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SUSPENSION SYSTEMS FOR MARS ROVER
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Lockheed
Missiles & Space Company, Inc.
HUNTSVILLE RESEARCH & ENGINEERING CENTER

Cummings Research Park
4800 Bradford Drive,
Huntsville, Alabama

OPERATIONAL LOOPWHEEL SUSPENSION SYSTEMS FOR MARS ROVER DEMONSTRATION MODEL

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Final Report

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Prepared for Jet Propulsion Laboratory
Pasadena, California 91103

by

Wolfgang Trautwein
G. Dean Robinson

APPROVED: B. Hobson Shirley
B. Hobson Shirley, Manager
Loopwheel Program

J. S. Farrior
J. S. Farrior
Resident Director

FOREWORD

This report documents the results of work under Contract JPL 955050 to fabricate and deliver to the Jet Propulsion Laboratory (JPL) four traction elements for JPL's Mars Rover demonstration model utilizing Lockheed's Loopwheel concept. The JPL Technical Manager was Dr. G. Paine.

The work was performed by personnel of Lockheed Missiles & Space Company's Huntsville Research & Engineering Center in the Loopwheel Program Office managed by Mr B. Hobson Shirley. Dr. Wolfgang Trautwein was the Project Manager.

CONTENTS

Section 1
INTRODUCTION AND SUMMARY

Lockheed Missiles & Space Company's Huntsville Research & Engineering Center has for the last eight years developed the Loopwheel (or Elastic Loop) mobility concept, which appears to be uniquely qualified to provide a high degree of mobility at low weight and stowage requirements for the next Mars mission now in the early planning stage.

The development of the Loopwheel mobility concept was initiated at Lockheed-Huntsville in 1969 as a Company-funded project and has received continued Company support to this date. A first generation test unit was completed in 1970 under Lockheed's Independent Development Program. Tests of a second generation Loopwheel were conducted for NASA by the U.S. Army Engineer Waterways Experiment Station (WES) in Vicksburg, Mississippi. These tests have shown that the Loopwheel provides an 85 to 100% improvement in soft soil traction over the wheeled Lunar Roving Vehicle at lower power requirements.

The objective of this study effort was to provide the mobility system for JPL's Mars Rover demonstration model.

Loopwheel traction elements compatible with sterilization and Mars surface environmental constraints were designed under Contract JPL 954795 and described in Ref. 1. They are compatible with the rover mass, range and stowage requirements of JPL's point design Mars Rover (Ref. 2).

In order to save cost the Loopwheel suspensions for the demonstration model were made of S-glass/epoxy instead of titanium alloy specified for flight units. One of the four Loopwheel suspensions designed, fabricated, tested and delivered to JPL under this contract is shown in Figs. la and lb.

Fig. 1a - Loopwheel Suspension of 1.04 m (41 in.) Length, 12 Vdc Electrical Drive System and 712 N (160 lb) Load Capability Built for JPL Mars Rover Demonstration Model

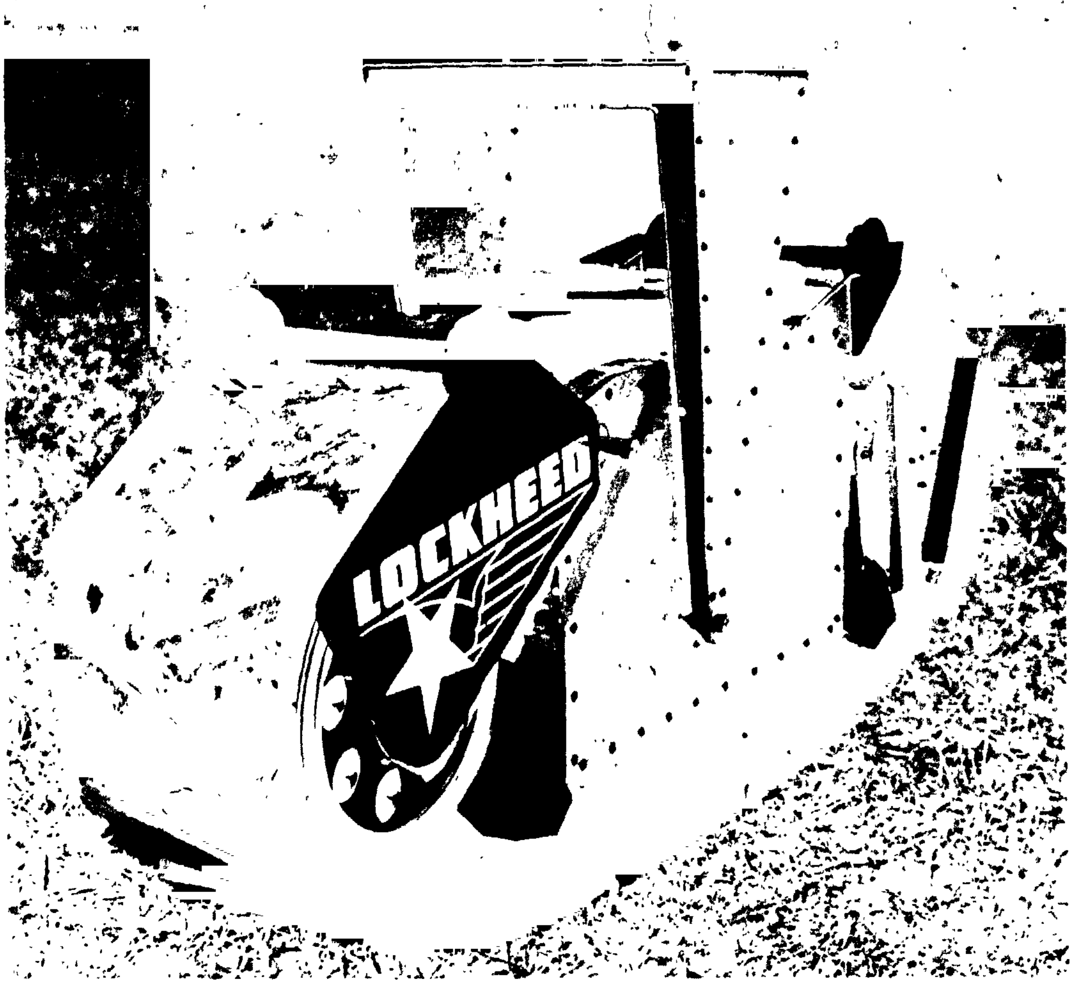


Fig. 1b - Front View of Loopwheel Suspension

The load carrying fiberglass loop core is covered by a rubber tread on the outside. Reinforced rubber gear belts bonded along the inside edges provide positive engagement and transmission of drive torques.

A 12 Vdc drive motor with a 167:1 gear head is installed in the payload section of the hull. A chain drive transmits the motor power to the rear sprocket, whereas future flight units would be directly driven by brushless hub motors within each sprocket, leaving the entire hull volume available for payload.

The complete four-Loopwheel mobility system is shown in Fig. 2 installed in the JPL Mars Rover Demonstration Model with double-Ackerman steering and independent four-leg height control.

The pitch articulation of each Loopwheel within its fork is demonstrated in Fig. 3, where a 30 cm (12 in.) stepup and stepdown obstacle is negotiated by the two right-hand Loopwheels. The rover chassis is held in a horizontal attitude by the height control system incorporated into the JPL chassis design.

