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A MOBILE HABITAT FOR EARLY LUNAR EXPLORATION

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ABSTRACT

The analysis and conceptual design of a mobile habitat for the early exploration of the Moon is presented. Conceived as a forerunner to the fixed base, rover operations are described in terms of precursor and ongoing activities. Precursor missions include early science and geological surveys for the siting of a permanent base and can be operated in either a manned or telerobotic mode. During construction and occupation of a fixed base, the rover serves as a tractor/transporter for materials and crew while continuing as a mobile platform for scientific exploration. Requirements and key design features of a Daylight Rover (figure 1) are described. Operating scenarios that incorporate contingencies, day/night excursions and extravehicular activity (EVA) are presented.

INTRODUCTION

Before rovers were added to the Apollo program, space suit consumables and physical endurance confined exploration to a small area around the lander. Our return to the Moon will use rovers to both expand the radius of exploration and provide an added measure of safety. Unpressurized rovers offering these features, however, are limited by space suit capabilities and the risk of radiation exposure. Pressurized rovers allow astronauts to explore without being limited by the space suit or by landing site constraints.

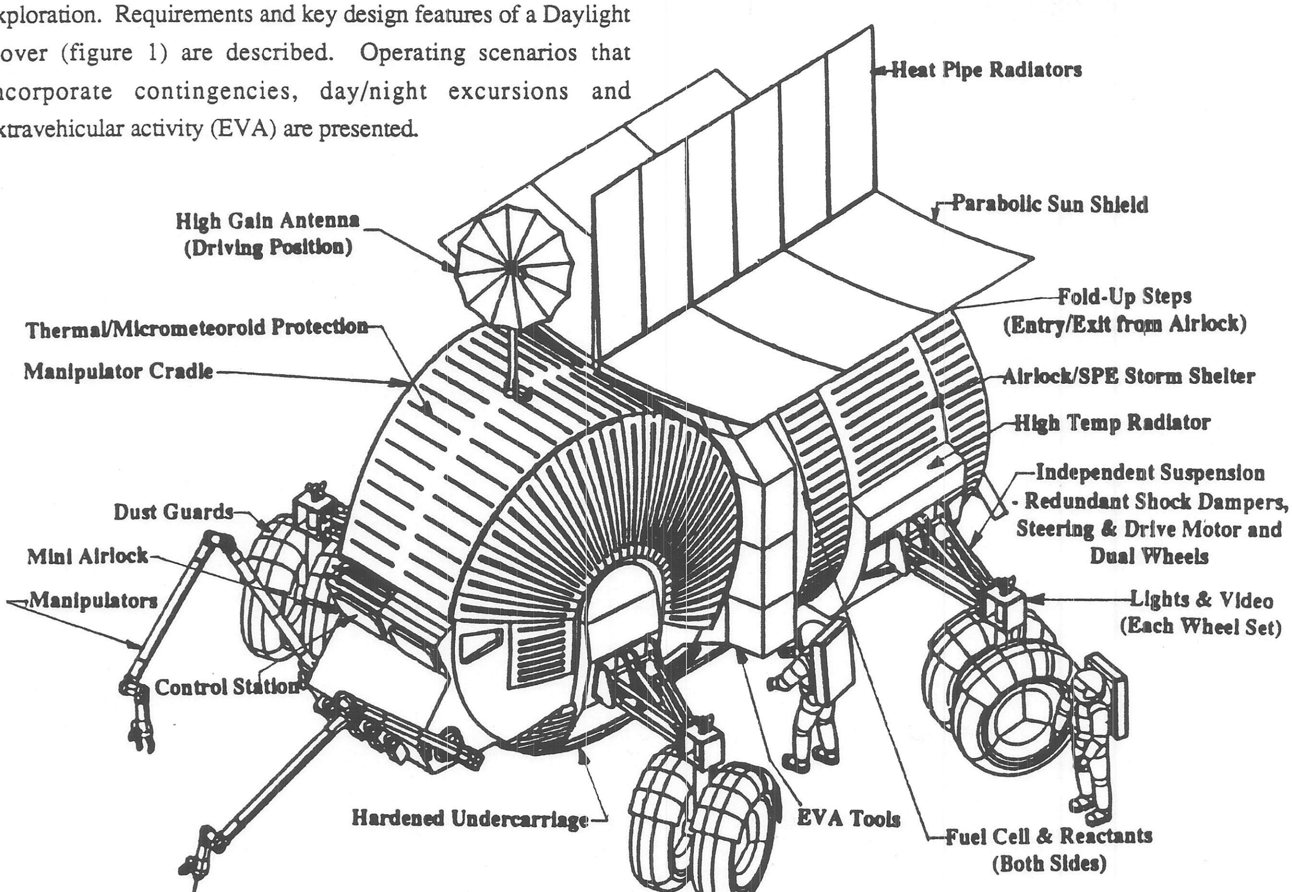


Figure 1. Two astronauts use the Daylight Rover for lunar exploration.

*Senior Member AIAA, Preliminary Design Manager

Subsystem	Description	Mass kg	Source
Structures	Pressure vessel, hatches, secondary structure, utilities, airlock	7651	SSF
ECLS	Closed water loop, air loop open (stored), shelf stable food	4629	SSF
Thermal Control	15kw, internal water loop, external ammonia	1725	SSF/Calc
Electric Power	10kw, regenerative fuel cells with solar array	3598	Calc
Data Management	SSF-derived data management	274	Est
Navigation	Inertial navigation system with satellite update	75	Est
Communications	EVA-to-EVA, EVA-to-rover, rover-to-base & earth	110	Est
