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# Status of Designs of Lunar Surface Vehicles

P. H. BLISS

The RAND Corporation

## I. INTRODUCTION

This report is made for the purpose of summarizing the activities of the various organizations that have been giving some thought and design effort to producing a lunar surface traversing vehicle. It is a state-of-the-art rather than a technical report, intended to see where we are in this effort and to survey the trend of the various designers.

The different types of vehicles being proposed are discussed, with some details of their size, type of traction, and motive power used. A description of the body styles and accessory provisions of the various vehicles will be presented. Where available, performance details will be given.

Because this report is unclassified and some of the most pertinent material on the Moon vehicles is classified Secret, details on some of the vehicles will necessarily be sketchy.

## II. GENERAL PROBLEM

### A. *Statement of Problem*

The problem is to design a vehicle for travel on the Moon's surface that will be entirely dependable, yet compact enough to be transported in a spacecraft to the Moon. This problem is increased by the lack of information on the surface conditions on the Moon and the fact that the first vehicle landed must work. Besides traversing the surface, the vehicle must be capable of performing all tasks required, including the provision of life-support features for the operator or crew.

### B. *Some Desirable Attributes of Lunar Surface Vehicles*

The most desirable attribute of a lunar surface vehicle would be absolute dependability. Speed is not considered a primary requirement, but trafficability over any surface conditions encountered is extremely important. The vehicle must either have a pressurized and air-conditioned compartment for the operator which is shielded against micrometeorites, or the operator will have to wear his space suit while moving around.

The motive power to propel the vehicle should be dependable and capable of covering the range of travel expected of it before having to return to the base for refueling or recharging. A backup source of motive power would be very desirable, especially if batteries are used for the primary power.

Mechanical arms or material-handling cranes would be desirable, with some cargo-handling space on the vehicle to transport payloads. The movement of materials around the lunar base will be of great importance.

The closed-cab vehicles should have some provision for life support for the crew for a minimum number of days as dictated by the mission. This would mean oxygen and air locks for ingress and egress of the operators, with sufficient stored air to permit several openings of the lock. Recirculation methods should be able to salvage part of the air prior to opening the lock.

## C. *Some of the Difficulties Confronting Designers*

### 1. Lack of Data on Soils or Rock Surface of the Moon

Theories exist on the composition of the Moon's surface ranging from fine lunar dust to hard igneous boulders, with indeterminate roughness or size of the boulders. Without knowledge of the type of surface on the Moon, it is most difficult to design a vehicle that will be best suited for the operation. It is planned that some of the present exploration programs will sample the materials on the surface of the Moon; if these plans are successful, we will be able to proceed more logically on one type of design. Until this happens, it appears to be most useful to devote our time to considering several alternate surface conditions and design several vehicles, with one or more types for each assumed terrain condition. Then, if data are obtained from *Surveyor* or *Prospector* Programs, we can concentrate on one of the preliminary designs and refine this design prior to final development.

A design procedure exists for off-the-road vehicles which was proffered by M. G. Bekker (Refs. 1, 2, 3) several years ago. To use it, the stress-strain characteristics of the soil must be known. In order to obtain these data on the Moon, the General Motors designed Bevameter will be soft-landed in the *Surveyor* Program, and readings of the penetration and shear value of the Moon's surface will be radioed back to Earth.

### 2. Vacuum-Caused Problems

The hard vacuum on the surface of the Moon causes several problems for lunar surface vehicle designers. Basic is the necessity for providing life-support facilities on any vehicles that are operated by a man not wearing a space suit. Considerable weight is necessarily involved in making a pressurized cabin provided with an air lock and the air tanks and pumps needed to handle the operation of the lock.

All lubricants in use today will boil away in a vacuum, leaving the metal-bearing surfaces bone dry. This means that bearing seals will have to withstand the vacuum condition as well as the temperature range of around 500°F if ordinary lubricants are used. Some metals sublimate in a vacuum and erode, which could cause rapid deterioration of these parts, especially at the higher temperatures. With inorganic compounds, both decomposition and evaporation are possible hazards. Some researchers are considering the use of pairs of metals in bearing and shaft surfaces that have the least tendency to seize when rubbing against each other. It will be difficult to design electrical motor bearings of these metals, however, for continuous operation.

### 3. Temperature Range, −244 to 260°F

Numerous problems exist due to this extreme temperature range. Hydraulic fluids in use today will not operate in such low temperature without becoming too viscous. The fluids designed for extremely low temperatures (−65°F being the lowest tested) are unsatisfactory at high temperatures.

The operation of many items of electronic equipment would be adversely affected at temperatures above 210°F. The strength of materials decreases appreciably with increase in temperature. At the extreme low temperatures, materials will have a higher yield point but will be so brittle that fatigue failures will occur rapidly.

