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LUNAR SURFACE MOBILITY SYSTEMS COMPARISON AND EVOLUTION (MOBEV)

FINAL REPORT

VOLUME III

RESEARCH AND TECHNOLOGY IMPLICATIONS

N67 19944
FACILITY FORM 602

N67 19944 (ACCESSION NUMBER)	(THRU) 1
26 (PAGES)	(CODE)
CR-82955 (NASA CR OR TMX OR AD NUMBER)	30 (CATEGORY)

BSR 1428

NOVEMBER 1966

THE Bendix CORPORATION Aerospace Systems Division

FINAL REPORT

VOLUME I

SUMMARY

VOLUME II

BOOK 1 – MOLEM, MOCOM, MOCAN

PART 1 – TECHNICAL REPORT

PART 2 – RESOURCE PLANNING

BOOK 2 – MISSION ANALYSIS

BOOK 3 – SYSTEMS ENGINEERING (LUNAR ROVING VEHICLES)

BOOK 4 – SYSTEMS ENGINEERING (LUNAR FLYING VEHICLES)

BOOK 5 – RESOURCE PLANNING

BOOK 6 – EVOLUTION METHODOLOGY DEVELOPMENT

BOOK 7 – EVOLUTION METHODOLOGY USER'S MANUAL

VOLUME III

➧ RESEARCH AND TECHNOLOGY IMPLICATIONS

THE BOOK YOU ARE READING IS INDICATED BY THE ARROW.

LUNAR SURFACE MOBILITY SYSTEMS COMPARISON AND EVOLUTION (MOBEV)

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VOLUME III

RESEARCH AND TECHNOLOGY IMPLICATIONS

BSR 1428

PREPARED FOR

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GEORGE C. MARSHALL SPACE FLIGHT CENTER,
HUNTSVILLE, ALABAMA
UNDER CONTRACT NO. NAS8 - 20334

Approved by: C. J. Weatherred
C. J. Weatherred, Director
Lunar Vehicle Programs

NOVEMBER 1966

The Bendix Corporation
Aerospace Systems Division

FOREWORD

This document presents the results of the Lunar Surface Mobility Systems Comparison and Evolution Study (MOBEV) conducted for the National Aeronautics and Space Administration, Marshall Space Flight Center, Huntsville, Alabama, under Contract NAS8-20334. The Bendix team responsible for the MOBEV Study includes Bendix Systems Division of The Bendix Corporation, Bell Aerosystems Company, and Lockheed Missiles and Space Company. Bendix, in addition to overall program management and system integration, has been responsible for LRV Systems, Mission Studies, and the MOBEV Methodology. Bell has been responsible for the Flying Vehicle Systems; Lockheed has been responsible for the LRV Human Factors, Environmental Control, Life Support, and Cabin Structures.

The study was performed by personnel of the Lunar Vehicle Program Directorate of Bendix Systems Division, The Bendix Corporation, under the direction of Mr. C. J. Weatherred, Program Director; Mr. R. E. Wong, Engineering Manager; and Mr. C. J. Muscolino, Project Manager, MOBEV. The NASA Technical Supervisor for the contract was Mr. Richard Love, R-P&VE-AA, Marshall Space Flight Center.

CONTENTS

CONTENTS (CONT.)