Man-Systems	Command/control, sleeping, eating, hygiene, exercise, medical	3575	SSF
EVA Consumables	2-7hr EVAs/wk - 2 crew each (shuttle-type PLSS)	733	Shuttle
Robotics	2 manipulators with end effectors	162	Est
Science	Allocation - includes 100kg for sample return	300	Allocation
Mission Range = 1000km **Crew = 2** **Duration = 80 days (66 + 20% contingency)**	**Velocity = 4km (avg. daylight) = 2km (avg. night)** **Duty Cycle = 10hrs/day (driving) = 14hrs/day (stopped, with solar arrays deployed)** Total	22832	
	- Uncertainty = .10	2283	
	Total	25115	

Figure 2. Results from 1000km rover parametric analysis suggest a heavy vehicle.

REQUIREMENTS

Under a NASA Planetary Surface Systems contract, a detailed parametric analysis for a 1000km rover was conducted. Although the material was parametric, the sum of minimum subsystems produced a 25mt vehicle and required an 80-day mission to reach the 1000km radius and return. See figure 2.

Range Because of the impact on vehicle size, the 1000km range was reviewed and alternatives were analyzed. The 1000km range was considered overly ambitious for early exploration and findings from the Lunar Outpost Site Selection Workshop, (NASA, JSC, April 1990) concluded that rovers with a 100km range provided good science from the six separate study sites. The 14-day (336hr.) lunar night also played a role in limiting the range, more from the stand-point of sizing the electrical power system than driving during the night. Considering all factors and the rover speed (discussed under Rate), *240km was established as the maximum range.*

Rate The Apollo rover averaged 8km/hr. This rate was used for the pressurized rover and was combined with the 6w ride quality requirement (figure 3) to determine suspension and wheel characteristics for rough terrain handling. Furthermore, the 240km range was determined to be radius in distance. Travel on the Moon will not be in a straight line along the radius. Therefore, 4km/hr was used as the rate of progress against the

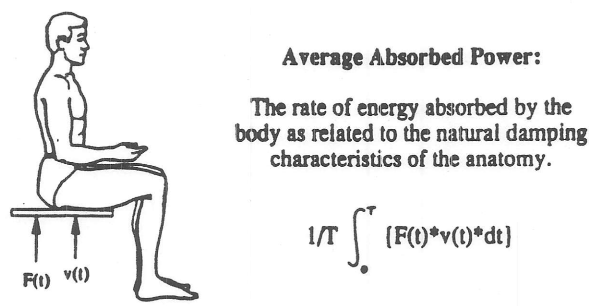


Figure 3. Rover suspension system designed to meet ride quality requirement.