The suspension system design and analysis is described in Section 2. The operational characteristics as demonstrated and evaluated during the shakedown and acceptance tests included:

- 32 deg slope climbing on clay
- 56 cm (22 in.) step obstacle negotiation with all four Loopwheels (two at a time, Fig. 4)
- Tractive force per Loopwheel equal to the Loopwheel's vertical load of 712 N (160 lb)
- Scuff steering on hard and soft ground, and
- Removal of rocks from inside the Loopwheel's envelope.

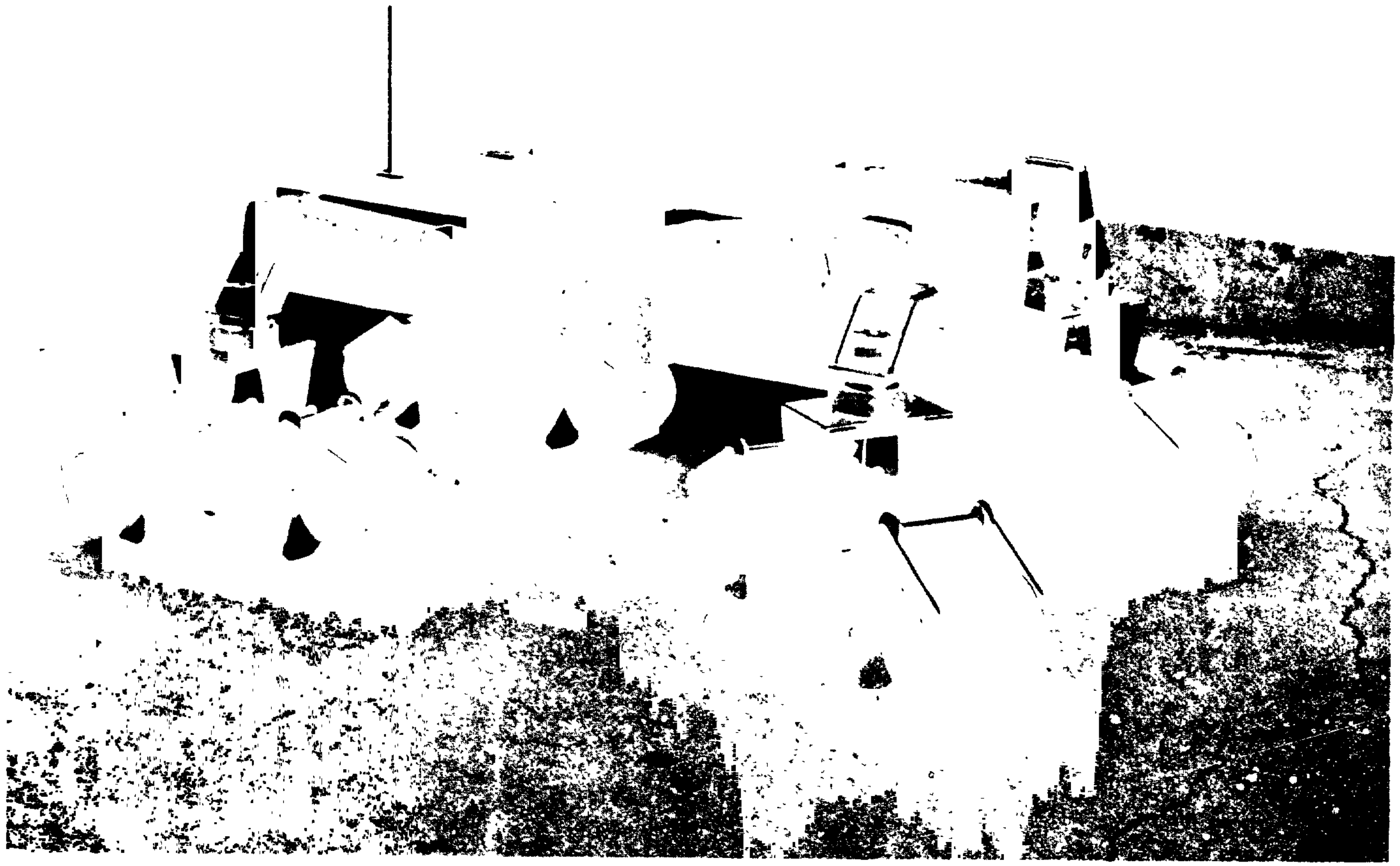


Fig. 2 - Four-Loopwheel Mobility System Installed in JPL's Mars Rover Demonstration Model During Acceptance Tests 29 November through 1 December 1978

Fig. 3 - Step-up/Step-down Obstacle of 30 cm (12 in.) Height Demonstrates Independent Pitch Articulation Capability for Each Loopwheel

Fig. 4 - Climbing of 56 cm (22 in.) Step Obstacle During Shakedown Tests

Section 2

LOOPWHEEL SUSPENSION ANALYSIS AND DESIGN

2.1 LOOPWHEEL CONFIGURATION

The major Loopwheel dimensions for a Mars roving vehicle were established and documented in Ref. 1 by parametric studies and finite element structural analysis computer runs. A titanium alloy (Ti-5 Al-2.5 Sn) was determined to best withstand the high and low temperature extremes of sterilization and Martian night and would safely withstand a sufficient number of stress cycles for a 500 km (310 mi) range.

In order to save cost fiberglass loop cores were substituted for titanium for the present demonstration model for which a design life of 10,000 load cycles or 12 km (7.5 mi) range was assumed at temperatures between 40 and 120 F.

