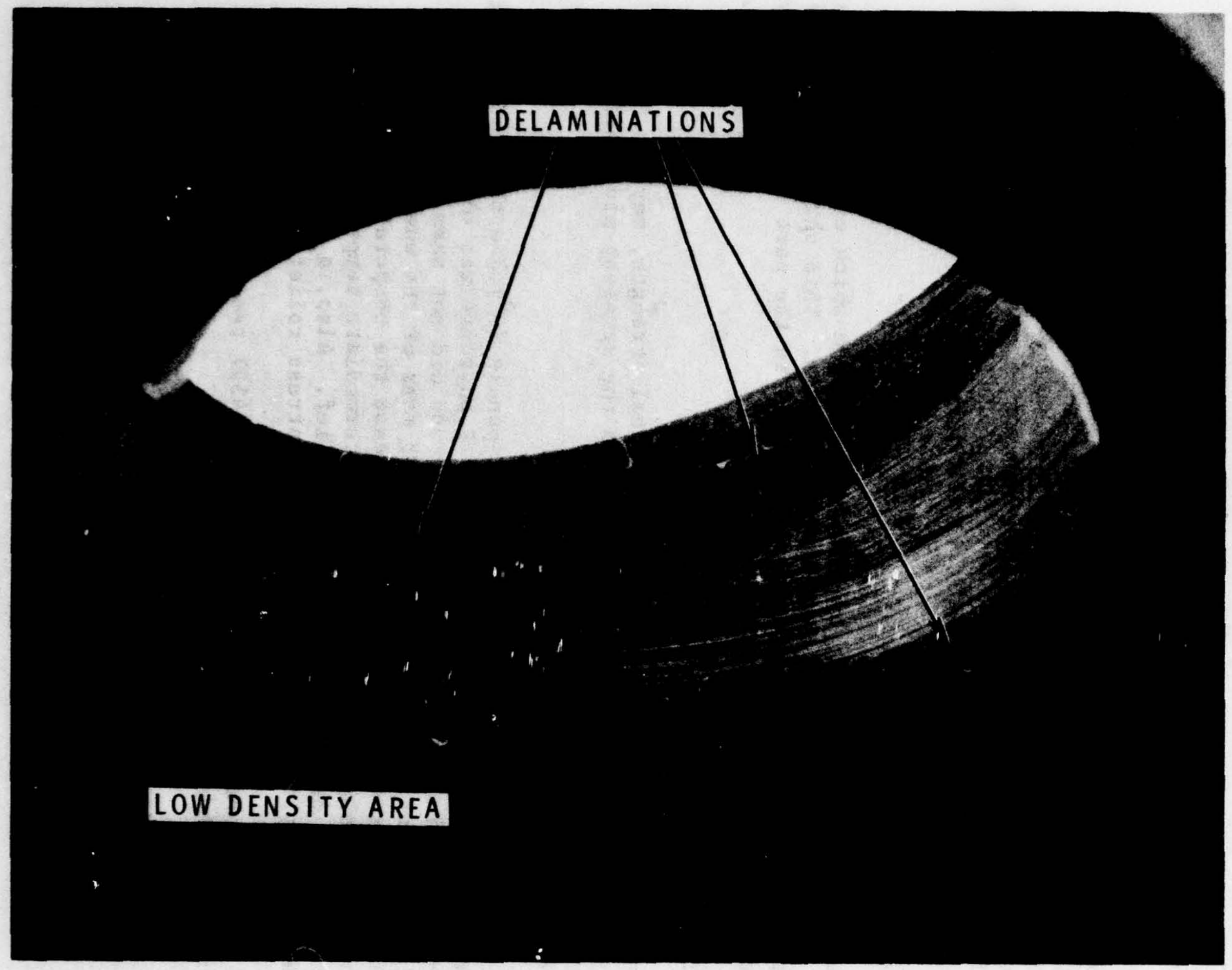


Figure 29. Postcured Inner Wheel Half Composite Defects as Viewed from Brake Side of Cooling Hole

(2) Change cure cycle to reduce time at 450° F (eliminate if possible) to reduce heatup rate and to increase cooldown time.

(3) Analyze layup geometry for any potential problem with stress buildup from resin shrinkage and from low resin elongation. Change ply orientation if suggested by this analysis to minimize stresses.

SECTION VI

STRUCTURAL TEST INSTRUMENTATION AND QUALITY ASSURANCE

A. STRUCTURAL TEST INSTRUMENTATION

The suggested instrumentation for wheel structural tests (Figure 30) consists of bonding strain gages and thermocouples in critical areas. Gages marked with an asterisk are typical for both inner and outer wheel sections.

Thermocouples are shown placed on the brake key, on the composite inner rim adjacent and between brake keys, and on the composite bearing hub. Six thermocouples are proposed.

Strain gages are shown placed on the inner rim surface between brake keys, on the composite bearing hub, and on the radial surface of the wheel just inboard the 1.490-inch-diameter holes. Ten strain gages are proposed.

B. QUALITY ASSURANCE

The quality assurance effort during fabrication was to ensure that only conforming parts and materials were used, that the procedure was followed, and that final machining dimensions were recorded.

