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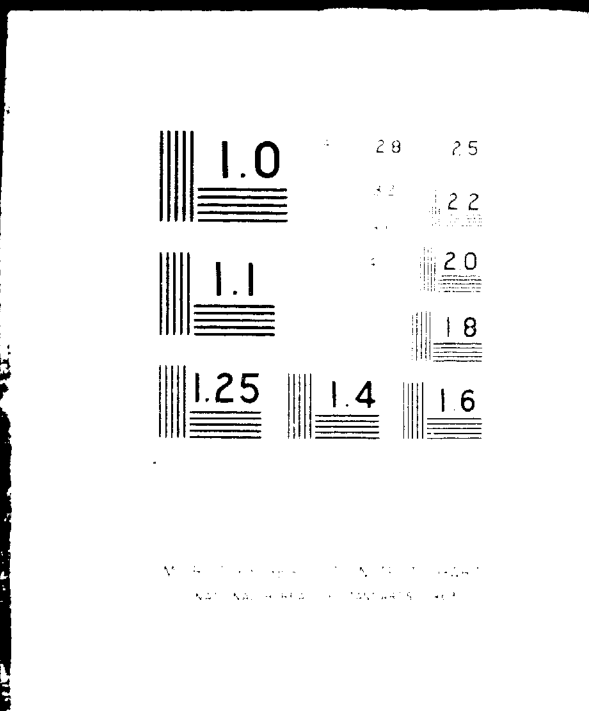

B.F.Goodrich

B.F.Goodrich Aerospace & Defense Products
A Division of The B.F.Goodrich Company
Wheel and Brake Plant
Troy, Ohio

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CR-134117

ENGINEERING REPORT NO 4239

PART II

NASA Wheel and Brake Material Tradeoff Study for Space Shuttle Type Environmental Requirements

May 8, 1973

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Wheel and Brake Plant
Troy, Ohio

H. C. Sunderman

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Chief Engineer

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ABSTRACT

NASA Wheel and Brake Material Trade-Off Study

This investigation covers material selection and trade-off for the structural components of the wheel and brake optimizing weight vs cost and feasibility for the space shuttle type application. Analytical methods were used to determine section thickness for various materials ending with a table showing weight vs. cost trade-off. The wheel and brake were further optimized by considering design philosophies that deviate from standard aircraft specifications and designs that best utilize the materials being considered.

INTRODUCTION:

The purpose of this study was to design a lightweight wheel and brake which would be lighter than the latest state-of-the-art designs. To insure optimization between weight and cost, five basic metals were considered: Steel, titanium, aluminum, magnesium, and beryllium. For the wheel, the optimum material was selected and the design was subjected to four additional loading philisophies.

RESULTS:

BRAKE MATERIAL TRADE-OFF STUDY

Table I lists the material weight cost trade-off for the structural components of the brake as shown by 14-1493-2. These components when combined with the heat sink material, make up the total brake weight. There are two lightweight and heat sink materials under consideration for the space shuttle type application; one being structural carbon and the other being carbon or sintered iron lined beryllium. The heat sink evaluation and study is reported in Engineering Report No. 4239, Part III.

TABLE I

BRAKE MATERIAL TRADE-OFF STUDY

MATERIAL	WEIGHT LBS	WEIGHT SAVED (LBS)	BUDGETARY PRICES**	* COST/ LBS SAVED
Piston Housing				
Aluminum	15.4	----	$ 340.00	----
Magnesium	9.6	5.8	$ 400.00	$10.20
Torque Tube				
Steel	34.6	----	$ 525.00	----
Titanium	19.7	15.0	$1,878.00	90.2
Beryllium	12.7	21.9	$6,600.00	$277.69
Back Plate				
Titanium	7.769	----	$ 800.00	----
Beryllium	7.098	.671	$2,200.00	$2,100.00

$$* \text{ COST/LBS SAVED} = \frac{\text{Difference in Price}}{\text{Difference in Weight}}$$

** Based on 100 Piece Order

RESULTS: (continued)

The magnesium piston housing offers a cheap weight saving but presents a fire hazard. The fire hazard would be more probable with the carbon heat sink since it must operate approximately 1000°F hotter than the beryllium heat sink to be weight effective.

Three materials were considered for the torque tube. Steel being the state-of-the-art for the high performance carbon heat sink and titanium state-of-the art for the beryllium heat sink. The titanium torque would need to be proven compatible with the carbon heat sink designed to the space shuttle requirements. Beryllium, the lightest torque tube has not been tried in a torque tube application although it has proven successful in other structural applications. The high heat capacity and conductivity of the beryllium torque tube could make it compatible with both the carbon and beryllium heat sinks.

Both beryllium and titanium back plates are in production on high-performance military aircraft. The material selection for the back plate depends only on the cost trade-off.

WHEEL MATERIAL TRADE-OFF STUDY

Table II lists the material weight cost trade-off for the wheel. The table lists the aluminum and beryllium wheel weights based on the same design, and a beryllium wheel with the design optimized for the beryllium material.

RESULTS (continued)

TABLE II

WHEEL WEIGHT - COST TRADE-OFF

Material	Weight LBS	Budgetary Cost*	Cost/ Lbs/Saved
Aluminum	116.5	$ 1325.00	----
Beryllium	79.9	----	----
Optimized Beryllium	70.4	$7200.00	$1530.00

* Based on 100-Piece Order

WHEEL DESIGN STUDY:

The design philosophy and specifications used for commercial aircraft wheels were reviewed for possible changes that would allow additional weight reduction. Table III shows a comparison of design conditions vs weight for the optimized beryllium wheel design.

RESULTS: (continued)

TABLE III

DESIGN CONDITION VS WEIGHT

Load Condition *	Tire Deflection @ Rotor Load @ -55°F	Burst Pressure	Design Load	Weight
1 **	37%	1.5 x Bottoming Pressure	Limit Comb.	70.4
2	32%	3.5 x Rated Inflation	Ultimate Comb.	91.6
3	40%	1.5 x Bottoming Pressure	Limit Comb.	68.6
4	40%	3.5 x Rated Inflation	Ultimate Comb.	84.7
5	40%	3.5 x Rated Inflation	Limit Comb.	77.2

** Load Condition used in the weight cost trade-off study.

* Roll Life 100 miles for all conditions.