ABBREVIATIONS AND VEHICLE NOMENCLATURE

LM	-	Apollo Lunar Module
CM	-	Apollo Command Module
CAN	-	Multimission Module
LM-Shelter	-	Two-Man Lunar Shelter derived from Apollo Lunar Module
LM-Truck (LM-T)	-	Logistics Delivery System derived from Apollo Lunar Module descent stage
MOLEM	-	Lunar Surface Mobility System derived from LM
MOCOM	-	Lunar Surface Mobility System derived from CM
MOCAN	-	Lunar Surface Mobility System derived from CAN
ECS	-	Environmental Control System
RTG	-	Radiosotope Thermoelectric Generator
ELMS	-	Engineering Lunar Model Surface
PLSS	-	Portable Life Support System
LIOH	-	Lithium Hydroxide
EVA	-	Extra Vehicular Activity
O_2	-	Oxygen
H_2	-	Hydrogen
EPS	-	Electrical Power System
SNAP	-	Space Nuclear Auxilary Power System
TDM	-	Traction Drive Motor
SDM	-	Steering Drive Mechanism
IMU	-	Inertial Measurement Unit
AOT	-	Alignment Optical Telescope
ALSS	-	Apollo Logistics Support Systems
P&W	-	Pratt and Whitney
MTA	-	Mobility Test Article
SRC	-	Specific Reactant Consumption
LSSM	-	Local Scientific Survey Module
MSFN	-	Manned Space Flight Network
KSC	-	Kennedy Space Center
MOLAB	-	Mobile Laboratory
MCC	-	Mission Control Center
A/L	-	Dimension from rear wheels to CG over total length
I_{opt}	-	Point of Slip at which maximum thrust is developed
AES	-	Apollo Extension Systems
LESA	-	Lunar Exploration Systems for Apollo
AAP	-	Apollo Applications Program

The following nomenclature is used throughout the report and was adopted to facilitate recognition of the large number of vehicles and missions considered.

ROVING VEHICLES

1. First (letter) (R) defines vehicle as Rover.

2. Second (number) (0 through 3) defines vehicle crew size.

3. Third (letter) (A through D) defines specific mission of vehicle.

4. Fourth (letter) (E or B) defines vehicle as being Exploration or Base Support vehicle.

Example: R1BE (rover—one man—vehicle B mission—exploration vehicle)

FLYING VEHICLES

1. First (letter) (F) defines vehicle as Flyer.

2. Second (number) (0 through 3) defines vehicle crew size.

3. Third (letter) (A through E) defines specific mission of vehicle.

Example: F1B (flyer—one man—vehicle B mission)

CSM	-	Apollo Command and Service Module
G&N	-	Guidance and Navigation
AES-MLS	-	AES Manned Lunar Surface
ALSEP	-	Apollo Lunar Surface Experiments Package
LFV	-	Lunar Flying Vehicle
MFS	-	Manned Flying System
MIMOSA	-	Mission Modes and Systems Analysis for Lunar Exploration
SLRV	-	Surveyor Lunar Roving Vehicle
DPV	-	Design Point Vehicles
LLV	-	Lunar Logistics Vehicle
ESS	-	Emplaced Scientific Station

SECTION 1

INTRODUCTION

Results obtained on the Lunar Surface Mobility Systems Comparison and Evolution Study (MOBEV) indicate that further efforts in certain areas of research and advanced technology would be desirable. The recommendations are summarized in this volume and are listed under the following categories:

- Aeronautics
- Biotechnology and Human Research
- Electronics and Control
- Materials and Structures
- Nuclear Systems
- Propulsion and Power Generation.

SECTION 2

AERONAUTICS

No aeronautics problems requiring research and technology advances are foreseen.

SECTION 3

BIOTECHNOLOGY AND HUMAN RESEARCH

3.1 LIFE SUPPORT

The development of life support system components and subsystems for the Gemini, Apollo, and LM Programs as well as the independent research and development efforts will provide a firm basis for development of the MOLAB and MOBEX families of vehicles.

The MOLAB vehicles utilize concepts identical or very similar to the approaches used in the currently funded hardware programs. It is estimated that as much as 50% of the life support components required for MOLAB vehicles will be directly available from other programs while 35% will require only slight modification. As low as 15% will be new component design, and these will be well within the existing technology. The development of an airlock pumping system, improved space radiator design for lunar surface operation (dust removal, improved surface characteristics, folding capability), improved suit design for increased mobility, improved waste-collection componentry, and improved PLSS design for greater operational use are required for the MOLAB vehicles.

In addition to the development work outlined above, the MOBEX vehicles present new technology problems arising from the new life support system concepts applicable to the longer missions. The introduction of a two-gas atmosphere, regenerable molecular sieve CO_2 removal, and vacuum-drying waste disposal present development problems. The extended mission places greater emphasis on the development of space radiators (meteoroid puncture problems and ultraviolet (UV) degradation of thermal coatings), stored food with higher package density and greater ease of rehydration, and pressure suits with greater flexibility of operation (possibly the hardsuit).