range. Because of the rough ride, driving was considered an exclusive operation, meaning that other activities were performed while the vehicle was stopped. A 10hr work day was divided into three alternative proportions of driving and science (see figure 4). Vehicle sizing considered a maximum 12-day mission with two days for contingency. Therefore, *a 12-day mission driving at 4km/hr for 10hrs a day enables a round trip of 480km* (240km range). Figure 5 describes the features and benefits of the Daylight Rover range and rate.

Rescue Another important factor considered in both the vehicle sizing and range was the capability for rescue. Figure 6 shows that if a rover is disabled at its maximum range, *another*

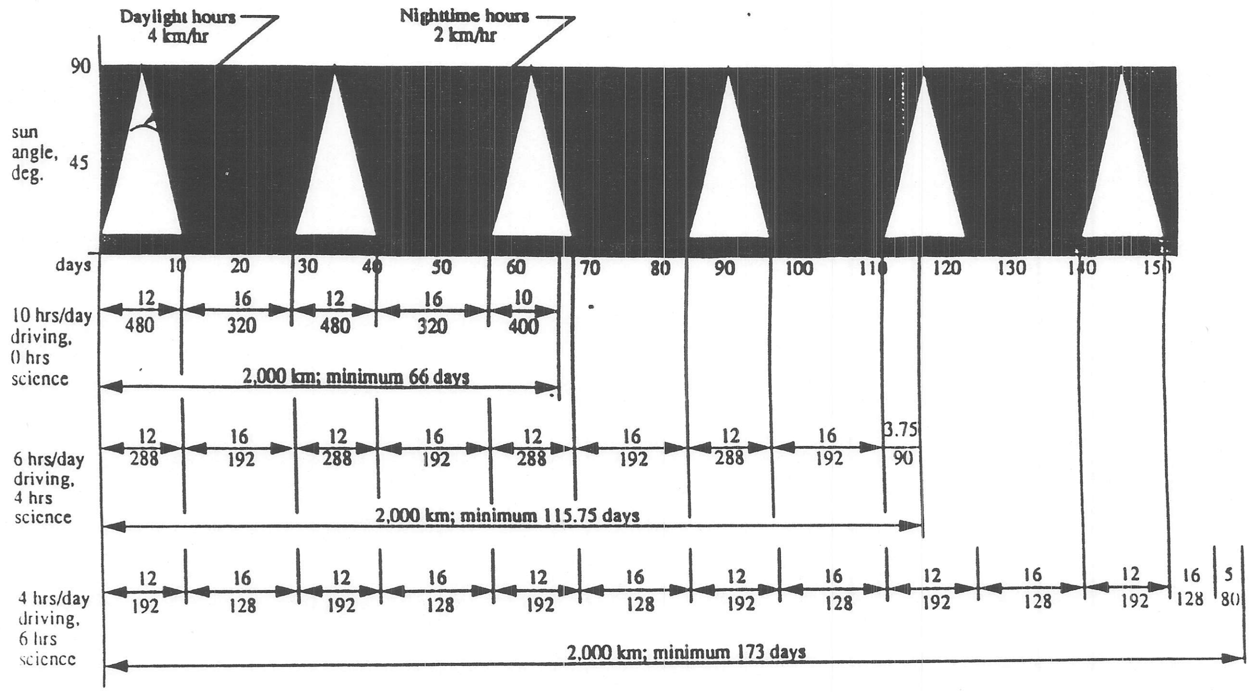


Figure 4. Lunar day/night cycles and rover operations determine mission length.

rover traveling continuously at 4km/hr can rescue the crew and return within the lunar day. In fact, the return rate can be adjusted to 1.8km/hr to provide an easier ride for injured crewmembers while still completing the rescue within one lunar day.