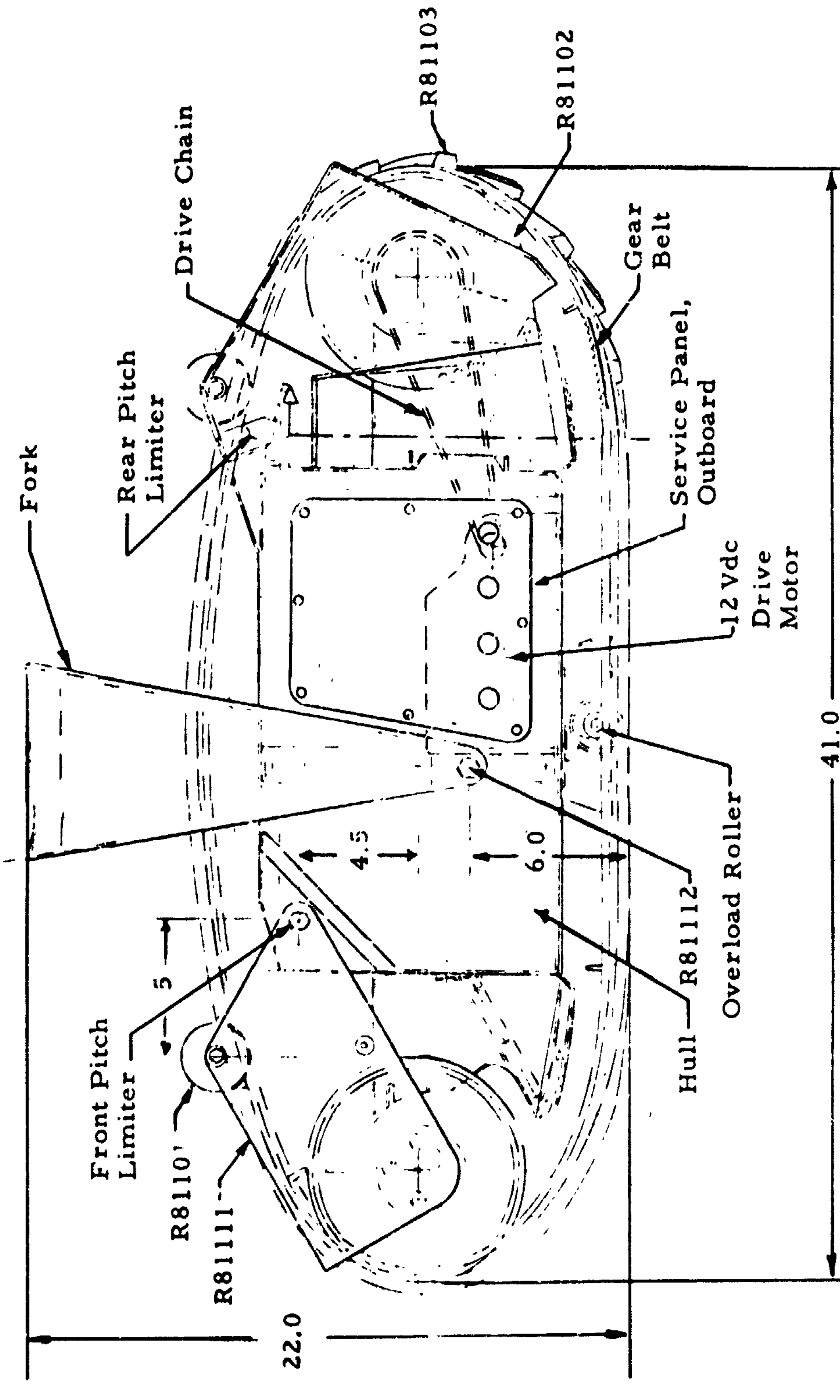
The selected configuration is shown in Fig. 5. The major dimensions were adapted from the rover point design of Refs. 1 and 2. However, the drive motor is located in the payload bay of the hull chain-driving the rear sprocket whereas hub motors in both sprockets were selected for the flight units. Details of the Loopwheel design are shown in Fig. 6. The core material, S-glass reinforced epoxy, is being used by Lockheed for Loopwheels to be installed in combat vehicle prototypes.

Using the notations of Fig. 7, maximum bending stresses in the loop core can be estimated based on the peak strain at the minimum bend radius:

$$\epsilon = \frac{t}{2}\left(\frac{1}{R} - \frac{1}{R_o}\right)$$

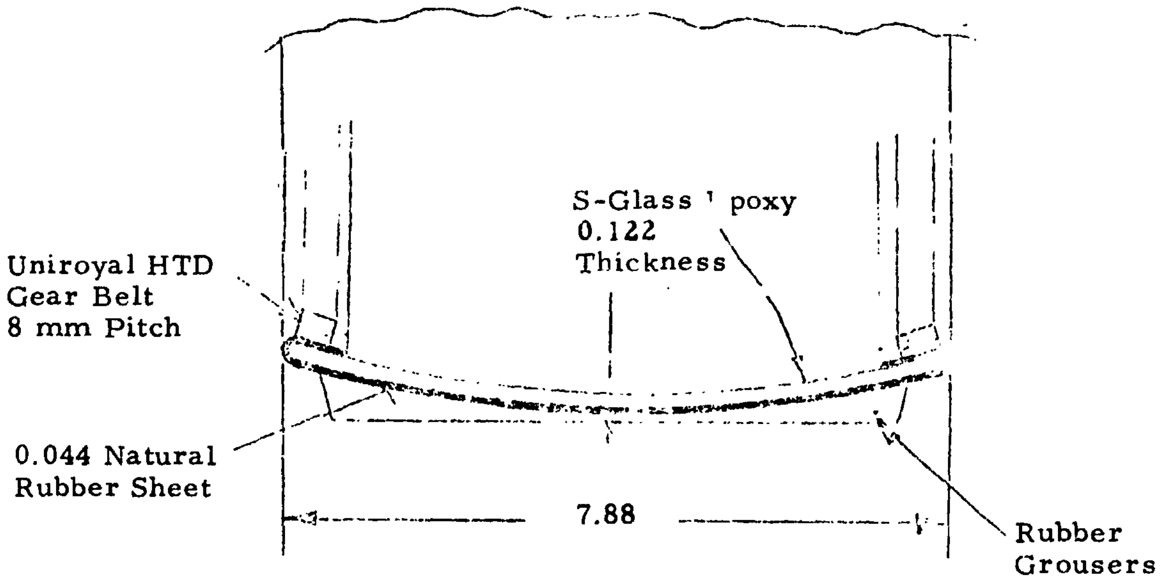
where

R_o = 15 in.
R = 3.98 in. (radius of drive sprocket = minimum radius)
t = 0.122 in.



Note: Dimensions in inches.

Fig. 5 - Loopwheel Suspension Configuration and Major Dimensions (R811xx numbers refer to Lockheed drawings.)



Note: Dimensions in inches.

Fig. 6 - Loop Core Details

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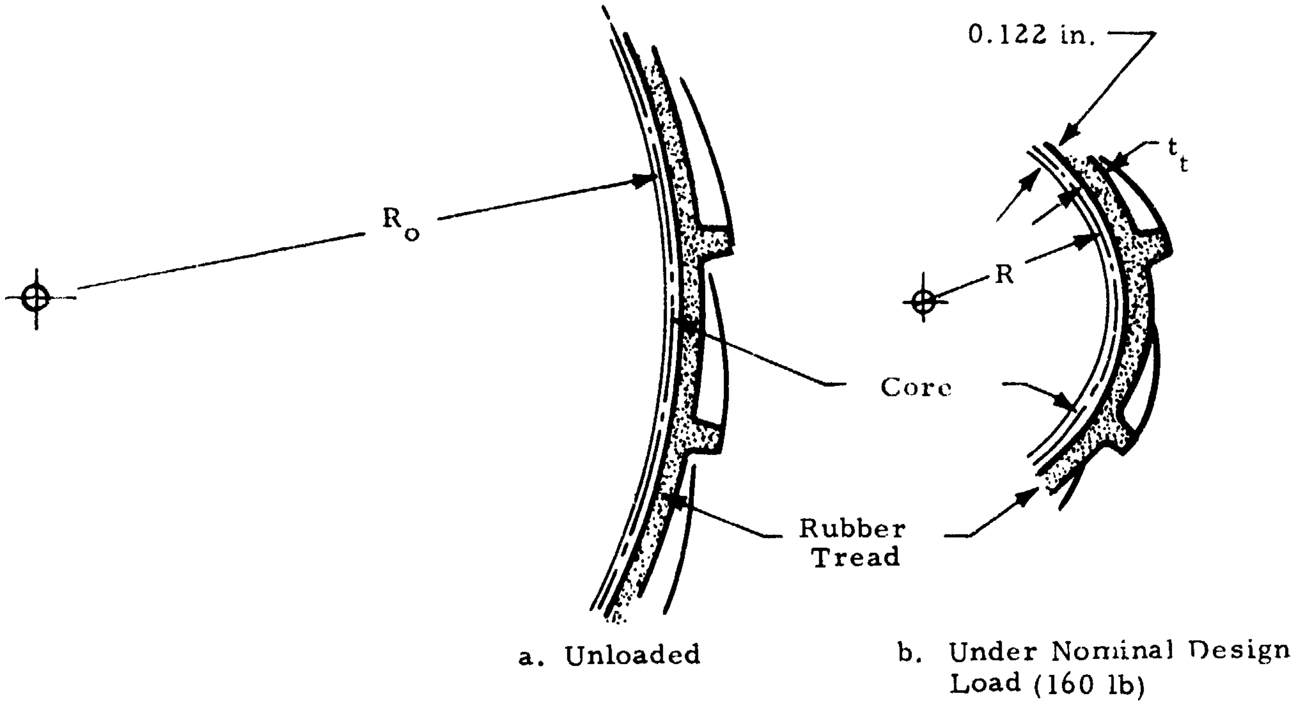

a. Unloaded

b. Under Nominal Design Load (160 lb)