Unequal expansion and contraction of dissimilar metals in equipment would have to be considered in design; otherwise, parts would get out of alignment. Liquid propellant stored on the vehicle would have to be insulated against the temperature change, or most of the propellant would be lost. Radiators and heat-dissipating devices will be critically affected by the temperature extremes on the Moon and would have to be oriented properly at all times. Different metals would be required on radiation devices, with one metal exposed for removing and the other for absorbing heat.

### 4. Meteorites and Micrometeorites

Meteorites hitting the vehicle would either penetrate the shell, causing loss of air pressure and possible explosion of the oxygen content, or cause chipping of the vehicle surface. Repeated chipping could also result in progressive thinning of the shell or cracking, causing failure by leaks. One answer to this problem is to use double walls, with highly resistant metals, such as molybdenum or beryllium, forming one or both of the walls. The best would be beryllium because of its high elastic modulus-to-density ratio. Some automatic method of detecting and sealing punctures would have to be provided, since the operator could only survive for about 15 sec if the pressure dropped to 3.0 psi of air.

Micrometeorites would not be as dangerous as the larger meteorites, but continual bombardment would give rise to problems. Also, they might damage the space suits with their lighter shielding.

### 5. Lack of Oxygen

The lack of air or oxygen on the surface of the Moon limits the type of motive power that can be employed. The internal combustion engine could not be used without a supply of oxygen. The lack of oxygen also makes the design of a vehicle more complicated, since the operator must wear a space suit or be provided with a pressurized cabin with the life-sustaining environment. This life-support requirement alone accounts for almost half the bulk and weight of the vehicle.

### 6. Solar Flares

The extremely large flux of high-energy protons following a solar flare is of great danger to man and necessitates constant shielding. The radiation dose would be about ten times the lethal amount for man but can be reduced to allowable tolerances by carbon shielding.

Solar flares vary in frequency from year to year and from month to month. Predictions have been made that as many as 180 flares of significant intensities will occur in 1968 (Ref. 4), with the years just preceding and following being almost as bad. Low-frequency years are 1964, 1972, and 1973. The frequency of solar flares appears to be at a minimum during the months of December and January. This suggests the possibility of scheduling lunar flights having personnel aboard during the periods of lowest occurrence of solar flares. Manned expeditions could also be working on the dark side of the Moon during flares, or the personnel could retire to heavily shielded storm shelters when such flares were expected.

The shielding on a lunar surface vehicle required for protection against meteorite bombardment would also protect the operator against solar flares of limited magnitude, thus making it possible for the vehicle to be out and operating during such flares.

### 7. Galactic Cosmic Rays

The intensity of these cosmic rays is of such a low value that the human body can tolerate many hours of exposure. The shielding which would be required to eliminate these rays would be extremely thick and impractical, since the galactic cosmic rays have a very high penetration ability.

### 8. Van Allen Belt Radiation and Natural Radiation

Shielding required to reduce the danger from the high-energy Van Allen Belt protons, if found near the surface of the Moon, would have to be excessively thick, because the damage is done in the low-energy range. The probable dosage is not too significant, however, because personnel could tolerate the rays without shielding for periods of 250 hr or more, and thus would have to be limited only in the number of missions per year or the hours per mission.

Natural radiation from the surface of the Moon could be very hazardous and, unfortunately, very little is known about the presence or intensity of such radiation. If surface radiation is intense and universally distributed over the surface of the Moon, it could mean that habitation of the Moon is impossible; a Moon roving vehicle would then be unnecessary. On the other hand, the radiation may be low enough to permit shielding the personnel from its effects in the design of the vehicle without increasing its weight beyond that permissible.

### 9. Weight and Size Limitations of Vehicle Due to Limited Transport

One of the first parameters confronting the designer of a lunar surface vehicle is the weight and size limitations imposed by the cargo space and capacity of the space missile that transports the vehicle to the Moon. Integration of facilities and components is one way to save both space and weight. Some designers are proposing the use of the hull of the missile as the body of the lunar surface vehicle, with the communications facilities built into the vehicle that will be used both during flight to the Moon and later, while roving on the surface. Others are building collapsible components for their vehicles that can be expanded after landing.

The payload available for the vehicle that will traverse the Moon is now generally assumed as being 20,000 lb or less. This weight could increase if larger boosters become available.

## III. SPECIFIC DESIGNS

The lunar surface vehicle designs will be discussed by the companies proposing them. Not all of the companies working on these vehicles are included, but the majority are represented. At least, a sufficient number are cited to give a good sampling of the trends in design.