CONCLUSICNS:

1. The lightest brake would consist of a magnesium piston housing, beryllium torque tube and beryllium back plate.

2. The magnesium piston housing and beryllium back plate are current state-of-the art designs and need no development. The beryllium torque tube would require development, but would offer a low cost weight saving even when compared to the titanium torque tube.

3. The beryllium wheel offers the greatest potential weight saving in current lightweight wheel and brake designs. The development of the wheel would be expensive and the application would have to justify $1,500.00 cost per pound weight saved.

4. The wheel design study indicated that design philosophies and specifications used for commercial and military applications could unnecessarily penalize the space shuttle, weight wise. Careful consideration should be given to tire deflection, wheel burst pressure, and trade-off in designing the wheel to limit or ultimate load conditions.

BRAKE MATERIAL TRADE-OFF STUDY

BRAKE CALCULATIONS

Loads

The brake structural components were designed to the following load conditions:

Condition	Load	Strength Criteria
Normal Operating Pressure	1000 psi	
Maximum Operating Pressure	2000 psi	
Proof Pressure	3000 psi	No Yield
Burst Pressure	4000 psi	No Failure
Max. Static Torque (0.55 Gnd. Coef.)	54700 lb-ft	No Yield
Hot Ult. Structural Torque (0.80 Gnd. Coef.)	79564 lb-ft	No Failure
Cold Ult. Structural Torque (1.20 Gnd. Coef.)	119400 lb-ft	No Failure

Materials

The following materials were considered for the various components of the brake. Aluminum and magnesium were not evaluated on the components in direct contact with the heat sink because of their temperature limitation. See Table IV for material properties:

A. Piston Housing Assembly

1. 7175-T66 Forged Aluminum
2. Ti-7Al-4mo Forged Titanium
3. AZ80A-T5 Forged Magnesium
4. S-240 Beryllium

B. Torque Tube

1. 4140 Forged Steel
2. Ti-7Al-4mo Forged Titanium
3. S-240 Beryllium

C. Backplate

1. 4140 Forged Steel
2. Ti-7Al-4mo Forged Titanium
3. S-240 Beryllium

Maximum operating temperature for each material was limited to that temperature which produced a loss of 40 percent of room temperature properties.

Steel	$950^{\circ}F$
Titanium	$900^{\circ}F$
Beryllium	$825^{\circ}F$

The piston housing was analyzed for room temperature only because it is insulated from the heat sink.

TABLE IV

MATERIAL PROPERTIES

MATERIAL	ROOM TEMPERATURE STRENGTH				MAX. OPERATING TEMP. STRENGTH			
	Ultimate Tensile (psi)	Yield Tensile (psi)	Ultimate Shear (psi)	Yield Shear (psi)	Ultimate Tensile (psi)	Yield Tensile (psi)	Ultimate Shear (psi)	Yield Shear (psi)
7175-T66 Aluminum Forging	86,000	76,000						
AZ80 A-T5 Magnesium Forging	50,000	34,000						
S-240 Beryllium	40,000	30,000	24,000	18,000	24,000 ($825^{\circ}F$)	18,000 ($825^{\circ}F$)	14,4000 ($825^{\circ}F$)	11,9000 ($825^{\circ}F$)
Ti-7Al-4Mo Titanium	160,000	150,000	96,000	90,000	96,000 ($900^{\circ}F$)	90,000 ($900^{\circ}F$)	57,600 ($900^{\circ}F$)	54,000 ($900^{\circ}F$)
4140 Steel Forging	180,000	163,000	108,000	98,000	108,000 ($950^{\circ}F$)	98,000 ($950^{\circ}F$)	64,800 ($950^{\circ}F$)	58,600 ($950^{\circ}F$)

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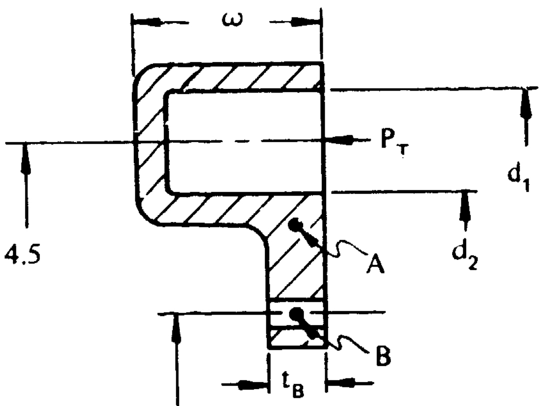
ANALYSIS

The methods of anaysis are shown here and not the actual values for each component of the brake:

Piston Housing:



P_T = total thrust load
= 19.8 p

$$\text{Moment at A} = \frac{1.5\,(d - d_A)\,(d_1 + d_2)^2/2\pi d\,(6\omega + d_1 - d_2)\omega^3 - a\,(\lambda a_3 - \lambda a_1\,\lambda b_3/\lambda b_1)/t^3}{1.5\,(d_1 + d_2)^2/6\omega + d_1 - d_2)\omega^3 + a\,(\lambda a_2 - \lambda a_1\;\lambda b_2/\lambda b_1)/t^3}$$

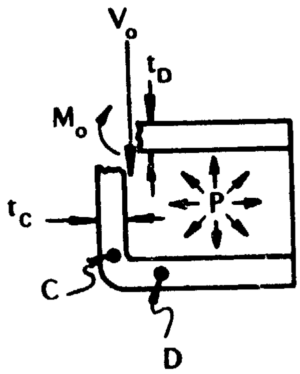
where:
$\lambda a_1 = 24/[(a/b) - 1]$
$\lambda b_1 = 15.6[(a/b)^2 + .539]/a/b[(a/b)^2 - 1]$
$\lambda a_2 = 15.6[.539(a/b)^2 + 1]/[(a/b)^2 - 1]$
$\lambda b_2 = 24a/b/[(a/b)^2 - 1]$
$\lambda a_3 = \{(2.483\ \ln a/b/[(a/b)^2 - 1]\} + .668$
$\lambda b_3 = \{(2.483\ a/b\ \ln a/b)/[(a/b)^2 - 1]\} + .668/a/b$
$a = d_A/2$
$b = d_B/2$

$$\text{Moment at B} = (\lambda_{b_3} P_T + \lambda_{b_2} M_A)/\lambda_{b_1}$$

and stresses at A & B are:

$$\sigma_A = 6M_A/t_A^{\,2}$$
$$\sigma_B = 6M_B/t^2$$

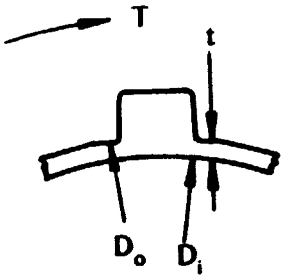
Mo & Vo are determined from the deflections & rotations of the cylinder - head junction – Ref. 1.