Fig. 7 - Loopwheel with Tread in Unloaded and Loaded Configuration

The selected fiber orientation results in a modulus in flexure

$$E = 4.7 \times 10^6 \text{ psi}$$

which leads to cyclic bending stresses

$$\begin{aligned} \sigma &= \epsilon E \\ &= \frac{tE}{2} \left(\frac{1}{R} - \frac{1}{R_o} \right) \\ &= 52{,}922 \text{ psi} \end{aligned}$$

The stress cycles are approximately symmetric in tension and compression. Therefore, the S-N curves for zero mean testing of S-glass in

Fig. 8 apply. The mean fatigue stress for a 50 percent probability of achieving 10^4 cycles is 75,000 psi whereas the 3σ probability or 99.87 percent life expectancy at 10^4 cycles for this composite material is 57,000 psi. The predicted cyclic stresses of 52,922 psi therefore are 7 percent below the 3σ fatigue limit. These calculations are based on conservative worst case assumptions and are considered acceptable for an experimental demonstration model.

The outer loop surface is protected from scratches by a 0.044 in. sheet of rubber bonded to the fiberglass and wrapped around the edges. Rubber tread lugs are bonded in a 4-in. pitch chevron pattern to the outer rubber sheet for improved traction. The lug bond can be strengthened by adding 1/8 inch rivets with steel washers at each end through the lugs and fiberglass core at two places per lug, approximately 1.0 inch from the inner and outer lug edges. An analysis of the fatigue life reduction of the fiberglass core because of the addition of the holes gives a life expectancy of 6.4×10^3 cycles, approximately 35% less than that of the unperforated loop.

2.2 HULL AND FORK DESIGN

The riveted aluminum alloy hull supports load rollers, swing arms and drive sprockets and transmits all loads from the Loopwheel to the rover chassis via a pivoting fork (Fig. 9). The structural design was based on the following load assumptions per Loopwheel:

Maximum Vertical Load:	330 lb
Maximum Side Load:	290 lb

A 0.063 in. thickness of 2024-T3 aluminum alloy was found to provide sufficient stiffness for the box section of the hull. A structural analysis was performed to determine stresses and maximum deflections of the forks, also

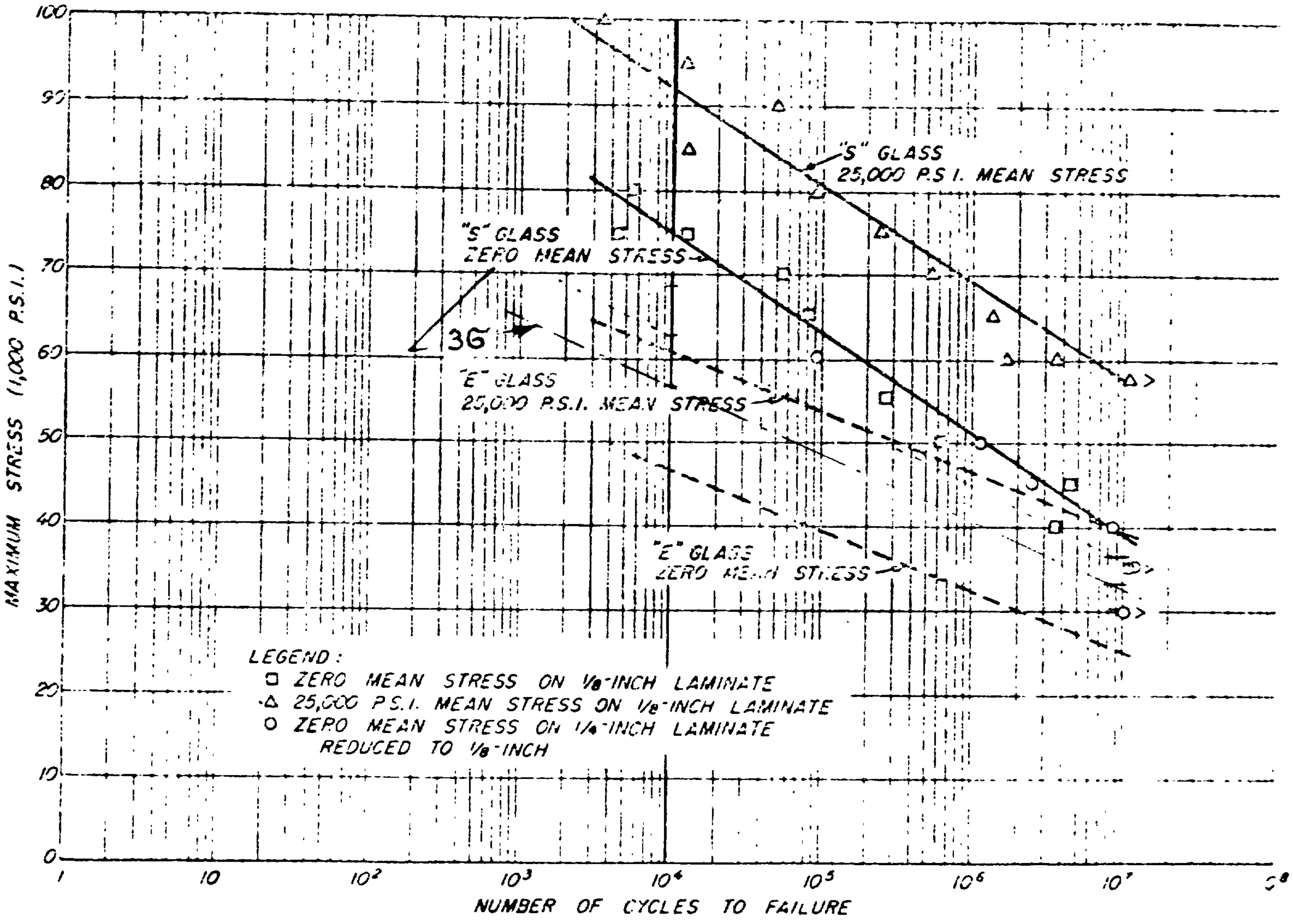

Fig. 8 - S-N Curves of Laminates Made of Scotchply 1002 Resin and Unwoven "S" Glass Fibers. All Oriented Parallel to the Principal Axis. Tested at 73 F and 50 Percent Relative Humidity, 900 Cycles per Minute, and Two Mean Stress Levels (from Ref. 3).