3.1.1 Two-Gas Control System Oxygen Partial Pressure Sensor

Numerous studies have been conducted which tend to substantiate the need for a two-gas system when astronauts are in a confined cabin environment for more than 28 days. Although two-gas control systems have been operated successfully for periods exceeding 90 days in laboratory and flight prototype systems, periodic calibration of the oxygen partial pressure sensor has been required. This presents an area for significant development effort. Without the development of a longer life, more stable oxygen partial pressure sensor, periodic calibration (probably every seven days) by the crew will be required. Such calibration has been proved feasible in simulated flight operations, but requires additional equipment and some operator time (approximately 10 minutes per calibration). The polargraphic PO_2 sensor offers the greatest potential at this time. Development efforts for this sensor must deal with the electrolyte drying problem as the most significant variable affecting stability and life.

3.1.2 Regenerative Molecular Sieve CO_2 Removal

The regenerable molecular sieve concept for CO_2 removal has received a considerable amount of development work. A large number of laboratory and flight prototype units have been built and tested. Several long duration runs, up to 60 days, have been completed. Problems have been encountered during many of these runs that were primarily associated with component life and loading of the molecular sieve beds with water vapor. The latter problem has been solved by periodic heating of the molecular sieve bed during CO_2 desorption to also remove waste vapor.

Little, if any, basic development work is needed for the regenerable molecular sieve system, but functional and reliability testing of a flight unit should be initiated early in the program to allow time for component life upgrading.

3.1.3 Vacuum-Drying Waste Processing

A number of laboratory vacuum-drying waste processing systems have been built and tested. Feasibility of this concept of waste processing and storage had been demonstrated, but much work remains to provide a unit that is suitable for operational use. The following methods need to be investigated: (1) loading and unloading waste material to minimize operator involvement, (2) reducing drying time by increasing contact between heating source and the waste material, and (3) preventing clogging of valves, seals, and filters by waste material. Waste-collection processing and storage has in general received much less than its share of development attention.

3.1.4 Pressure Suits

The restrictions of state-of-the-art pressure suits are well recognized by most vehicle systems developers. A considerable amount of development effort is directed toward improving this situation by developing a better softsuit and development of a hardsuit. Assuming this development effort continues and is successful, the primary remaining problem is one of suit life. The longer duration missions of the MOBEX vehicles with greater EVA place a severe strain on the life of suit joints, seals, cables, hoses, gloves, and the pressure shell itself. The current suit development program should be broadened to include increasing suit life and resistance to damage.

3.1.5 Portable Life Support Systems

One of the most critical operations in a mission is the exchange of the PLSS during a sortie. Mission requirements dictate that this exchange be made on the lunar surface by a single astronaut. The present PLSS and spacesuit designs do not permit this exchange; thus, several modifications are necessary on the PLSS. A dual connector fitting must be developed for the suit which would allow the oxygen connection from two PLSSs to be attached to the suit. Research is required on the sealing and disconnecting aspects of the PLSS to this fitting. Requirements for thermal protection during PLSS switching should be investigated.

Employing the PLSS exchange station for switching PLSSs will require a longer PLSS-to-suit hose than presently exists on the PLSS. Pressure drop and flow rate implications must be re-evaluated as they affect blower sizing.

3.2 HUMAN FACTORS AND SIMULATION

In the course of analyzing and developing the MOBEV vehicles in conceptual form, a number of human factors areas requiring further study have been uncovered. A brief description of future research needs and advanced technology requirements follows.

3.2.1 LRV Simulation Needs

To determine more precisely astronaut capabilities on the lunar surface, a more realistic simulation of the lunar surface environmental constraints is required. While attempts to simulate elements of the lunar environment have been made or are underway, an integration of these elements into a lunar surface test bed has been lacking. To provide the simulation realism required, the test bed should synthesize the following lunar environment elements: 1/6 gravity suspension, lunar illumination, lunar surface characteristics, vacuum conditions, lunar thermal conditions, and mockups, prototypes, or simulators for such lunar surface hardware systems as the lunar shelter and/or lunar roving vehicles.