### A. General Motors Corp.

The research into lunar surface vehicles in General Motors is headed by M. G. Bekker, formerly Chief, Land Locomotion Research Laboratories, U. S. Army, in Detroit, Michigan. Mr. Bekker is the author of authoritative texts on the design of vehicles for off-the-road travel (*The Theory of Land Locomotion,* 1956, and *Off-The-Road Locomotion,* 1960). He has also written several papers on the subject of lunar transportation within the last year (Refs. 1, 2, 3). Under his direction, several types of lunar vehicles have been constructed in scale-model sizes and tested in the laboratory over several different materials, such as large boulders, coarse gravel in an uneven pile, and coarsely ground wheat flour.

One type of model tested was the articulated, flexibly connected, spiral screw vehicle (Fig. 1). This vehicle consists of two parallel pairs of rotors, mounted in tandem, with each rotor separately powered and the pairs of rotors connected with a flexible spring connection which allows considerable independent motion of each half of the vehicle. This permits each half to follow the contour of the ground surface quite closely, maintaining its tractive force at all times.

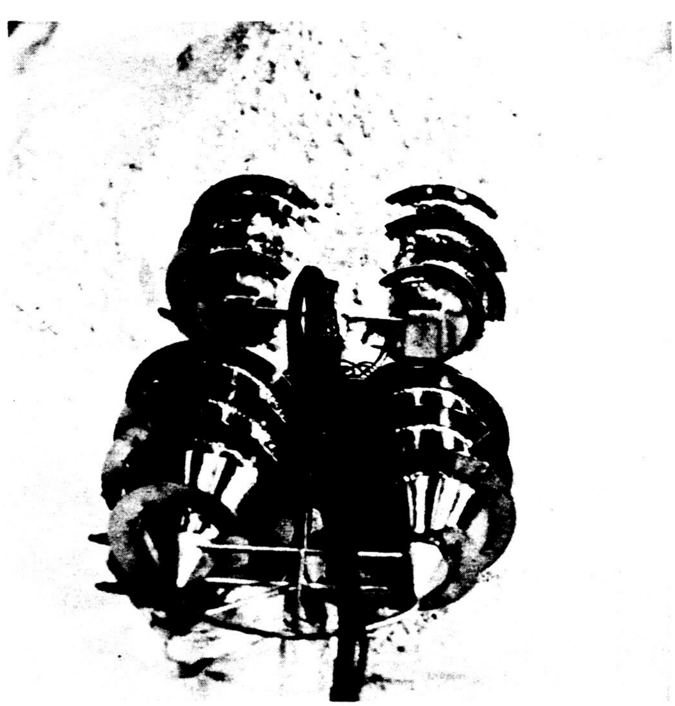

**Fig. 1. Spiral screw vehicle proposed by General Motors Corp., traversing simulated lunar dust**

The spiral rotor machine was tested particularly in the flour, which might simulate the lunar dust (if there is any dust), and it performed quite well. The photograph (Fig. 1) shows it operating in this medium. This type of vehicle would not be proposed for operating on hard surfaces.

The second type of vehicle model was made with 4, 6, and 8 pairs of individually powered donut wheels. Each axle was connected to the next by a flexible coupling made of spring wires which allowed a specific but limited amount of twist between the axles and considerable longitudinal motion between the axles (Fig. 2). The unit would climb straight up a wall, with the forward motion stopped when the last pair of wheels at the foot of the wall were spinning. Because of its low bearing pressure, this vehicle would go over the soft flour with only a slight depression in the surface. It would climb over the boulder and over the large rockstrewn hill (Fig. 3). The mobility of this vehicle was the best of all tested and indicates that the design would probably work equally well in lunar dust as over rough boulders. The train concept makes the load-carrying capacity a matter of how many wheels are hooked together. The sets of wheels could be added, one pair at a time. The more wheels, the more mobility the vehicle would have in varied terrain because some of the wheels would always have traction, while others might be suspended clear of the ground. The longer trains could also climb the higher vertical rises, since the front wheels would have a chance to drop over the top and gain a foothold on the top of the plateau.

The third vehicle proposed had spaced link tracks, supported and driven by a connection in the center (Fig. 4). Being made of spring steel, the ends of the track could be bent in any direction and were extremely flexible. In addition, spring cleats that could retract entirely on hard surfaces were evenly spaced across the track, with only the spring action gripping the surface.