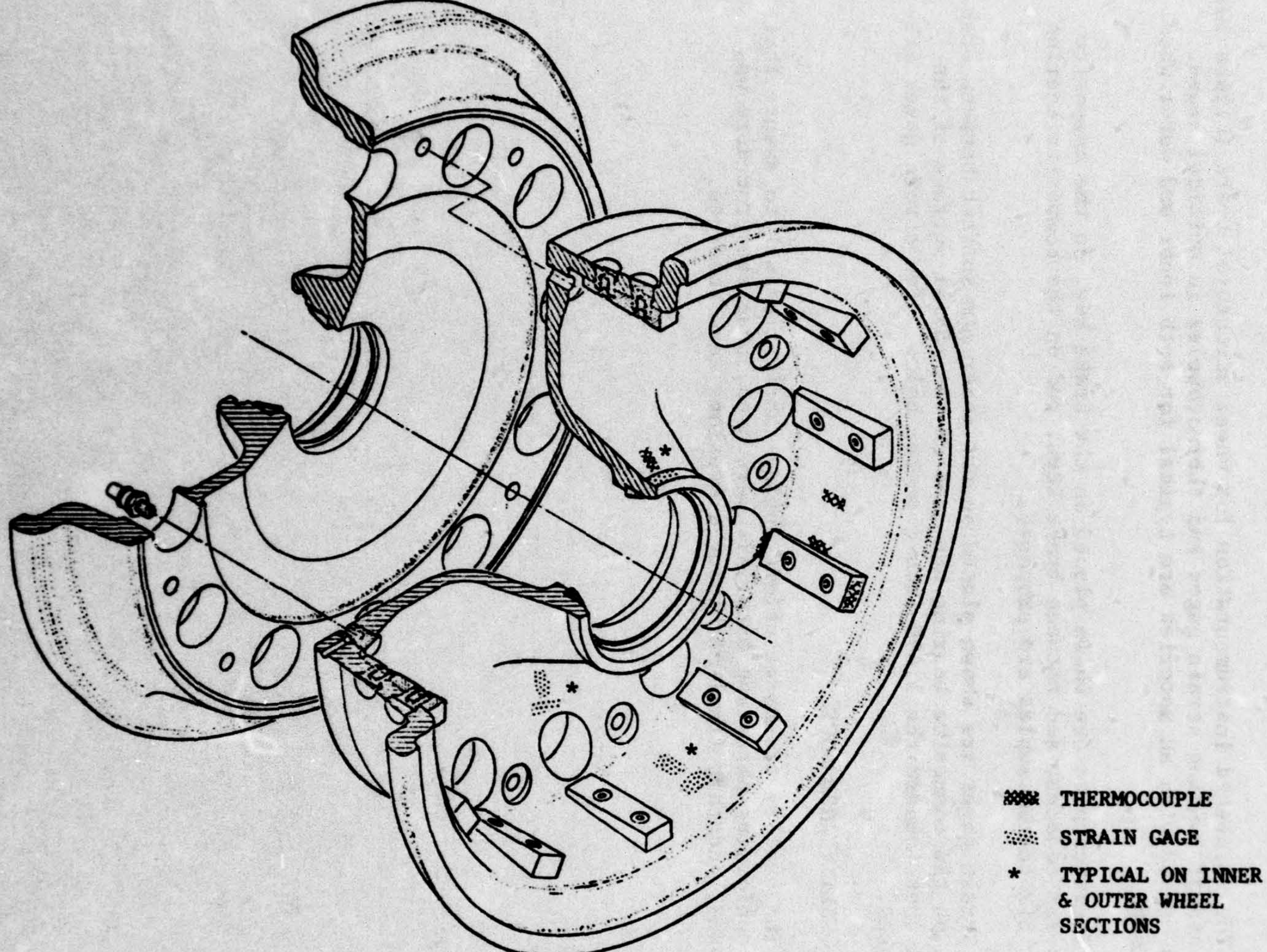


Figure 30. Proposed Instrumentation, Graphite Composite Wheel Structural Test

APPENDIX A

FABRICATION AND CURE OF THE GRAPHITE COMPOSITE T-39 INNER WHEEL HALF

1. **OPERATION**

1.1 **Preparation**

1.1.1 **Disassemble wheel mold and clean using Scotch Brite and MEK.**

1.1.2 **Scrub wheel mold with Alconox and water, rinse and air dry.**

1.1.3 **Spray Frekote 33 over all surfaces of wheel mold and bake at 350°F for 1/2 hour.**

1.1.4 **Assemble wheel mold using rubber O-rings in the appropriate places.**

1.2 Insert Fabrication

1.2.1 Using 4397/12-inch prepreg tape lay up 6 feet of 5 layer prepreg as follows:

1.2.1.1 Preheat aluminum plate to 145°F. and cover with release paper.

1.2.1.2 Lay a 6-foot section of 12-inch tape on the plate and allow time to heat the tape.

1.2.1.3 Cover the 6-foot section of 0° tape with sections of 45° pre-cut tape. Turn over the 2 layers of 0, -45° tape and strip the release paper off the 0° side. Cover this side with 45° prepreg.