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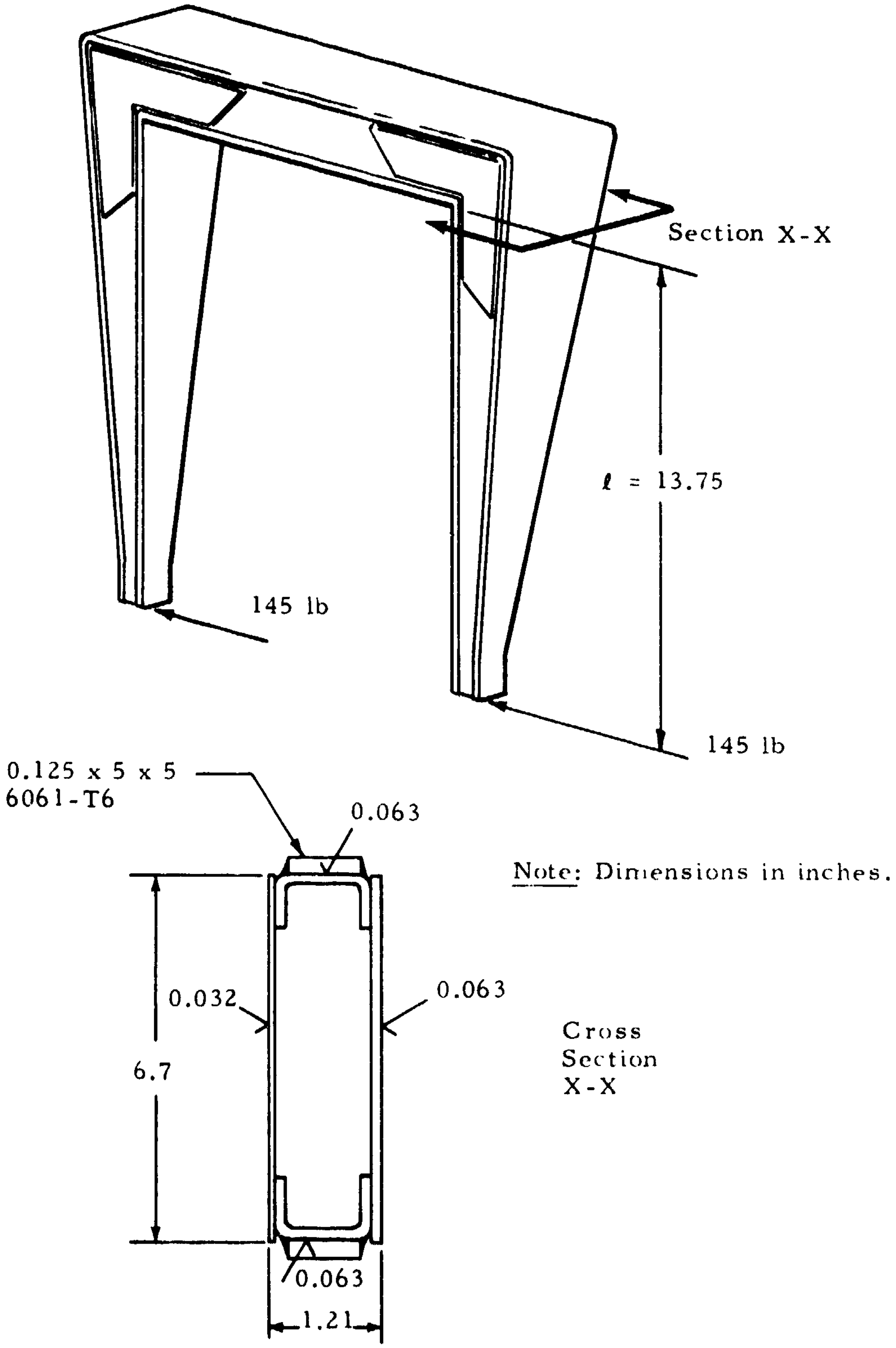

Fig. 9 - Fork Layout

based on the 0.063 in. thick aluminum alloy. The moment of inertia in the critical section x-x was calculated to be

$$I_{xx} = 0.2105 \text{ in}^4$$

which results in a deflection under side load P = 145 lb of

$$\delta = \frac{2}{3} \frac{P\ell^3}{EI} = 0.119 \text{ in.}$$

and maximum stresses

$$\sigma_{xx} = \frac{P\ell y}{I_{xx}} = \frac{145 \times 13.75 \times 0.742}{0.2105}$$

$$= 7,030 \text{ psi}$$

These calculations were based on conservative, worst case assumptions and are considered to be acceptable.

2.3 SUSPENSION COMPONENTS

Bearing selection for the load rollers was based on a maximum radial load of 330/4 = 82.5 lb since there are four bearings per Loopwheel. The ball bearing size (New Hampshire SR6-5 PPD) is rated for 203 lb radial load and 1000 hr life at 100 rpm. Although over designed with respect to load and speed capability this size was selected because it could be readily integrated into the axle and housing design.

The load roller axle shown in Drawing R81101 was analyzed for maximum bending stresses. The axial moment of intertia was calculated to be

$$I = \pi/64 \, (d_1^4 - d_o^4)$$
$$= 0.000853 \text{ in}^4.$$

The bearing load acts on a moment arm 0.375 in. long. This results in a maximum bending stress in the axle of

$$\sigma_a = \frac{85 \times 0.375 \times 0.4375}{0.000853} = 16,349 \text{ psi}$$

For the selected aluminum alloy 2024-T3 with ultimate tensile strength of 64,000 psi there is an adequate margin of safety:

$$\text{M.S.} = \frac{64,000}{16,349} - 1 = 2.9 .$$

The swing arms were also analyzed for lateral deflection due to maximum side loads and for associated bending stresses. Assuming an average load carrying width of 2.0 in. for each 0.25 in. thick swing arm, a maximum lateral deflection between sprocket and swing arm pivot point of $\delta = 0.033$ in. was calculated with associated bending stresses under 10,000 psi. Deflection and stress levels were acceptable.

2.4 DRIVE SYSTEM

The primary requirement to be met by the drive system was a 160 lb tractive force developed at the Loopwheel/ground interface without stall and a no-load forward speed in the order of 2.7 in./sec (250 m/hr) or better with 12 Vdc input power.

An off-the-shelf gear motor, Von Weise Model VW33-A1B2, was found which meets these requirements. Its major performance characteristics are given in Fig. 10. The no-load motor speed of 2350 rpm results in 2350/167 = 14.07 rpm at the gear head. A further gear reduction in the chain drive

$$\eta_c = 2.045:1$$

reduces this speed to 6.88 rpm at the drive sprocket or

$$V_o = 2.86 \text{ in./sec} \quad (262 \text{ m/hr}) .$$

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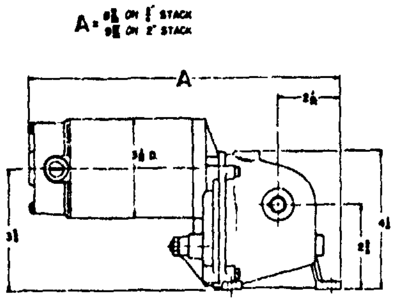
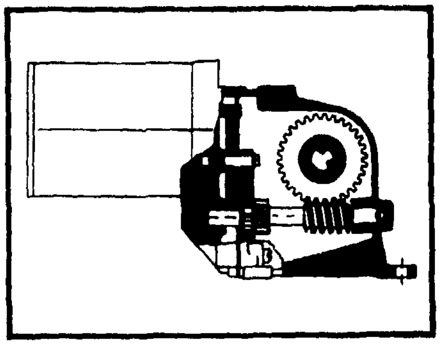
MODEL
VW33

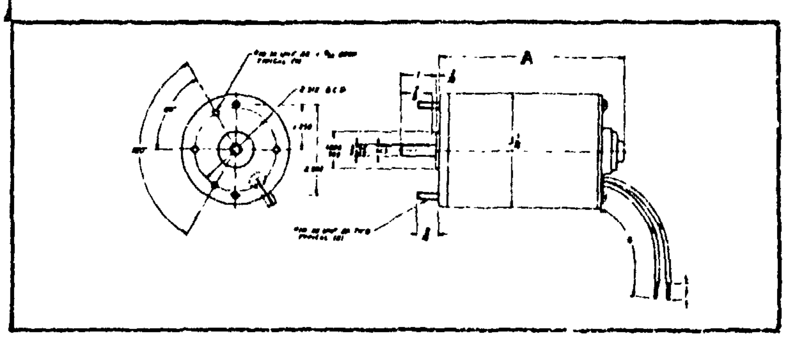




B2 MOTOR

The B2 motor is designed principally for 12 Volt D.C. It features 10 slot lamination, a 10 bar commutator, ball or sleave bearings and internal or external brushes.