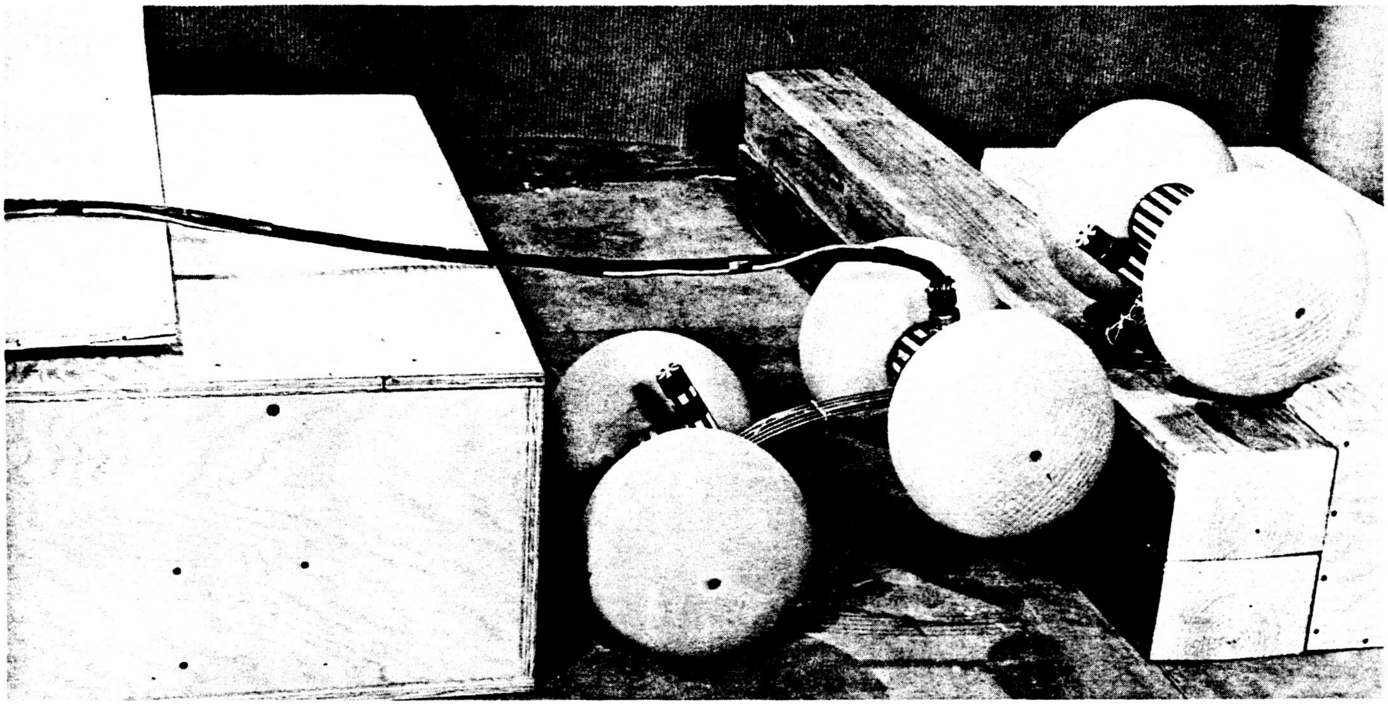

Fig. 2. Flexibly connected donut-wheeled vehicle proposed by General Motors Corp., traversing blocks of wood