$$\sigma_C = \frac{6Mo}{t_C^{\,2}} + \frac{Vo}{t_C}$$

$$\sigma_D = \frac{6Mo}{t_D^{\,2}} + \frac{pr}{2t_D}$$

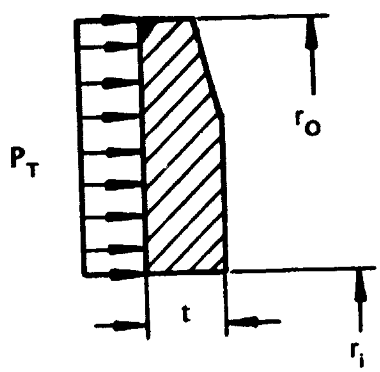
Torque Tube:



T = total brake torque

Torsional Shear Stress: $\tau_1 = \dfrac{16 \cdot T \cdot D_o}{\pi\,(D_o^{\,4} - D_i^{\,4})}$

Backplate:



$$\sigma_{max} = \frac{\beta p_o r_o}{t^2}$$ Ref. 2

where: $\beta = \text{fn} \left\{ r_o/r_i \right\}$

$p_o = P_T / \pi\,(r_o^{\,2} - r_i^{\,2})$

RESULTS

MATERIAL	PISTON HOUSING	TORQUE TUBE	BACK PLATE
Aluminum	15.347 lbs.	—	—
Magnesium	9.619 lbs.	—	—
Beryllium	10 127 lbs.	12.745 lbs.	7.098 lbs.
Titanium	23.050 lbs.	19.699 lbs.	7.769 lbs.
Steel	—	34.317 lbs.	11.794 lbs.

The following materials are recommended for the various structural members of the brake assembly based on weight saved only:

Piston Housing	Magnesium	AZ80A-T5
Torque Tube	Beryllium	S-240
Back Plate	Beryllium	S-240

WHEEL MATERIAL TRADE-OFF STUDY

WHEEL CALCULATIONS:

PART I: MATERIAL TRADE-OFF

Loads

The loads shown assume a 49 x 17 tire loaded to 37% deflection:

Inflation Pressure	293 psi @ RT 224 psi @ -55°F
Burst Pressure	510 psi @ RT
Limit Combined Load	168,000 lb. radial ± 59,000 lb. side @ -55°F
Roll Load	60,000 lb. for 100 miles @ RT

MATERIALS

All materials are forged except for beryllium which is hot pressed. See Table V.

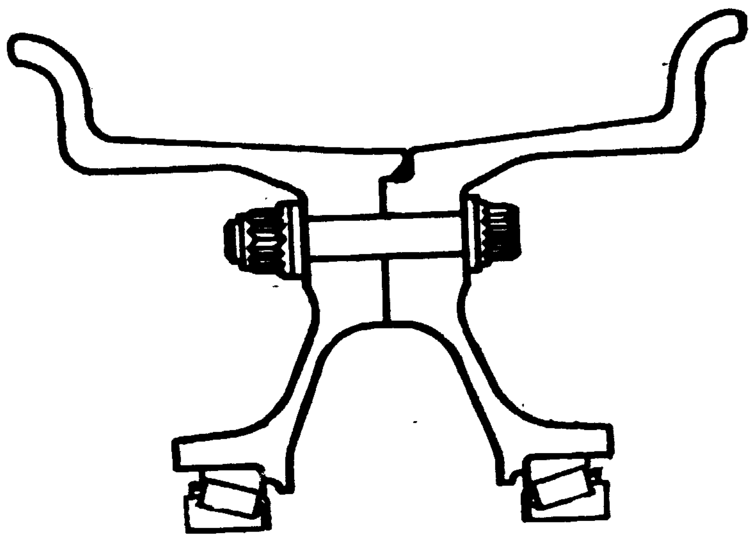
TABLE V

MATERIAL PROPERTIES (Values are in ksi)

Material	F_{tu}	F_{tu}	F_{tu} @ -55	F_{ty} @ -55	Fatigue F[illegible]
7049-T73 Alum.	72.0	62.0	74.0	65.0	10.5
2014-T6 Alum.	65.0	55.0	67.0	57.5	10.5
7075-T73 Alum.	66.0	56.0	68.0	58.5	9.0
7175-T66 Alum.	86.0	76.0	88.5	79.5	10.5
ZK60A-T6 Mag.	42.0	26.0	45.0	28.5	5.0
EK31A-T6 Mag.	45.0	26.0	48.0	28.5	5.0
Ti-6Al-4V-Tit.	160.0	150.0	181.0	171.0	37.0
Ti-7Al-4Mo Tit.	170.0	160.0	192.0	182.5	37.0
4340 Steel	180.0	163.0	186.0	170.0	38.0
4140 Steel	180.0	163.0	186.0	170.0	38.0
(Brush S-350) Beryllium	66.0	55.0	71.0	60.0	38.0

ANALYSIS

The wheel configuration used for this part was a split wheel held together with bolts and one bearing in each wheel half.



The methods used include analysis for rings, cylinders, and circular plates. The bearing reactions are calculated using the methods given in the "Timken Engineering Journal" (Reference 3). A computer program was used to calculate the section thicknesses required. This program uses the thickness as a variable and iterates until a specified margin of safety is reached. The results of the computer are shown in the following pages.