3.2.2 LRV Mission Simulation Studies

With the simulation tools described above, time-line studies should be conducted to establish performance times required to accomplish scientific mission objectives and vehicle or shelter station-keeping functions. These data would be considerably more accurate than the armchair estimates available to date. These empirical data are required for accurate formulation of scientific objectives, scientific equipment payloads, and crew activity scheduling.

3.2.3 LFV Free Flight Simulation

Definitive data are lacking on man's ability to fly and land in the lunar environment under the constraints of lunar lighting and visual conditions, unfamiliar surface features, reduced gravity, and the pressure suit. The LM is designed for a single relatively hard landing, as compared to earth VTOL landings, at a level unobstructed site. On the other hand, an exploration vehicle must make repeated landings at many unfamiliar sites, possibly on rough and difficult surfaces.

For lack of suitable lunar flight data, a conservative design approach has been taken in the flying vehicles. Flight instrumentation, landing stability, and impact capability have been designed into the vehicle in excess of that usually employed on earth VTOL vehicles. If better data could be obtained on man's ability to navigate, control, and land a small lunar flying vehicle, it might be possible to make design simplifications to reduce weight, cost, and development time.

Previous work in this field has employed either fixed-base simulation devices or the free-flight Lunar Landing Research Vehicle landing on a familiar prepared hard surface.

To research man's ability to recognize, fly to, and land on lunar surface features under varying lighting angles, a small, free-flight, rocket-supported, simulated lunar vehicle should be developed. This can be flown over a realistic lunar scene of the correct albedo and illuminated from various angles. Using a pressure-suited operator, typical lunar sorties can be flown, simulating all lunar tasks both in-flight and at the exploration site.

3.2.4 LFV Visual Display Research

The open-cockpit configuration of flying vehicles presents a unique situation with regard to instrument panel and lunar scene visibility under lunar ambient light levels and varying sun-earth-moon angles. Clear unambiguous information must be available to ensure the optimum desired functioning of the astronaut-vehicle system. Research is required on the design of displays that can be easily read under all lunar lighting conditions by a pressure-suited operator. These lighting conditions should be simulated, especially the problems of faceplate reflections and instrument lighting during sudden transitions from sunlight to shadow. New concepts in instrument lighting, such as systems which respond rapidly to ambient illumination levels, should be developed. Simulators should also be used to investigate the astronaut's ability to shift his reference and context back and forth between the instrument panel information and outside visual cues. In conjunction with the lunar lighting simulation, various types and designs of instruments and glare filters should be evaluated.

3.2.5 Lunar Celestial Azimuth Reference

Since neither magnetic nor gyrocompassing navigation is practical on the moon, the flying vehicles have been designed to include a low-drift gyro as a heading reference. This is preset from map and celestial data prior to flight.

A simple sextant plus a lunar navigation almanac would be a valuable aid for establishing initial headings for an inertial guidance system before take-off. Sextants for airborne and shipboard use have not been designed for use by an astronaut encumbered by a pressure suit. A pelorus for measuring azimuth angles would be suitable, however, and research should be conducted to develop an instrument of the required accuracy. A selenocentric star almanac should be prepared to assist the astronaut in making and reducing observations. Research work and field trials should be conducted to determine accuracies obtainable and to refine pelorus designs and operating techniques.

3.2.6 Maintenance Capabilities of the Astronaut

The capability of the astronaut to perform maintenance tasks on the lunar surface must be precisly assessed. This capability must be established for both the intracabin environment and the EVA tasks. Maximum utilization of the lunar astronaut for system maintenance activities has broad implications for overall system reliability and the need for remote diagnosis, remote control, and redundant systems. Consideration of man's maintenance capabilities on the lunar surface should include tool studies, development of candidate maintenance approaches, and spares requirements.

3.2.7 Crew Composition Studies

As crew size increases for the more advanced lunar missions, a greater diversity of technical and scientific specialties will probably be included in the various lunar vehicle crews. The optimal mix of specialties to perform station keeping, scientific, medical, and other duties should be the subject of intensive study.