STACK	A DIM
3/4	4 153
→ 2	5 403



VW NUMBER	VOLT DC	H.P.	DUTY	STACK - INCHES	NO LOAD SPEED	NO LOAD AMPS	FULL LOAD SPEED	FULL LOAD AMPS	TORQUE IN. OZ.
AAB2	12	1/10	Cont	2	6100	.9	5000	9.2	20
ABB2	12	1/6	Int.	2	6300	1.3	5000	16	33
ACB2	12	1/20	Cont.	3/4	5800	.4	5000	5.1	10
ADB2	12	1/12	Int.	3/4	6000	.55	5000	7.4	17
AEB2	12	1/10	Cont.	2	4000	.95	3300	10	33
AFB2	12	1/6	Int.	2	4200	1.4	3300	16.5	48
AGB2	12	1/20	Cont.	3/4	3800	.5	3300	5	15
AHB2	12	1/12	Int.	3/4	3950	.6	3300	7	30
→ AIB2	12	1/10	Cont.	2	2350	1	1650	9.8	57
AJB2	12	1/6	Int.	2	2450	1.35	1650	16.6	95
AKB2	12	1/20	Cont.	3/4	2400	.45	1650	4.7	30
ALB2	12	1/12	Int.	3/4	2500	.6	1650	7.3	47

Fig. 10 - Drive Motor with 167:1 Worm Gear Reduction. Model VW33-A1B2 Manufactured by Von Weise Gear Company, St. Louis, Mo.

During acceptance tests performed upon motor delivery the torque/speed/current data of Table 1 were recorded with 12 Vdc input power. The bench-mounted gear motors were loaded by well defined torques applied by a pulley/cable/weight arrangement. In view of the short operating time of the tests their performance was sufficiently uniform for the application. The tested torque levels were found to provide the required tractive force at acceptable speed and current values.

Table 1

DRIVE MOTOR ACCEPTANCE BENCH TEST DATA

Motor No.	I (amp)	Gear Output Speed (rpm)	Torque (in./lb)	Tractive Force at Loop (lb)	Rover Speed (in./sec)
1	6.4	9.83	260	133	2.38
1	8.2	9.23	313	161	2.24
2	6.8	9.37	260	133	2.27
2	8.8	8.82	349	179	2.13
3	6.7	9.23	260	133	2.24
3	8.9	8.57	349	179	2.06
4	6.9	9.23	260	133	2.24
4	9.2	8.57	349	179	2.06

The chain drive from gear motor to drive sprocket must safely transmit the maximum tractive force at the Loopwheel multiplied by the ratio of Loopwheel effective radius (3.98 in.) to chain sprocket pitch radius (1.792 in.) or

$$F_{chain} = 160 \times \frac{3.92}{1.792} = 350 \text{ lb}$$

The tensile strength of a standard 0.25 in. pitch roller chain is 900 lb for a margin of safety on the order of

$$\frac{900}{350} - 1 = 1.57,$$

which was considered to be sufficient even in view of occasional shock loads above F_{chain}.

2.5 ROCK REMOVAL SYSTEM

An autonomous rock removal system has been incorporated into the loopwheel mobility system. The concept is shown in Fig. 11. A set of five wipers is spaced equal distances along the inside of the Loopwheel. Rocks up to the maximum gap size between hull bottom and loopwheel which may fall into the Loopwheel are moved to the rear (Fig. 12) and lifted by one of the wipers at the rear section of the loop. The lifting operation is assisted by two sets of rakes – made of coil springs – extending radially from two places around each sprocket hub.

A large rock is removed whenever the wiper transporting the rock is aligned with one of the rake arrays for positive lifting. This occurs every 1.5 sprocket revolutions. The wipers are aligned with rakes in the following sequence:

Wiper 1, 3, 5, 2, 4, 1, . . .

Therefore, a rock will be lifted by a wiper two to three times before a rake is in alignment with the wiper for positive removal. In the present configuration only the rear chutes were optimally shaped for rock removal in forward direction. No attempt was made to optimize the rock removal system in the front section which has to remove rocks during extended travel in reverse direction.