COMPUTER SOLUTION

97153 WHEEL DESIGN PROGRAM

WHEEL - NASA SPACE SHUTTLE
MAT'L -[illegible]-T73 FORGED ALUM
DESIGN LOADS -
1 BURST 510.PSI
2 ULT COMB 100000.RADIAL 59000.SIDE
3 ROLL 60000.RADIAL FOR 100.MILES
SURF COMPRESSIVE STRESS 15000.PSI

SECTION	X	THICKNESS	MS-BURST	MS-ULT	MS-ROLL
FLANGE		0.5900	59.1	36.4	1.0
RIM	0.44	0.7650	55.6	36.2	0.8
RIM	0.81	0.7040	55.8	36.2	0.8
RIM	1.19	0.6340	[illegible]	36.2	0.8
RIM	1.56	0.5500	55.8	36.2	0.7
RIM	1.94	0.4650	55.7	36.1	0.7
RIM	2.31	0.3430	55.9	36.3	0.9
RIM	2.69	0.1770	5[illegible].7	36.1	0.7
RIM	3.06	0.2090	57.8	35.4	0.0
RIM	3.44	0.2270	55.6	36.0	0.6
RIM	3.81	0.2200	55.5	35.9	0.5
RIM	4.19	0.2150	55.9	36.2	0.8
RIM	4.56	0.1700	53.8	36.2	0.8
RIM	4.94	0.1500	53.0	35.5	0.1
RIMWEB	6.85	0.2150	152.9	32.3	0.5
RIMWEB	7.04	0.1910	131.7	32.6	0.4
RIMWEB	7.22	0.1628	102.2	34.2	0.9
RIMWEB	7.41	0.2340	122.7	34.4	0.6
RIMWEB	7.60	0.2030	107.1	38.2	0.4
RIMWEB	7.79	0.3215	122.7	34.4	0.6
RIMWEB	7.97	0.3507	102.2	34.2	0.9
RIMWEB	8.16	0.3758	131.7	32.6	0.4
RIMWEB	8.35	0.4070	152.9	32.3	0.5
TIEBOLT	N=16	DO= 0.375	235.3	151.3	370.4
WEB-RO		1.0700	1140.0	0.1	100.0
WEB-RI		1.8600	1140.0	0.0	100.0
HUB		0.4000	1140.0	0.1	100.0

WHEEL DIMENSIONS -
D=20.000 H= 1.750 W= 1.200 WC= 1.500
D1=19.430 D2=16.950 H'= 1.950 T2= 1.250
L1= 9.600 RI= 4.700 RO= 3.400

TIRE OD=47.950 BOLT STR= 150KSI

BASIC WHEEL DESIGN PROGRAM

WHEEL - NASA SPACE SHUTTLE
MAT'L -[illegible]-T6 ALUM FORGING
DESIGN LOADS -
1 BURST 510.PSI
2 ULT COMB 100000.RADIAL 59000.SIDE
3 ROLL 60000.RADIAL FOR 100.MILES
SURF COMPRESSIVE STRESS 15000.PSI

SECTION	X	THICKNESS	MS-BURST	MS-ULT	MS-ROLL
FLANGE		0.5330	17.3	0.6	27.9
RIM	0.44	0.6000	17.6	0.9	28.4
RIM	0.81	0.6040	17.4	0.7	[illegible]
RIM	1.19	0.5370	17.6	0.9	26.3
RIM	1.56	0.4000	17.0	0.3	27.4
RIM	1.94	0.3700	[illegible]	0.1	27.1
RIM	2.31	0.2100	17.7	1.0	[illegible]
RIM	2.69	0.1007	17.7	1.0	[illegible]
RIM	3.06	0.1400	16.7	0.1	27.0
RIM	3.44	0.1970	17.1	0.4	27.6
RIM	3.81	0.1000	17.5	0.3	[illegible]
RIM	4.19	0.1500	17.0	0.9	[illegible]
RIM	4.56	0.1000	17.6	0.9	[illegible]
RIM	4.94	0.1100	17.4	0.7	[illegible]
RIMWEB	6.85	0.1900	101.5	0.3	[illegible]
RIMWEB	7.04	0.1770	37.0	0.8	56.9
RIMWEB	7.22	0.1520	60.1	1.0	55.5
RIMWEB	7.41	0.1500	31.4	0.8	[illegible]
RIMWEB	7.60	0.2040	73.5	0.6	55.2
RIMWEB	7.79	0.3000	81.4	0.3	[illegible]
RIMWEB	7.97	0.3200	60.1	1.0	55.3
RIMWEB	8.16	0.3500	37.6	0.8	56.9
RIMWEB	8.35	0.3010	101.5	0.3	57.1
TIEBOLT	N=18	DO= 0.375	210.1	120.2	573.0
WEB-RO		1.1400	1000.0	0.0	100.0
WEB-RI		1.9000	1000.0	0.7	100.0
HUB		0.4000	1000.0	0.9	100.0

WHEEL DIMENSIONS -
D=20.000 H= 1.750 W= 1.200 WC= 1.500
D1=19.430 D2=16.950 H'= 1.550 T2= 1.250
L1= 9.600 RI= 4.700 RO= 8.400

TIRE OD=47.950 BOLT STR= 180KSI

BASIC WHEEL DESIGN PROGRAM

WHEEL - NASA SPACE SHUTTLE
MAT'L -7075-T73 AL FORGING
DESIGN LOADS -
1 BURST 510.PSI
2 ULT COMB 100000.RADIAL 59000.SIDE
3 ROLL 60000.RADIAL FOR 100.MILES
SURF COMPRESSIVE STRESS 15000.PSI