1.2.1.4 Add one ply 0° tape and one ply 90° tape to the 3 layers for a total of 5 layers oriented at +45°, 0°, -45°, 0°, 90°. Allow all layers to heat until all ared tacked together.

1.2.1.5 Using cutter W-102-003, cut 56 pieces of 5 layer prepreg prepared in steps 6.2.1 thru 6.2.1.4.

1.2.1.6 Place the cut pieces on mold W103-002, 004, 006 place in press and cure.

1.2.1.6.1 Heat press to 275°F. for 50 minutes, then apply 100 psi. Hold at 275°F. and 100 psi for 30 minutes. Raise heat to 400°F. and hold for two hours. Cool to room temperature.

1.2.1.7 Machine insert as indicated in Sketch A.

1.3 Mold Layup Notes

1.3.1 Each layer shall be indexed so as to stagger the joints approximately 10° from previous joints in a clockwise direction.

1.3.2 The layers of 5 ply segments +45, 0, -45, 0, 90 shall alternately be placed 90° side up and 90° side down.

1.3.3 If lapse time is to be greater than 4 hours, keep wheel assembly at room temperature and under vacuum at all times when not being worked on.

1.3.4 Use sketch B to reference all zone locations.

1.3.5 The various cutters will be oriented so that 0^o is in the radial direction.

1.4 Fabrication (Refer to Table A-1)

1.4.1 Starting at index 0 lay up 1/8 section (plies 1 thru 5) of 5 layer prepreg (+45, 0, -45, 0, 90) to cover all zones (see Sketch B). Cut 1/8 sections using cutter W124. Lay each section on top of the wheel mold and heat with heat lamp until the prepreg can be formed to the contour of the wheel mold.

1.4.2 Starting at index one (1) layup 1/8 sections (plies 6 thru 10) of 5 layer prepreg to cover all zones using cutter W124.

1.4.3 Compact the 10 plies using a vacuum bag and oven temperature of 200^oF. for 30 minutes. Use heavy Armalon and 3 layers of Blue Peel.

1.4.4 Starting at index two (2) lay up 1/8 sections (plies 11 thru 15) of 5 layer prepreg to cover all zones using cutter W124.

1.4.5 Starting at index three (3) lay up 1/8 sections (plies 16 thru 20) of 5 layer prepreg to cover all zones using cutter W124.

1.4.6 Compact using a vacuum bag and oven temperature of 200^oF. for 40 minutes. Use heavy Armalon and three layers of Blue Peel.

1.4.7 Starting at index four (4) lay up 1/8 sections (plies 21 thru 25) of 5 layer prepreg to cover all zones using cutter W124.

1.4.8 Starting at index zero(0) lay up 1/8 sections (plies 26 thru 30) of 5 layer prepreg to cover all zones using cutter W124.

1.4.9 Compact using a vacuum bag and oven temperature of 200^oF. for 40 minutes. Use heavy Armalon and three layers of Blue Peel.

1.4.10 Starting at index one (1) layup 1/8 sections (plies 31 thru 35)

1.4.10 (cont'd) of 5 layer prepreg in zones C thru E using cutter W124 and trimming to fit.

1.4.11 Starting at index two (2) layup 1/8 sections (plies 36 thru 40) of 5 layer prepreg in zones C thru E using cutter W124 and trimming to fit.

1.4.12 Starting at index three (3), layup 1/8 sections (plies 41 thru 45) of 5 layer prepreg in zones C thru E using cutter W124 and trimming to fit.

1.4.13 Starting at index four (4) layup 1/8 sections (plies 46 to 50) of 5 layer prepreg in zones C thru E using cutter W124 and trimming to fit.

1.4.14 Compact using a vacuum bag and oven temperature of 200°F. for 50 minutes. Use heavy Armalon and three layers of Blue Peel.

1.4.15 Install washer IW2 and ring IR1, put the wheel mold, under vacuum, in the oven for 40 minutes at 200°F. While ring, washer, and wheel are still under vacuum place them in the press and apply 8 tons pressure. Cool to room temperature.

1.4.16 Starting at index 0 and 1, layup 2 layers 1/4 sections (plies 51 thru 60) of 5 ply prepreg in Zone C using cutter W123-007.

1.4.17 Starting at index 2 and 3, layup 2 layers of 1/4 sections (plies 61 thru 70) of 5 ply prepreg in zone C using cutter W123-006.

1.4.18 Starting at index 4 and 0 layup 2 layers of 1/4 sections (plies71 thru 80) of 5 ply prepreg in zone C using cutter W123-005.

1.4.19 Starting at index 1 and 2, layup 2 layers of 1/4 sections (plies 81 thru 90) of 5 ply prepreg in zone C using cutter W123-004.

1.4.20 Starting at index 3 and 4, layup 2 layers of 1/4 sections (plies 91 thru 100) of 5 ply prepreg in zone C using cutter W123-003.

1.4.21 Starting at index 0 and 1, layup 2 layers of 1/4 sections (plies 101 thru 110) of 5 ply prepreg in zone C using cutter W123-002.

1.4.22 Starting at index 0 and 1, layup 2 layers of 1/4 sections (plies 111 thru 120) of 5 ply prepreg in zone C using cutter W123-001.