Crew Size Crew size is an important factor in rover design. Skill mix, cross-training, automation, maintainability, subsystem sizing, consumables and many other characteristics are dependent on the number of crew. A *minimum crew of two was selected* for the rover in order to provide the most effective combination of resources and vehicle mass. The crew sizing analysis included rover operations with both personnel and vehicle contingencies as well as considerations for the buddy-system for EVA. Another factor in determining the number of crew was sizing the environmental control and life support system (ECLSS). For the reasons of rescuing and returning two additional astronauts and maintaining cost saving commonality with Space Station Freedom, a system capable of sustaining a crew of four was selected.

Feature	Benefit
12-Day Excursion	- Daylight operations afford good visibility for mobility and science - STS-type crew accommodations - Open ECLS (retain waste and process at base)
2-Day Contingency	- 2-day contingency + 12-day mission = 14 days daylight - Daylight rescue by second rover is possible
4km/hr Speed	- 240km (radius), 480km mission - Exceeds 100km "good science" radius
10hr/day Driving	- 14hr/day for stationary science and off-duty time
4 EVAs/12-Day Mission	- Low consumables loss (airlock & EMU cooling) - No onboard laundry provisions - Minimum field servicing of EMU - Not critical for contingency rescue
SPE Protection	- Airlock doubles as SPE storm shelter - Vehicle control from shelter maintains daylight traverse

Figure 5. The Daylight Rover offers benefits without compromise to science.

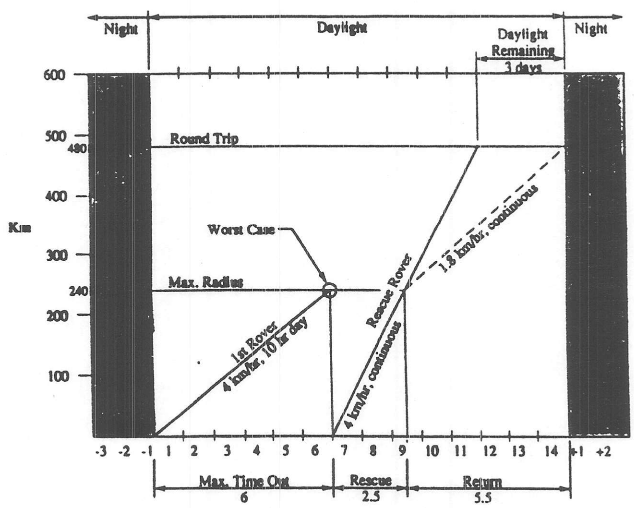


Figure 6. Rover rescue possible within one lunar day.

KEY DESIGN FEATURES

The Daylight Rover provides added safety against the uncertainties of exploration through *two separate pressure vessels*. The larger, forward section is the *crew cab* and contains the primary command-control station along with science and off-duty provisions. The smaller, aft section is a combination EVA *airlock* and solar *storm shelter* and is equipped for emergencies, including a portable workstation for backup control.

Crew Cab Astronauts will spend a majority of their time in the crew cab and much of that will be spent driving. Alternative control station designs were analyzed and a conventional side-by-side arrangement was selected. It offered a center console with the benefits of shared controls and displays, and provided direct viewing of one another for improved communications. The three elements that contributed to the shape and size of the crew cab were 1) good visibility for driving, manipulator control and scientific observation; 2) enclosing subsystems and crew activities within an efficient pressure vessel; and 3) compatibility with the Space Shuttle payload bay dimensions. A *tapered cylinder with ellipsoidal end-domes* (figure 7) was used to provide good wrap-around visibility while accommodating crew activities and subsystem hardware. Much like commercial airliners, the tapered shape matched the functional layout by transitioning from a narrow control station to a central aisle in the cabin body. The control station allows either astronaut to drive, but divides up responsibilities by designating the left seat as the commander's and the right seat as the science station. The accommodations for crew systems were selected according to mission duration. That is to say, the rover was provisioned for a maximum mission of 14 days; more like the Shuttle than Space Station Freedom (figure 8).