SECTION	X	THICKNESS	MS-BURST	MS-ULT	MS-ROLL
FLANGE		0.5340	17.7	0.9	14.6
RIM	0.44	0.6570	17.7	1.0	14.6
RIM	0.81	0.5950	17.5	0.7	14.3
RIM	1.19	0.5200	17.5	0.8	14.4
RIM	1.56	0.4500	17.6	0.9	14.5
RIM	1.94	0.3050	17.5	0.7	14.3
RIM	2.31	0.1200	17.5	0.7	14.3
RIM	2.69	0.1650	16.8	0.2	13.4
RIM	3.06	0.1070	16.7	0.1	13.3
RIM	3.44	0.1940	17.1	0.4	13.8
RIM	3.81	0.1050	17.6	0.9	14.5
RIM	4.19	0.1550	17.8	1.0	14.7
RIM	4.56	0.1950	[illegible]	0.5	13.9
RIM	4.94	0.1100	16.9	0.3	13.6
RIMWEB	6.85	0.1940	102.8	0.3	23.3
RIMWEB	7.04	0.1750	88.5	0.2	22.2
RIMWEB	7.22	0.1517	67.7	0.2	21.3
RIMWEB	7.41	0.1249	40.4	1.0	13.4
RIMWEB	7.60	0.2620	31.8	0.9	22.2
RIMWEB	7.79	0.2900	40.4	1.0	18.4
RIMWEB	7.97	0.3200	67.7	0.8	21.3
RIMWEB	8.16	0.3540	88.5	0.2	22.2
RIMWEB	8.35	0.3700	102.8	0.3	23.3
TIEBOLT	N=1[illegible]	DO= 0.875	[illegible]	123.1	370.5
WEB-RO		1.1500	1020.0	0.2	100.0
WEB-RI		1.9700	1020.0	0.6	100.0
HUB		0.4500	1020.0	0.7	100.0

WHEEL DIMENSIONS -
D=20.000 H= 1.750 W= 1.200 WC= 1.500
D1=19.430 D2=16.950 H'= 1.[illegible] T2= 1.250
L1= 9.600 RI= 4.700 RO= 3.400

TIRE OD=47.950 BOLT STR= 130KSI

BASIC WHEEL DESIGN PROGRAM

WHEEL - NASA SPACE SHUTTLE
MAT'L -7175-T66 FORG ALUM
DESIGN LOADS -
1 BURST 510.PSI
2 ULT COMB 100000.RADIAL 59000.SIDE
3 ROLL 60000.RADIAL FOR 100.MILES
SURF COMPRESSIVE STRESS 15000.PSI

SECTION	X	THICKNESS	MS-BURST	MS-ULT	MS-ROLL
FLANGE		0.4870	32.8	13.9	0.7
RIM	0.44	0.5600	33.1	14.1	1.0
RIM	0.81	0.5000	32.7	13.8	0.6
RIM	1.19	0.4440	32.6	13.7	0.5
RIM	1.56	0.3700	32.3	13.5	0.2
RIM	1.94	0.2700	32.6	13.7	0.5
RIM	2.31	0.1243	32.9	14.0	0.8
RIM	2.69	0.1530	32.7	13.8	0.6
RIM	3.06	0.1000	32.9	13.9	0.7
RIM	3.44	0.1620	32.3	13.5	0.2
RIM	3.81	0.1340	32.6	13.8	0.5
RIM	4.19	0.0970	32.5	13.6	0.3
RIM	4.56	0.0920	32.0	13.7	0.5
RIM	4.94	0.0937	33.1	14.1	1.0
RIMWEB	6.85	0.1600	137.4	6.3	0.4
RIMWEB	7.04	0.1500	124.0	6.6	0.3
RIMWEB	7.22	0.1329	105.4	8.3	1.0
RIMWEB	7.41	0.1175	77.5	9.9	1.0
RIMWEB	7.60	0.2240	137.0	[illegible]	1.0
RIMWEB	7.79	0.2720	77.5	9.9	1.0
RIMWEB	7.97	0.3060	105.4	8.3	1.0
RIMWEB	8.16	0.3300	124.8	6.6	0.3
RIMWEB	8.35	0.3650	137.4	6.3	0.4
TIEBOLT	N=18	DO= 0.875	[illegible]	107.1	370.5
WEB-RO		0.9600	1420.0	0.0	100.0
WEB-RI		1.6700	1420.0	0.1	100.0
HUB		0.3240	1420.0	0.9	632.0

WHEEL DIMENSIONS -
D=20.000 H= 1.750 W= 1.200 WC= 1.500
D1=19.430 D2=16.950 H'= 1.950 T2= 1.250
L1= 9.600 RI= 4.700 RO= 8.400

TIRE OD=47.950 BOLT STR= 180KSI

COMPUTER SOLUTION

BASIC WHEEL DESIGN PROGRAM

WHEEL - NASA SPACE SHUTTLE
MAT'L -6AL-4V TITANIUM FORG
DESIGN LOADS -
1 BURST 510.PSI
2 ULT COMB 160000.RADIAL 59000.SIDE
3 ROLL 60000.RADIAL FOR 100.MILES
SURF COMPRESSIVE STRESS 15000.PSI

SECTION	X	THICKNESS	MS-BURST	MS-ULT	MS-ROLL
FLANGE		0.3370	25.6	7.7	0.6
RIM	0.44	0.3470	25.7	7.8	0.8
RIM	0.81	0.2970	25.4	7.6	0.5
RIM	1.19	0.2410	25.3	7.5	0.3
RIM	1.56	0.1700	25.0	7.3	0.0
RIM	1.94	0.0753	25.6	7.7	0.6
RIM	2.31	0.0930	25.5	7.7	0.6
RIM	2.69	0.0530	25.9	8.0	1.0
RIM	3.06	0.0415	25.4	7.5	0.4
RIM	3.44	0.0456	25.6	7.8	0.7
RIM	3.81	0.0454	25.3	7.9	0.8
RIM	4.19	0.0430	25.6	7.7	0.6
RIM	4.56	0.0419	25.8	7.9	0.8
RIM	4.94	0.0420	25.2	7.4	0.2
RIMWEB	6.95	0.1040	188.9	0.4	5.3
RIMWEB	7.14	0.1030	137.2	0.2	5.0
RIMWEB	7.32	0.0976	176.5	0.9	5.4
RIMWEB	7.51	0.0874	155.2	1.0	4.4
RIMWEB	7.70	0.0734	117.3	0.6	2.2
RIMWEB	7.89	0.1000	155.2	1.0	4.4
RIMWEB	8.07	0.2050	176.5	0.9	5.4
RIMWEB	8.26	0.2310	137.2	0.2	5.0
RIMWEB	8.45	0.2550	188.9	0.4	5.3
TIEBOLT	N=18	DO= 0.375	156.5	89.4	549.2
WEB-RO		0.6750	2900.0	1.0	333.0
WEB-RI		1.1700	2900.0	0.4	280.4
HUB		0.1530	2900.0	0.6	141.2