1.4.23 Compact using a vacuum bag, washer IW2 and ring IR1. Heat in oven at 200°F. for 30 minutes.

1.4.24 Remove ring IR1 and washer IW2.

1.4.25 Starting at index 0, layup 1/8 sections (plies 121 thru 125) of 5 ply prepreg in all zones using cutter W125.

1.4.26 Starting at index 1, layup 1/8 sections (plies 126 thru 130) of 5 ply prepreg in all zones using cutter W125.

1.4.27 Starting at index 2, layup 1/8 sections (plies 131 to 135) of 5 ply prepreg in all zones using cutter W125.

1.4.28 Compact for 30 minutes at 200°F. with vacuum bag.

1.4.29 Install cured insert as follows:

1.4.29.1 Place wheel and insert in a vacuum bag.

1.4.29.2 Heat in Geco 033 oven and under vacuum to 200°F. for one hour.

1.4.29.3 Keeping vacuum pressure on wheel at all times, transfer wheel assembly to large hydro-air press and apply a maximum of 5 ton pressure to properly place insert into wheel.

1.4.29.4 Cool in press and remove when part reaches room temperatures.

1.4.30 Starting at index 3, layup 1/8 sections (plies 136 thru 140) of 5 ply prepreg in all zones using cutter W125.

1.4.31 Starting at index 4, layup 1/8 sections (plies 141 thru 145) of 5 ply prepreg in all zones using cutter W125.

1.4.32 Compact for 30 minutes at 200°F. with vacuum.

1.4.33 Starting at index 0, layup 1/8 sections (plies 146 thru 150) of 5 ply prepreg in all zones using cutter W125.

1.4.34 Starting at index 1, layup 1/8 sections (plies 151 thru 155) of 5 ply prepreg in all zones using cutter W125.

1.4.35 Starting at index 2, layup 1/8 sections (plies 156 thru 160) of 5 ply prepreg in all zones using cutter W125.

1.4.36 Compact for 30 minutes at 200° with vacuum.

1.4.37 Starting a index 3, layup 1/8 sections (plies 161 thru 165) of 5 ply prepreg in zone E using cutter W112.

1.4.38 Starting at index 4, layup 1/8 sections (plies 166 to 170) of 5 ply prepreg in zone E using Cutter W112.

1.4.39 Starting a index 0, layup 1/8 sections (plies 171 to 175) of 5 ply prepreg in zone E using cutter W112.

1.4.40 Strating at index 1, layup 1/8 sections (plies 176 to 180) of 5 ply prepreg in Zone E using cutter W112.

1.5 <u>Prepare For Cure</u>

1.5.1 Trim excess material from base plate area.

1.5.2 Install one thermocouple under lay up, against mold and one thermocouple on top of lay up. Apply one ply of heavy Armalon.