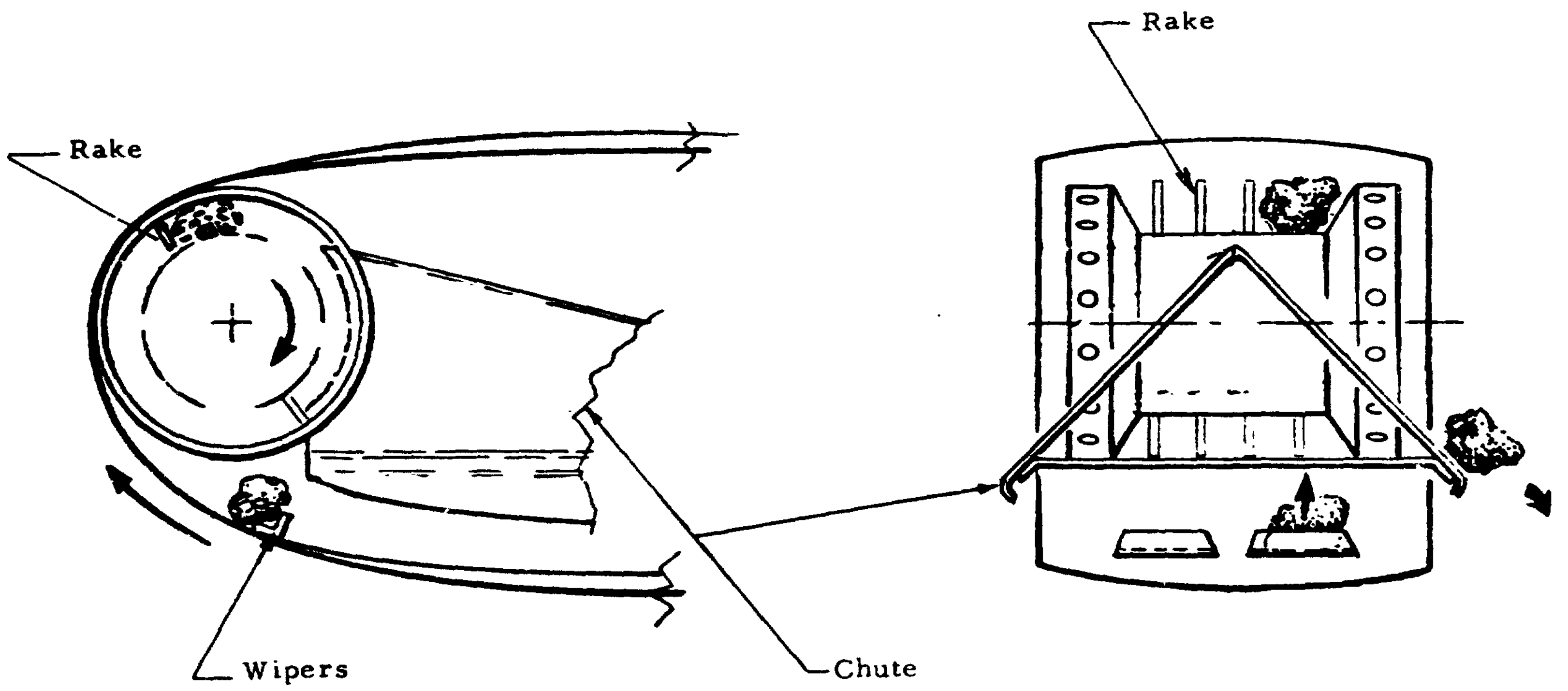


Fig. 11 - Rocks Inside Loopwheel are Transported Around Rear Sprocket by Wiper/Rake Arrays and Removed from Inside by Sliding Down One of the Chutes

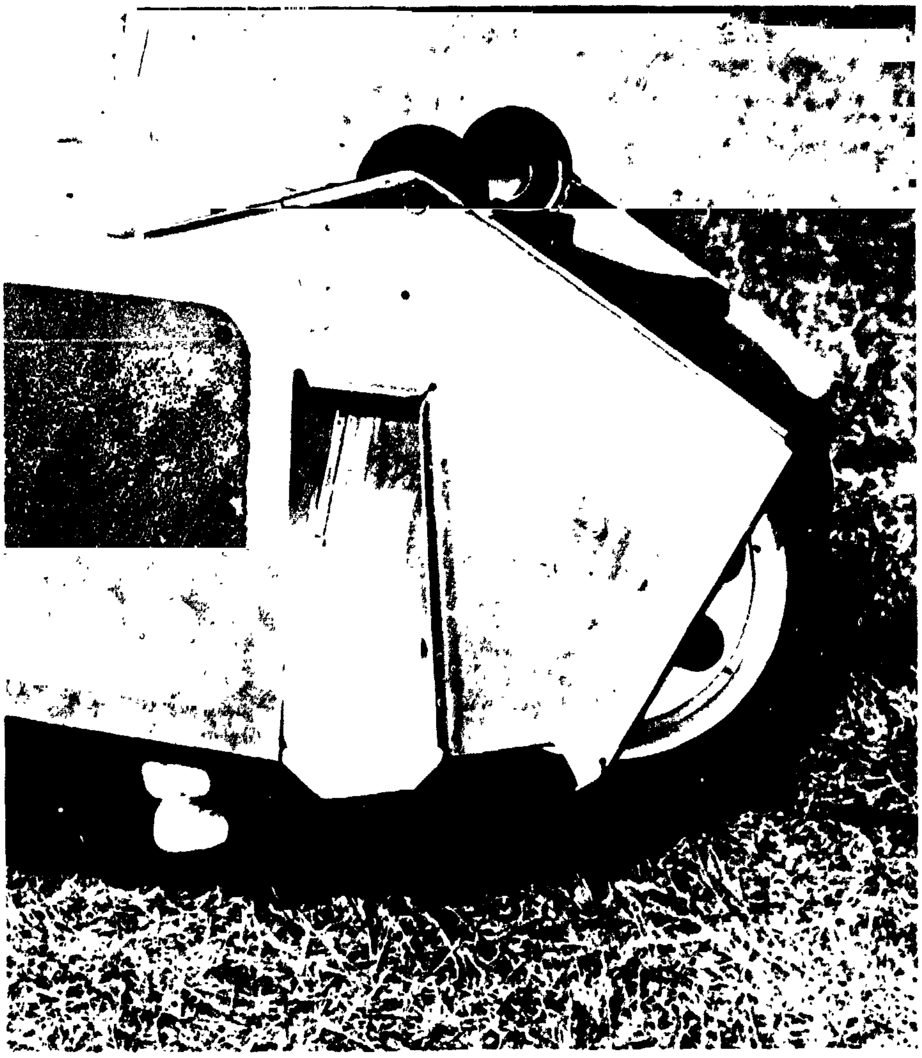


Fig. 12 - Five Wipers are Installed at the Inner Surface of the Loopwheels

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Section 3
PERFORMANCE CHARACTERISTICS

For Lockheed's performance evaluation of the complete four-Loopwheel mobility system a wooden chassis was built with roll articulation between front and rear modules as shown in Fig. 13. The forks were rigidly mounted to corners of the chassis. Wheel base and width was identical to JPL's rover demonstration model. Two 20 A power supplies were installed inside the chassis. A 250 ft, 115 V umbilical cable provided power.

During the functional tests the following performance characteristics were validated:

- Cruise Speed Forward and Reverse on Level Ground, 640 lb Total Rover Weight

Voltage (V)	Average Current per Motor (A)	Speed (in./sec)	m/h
12	0.94	2.34	214
14	1.08	2.90	265
16	1.12	3.33	304
18	1.12	3.80	347

- Scuff Steering on Smooth Concrete (Coefficient of Friction ≈ 0.5) Turn Rate Approximately 90 deg per Minute at 12 V, Average Current per Loopwheel 4.6 A; Rover Weight 640 lb.

- Scuff Steering on Gravel at 12 V Input Voltage, Average Current per Loopwheel 4.4 A; Rover Weight 640 lb.

- Slope Climbing on Grassy Slopes up to 32 deg at 640 lb Rover Weight without Apparent Slip.

Fig. 13 - Mockup of JPL Mars Rover Model with Four Loopwheel Mobility Systems

- Step Obstacle Climbing Up to 22 in. (56 cm) (Fig. 4) at 640 lb Rover Weight, 12 V, Maximum Current per Loopwheel = 6.6 A.
- Tractive Force (Pull) at 640 lb Rover Weight on Grass >640 lb.

Section 4

CONCLUSIONS AND RECOMMENDATIONS

Like earlier prototypes the present Loopwheel mobility system demonstrates a very high degree of mobility at a favorable payload-to-mass ratio. The system also has a closed payload bay of over 24,585 cm^3 (1500 in^3) volume with its bottom only 7.6 cm (3 in.) above ground.

Installed in the JPL Mars Rover demonstration model the four-Loopwheel suspension with independent pitch articulation, double-Ackerman steering and independent height control in at least two legs represents a maximum mobility configuration attractive for autonomous long range rover missions of over 100 Km (62 miles) range and total rover mass of 400 Kg (880 lb) or more. A similar degree of mobility has earlier been demonstrated for a three-Loopwheel configuration with pitch and yaw articulation between a single-loop front module and a dual-loop rear module under contract NAS8-28437. However, more recent Mars mission planning calls for a much smaller mass and stowage volume allocation for a rover with a typical mass for a "midi" class rover of 120 Kg (265 lb) and a mobility range of one to several kilometers.

Several very attractive options exist which take advantage of the Loopwheels's excellent traction, inherent stability due to its low c.g. and its ideal science payload bay near the ground, yet reduce substantially mobility system mass, volume and complexity.