3.2.8 Spacesuit Performance Characteristics

Spacesuit development for lunar surface missions is still in an evolutionary stage. As suit design evolves, the capabilities of the astronaut with respect to a given suit must be quantified. Endurance limits of the suited astronaut for various lunar activities must be determined, since this will have a major effect on the length of open cabin vehicle sortie durations. The performance decrements associated with relatively long-term suited/pressurized performance will also influence the requirement for a cabin vs a cabinless lunar vehicle.

3.2.9 Metabolic Rates

The metabolic rates for various astronaut functions must continuously be refined to ensure realistic mission planning. The effect of the walking rate in terms of both speed and expenditure of oxygen and coolant must be considered in abort and emergency situations. As the definitions of lunar soil and terrain conditions are improved, metabolic rate data must also be improved by further research.

3.2.10 LRV Vehicle Vibrations

The effect of low-frequency vibrations characteristic of the nominal vehicle dynamic frequencies at the cg must be evaluated on the driver. Amplification factors through the structure and driving station and the suit itself would be considered. Primary evaluations would involve: astronaut reactions (nausea), visual acuity for reading controls and displays and discerning geographical points of interest, and operation of the control stick.

3.2.11 Crew Safety Studies

Emergency abort and rescue options being considered for lunar missions require astronaut performance studies. For example, the maximum distance over which an astronaut can safely walk back to a shelter from a disabled lunar vehicle will affect sortie distance or the requirement for an auxiliary energy return system. Similarly, the capability of the shelter astronaut to walk to an injured astronaut on the lunar surface will affect the surface astronaut's range of operations.

SECTION 4

ELECTRONICS AND CONTROL

Electronics in the communications equipment will be modifications of existing Apollo designs for which much research has already been performed. Further research is not required; repackaging is required.

4.1 ROVING VEHICLES

More research should be done on the characteristics of wheel slippage on various types of soils. By determination of techniques for correlating slippage and soil characteristics, it should be possible to control the errors in navigation system distance measurements. The research would involve primarily empirical data on various soil-wheel models in which the soil characteristics are based on the latest Surveyor data.

The slippage research recommendation is the only one related to rover astrionics equipment.

4.2 FLYING VEHICLES

Detailed investigations of the emergency return-to-orbit mission are suggested in order to determine guidance system requirements, minimum guidance systems that will enable emergency vehicles to successfully ascend to orbit, error analyses, and the trade-offs in total mass required for different systems. The investigations should include consideration of simple sighting devices as well as electronic systems. Research to determine a crewman's ability to acquire and track an orbiting vehicle with simple systems is suggested.

SECTION 5

MATERIALS AND STRUCTURES

5.1 FLUID DAMPING SUSPENSION SYSTEMS

Research should be performed on fluid damper materials and techniques for the rover suspension systems. Problems exist relative to the choice of fluid and orifice design which exhibits constant damping properties over a wide temperature range. The fluid freezing point should be below -100°C.

5.2 LUBRICANTS

Research should be performed on solid film and low-volatility grease lubricants for use in the dynamically sealed gears and bearings of rovers. Solid-film material and adhesive material should remain stable down to 10^{-11} mm of Hg pressure and from -100°C to 150°C temperature. Low-volatility grease should exhibit fairly constant sublimation rates in the environmental extremes.

5.3 EXTERNAL SURFACE MATERIALS

Research should be performed on special materials for external surfaces of the rovers which might be affected by dust accumulations. Dust, if present, could stick due to adhesion or static electricity. These phenomena should be investigated with various materials so that effective coatings or other surface treatments can be developed.

5.4 COLD WELDING

Research should be performed on techniques and materials for the prevention of cold welding between rover parts. The required emphasis here is on prevention rather than investigation of the phenomena. This would especially be a problem in the wheels, controls, antenna, and other moving parts.

5.5 THERMAL COATING RESEARCH

The need for controlled surface coating absorptivities and emissivities is of utmost importance to a passive thermal control for the flying vehicles. A good deal of information is available concerning α and ϵ for many materials in orbital environments. The problems and limitations hinge upon the durability of the surface finish as a function of time and environment. Several surface finishes should be subjected to simulated lunar environment for extended periods at various temperature levels and cyclic variations. Considerable effort of this type has been done by several investigators for orbital environment and should be extended to include the lunar surface environment.