1.5.3 Apply 3 plies of Blue Peel in the washer area.

1.5.4 Install washer IW2.

1.5.5 Apply 24 plies of Blue Peel.

1.5.6 Vacuum bag

1.6 <u>Cure</u>

1.6.1 Pull full vacuum

1.6.2 Heat from room temperature to 275°F. (highest part temperature) at 4 to 6°F. per minute.

1.6.3 When highest part temperature reaches 275°F. apply 100 psi and hold for 60 minutes.

1.6.4 Heat to 400°F. at 4 to 6°F. per minute.

1.6.5 Hold at 400°F. full vacuum and 100 psi for 120 minutes.

1.6.6 Cool from 400°F. to 150°F. at 2 to 3°F. per minute under full vacuum and 100 psi.

1.6.7 Release pressure and vacuum and allow to cool to room temperature.

1.6.8 Remove bleeder materials and remove from mold.

1.7 <u>Postcure</u>

1.7.1 Place in room temperature oven and heat to 350°F. at 2°F. per minute.

1.7.2 Hold at 350°F. for 2 hours.

1.7.3 Heat to 400°F. at 2°F. per minute.

1.7.4 Hold at 400°F. for 2 hours.

1.7.5 Heat to 450°F. at 2°F. per minute.

1.7.6 Hold at 450°F. for 48 hours.

1.7.7 Cool to below 150°F. at 1°F. per minute or less before removing from oven.

TABLE A-1

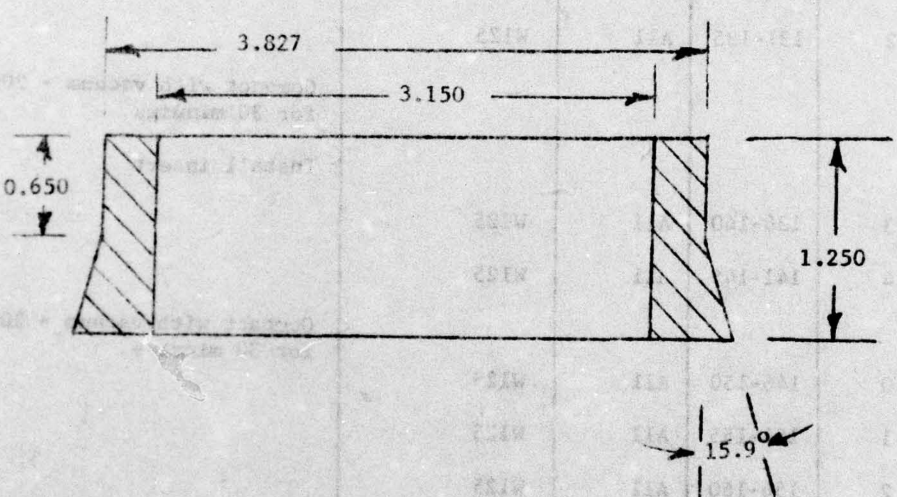
FABRICATION SEQUENCE

STEP	INDEX	PLY	ZONE	CUTTER	TOOLING/NOTES
1.4.1	0	1-5	All	W124	
1.4.2	1	6-10	All	W124	
1.4.3				W124	Compact with vacuum - 200°F. 30 minutes.
1.4.4	2	11-15	All	W124	
1.4.5	3	16-20	All	W124	
1.4.6				W124	Compact with vacuum - 200°F. 40 minutes.
1.4.7	4	21-25	All	W124	
1.4.8	0	26-30	All	W124	
1.4.9					Compact with vacuum - 200°F. 40 minutes.
1.4.10	1	31-35	C thru E	W124 and trim	
1.4.11	2	36-40	C, D, E	W124 and trim	
1.4.12	3	41-45	C, D, E	W124 and trim	
1.4.13	4	46-50	C, D, E	W124 and trim	
1.4.14					Compact with vacuum - 200°F. 50 minutes.
1.4.15					Washer IWL, Ring IRl with vacuum - 200°F. - 40 minutes 8 tons pressure.
1.4.16	0,1	51-60	C	W123-007	
1.4.17	2,3	61-70	C	W123-006	
1.4.18	4,0	71-80	C	W123-005	
1.4.19	1,2	81-90	C	W123-004	
1.4.20	3,4	91-100	C	W123-003	
1.4.21	0,1	101-110	C	W123-002	

TABLE A-1 (Cont)

FABRICATION SEQUENCE

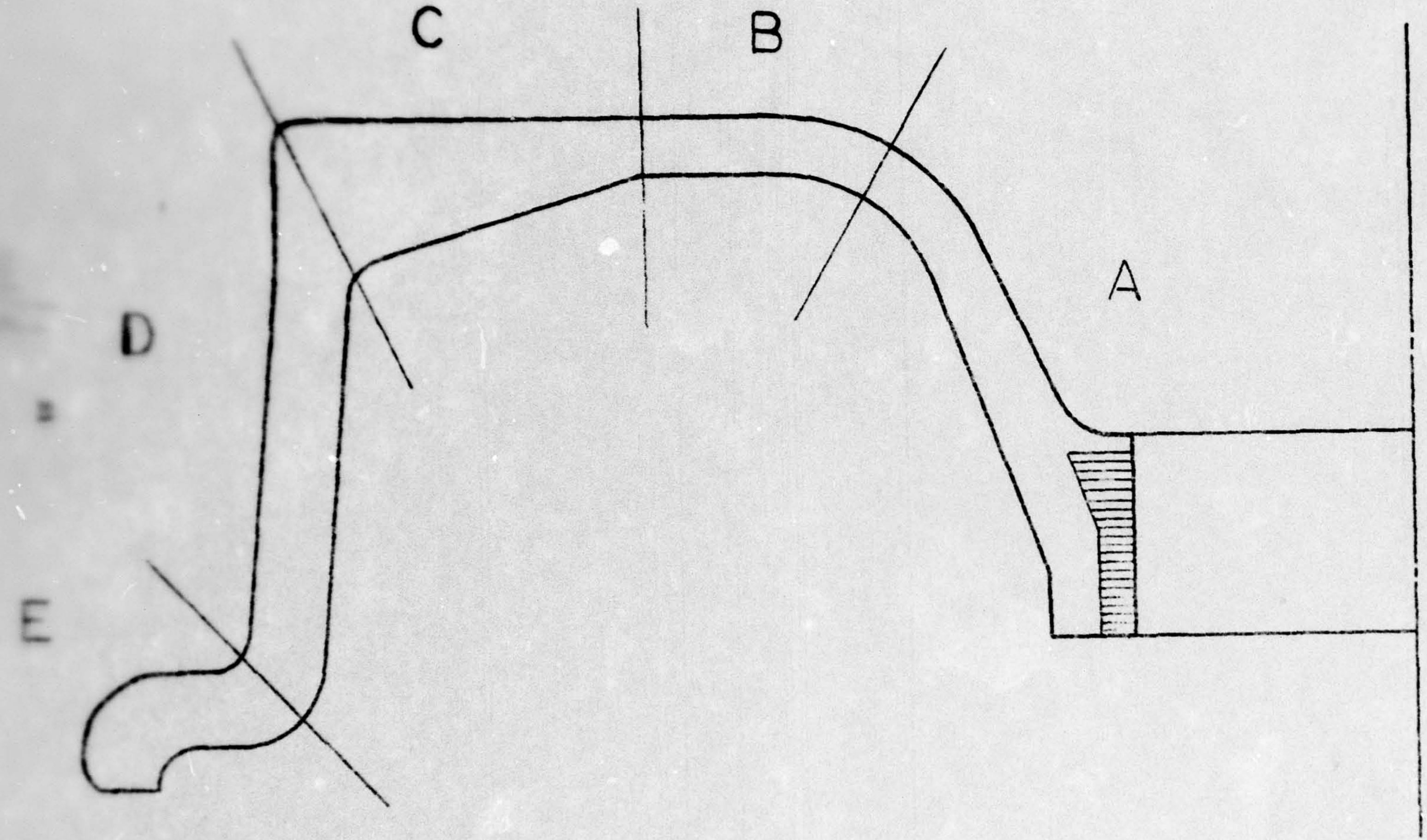
STEP	INDEX	PLY	ZONE	CUTTER	TOOLING/NOTES
1.4.22	2,3	111-120	C	W123-001	
1.4.23					Compact with ring, washer and vacuum at 200°F. for 30 minutes
1.4.24					Remove ring and washer.
1.4.25	0	121-125	All	W125	
1.4.26	1	126-130	All	W125	
1.4.27	2	131-135	All	W125	
1.4.28					Compact with vacuum - 200°F. for 30 minutes.
1.4.29					Install insert
1.4.30	3	136-140	All	W125	
1.4.31	4	141-145	All	W125	
1.4.32					Compact with vacuum - 200°F. for 30 minutes.
1.4.33	0	146-150	All	W125	
1.4.34	1	151-155	All	W125	
1.4.35	2	156-160	All	W125	
1.4.36					Compact with vacuum - 200°F. for 30 minutes
1.4.37	3	161-165	E	W112	
1.4.38	4	166-170	E	W112	
1.4.39	0	171-175	E	W112	
1.4.40	1	176-180	E	W112	
1.5					Prepare for cure
1.6					Cure
1.6.8					Remove from tooling
1.7					Post cure