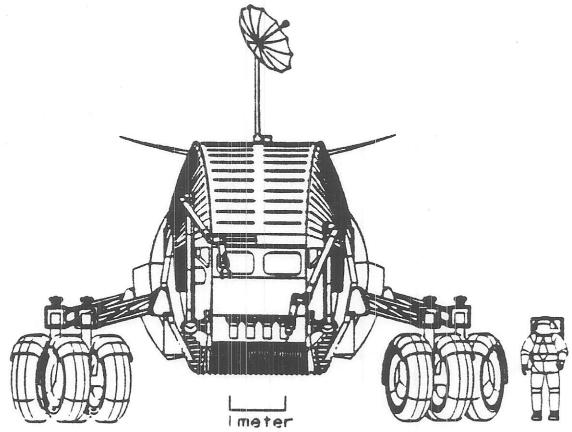


Figure 7. Front view of the rover shows how the tapered front-end offers good visibility.

Airlock/Storm Shelter The shape, size and orientation of the EVA airlock was determined by examining the volume required for donning and doffing space suits in a gravity environment. A *horizontal cylinder with hatches in the end-domes* provided the most useful configuration. This arrangement combined the airlock functions with access to both crew cab and outside. In addition, overall vehicle weight was reduced by using the structural ring frames as hardpoints for attaching the mobility system and the electrical power system.

The radiation storm shelter function of the airlock evolved from a uniform distribution of dead mass to an *integrated concept using existing on-board subsystems*. The fuel cell hydrogen and oxygen reactants tanks were configured to wrap around the airlock providing 2pi steradian shielding against an equivalent 1972 anomalously large solar proton event. In order to maintain constant protection, the water produced from generating electricity is plumbed to conformal tanks replacing the shielding lost from depleted reactants. A detailed radiation analysis using the Boeing Radiation Exposure Model (BREM),

Assumptions	Major Functional Elements
• Space shuttle (STS) used as precedent for privacy considerations • No crew health care (CHC) facility required • No exercise equipment required • Soiled clothing cleaned upon return • Waste products compacted and stored	• Personal hygiene/waste management (PH/WM) • Galley • Multi-purpose space • Crew bunks • Crew health care (CHC) storage • EVA suit storage • Control station
System Description	**System Characteristics**
• STS proven precendent for < 14-day missions • Can accommodate 4-man crew for contingency operations • Deployable furniture allows multi-use of spaces	• Mass = 1260kg • Power = 2133we (peak usage) • Volume = 13.22m^3

Figure 8. Daylight Rover man-systems hardware accommodations.

Subsystem	Description	Mass kg	Source
Structures	Pressure vessel, hatches, secondary structure, utilities, airlock	2496	SSF
ECLS	Open loop, deterred processing, LiOH for CO , H O from fuel cells	907	SSF
Thermal Control	10kw, shielded radiator	765	SSF/Calc
Electric Power	10kw, fuel cells	2327	Calc
Data Management	SSF-derived data management	274	SSF
Navigation	Inertial navigation system with satellite update	75	Est
Communications	EVA-to-EVA, EVA-to-rover, rover-to-base & earth	110	Est
Man-Systems	Command/control station, shuttle-type provisions	1260	SSF
EVA Consumables	2-7hr EVAs/wk - 4 missions - 2 crew/EVA - vent airlock	40	Shuttle
Robotics	2 manipulators with end effectors	162	Est
Science	Allocation - includes 100kg for sample return	300	Allocation

Mission Range = 240km
Crew = 2
Duration = 14 days (12 + 2 days contingency)
Velocity = 4km (avg. daylight)
Duty Cycle = 10hrs/day (driving)
= 14hrs/day (stopped)

*** Brem - Boeing Radiation Exposure Model**

Total	8716		
Uncertainty = .10	872		
Total	9588		
SPE Protection	7426 4π Airlock	3000 Target	238 Brem*
Grand Total	17008	12588	9826

Figure 9. Weight breakout of the Daylight Rover subsystems including radiation protection

NASA transport codes and the 3-D computer aided design (CAD), rover data base verified dosages below NASA Standard 3000 limits. The effectiveness of this approach was demonstrated by reducing the total vehicle mass from 17008kg to 9827kg, while incurring a penalty of only 238kg in the suboptimization of fuel cell tankage and plumbing (figure 9).