5.6 LOW-CONDUCTIVITY TANK SUPPORT STRUCTURE

The thermal analysis of the Manned Flying System propellant feed system which is very similar to that of the MOBEV vehicles indicated that the major heat transfer to the propellant tank is through the tank supports. The nonthermal approach is to employ supports of high strength-to-weight ratio material, usually a light metal with high thermal conductivity, attached directly to the tank well. The net result is almost always a thermal short as compared with the heat flux to the tank by other means, unless the tank support is optimized from the thermal aspect. Several nonconventional types of tanks supports have been suggested in the literature, e.g., chains. However, empirical methods of analysis to estimate the heat transfer through such supports are not generally available and would be valuable in efforts to optimize tank support structure. A test program to obtain thermal design data for nonconventional tank supports is recommended.

5.7 HIGH-TEMPERATURE INSULATION

The need for high-performance, high-temperature insulation is important to reduce the weight of the recessed engine configurations. Currently, the flying vehicles employ a multilayer combination of columbium and copper foils interspaced with quartz. Further investigation of systems employing different combinations of foils and/or spacer materials as well as consideration of opacified powder types of high-temperature insulating materials may permit significant weight savings.

5.8 MICROMETEORITE PROTECTION

The present MOBEV multiman flying vehicles take advantage of a structural aluminum skin backed up with multilayer thermal insulation to provide micrometeorite protection for internal components. The respective thicknesses and spacings required for structural and thermal requirements are more than adequate for calculated micrometeorite protection. A micrometeorite penetration test program could provide data to confirm these calculations. Past experimental programs should be expanded to include the materials and spacing suggested for flying vehicle applications. Tests should include protective coverings for tanks not enclosed by a protective body as are suggested for one-man vehicles.

5.9 ENERGY ABSORPTION TECHNIQUES

A lunar flying vehicle, to be practical as an exploration mobility aid, must be provided with a reusable landing gear. This landing gear must absorb energy with a device which requires no servicing between landings. The use of crushable aluminum honeycomb, as in LM, is not practical because of the replacement problem, and earth-type air/oil struts are undesirable because of the temperature extremes and leakage problems. Studies conducted under the Manned Flying System contract disclosed that the simplest energy absorber for lunar use would dissipate the energy by means of friction surfaces. Many extremely simple and reliable friction-type absorbers have been made to operate in the earth environment. However, for lunar use all of these require a solution to the same problem, that of finding suitable friction surface materials for the lunar environment. These must provide a high coefficient of friction, but not cold weld under storage conditions. Those materials which do not cold weld, such as Teflon on metal, unfortunately provide a very low coefficient of friction.

A basic research and test program is recommended to develop friction brake materials having the required properties for the lunar environment. These should provide high coefficient of friction, resistance to cold welding, and resistance to cold flow under pressure, at lunar environmental temperatures. Vacuum chamber tests should be run on outgassed samples finished to the required surface tolerances at the extremes of temperature and pressure likely to be encountered in actual designs.

Such experimental data could be used in the design of energy absorbers for all lunar applications.

5.10 DAMPED SPRING MATERIAL INVESTIGATION

Current landing gear designs for flying vehicles are complex and heavy, as compared to helicopter-type landing skids, but represent the current state of the art in lunar landing gears. Designs based on helicopter skid-type landing gears have proved impractical for landing on slopes due to the low damping characteristics of skid gears using available structural materials.

Development of new materials with high internal damping will simplify landing gear designs and result in considerable weight and stowability reductions. Composite and bonded materials and fiberglass/metal laminates should be developed and tested for this application.

SECTION 6

NUCLEAR SYSTEMS

Three nuclear systems are utilized by MOBEV rovers as sources of power. These systems are the Radioisotope Thermoelectric Generator (RTG), Radioisotope Thermionic Generator (RTIG), and the Rankine system. Each system has particular development problems which must be analyzed and solved.