SKETCH A
MACHINE GEOMETRY
IB INNER WHEEL HALF INSERT

SKETCH B

ZONE IDENTIFICATION - INNER WHEEL



APPENDIX B

FABRICATION AND CURE OF THE

GRAPHITE COMPOSITE T-39 OUTER WHEEL HALF

1. <u>OPERATION</u>

1.1 <u>Preparation</u>

1.1.1 Disassemble wheel mold and clean using Scotch Brite and MEK.

1.1.2 Scrub wheel mold with alconox and water, rinse and air dry.

1.1.3 Spray Frekote 33 over all surfaces of wheel mold and bake in oven at 350°F. for 1/2 hour.

1.1.4 Assemble wheel mold using rubber O-rings in the appropriate places.

1.1.5 Using 3501-6 prepreg tape, lay up 2 sheets (3' x 3' and 3' x 100") with the layers oriented +45, 0, -45, 0, 90.

1.1.6 Cut the 5 layer sheets into the following segments:

3' x 3' into - 3 ea 5" x 3' strips with 0° in the 3' direction

- 8 ea 2 1/2" x 3' strips with 0° in the 3' direction

3' x 100" into - 11" x 36" strips with 0° in the 36" direction.

1.1.7 The electric press may be used to cut patterns with the cutters. Up to 25 plies may be cut at one time in the press.

1.2 Insert Fabrication :

1.2.1 Using a 3' x 8' sheet of 5 layer prepreg (described in 6.1.5) and cutter No. W102 stamp out 58 pieces.

1.2.2 Assemble 5 layer pieces onto insert mold No. W104.

1.2.3 Cure: Place in press, apply 200 psi.

Increase temperature to 350°F. at 5°/minute.

Hold 350°F. for 2 hours.

Machine insert to shape per sketch A.

1.3 Mold Layup Notes

1.3.1 Each layer shall be indexed so as to stagger the joints approximately 10° from previous joints in a clockwise direction.

1.3.2 The layers of 5 ply segments +45, 0, -45, 0, 90 shall alternately be placed 90° side up and 90° side down. 0° is in radial direction.

1.3.3 If lapse time is to be greater than 4 hours, keep wheel assembly at room temperature and under vacuum at all times when not being worked on.

1.3.4 Use sketch B . to reference all zone locations.

1.3.5 The various cutters will be oriented so that 0° is in the radial direction.

1.4 <u>Fabrication</u>

1.4.1 Using cutter No. W114 cut out 16 pieces of 5 ply prepreg and lay them in Zone C, D, E, in 2 layers (ply 1 to 10).

1.4.2 Using cutter No. W113 cut out 48 pieces of 5 ply prepreg and lay them in Zone C in 6 layers (ply 11 to 40).

1.4.3 Compact using a vacuum bag and oven temperature of 250°F. for 30 minutes. Use heavy Armalon and 4 plies of bleeder material.