Mobility System Although lunar soil has been well characterized, the rough terrain and unpredictable nature of exploration suggested a conservative approach to the rover mobility system. In positioning the wheels, a *wide footprint* provided greater stability while *all-wheel steering and drive* added improved control and reliability. The analysis used to size the mobility system incorporated 1) thrust as a function of soil strength, slip and wheel/ground contact area; 2) motion resistance; and 3) drawbar pull (figure 10). From this sizing analysis, energy consumption was calculated and factored into both the sizing of motors and vehicle operational characteristics. An all-wheel drive and steering system with *four sets of dual*

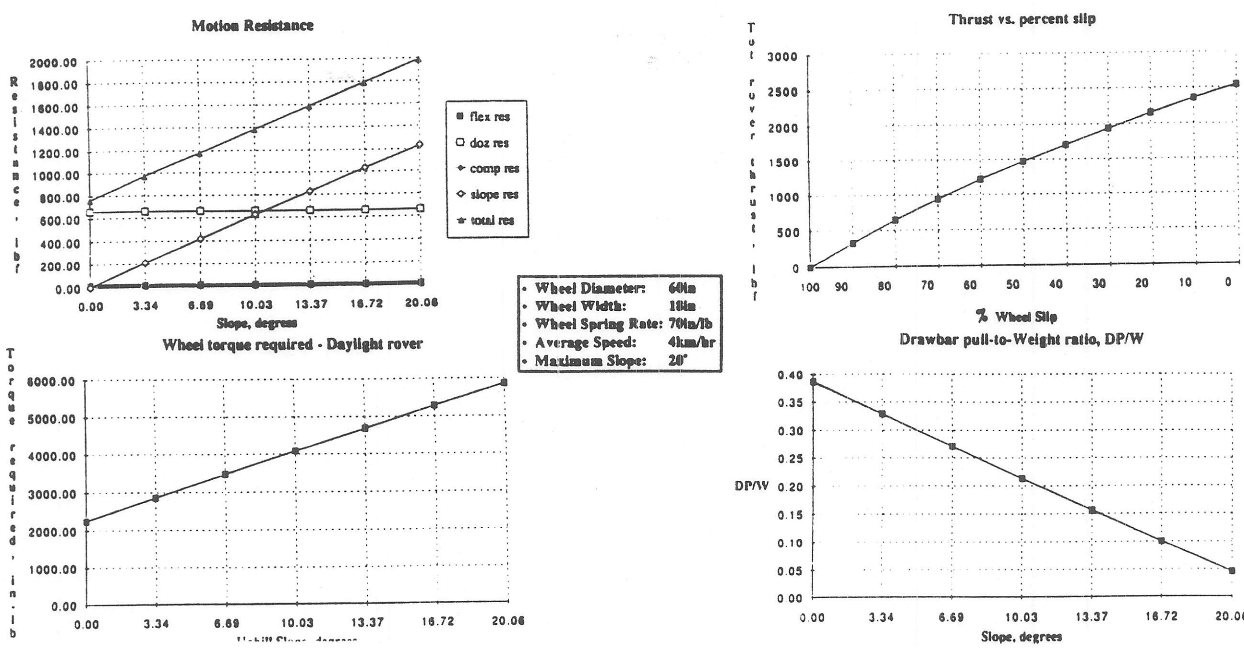
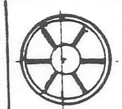
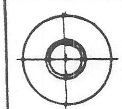
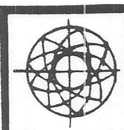
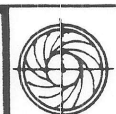
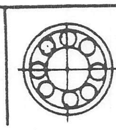
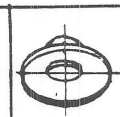
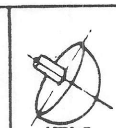
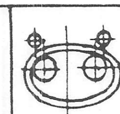


Figure 10. Analysis for sizing the Daylight Rover mobility system.