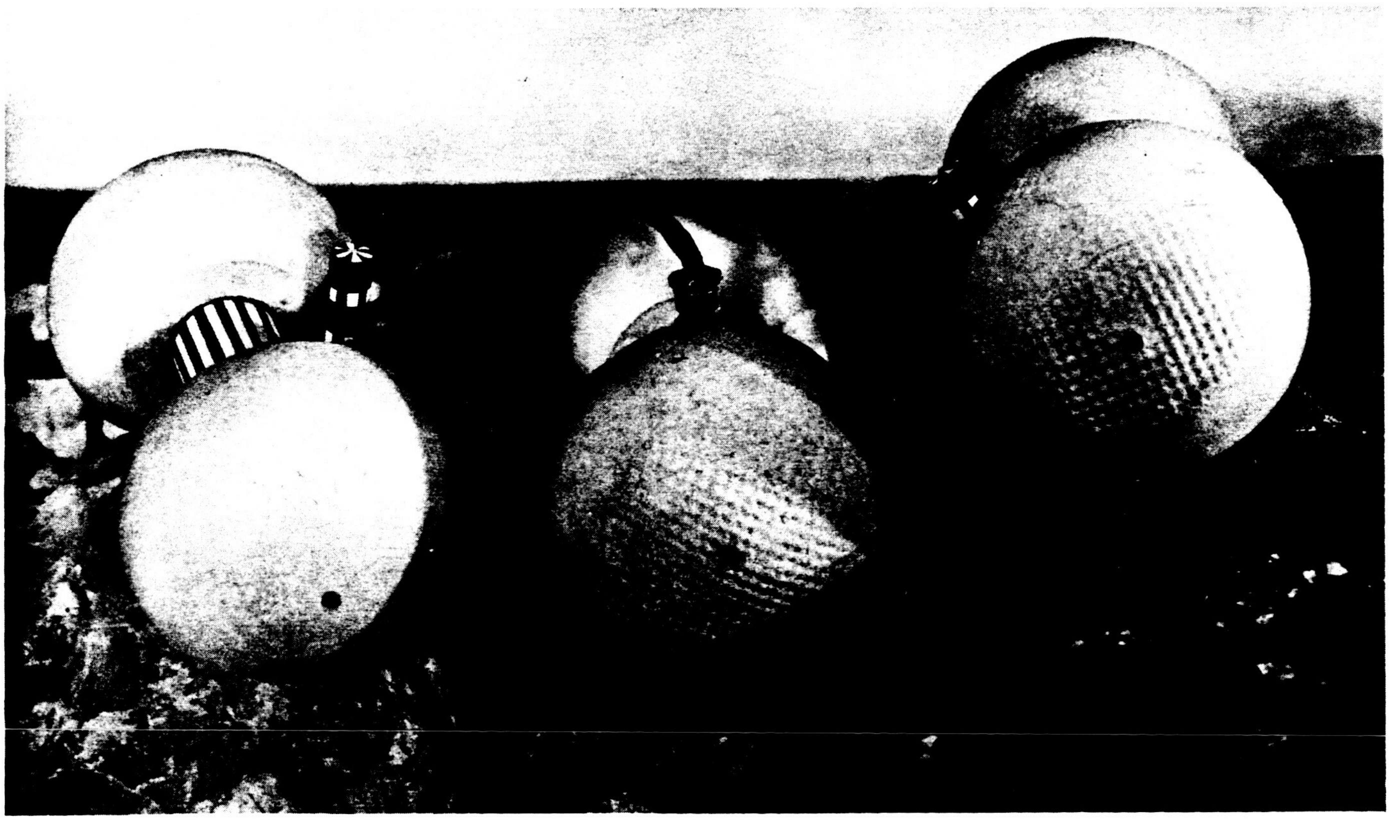

Fig. 3. Flexibly connected donut-wheeled vehicle proposed by General Motors Corp., traversing boulders and gravel