1.4.4 Using cutter No. W120 cut out 72 pieces of 5 ply prepreg and lay them in all Zones in 9 layers (plies 41-85).

1.4.5 Install preform tool No. OW1 and place in vacuum bag and leave for 8 hours.

1.4.6 Compact as in step 6.4.3 then remove preform tool No. OW1.

1.4.7 Heat insert and alignment plug No. OW2 to approximately 180°F. with heat gun and install them into wheel center.

1.4.8 Using cutter No. W120 cut out 40 pieces of 5 ply prepreg and lay them in all Zones in 5 layers (plies 86-110).

1.4.9 Compact as in step 6.4.3.

1.4.10 Install Ring No. OW2, to maintain correct geometry.

1.4.11 Using cutter No. W113 cut out 24 pieces of 5 ply prepreg and lay them in Zone C in 3 layers (ply 111-125).

1.4.12 Install corner filler as follows:

1.4.12.1 Cut 8 pieces of 181 glass cloth/3501-5 prepreg 3 5/8" x 6".

1.4.12.2 Form each piece into a 6-inch jelly roll.

1.4.12.3 Shape in mold No. HK243 using heat and hand press.

1.4.12.4 Flatten top surface of wheel assembly using Ring No. OW3, and the large press (or vacuum for 8 hours). Washer No. OW5 may be used to hold Ring No. OW3 in place.

1.4.12.5 Install rolled filler pieces around thecircumference of the wheel assembly using a heat gun. Wrap the filler pieces with 6 layers of cellotape and heat with heat gun to compact.

1.4.13 Using cutter No. W111, cut 32 pieces of 5 ply prepreg and lay them in Zone C & D in 4 layers (ply 126 - 145).

1.4.14 Compact as in step 6.4.3, but, use no bleeder plies.

1.4.15 Using cutter No. W120 and modifying it to fit, cut 16 pieces of 5 ply prepreg and lay them in Zones C, D, and E in 2 layers (plies 146-155).

1.4.16 Using cutter No. W112 cut 24 pieces of 5 ply prepreg and lay them in Zone E in 3 layers (ply 156-170).

1.4.17 Apply heavy Armalon in Zone C, D, E, then install ring No. OW3. Put heavy Armalon in Zone A. Place 10 layers of 120 glass cloth and 2 plies of blue peel over all zones. Install 3 thermocouples into prepreg in Zone E as indicated in Sketch B. Place in vacuum bag.

1.5 <u>Cure</u>

1.5.1 Increase temperature to 275° at 5°/minute.

1.5.2 Hold at 275°F. for 30 minutes with vacuum press.

1.5.3 Pressurize to 100 psi.

1.5.4 Hold 275° and 100 psi for 30 minutes.

1.5.5 Raise temperature to 300°F., hold 30 minutes.

1.5.6 Raise temperature to 350°F., hold for 2 hours.

1.5.7 Cool to 150°F. before releasing pressure . Maximum cooldown rate = 5°/minute.

1.6 **Postcure**

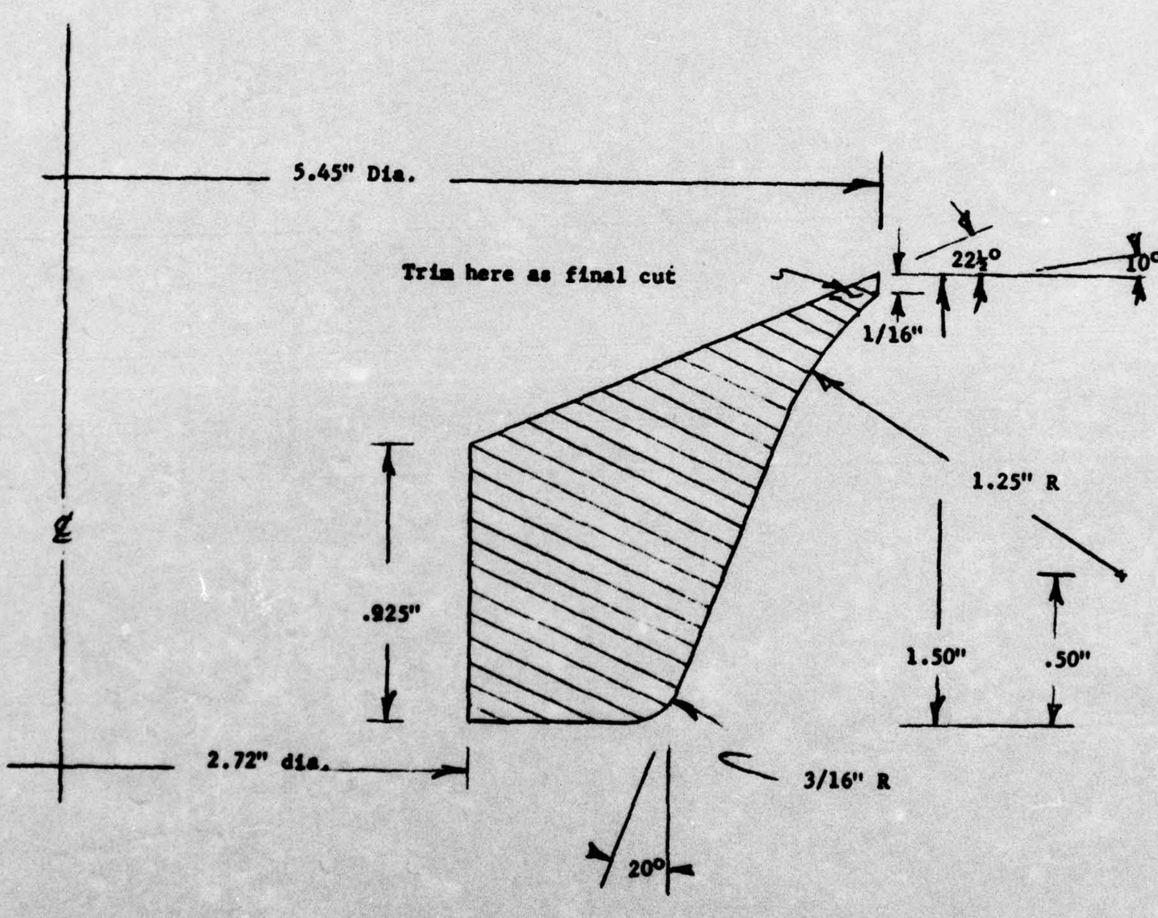
1.6.1 Increase temperature at 1° per minute to 400°F.