CRITERIA	RELATIVE VALUE FACTORS	 RIGID WHEEL	 PNEUMATIC TIRE	 WIRE MESH TIRE	 METAL-ELASTIC TIRES		 ELLIPTI-CAL WHEEL	 HEMI-SPHERICAL TIRE	 HUBLESS WHEEL
Mechanical Reliability	15	90.0	67.5	75.0	70.5	70.5	25.5	60.0	28.5
Weight	14	92.0	46.2	121.8	35.0	63.0	14.0	81.2	7.0
Soft Ground Performance*	14	53.0	101.5	101.5	121.1	121.1	114.8	116.4	121.1
Obstacle Performance**	10	68.0	74.0	74.0	64.0	64.0	68.0	74.0	64.0
Steerability	6	43.8	34.8	34.8	12.0	12.0	24.6	39.6	12.0
Ride Comfort	13	ZERO	104.0	117.0	39.0	65.0	78.0	26.0	39.0
Stability	8	64.0	56.0	56.0	22.4	45.6	34.4	56.0	22.4
Wear Resisistance	8	24.0	12.0	42.0	48.0	48.0	48.0	42.0	48.0
Environment Compatibility	6	48.0	ZERO	36.0	42.0	42.0	36.0	36.0	18.0
Development Risk & Cost	6	64.0	8.0	48.0	48.0	48.0	24.0	32.0	16.0
Total	100	Eliminated	Eliminated	706.0	502.0	579.0	467.0	553.0	376.0

* Includes Slopes and Slip
** Includes vertical obstacles and Crevasses

Figure 11. M. G. Bekker's rover wheel comparison.

1.5m diameter wire mesh wheels was selected based on the analysis from M. G. Bekker's comparison of 8-wheel types (figure 11) and actual Apollo LRV experience. Wrap-around windows in the crew cab allow direct viewing of the front wheels, however, each wheel set is equipped with video camera and lights for close inspection of the area around the wheels.

Manipulators A pair of mechanical arms give the astronauts the ability to explore without leaving the rover. The three-segment arms have shoulder, elbow and wrist joints for anthropomorphic operations and come with *interchangeable end-effectors* for scientific investigations. Cameras and lights on the arms afford close-up inspection, however, samples can be brought to the window for eyes-on viewing or can be placed in a *mini-airlock* on the science station side of the crew cab for "hands-on" examination. In addition to the scientific operations, the cameras on the arms are to be used as roving eyes for inspecting parts of the vehicle outside the viewing area.

Micrometeoroid/Ground Obstacle Protection The upper portion of the rover is protected from micrometeoriods by a thin aluminum skin. The skin has *beaded panels* for geometric stiffening and like SSF, stands-off from the pressure hull to accommodate multi-layer insulation and allow energy dissipation from impact. The forward section and undercarriage of the rover are reinforced by corrugated aluminum to protect against rocks scraping the pressure vessel.

SUMMARY

The Daylight Rover is designed for early lunar delivery allowing astronauts to conduct science, transport equipment and return samples from a mobile base. As an element of a larger infrastructure, the rover can arrive ahead of the crew to checkout vehicle systems, perform reconnaissance, and collect samples from many diverse regions. It improves overall system safety and reliability by allowing the arriving crew to select conservative and economical landing sites. The awaiting rover offers preselected samples and provides access to the rugged, scientifically interesting sites. In addition, the radiation storm shelter on the rover relieves the landers of the recurring weight penalty for shielding.

Rovers play an inevitable role in planetary development and the Daylight Rover embodies the features required for early exploration.

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