WHEEL DIMENSIONS -
D=20.000 H= 1.750 W= 1.200 WC= 1.000
D1=19.430 D2=16.950 H'= 1.950 T2= 1.150
L1= 9.600 RI= 4.700 RO= 8.400

TIRE OD=47.950 BOLT STR 130KSI

BASIC WHEEL DESIGN PROGRAM

WHEEL - NASA SPACE SHUTTLE
MAT'L -[illegible] TITANIUM FORG
DESIGN LOADS -
1 BURST 510.PSI
2 ULT COMB 160000.RADIAL 59000.SIDE
3 ROLL 60000.RADIAL FOR 100.MILES
SURF COMPRESSIVE STRESS 15000.PSI

SECTION	X	THICKNESS	MS-BURST	MS-ULT	MS-ROLL
FLANGE		0.3350	32.3	13.5	0.5
RIM	0.44	0.3449	32.6	13.7	0.8
RIM	0.81	0.2940	32.2	13.4	0.4
RIM	1.19	0.2330	31.9	13.2	0.1
RIM	1.56	0.1030	32.7	13.8	0.9
RIM	1.94	0.0756	32.6	13.7	0.8
RIM	2.31	0.0925	32.7	13.8	0.9
RIM	2.69	0.0920	32.0	13.2	0.2
RIM	3.06	0.0415	32.4	13.6	0.6
RIM	3.44	0.0450	31.9	13.1	0.0
RIM	3.81	0.0440	32.6	13.8	0.8
RIM	4.19	0.0425	32.7	13.8	0.9
RIM	4.56	0.0424	32.7	13.8	0.9
RIM	4.94	0.0417	32.6	13.7	0.8
RIMWEB	6.95	0.1007	199.5	2.9	0.9
RIMWEB	7.14	0.1005	199.4	2.8	0.8
RIMWEB	7.32	0.0955	188.6	3.2	0.9
RIMWEB	7.51	0.0860	165.5	3.6	0.4
RIMWEB	7.70	0.0750	130.4	5.4	0.8
RIMWEB	7.89	0.1500	165.5	3.6	0.4
RIMWEB	8.07	0.1900	188.6	3.2	0.9
RIMWEB	8.26	0.2250	199.4	2.8	0.8
RIMWEB	8.45	0.2500	199.5	2.9	0.9
TIEBOLT	N=18	DO= 0.375	161.5	93.9	571.1
WEB-RO		0.6500	3100.0	0.2	254.7
WEB-RI		1.1300	3100.0	0.2	220.3
HUB		0.1400	3100.0	0.7	125.1

WHEEL DIMENSIONS -
D=20.000 H= 1.750 W= 1.200 WC= 1.000
D1=19.430 D2=16.950 H'= 1.950 T2= 1.150
L1= 9.600 RI= 4.700 RO= 8.400

TIRE OD=47.350 BOLT STR= 130KSI

BASIC WHEEL DESIGN PROGRAM

WHEEL - NASA SPACE SHUTTLE
MAT'L - ZK60A MAG FORG
DESIGN LOADS -
1 BURST 510.PSI
2 ULT COMB 166000.RADIAL 59000.SIDE
3 ROLL 60000.RADIAL FOR 100.MILES
SURF COMPRESSIVE STRESS 6000.PSI

SECTION	X	THICKNESS	MS-BURST	MS-ULT	MS-ROLL
FLANGE		0.7850	17.5	0.8	31.6
RIM	0.44	1.2200	17.1	0.4	31.0
RIM	0.81	1.1500	17.2	0.5	31.1
RIM	1.19	1.0700	16.7	0.1	30.4
RIM	1.56	0.9300	17.7	1.0	31.9
RIM	1.94	0.8950	17.6	0.9	31.7
RIM	2.31	0.7400	17.8	1.0	32.0
RIM	2.69	0.6000	17.5	0.8	31.6
RIM	3.06	0.4000	17.3	0.6	31.3
RIM	3.44	0.3030	17.3	0.6	31.4
RIM	3.81	0.3430	17.6	0.9	31.8
RIM	4.19	0.3680	17.5	0.7	31.6
RIM	4.56	0.3790	17.5	0.8	31.6
RIM	4.94	0.3700	17.7	1.0	31.9
RIMWEB	6.85	0.5200	121.4	0.2	76.1
RIMWEB	7.04	0.8400	173.6	0.7	85.4
RIMWEB	7.22	0.2640	9.5	0.5	28.4
RIMWEB	7.41	0.3110	1.7	0.2	23.0
RIMWEB	7.50	0.4100	0.4	33.9	160.7
RIMWEB	7.79	0.4800	1.7	0.2	23.0
RIMWEB	7.97	0.7300	9.5	0.5	28.4
RIMWEB	8.16	0.5200	173.6	0.7	85.4
RIMWEB	8.35	0.6100	121.4	0.2	76.1
TIEBOLT	N=18	DO= 0.750	241.0	155.6	33.2
WEB-RO		1.7200	420.0	1.0	400.0
WEB-RI		2.9900	420.0	0.7	100.0
HUB		1.0900	420.0	0.4	245.0

WHEEL DIMENSIONS -
D=20.000 H= 1.750 W= 1.200 WC= 1.500
D1=19.430 D2=16.950 H'= 1.950 T2= 1.250
L1= 9.600 RI= 4.700 RO= 8.400

TIRE OD=47.950 BOLT STR= 180KSI

BASIC WHEEL DESIGN PROGRAM

WHEEL - NASA SPACE SHUTTLE
MAT'L -EK31A-T6 MAG FORG
DESIGN LOADS -
1 BURST 510.PSI
2 ULT COMB 160000.RADIAL 59000.SIDE
3 ROLL 60000.RADIAL FOR 100.MILES
SURF COMPRESSIVE STRESS 6000.PSI