6.1 RTG

The effects of nuclear radiation from the RTG could be a problem for some of the rover scientific equipment. The film of the ground truth package might be overexposed, and any nuclear instrumentation could be erroneously biased by extraneous radiation. Shielding on these instruments or on the RTG might be a solution. However, research into cleaner nuclear fuels might be desired, if the problem appeared unresolvable otherwise.

6.2 RTIG

The problem of containment of high-temperature fuel at impact may require development of a new fuel form. Corrosion of the tantalum liner of the fuel container by fuel is another problem which must be solved. A seal must be developed for the electrical lead through the fuel container wall such that the seal will maintain its integrity through impact. Research must be conducted to determine the reliability of thermionic diodes and to improve their reliability if necessary.

All shielding problems associated with the RTG also apply to the RTIG.

6.3 RANKINE SYSTEM

Containment of fluid at the specified temperatures still represents a problem in this cycle. Mass transfer of material from the hot area to cooler portions of the system, such as turbine blades, the condenser, or pump, could present a serious problem to efficient system operation. The vapor quality also remains a significant problem.

All shielding problems associated with the RTG also apply to the Rankine system.

SECTION 7

PROPULSION AND POWER GENERATION

7.1 TRACTION DRIVE MECHANISMS

The rover traction drive mechanisms (TDMs) require some further research. In addition, research in the area of lubricants and hermetic sealing of the TDMs is required. Of particular concern is the hermetic seal diaphragm or bellows which must transmit high tangential torques while being cycled at high frequency and amplitude in the transverse direction. Experimental verification of known materials for this application will be required.

7.2 RADIATION-COOLED THROTTLEABLE ENGINE DEVELOPMENT

All MOBEV lunar flying vehicles can utilize throttleable rocket engines in the 80- to 475-lb maximum thrust class, throttleable over an eight to one range. Such engines can be employed, either in a buried installation in the center of the vehicle or mounted outboard of the vehicle with radiation shielding between the rocket engine and the vehicle. Past and current rocket contracts are developing nonthrottleable rocket engines for buried installations, and throttleable engines which have not been demonstrated on a buried or partially shielded installation. Thermal analyses based on test data with both unshielded and completely shielded engines indicate that engine thermal requirements can be met. However, more sophisticated thermal analyses and a test program are highly desirable on appropriate sizes of throttleable engines. These should be run in vacuum in completely enclosed clusters and in partially enclosed installations where only one side is free to radiate to space. These test data can then be used in future lunar vehicle designs and to establish higher confidence levels in specification requirements for future engine procurements.

7.3 ROCKET EXHAUST PLUME EFFECTS

Very little reliable data are currently available on the shape and interactions of the exhaust plumes of single or multiple engines and on possible effects of the exhaust plumes on surrounding media.

Tests should be conducted in earth orbit to investigate the temperature and degradation effects of a rocket exhaust plume on adjacent structure and thermal coatings. Similar tests should evaluate possible effects on the transmission of electromagnetic radiation through the plumes.

7.4 PHOTOGRAPHY THROUGH ROCKET EXHAUST PLUMES

Lunar exploration studies have indicated that one of the most valuable applications for a lunar flying vehicle is to obtain geologic reconnaissance photographs of the lunar surface while flying over lurain impassible to surface travel, or while on the way to remote sites for surface exploration. The equipment techniques and geologic applications have been well developed and proven by earth-flight experience. However, since the lunar vehicle must be rocket supported during flight, the rockets must be shut down to take photographs, or the photographs must be taken at a flat angle to avoid the rocket exhaust, or the photographs must be taken through the exhaust plume. To determine whether photography through an exhaust plume is feasible, photographs have been taken through the plume of a 100-lb rocket using LM propellants firing in an altitude chamber. The camera, film, and processing techniques were of moderate resolution, and no degradation was observed. These results were encouraging, and it is recommended that additional tests be undertaken, either in an altitude test chamber or in an earth orbital experiment, using the highest resolution cameras, film, and processing techniques currently available. An orbital test will much more closely simulate photography of the lunar surface, but will require either in-orbit processing and examination of the film or recovery of the film from orbit. The latter approach is recommended as a "piggyback" experiment on other satellite programs.