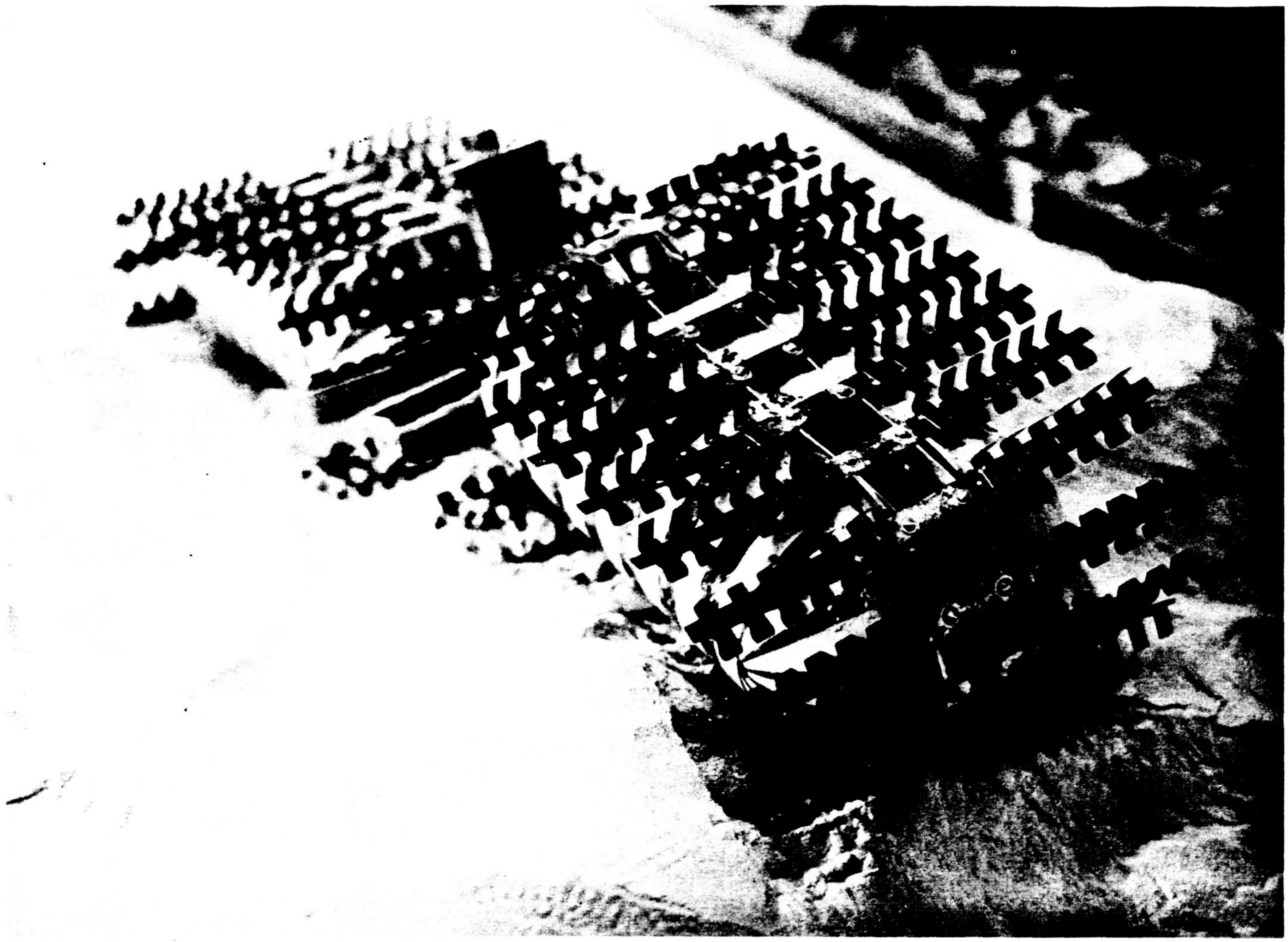

Fig. 4. Spaced-link flexible-tracked vehicle proposed by General Motors Corp., traversing lunar dust

In soft material, the entire area of the cleat would be used for gaining traction. This vehicle was also articulated and performed quite well in the flour or gravel pile but was not as agile over the large boulders as the previous model. For shipping, the tracks are curved around the body and clamped, making a cylindrical load of much smaller diameter than when they are extended.

### B. Martin Co.

The Martin Co. analyzed various types of vehicles for a series of performance characteristics. Considered were wheeled, unicycle, tracked, reaction, amoeboid, walking, pogo-stick, leap-frog, and jumping platform vehicles. According to the analysis, the tracked rated first, followed by the wheeled, and then the reaction type. The tracked vehicle is called a Manned Lunar Surface Vehicle (MLSV). The vehicle body is a sealed capsule protecting the operator from the lunar environment, with 12-hr occupancy proposed before refueling. The vehicle may be remotely controlled or operated from the capsule. Fabric-reinforced belting with aluminum bars is suggested for the MLSV.

The power source proposed is batteries and a low-temperature liquid hydrogen turbine engine with a peak of about 30 hp.

### C. Hughes Aircraft Co.

The Hughes concept of vehicles for traversing the Moon is called the Lunar Roving Vehicle (LRV). Several configurations are proposed. One has wheels made like an umbrella that fold up in a cylindrical shape and can be projected out of the capsule upon landing. The umbrellas expand and lift the vehicle up on its wheels automatically (Fig. 5). The space required for the flight to the Moon is thereby conserved. The bodies of the vehicles consist of two sections of cylindrical shape, one topped by the operator's dome. The vehicle has been named TREEL (Tractive Regulation for Extreme Environmental Location). One of its space-saving features is that the radio used in flight to the Moon is the same one that will be used on the Moon by the LRV for local and Earth transmissions. The LRV has a crane and several manipulators that are operated with a TV camera control.

Another configuration proposed by Hughes has roller drums, which propel a belt track. This motivation is attached to a life-support cylinder and to utility vehicles.

A third configuration makes use of large, inflated donut tires or wire-formed tires. Here, wire ribs hold the load, and the rubber cover acts to tie them together and provide flotation. The covering is loose over the wire so that, in soft material, the cover depresses between the wires to give better traction.

Power sources proposed for these vehicles are not definitely selected, but under consideration are solar-energy engines or chemical, battery, and nuclear engines and fuel cells. Of these, nuclear energy is best for long duration and high power requirements; the chemical battery is best for simplicity and short duration; and solar-energy engines are best for long duration and up to 50 kw maximum power requirements. In addition to weight considerations, reliability, cost, vehicle integration, mission integration, and personnel safety should be the most important considerations in power system selection.

### D. American Machine and Foundry Co.

The Lunar Traversing Device (LTD), proposed by the American Machine and Foundry Co., is a large rubber-tired vehicle with a cylindrical body. Each tire is driven by an individual DC motor powered by fuel cells. The 20-hp model weight is estimated at 6000 lb and the 40-hp model at 7000 lb.