One such midi-rover configuration is shown in Fig. 14. Two Loopwheel suspensions are mounted to the chassis side-by-side. Obstacle climbing and terrain-slope mapping capability is greatly improved by staggering the two loops longitudinally. Hazardous slopes are readily detected by the leading

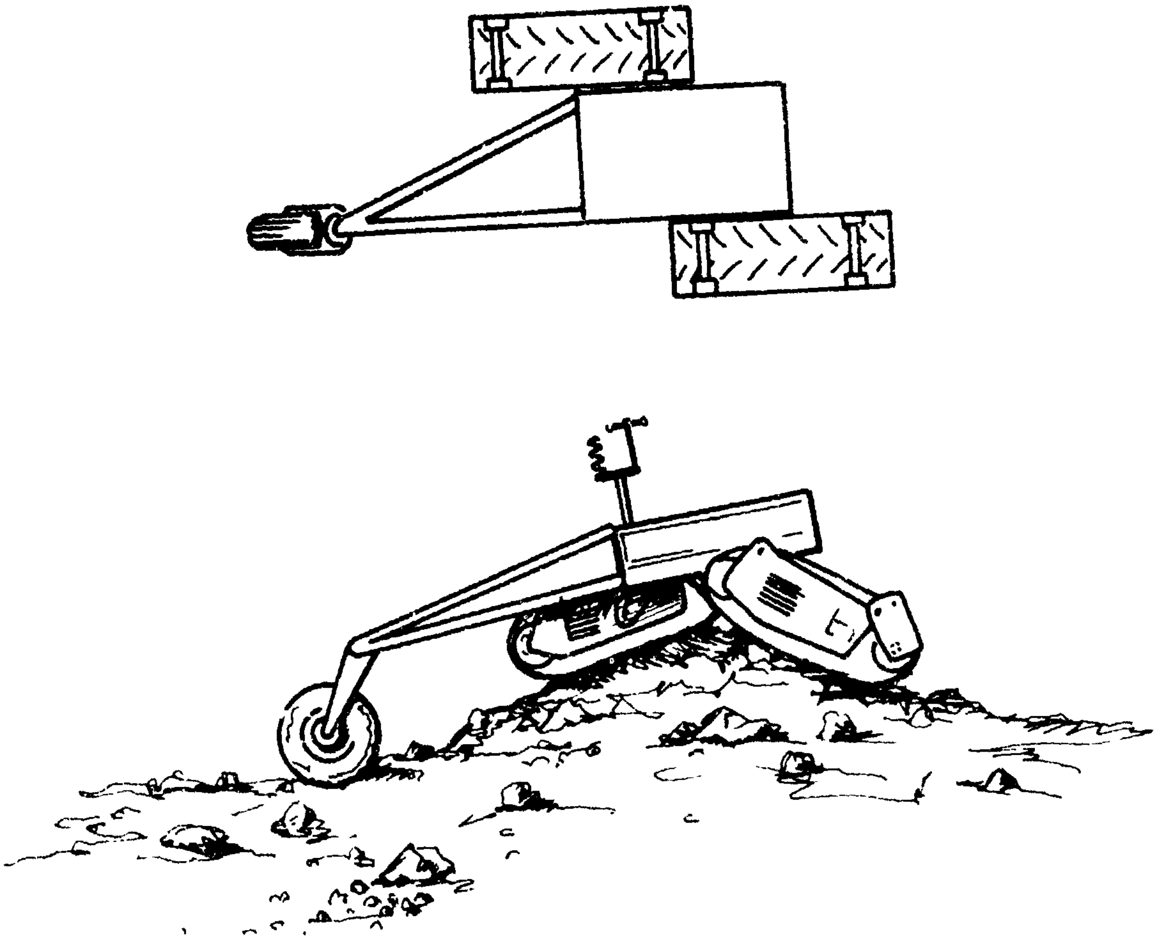

Fig. 14 - Dual-Loopwheel Midi-Rover Configuration. Two Pitch-Articulated Staggered Loopwheels and Wheeled Tail Provide Approximately 80% Capability of Four-or Three-Loopwheel Rover. Steering by Scuffing.

Loopwheel's pitch sensor while there is sufficient traction available to back off from excessive slopes. For minimum turn scuff steering, the tail wheel would be swiveled.

Further savings in weight, space and cost are possible with a single-Loopwheel mini-rover. A typical configuration is illustrated in Fig. 15. The high mobility of a pitch-articulated Loopwheel is used to provide traction and yaw-steering for the rover which is stabilized by two trailer wheels which could be deflatable for minimum space stowage. A pitch sensor in the Loopwheel fork provides terrain-slope mapping information and excessive slope hazard warning.

A recommendation is made that these and a range of other limited-capability rover options be evaluated by preliminary conceptual design, weight, performance and cost analysis. Components from the existing four-Loopwheel mobility system could be used to validate and optimize the predicted performance.

Thus a wide range of mobility options could be presented to the planetary science community and to NASA's mission planners to aid in the selection of a most cost-effective Mars mission.

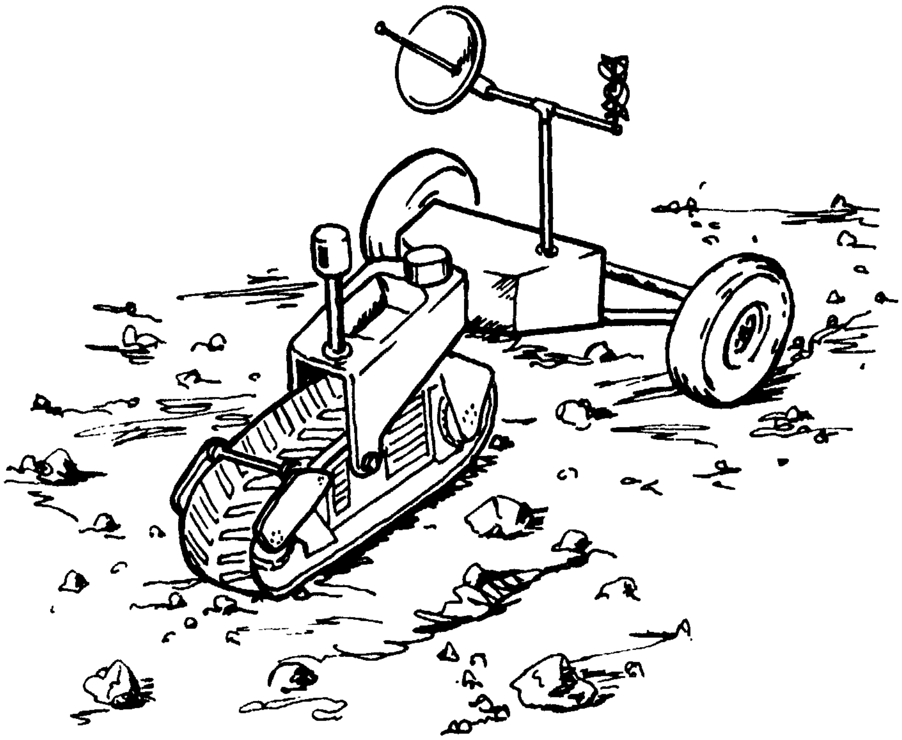

Fig. 15 - Single-Loopwheel Midi-Rover with Pitch-Articulated Loopwheel, Yaw-Steering and a Pair of Inflatable Trailer Wheels (Deflated for Stowage). Drive Motors in Each of the Two Sprockets Provide Dual-Redundant Drive Train.

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