SECTION	X	THICKNESS	MS-BURST	MS-ULT	MS-ROLL
FLANGE		0.7850	17.5	0.8	31.8
RIM	0.44	1.2200	17.4	0.7	31.8
RIM	0.81	1.1500	17.7	1.0	32.2
RIM	1.19	1.0700	17.4	0.7	31.8
RIM	1.56	0.9800	16.7	0.1	30.7
RIM	1.94	0.8390	17.6	0.9	32.0
RIM	2.31	0.7000	17.5	0.8	31.9
RIM	2.69	0.6500	17.7	0.9	32.1
RIM	3.06	0.2540	16.9	0.3	31.0
RIM	3.44	0.3000	16.9	0.3	31.0
RIM	3.81	0.3450	17.2	0.6	31.5
RIM	4.19	0.3690	17.3	0.6	31.5
RIM	4.56	0.3790	17.5	0.8	31.9
RIM	4.94	0.3740	17.6	0.9	32.1
RIMWEB	6.85	0.8100	179.2	0.7	75.3
RIMWEB	7.04	0.8200	166.4	0.1	82.2
RIMWEB	7.22	0.2630	10.7	0.8	29.4
RIMWEB	7.41	0.3120	3.5	0.4	23.7
RIMWEB	7.60	0.4000	0.6	50.0	119.0
RIMWEB	7.79	0.4770	3.5	0.4	23.7
RIMWEB	7.97	0.5300	10.7	0.3	29.4
RIMWEB	8.16	0.5700	166.4	0.1	82.2
RIMWEB	8.35	0.6100	179.2	0.7	75.3
TIEBOLT	N=18	DO= 0.750	236.5	130.9	29.2
WEB-RO		1.7200	420.0	1.0	100.0
WEB-RI		2.9900	420.0	0.7	100.0
HUB		1.8900	420.0	0.4	244.8

WHEEL DIMENSIONS -
D=20.000 H= 1.750 W= 1.200 WC= 1.500
D1=19.430 D2=16.950 H'= 1.950 T2= 1.250
L1= 9.600 RI= 4.700 RO= 8.400

TIRE OD=47.950 BOLT STR= 180KSI

COMPUTER SOLUTION

BASIC WHEEL DESIGN PROGRAM

WHEEL - NASA SPACE SHUTTLE
MAT'L -180KSI 4140 STEEL
DESIGN LOADS -
1 BURST 510.PSI
2 ULT COMB 160000.RADIAL 59000.SIDE
3 ROLL 60000.RADIAL FOR 100.MILES
SURF COMPRESSIVE STRESS 50000.PSI

SECTION	X	THICKNESS	MS-BURST	MS-ULT	MS-ROLL
FLANGE		0.3130	17.7	0.9	14.0
RIM	0.44	0.3180	17.3	0.6	13.6
RIM	0.81	0.2700	16.8	0.2	12.9
RIM	1.19	0.2170	17.5	0.9	13.9
RIM	1.56	0.1450	17.5	0.6	13.4
RIM	1.94	0.0725	17.4	0.7	13.6
RIM	2.31	0.0856	17.6	0.9	14.0
RIM	2.69	0.0800	16.6	0.0	12.6
RIM	3.06	0.0382	17.5	0.8	13.8
RIM	3.44	0.0400	17.6	0.9	13.9
RIM	3.81	0.0379	17.6	0.9	14.0
RIM	4.19	0.0360	17.3	0.6	13.5
RIM	4.56	0.0360	17.0	0.3	13.1
RIM	4.94	0.0360	16.7	0.1	12.7
RIMWEB	7.10	0.0960	177.6	0.5	29.1
RIMWEB	7.29	0.0960	178.4	0.7	29.3
RIMWEB	7.47	0.0910	170.3	0.9	29.1
RIMWEB	7.66	0.0815	150.1	0.8	27.8
RIMWEB	7.85	0.0678	115.9	1.0	25.9
RIMWEB	8.04	0.1580	150.1	0.8	27.8
RIMWEB	8.22	0.1740	170.3	0.9	29.1
RIMWEB	8.41	0.1970	178.4	0.7	29.3
RIMWEB	8.60	0.2160	177.6	0.5	29.1
TIEBOLT	N=18 DO=	0.875	151.0	37.8	956.8
WEB-RO		0.6460	3160.0	0.8	100.0
WEB-RI		1.1200	3160.0	0.4	100.0
HUB		0.1450	3160.0	0.6	2782.6

WHEEL DIMENSIONS -
D=20.000 H= 1.750 W= 1.200 WC= 0.600
D1=19.430 D2=16.950 H'= 1.950 T2= 1.000
L1= 9.600 RI= 4.700 RO= 8.400

TIRE OD=47.950 BOLT STR= 180KSI

BASIC WHEEL DESIGN PROGRAM

WHEEL - NASA SPACE SHUTTLE
MAT'L - S-350 BERYLLIUM
DESIGN LOADS -
1 BURST 510.PSI
2 ULT COMB 160000.RADIAL 59000.SIDE
3 ROLL 60000.RADIAL FOR 100.MILES
SURF COMPRESSIVE STRESS 0.PSI

SECTION	X	THICKNESS	MS-BURST	MS-ULT	MS-ROLL
FLANGE		0.5380	17.3	0.6	81.3
RIM	0.44	0.7260	17.7	1.0	82.2
RIM	0.81	0.6670	17.7	1.0	82.2
RIM	1.19	0.6000	17.6	0.8	81.3
RIM	1.56	0.5240	17.6	0.8	81.8
RIM	1.94	0.4330	17.5	0.8	81.8
RIM	2.31	0.2990	17.7	0.9	82.1
RIM	2.69	0.1700	17.3	0.6	81.2
RIM	3.06	0.1960	17.0	0.3	80.5
RIM	3.44	0.2070	17.3	0.6	81.3
RIM	3.81	0.2000	17.1	0.4	80.3
RIM	4.19	0.1690	17.5	0.8	81.8
RIM	4.56	0.1080	17.6	0.3	81.9
RIM	4.94	0.1130	16.8	0.2	80.1
RIMWEB	6.85	0.1980	99.6	0.8	104.2
RIMWEB	7.04	0.1800	87.8	0.4	100.3
RIMWEB	7.22	0.1570	69.0	0.1	96.1
RIMWEB	7.41	0.1307	43.9	0.9	91.5
RIMWEB	7.60	0.2540	73.2	0.5	103.9
RIMWEB	7.79	0.2930	43.9	0.9	91.5
RIMWEB	7.97	0.3220	69.0	0.1	96.1
RIMWEB	8.16	0.3470	87.8	0.4	100.3
RIMWEB	8.35	0.3710	99.6	0.8	104.2
TIEBOLT	N=13 DO=	0.750	254.8	192.4	91.0
WEB-RO		1.1400	1000.0	0.0	197.7
WEB-RI		1.9900	1000.0	0.7	138.3
HUB		0.4600	1000.0	0.9	337.5