1.6.2 Hold at 400° for 2 hours.

1.6.3 Cool down at 1° per minute to room temperature.

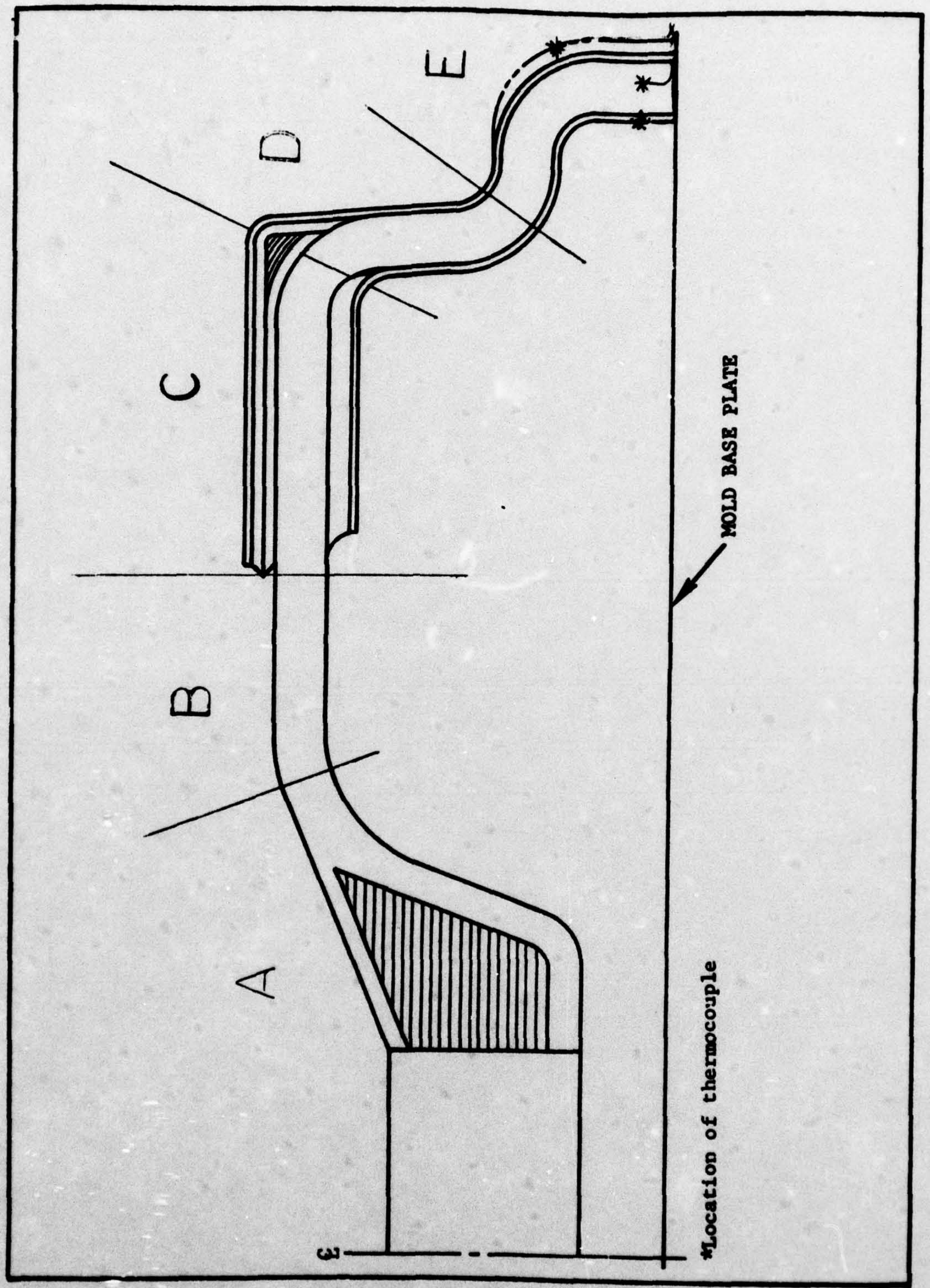
SKETCH A

MACHINING GEOMETRY, OB WHEEL HALF INSERT



Scale: 2/1

SKETCH B
ZONE IDENTIFICATION - OUTER WHEEL



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