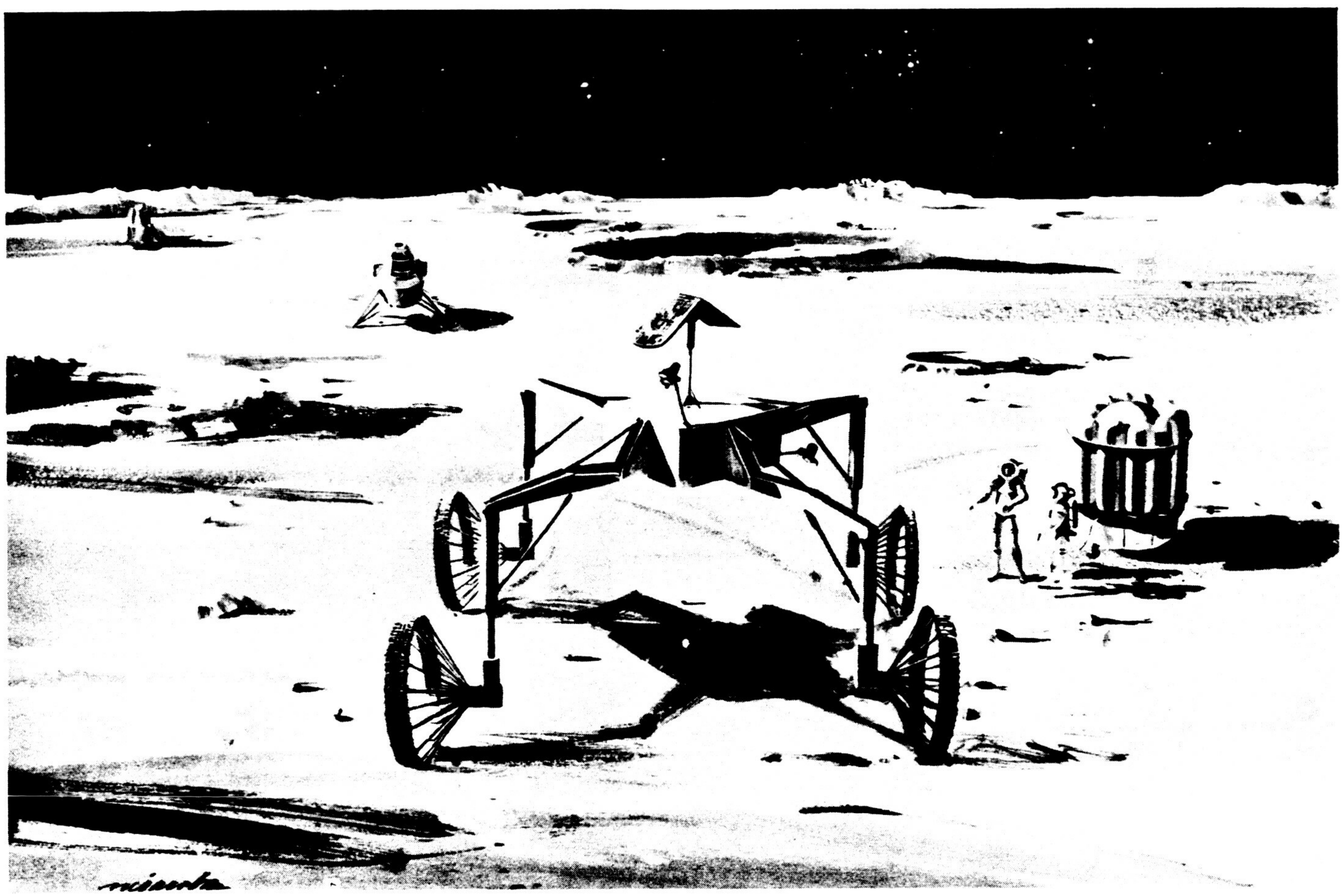

**Fig. 5. TREEL wheeled vehicle proposed by Hughes Aircraft Co.**

Three types of engines were studied: solar, nuclear, and chemical. The final selection was a combination fuel-cell–solar-collector device. Since the solar device could power the vehicle for one Moon day (13.6 Earth days), this would conserve fuel. The fuel cell has the byproduct of $H_2O$, which can be used as water or reconverted to hydrogen and oxygen.

### E. Ralph M. Parsons and General Electric Co.

Proposed is a compact vehicle to operate as a lunar surface material mover, personnel–cargo carrier, crane/boom, conveyor, winch, and surface auger. Preference is for tracks, based on Earth experience, but wheels might be used under certain conditions. Such a vehicle, called a UET (Universal Engineer Tractor), has been built by International Harvester for the Army. The power source proposed is a 40-kw fuel cell.