WHEEL DIMENSIONS -
D=20.000 H= 1.750 W= 1.200 WC= 0.600
D1=19.430 D2=16.950 H'= 1.950 T2= 1.250
L1= 9.600 RI= 4.700 RO= 8.400

TIRE OD=47.950 BOLT STR= 180KSI

RESULTS

Material	Density (lb/in^3)	Weight of Basic Wheel (lb.)
7049 Aluminum	.101	128.3
2014 Aluminum	.101	116.5
7075 Aluminum	.101	116.5
7175 Aluminum	.101	114.8
ZK60A Magnesium	.065	126.8
EK31A Magnesium	.065	126.8
Ti-6Al-4V	.163	134.8
Ti-7Al-4Mo	.163	134.3
4340 Steel	.283	214.8
4140 Steel	.283	214.8
S-350 Beryllium	.066	79.9

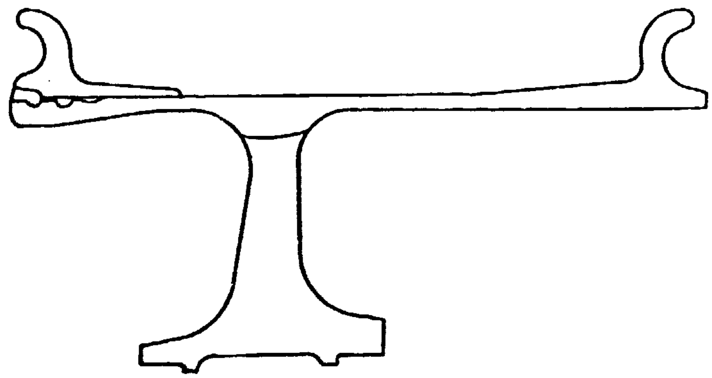
Beryllium is recommended as the best choice of the eleven materials studied.

WHEEL CALCULATIONS - PART II:

LOADS TRADE-OFF

From Part I, a beryllium wheel was chosen as being the best possible choice of the eleven materials studied.

To make the best advantage of a beryllium billet, thereby minimizing cost, it was decided that a configuration change was needed. The sketch below shows the wheel analyzed in this part:



Loads

The following loading conditions were analyzed in this part:

	Load 1	Load 2	Load 3	Load 4	Load 5
Tire Deflection @ -55°F	37%	32%	40%	40%	40%
Burst Pressure	510 psi	1236 psi	472 psi	924 psi	924 psi
Load Type	Limit	Ult	Limit	Ult	Limit
Combined Load (kips) Radial/Side	168 / 59	252 / 88.2	168 / 59	252 / 88.2	168 / 59
Roll Load (kips) Radial / Miles	60 / 100	60 / 100	60 / 100	60 / 100	60 / 100

The philosophy of designing with these loads was to compare the weight difference between the ultimate failure loading and the design limit loading. The ultimate loads are designed to the ultimate material strength and the limit loads are designed to the material yield strength.

Analysis

As in Part I, the analysis includes ring, cylinder, and plate methods; the results are shown in the Table VI below:

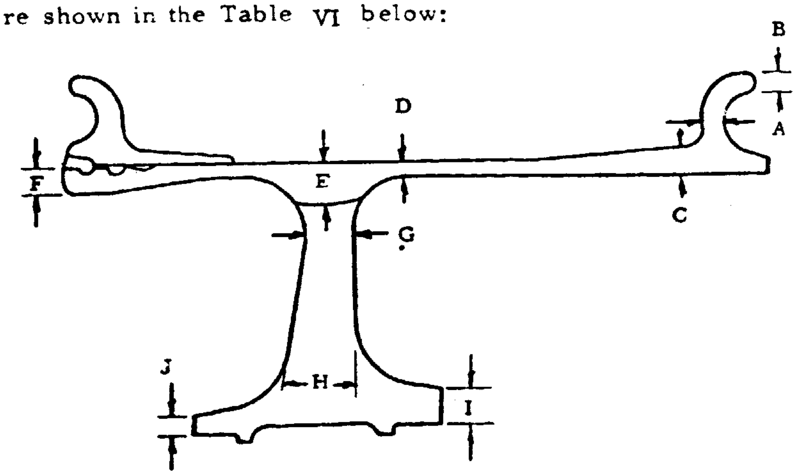


TABLE VI
THICKNESSES AT VARIOUS LOCATIONS

	Load 1	Load 2	Load 3	Load 4	Load 5
A	.450	.631	.430	.546	.546
B	.360	.505	.344	.437	.437
C	.500	.897	.444	.699	.699
D	.395	.637	.351	.482	.482
E	.850	1.100	.850	1.100	1.100
F	.680	1.030	.640	.860	.640
G	.894	.934	.894	.934	.894
H	1.556	1.631	1.556	1.631	1.556
I	.738	.965	.738	.965	.738
J	.512	.690	.512	.690	.512

RESULTS:

Load	Wheel Weight*
1	70.4 lbs.
2	91.6 lbs.
3	68.6 lbs.
4	84.7 lbs.
5	77.2 lbs.

*The weights given do not include the bearings.

Loading philosophy number 3 gives the lightest wheel design. This philosophy suggests designing a wheel to a 40% deflection, a burst pressure 1-1/2 times the tire bottoming pressure, and the limit combined load.

REFERENCES

1. Roark, R. J. "Formulas for Stress and Strain", McGraw-Hill Book Company, 1965 Table XIII - 30.

2. Roark, R. J. "Formulas for Stress and Strain", McGraw-Hill Book Company, 1965, Page 242.

3. The Timken Roller Bearing Company, "The Timken Engineering Journal", 1967.

END

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JAN 25 1974