### F. Bendix Corp.

The Bendix design incorporates a folding vehicle that emerges from the missile and moves around on flexible wheels. It could be powered by fuel cells and solar engines.

### G. Grumman Aircraft Engineering Corp.

The Grumman design uses Metalastic wheels made with a flexible 60-deg cone for a hub which supports the rim. Under load, the cone becomes elliptical in shape, elongating the ground contact surface of the rim, thus giving greater tractive effort. A second wheel tested was made with a series of spiral spokes, connected by a rim. This elastic wheel performed as a very efficient structural member, with good load distribution throughout the entire wheel. The report did not treat the shape of the vehicle body nor the source of power.

### H. Space-General Corp.

The Space General Moon Rover was propelled by three pairs of legs and powered by solar batteries attached to a roof. The machine had a TV camera and a mechanical hand for picking up and moving objects.

Space General also has proposed a wheeled vehicle made with a basic chassis which can accommodate attachments for functional purposes. Provision has been made for earth-moving and bulldozing, hauling materials and personnel, and for handling materials and life-support features. The bare chassis can be operated by a man in a space suit. With the life-support capsule added, the operator can be in shirt sleeves while operating. Upon return to the base, the door of the space vehicle is latched to the door of the living quarters, so that no loss of air will be sustained. This vehicle would weigh around 8000 lb with the life-sustaining capsule and would have a maximum diameter of 12 ft. The length is under 20 ft, so that two would fit into a $14 \times 40$ ft cargo missile.

Motive power considered for this vehicle was heat engine, fuel cell, battery, and solar engine, to be determined by the mission of the unit. For bulldozing, the company proposes the use of tracks to obtain greater tractive effort.

### I. Radio Corp. of America

RCA has studied two walking machines and one balloon vehicle. One six-legged walker proposed had a drill on the end of its manipulator arm for taking samples of the surface materials. The other walker was four-legged, with rubber-connected joints. The balloon vehicle was to be powered by a solar battery connected to a flat roof. The bag would be inflated after landing on the Moon and could roll around on its one plastic bag like a large rubber ball, rotated by the motors turning an axle through its center.

### J. Northrop Corp.

The Northrop concept uses tracked crawlers that are internally powered and can be placed under any pipe-shaped tank or body, one at each end, to make the object mobile. These crawlers look like a pair of conventional tracks and rollers removed from a caterpillar tractor. Several configurations of this vehicle were proposed for different uses, such as personnel housing, cargo carrying, and general utility. One other smaller vehicle, with a single pair of tracks resembling a truncated jeep, was proposed for hauling one man wearing a space suit.

# IV. CONCLUSIONS

Because of the lack of knowledge of the composition of the Moon's surface and environment, lunar vehicle design concepts are necessarily based on assumptions. The choice of surface contact between the vehicle and the Moon seems to tend toward conventional wheels and tracks. However, spiral screw devices, walking machines, and large rubber-ball machines are cropping up among the unconventional types.

The best recommendation for the final design of a lunar surface vehicle is to continue the study of various types of vehicles, based on certain assumptions of conditions on the Moon. When more data are available concerning lunar surface conditions, the most suitable design can be modified and refined toward a final design.

The unconventional types of vehicles should be thoroughly tested, with prototype models being built of each and an extensive program of testing instituted to determine exactly what each type is capable of doing in the different types of Earth terrain. This performance can then be matched with the type of soil and terrain found on the Moon, and the best vehicle selected. Considerable testing has been done on the conventional vehicles, and the performance of wheels and tracks is quite well established.

Since dependability of these Moon surface vehicles is the most important requirement, the cost of experimenting with various proposed vehicles in a scientific and systematic manner will be small compared to the cost of the mission. And if the success of the mission depends upon the surface vehicle, it is even more obvious that a very elaborate and thorough design and prototype testing program should be instituted, as expediently as possible, so as to be ready with the surface vehicle when the manned Moon exploration trips are made. Considering that it may cost a billion dollars or more to put a man on the Moon, it should not be out of line to spend 100 million dollars in lunar surface vehicle research and development.

# REFERENCES

1. Bekker, M. G., *Land Locomotion on the Surface of Planets,* General Motors Corporation, Paper No. 2015-61.
2. Bekker, M. G., *Some Problems of Lunar Soil Mechanics and Surface Locomotion,* General Motors Corporation, October 4, 1961.
3. Bekker, M. G., *Mechanics of Locomotion and Lunar Surface Vehicle Concepts,* General Motors Corporation, September 1962.
4. Jonah, F. C., *Report on Solar Flares for Permanent Satellite Base Study,* Vought Astronautics Internal Report, May 1961.